Fibres — Threads of Intelligence — Enable A New Generation of Wearable Systems

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Abstract

Fabrics represent a unique platform for seamlessly integrating electronics into everyday experiences. The advancements in functionalizing fabrics at both the single fibre level and within constructed fabrics have fundamentally altered their utility. The revolution in materials, structures, and functionality at the fibre level enables intimate and imperceptible integration, rapidly transforming fibres and fabrics into next-generation wearable devices and systems. In this review, we explore recent scientific and technological breakthroughs in smart fibre-enabled fabrics. We examine common challenges and bottlenecks in fibre materials, physics, chemistry, fabrication strategies, and applications that shape the future of fabric electronics. We propose a closed-loop smart fibre-enabled fabric ecosystem encompassing proactive sensing, interactive communication, data storage and processing, real-time feedback, and energy storage and harvesting, intended to tackle significant challenges in wearable technology. Finally, we envision computing fabrics as sophisticated wearable platforms with system-level attributes for data management, machine learning, artificial intelligence, and closed-loop intelligent networks.

1. Introduction

Fibres are the fundamental building blocks of all textiles, spanning from natural or synthetic fibres in everyday clothing to high-performance fibres in advanced composites for aerospace and military applications.[1-3] They also include pharmaceutical- or biologics-loaded fibres that facilitate advanced medical therapies, and optical fibres of waveguides that form the foundation of data transmission for modern telecommunications.[4, 5] The versatility and usefulness of fibres are due to their unique properties. They are highly flexible and bendable due to their very high length to diameter ratio, and even stretchable, while maintaining mechanical strength. They are also highly permeable and lightweight, yet shock and shear resistant.[6, 7] Additionally, they can be biocompatible, implantable, or even biodegradable.[8] These evolving physical and chemical properties as well as their functional applications epitomize fibres' rapid development throughout the entire history of human progress (Fig. 1).

Natural fibres are derived from biological sources such as plants and animals, with wool and dyed flax fibres being among the earliest natural fibres used by humans dating back to 36,000 BP.[9, 10] Many natural fibres such as cotton, hemp, and silk can be spun into filaments and yarns that are widely used to produce fabrics and garments.[11] Owing to the biological nature of natural fibres, they are highly biocompatible, renewable, and sustainable. The other type, synthetic fibres, are made of man-made polymers such as nylon, polyester, acrylic, and polyolefin.[12, 13] The study in synthetic fibres began in the early 1800s, and today they have account for approximately half of fibre consumption worldwidely.[14] Compared to natural fibres, synthetic fibres show improved performance in water-resistivity, durability, and lifespan. Carbon fibre, often referred to as "Black Gold", are a fascinating example known for their extremely high strength and stiffness used in automobile, extreme sports, aerospace, and military.[15, 16] Reducing the diameters of fibres made of these natural and synthetic materials forms micro- and nanofibers, which possess high specific surface area, interconnected nano-porosity, and tunable bioactivity. As a result, micro- and nano-fibres are the ideal platforms for drug delivery systems, tissue scaffolds, medications, and protective clothing.[17, 18] Particularly, the expanded global market raises an increasing demand for nano-fibres, which is expected for reaching up to 3350 million USD by 2030. While natural and synthetic fibres have been used

for centuries in many aspects, the desire for revolutionized technology has led to the development of smart fibres and fabrics with unprecedented capabilities. Driven by the needs for high bandwidth, low delay and stable long-distance communication, optical fibres made of silica have emerged as a transformative technology for connecting all the world together.[19]Around 500 million kilometers of optical fibres are produced per year.[20] Optical fibres have made a profound impact on the modern society. However, conventional optical fibres are solely used as waveguide for optical communication. The idea of using a photonic bandgap to trap light has led to the emergence of photonic bandgap fibres.[21] Since their first demonstration in 1999, hollow-core photonic bandgap fibres have drew considerable attention from research community and are opening new avenues for ultrahigh nonlinear optics, novel lasers and amplifiers.[22, 23] Another appealing type of photonic bandgap fibres relies on the construction of two alternative dielectric nanoscale layers with a high-refractive-index contrast.[24] Thanks to the intrinsic low Young's modulus of the fibre polymer, such photonic bandgap fibres are highly flexible and bendable, making them particularly useful for the production of colored fabrics for smart sensing, security, and fashion.[25]

While ubiquitous in everyday life, these fibres have not much ascended in terms of capability and functionality compared to the examples of rapid-developing fields such as semiconductor chip technology. This is primarily due to the fact that these fibres are made of single materials and possess simple architectures. Hence, started from early 2000s, the concept of integrating technologically significant materials such as dielectrics, semiconductors, and conductors which form the basis of the modern electronics industry into fibres arose.[26-28] The study of sophisticated in-fibre structures, and intimate interfaces between multiple materials has enabled unprecedented electronic and optoelectronic fibres.[29-31] Simultaneously, multiple devices with disparate functions can be constructed within a single strand of fibre, delivering higher level of integration of functions that might be unachievable at conventional planar-type devices.[32, 33] In addition, the feature size of each single material in the fibre spans a range from millimetres to nanometres, which leads to some peculiar fibre devices with performance on par with their counterparts.[34]

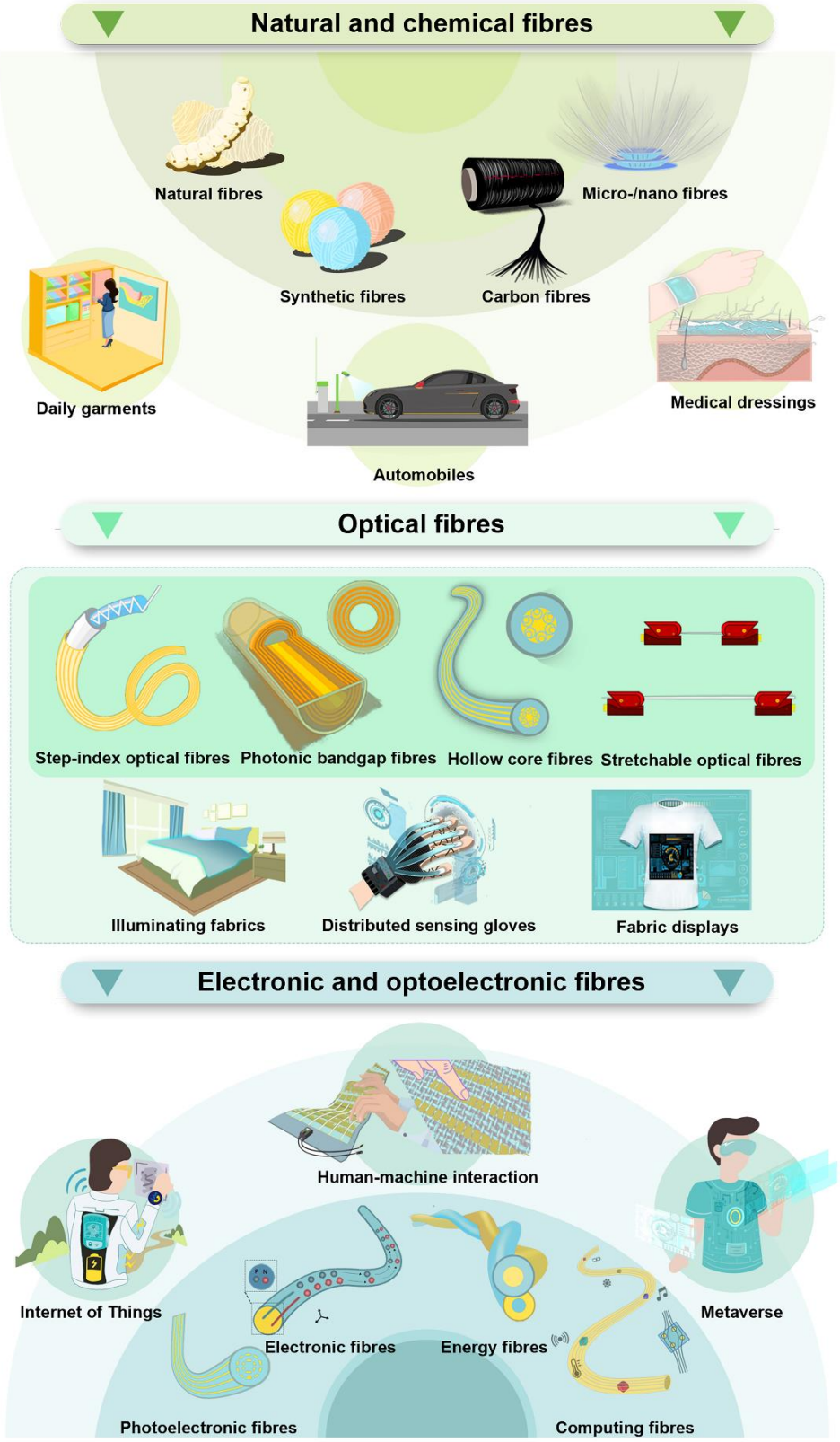

Fig 1. The ongoing evolution of fibres, including advancements in materials, chemistry, functions, and structures, has established a robust foundation for an array of promising applications.

Despite their multifunctionality, the new generation fibres still retain the desired features as the traditional ones, such as high flexibility, large aspect ratio, mechanical robustness,

permeability, and machine washability, which allow the production of smart fabrics using conventional large-scale manufacturing methods such as weaving and knitting in textile industry. This leads to the rapid evolution of functions and utilities of fabrics. Therefore, fabrics are evolving to become smarter and more advanced, surpassing their fundamental characteristics of pure physical protection and aesthetic purpose, and transforming into smart devices and systems.[35, 36]

Tremendous research momentums from both the academia and the industry have promoted breakthroughs fundamentally and technologically in fibre materials, structures, architectures, and fabrication strategies, which have enabled a new generation of smart fabrics capable of delivering a wide spectrum of functions and real-world applications. Consequently, this progress has spurred the development of wearable systems that leverage the unique form factor, structure, and functionality of fibres and fabrics. Even though there are some reviews on smart fabrics, they either focus on specific fibre materials or a certain type of fabrication methods or a few of particular applications.[5, 32, 37-42] This review offers a comprehensive and critical analysis of smart fibre-enabled fabrics, systematically examining recent fundamental and technological advancements in active materials, physical and chemical mechanisms, fabrication strategies, integration techniques, and novel functions (Fig. 2 and Table S1). We propose a closed-loop smart fibre-enabled fabric ecosystem encompassing proactive sensing, interactive communication, data storage and processing, real-time feedback, and energy harvesting and storage, enabling unique solutions to address challenges in wearable technology. Additionally, we provide insights into the key challenges and future opportunities faced by fibre-enabled fabrics, offering enabling strategies for much-needed fabric technologies in real-world applications and triggering the development of new research directions. Finally, we present our vision for future scientific and technological developments towards realizing computing fabrics, expected to be at the next frontier in data management, machine learning, artificial intelligence, and closed-loop smart networks. We conclude with our thoughts on how smart fabrics will evolve from mere goods into sophisticated computing platforms, offering a new generation of wearable systems.

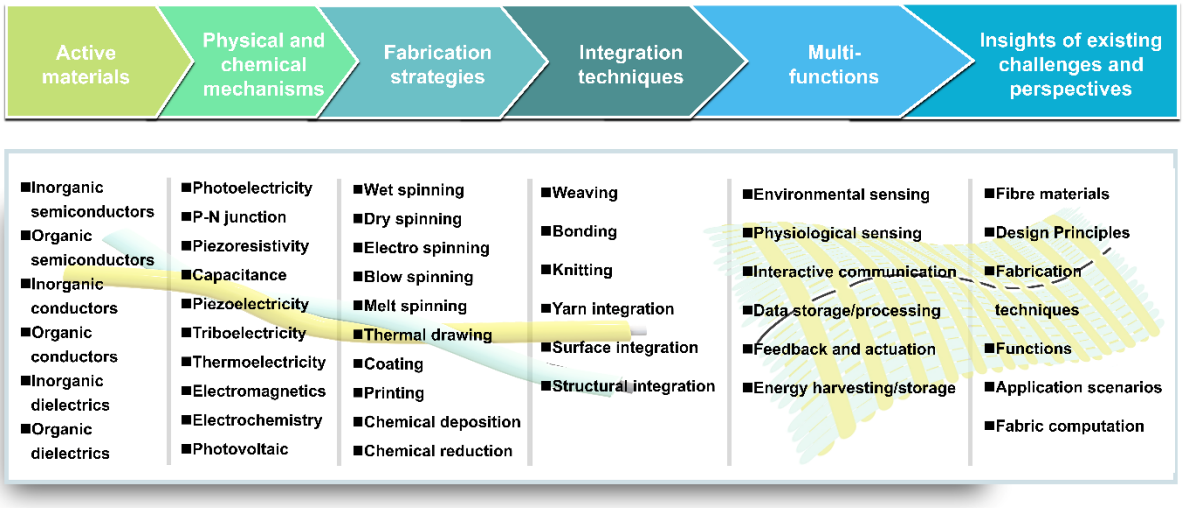

Fig. 2. The flow chart of this review.

2. Active Materials of Smart Fibres

The integration of semiconductors, conductors, and dielectric materials into fibres is rapidly transforming them into advanced devices and smart systems with a wealth of functionalities.[43-45] This section categorizes and summarizes the key active fibre materials that directly determine the functionalities and applications of the smart fabrics and focuses on the examination and discussion of the chemistry, physics, structure, and functions of these active fibre materials.

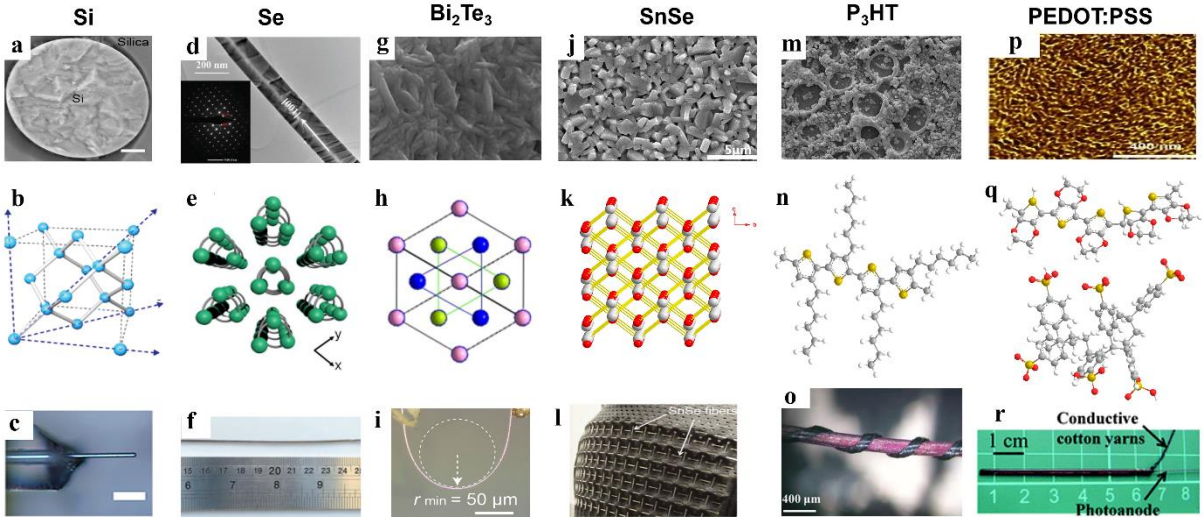

Fig 3. Inorganic and organic fibre semiconductors: (a) Scanning electron microscope (SEM) image of a core made of polycrystalline silicon. Reproduced from ref. 51 with permission from American Chemical Society, copyright 2016. (b) Schematic demonstration of the crystal structure of Si, which has a cubic structure. Reproduced from ref. 52 with permission from Wiley-VCH, copyright 2020. (c) Optical image illustrating the etched end of a Si fibre. Scale bar: 50 μm. Reproduced from ref. 51 with permission from American Chemical Society,

copyright 2016. (d) Transmission electron microscope (TEM) image of Se nanowires, accompanied by a selected area electron diffraction (SAED) pattern in the inset. Scale bar: 200 nm. Reproduced from ref. 34 with permission from Wiley-VCH, copyright 2017. (e) Atomic structure of Se. Reproduced from ref. 54 with permission from American Chemical Society, copyright 2017. (f) Photograph depicting a 15 cm Se-based fibre. Reproduced from ref. 34 with permission from Wiley-VCH, copyright 2017. (g) SEM image of Bi_2Te_3. Scale bar: 0.25 μm. Reproduced from ref. 71 with permission from Elsevier Ltd, copyright 2012. (h) Bi_2Te_3 forms a triangle lattice, viewing along the z-direction. Reproduced from ref. 72 with permission from Elsevier Ltd, copyright 2012. (i) Optical microscopy image demonstrating a bent Bi_2Te_3 fibre core. Reproduced from ref. 73 with permission from Wiley-VCH, copyright 2022. (j) SEM image of SnSe. Scale bar: 5 μm. Reproduced from ref. 75 with permission from Elsevier Ltd, copyright 2020. (k) Schematic illustration displaying the unit cell of SnSe crystal structure, viewing along an-axis. Reproduced from ref. 76 with permission from Elsevier Ltd, copyright 2018. (l) A large-area fabric woven from flexible SnSe fibres. Reproduced from ref. 77 with permission from Wiley-VCH, copyright 2020. (m) SEM image of P3HT. Scale bar: 10 μm. Reproduced from ref. 87 with permission from Wiley-VCH, copyright 2020. (n) Chemical structures of P3HT. Reproduced from ref. 88 with permission from American Chemical Society, copyright 2009. (o) Photograph of a fibre device based on P3HT. Reproduced from ref. 89 with permission from Wiley-VCH, copyright 2020. (p) Atomic force microscope (AFM) phase image of PEDOT:PSS. Scale bar: 400 nm. Reproduced from ref. 88 with permission from Wiley-VCH, copyright 2011. (q) Chemical structures of PEDOT and PSS. Reproduced from ref.90 with permission from American Chemical Society, copyright 2009. (r) Photograph of fibre solar cell derived from PEDOT:PSS. Reproduced from ref. 94 with permission from Royal Society of Chemistry, copyright 2012.

2.1. Inorganic and Organic Semiconductors

2.1.1 Inorganic Semiconductors

Inorganic semiconductors are derived from materials of group III, IV, and V elements and metal oxides or chalcogenides.[46] These materials display remarkable properties including unique optical, electrical, photoconductive, and piezoelectric characteristics.[47] Their thermal and crystallization properties, viscosity, energy bandgap and other physical or chemical properties can be tuned by modifying their composition. In addition, the incorporation of nanostructured semiconductors with improved mechanical, electrical, and optical performance into fibres enables unusual functions with great potential in smart photoelectric sensors, thermoelectric devices, and smart transistors.[48-50]

2.1.1.1 Inorganic Semiconductors for Photoelectric Fibres

Photoelectric fibres are becoming the central part of modern photodetection systems that are

applied in commercial and scientific community. Inorganic semiconductors are crucial in creating high-performance photoelectric fibres. These semiconductors enable the transformation from light to electronic signals. Due to its stable cubic single crystal structure and transparency at telecom wavelengths, silicon (Si) serves as the most attractive inorganic semiconductor, that can be incorporated into the core of optical fibres for detecting light at visible and near-infrared wavelength (Fig. 3a and 3b).[51, 52] High-pressure chemical vapor deposition and molten core drawing techniques have been adopted to manufacture Si-based photoelectrical fibres. Such fibres demonstrate the ability of overcoming the limited absorption range and weak absorbance of Si.[53] However, the intrinsic poor performances of amorphous or polycrystalline Si precludes fibre's potential applications. The fabrication of single-crystal Si along the entirety of the fibre length attracts lots of interest. Laser-based thermal annealing is a promising technique for the fabrication of long, monocrystalline Si optical fibres. This method facilitates the generation of a higher temperature gradient (104 K cm^{-1}), enabling rapid melting and subsequent recrystallization of the Si core material. As a result, the optical loss of a Si fibre can be as low as 0.47 dB cm^{-1} at the standard telecommunication wavelength, enabling a superior photosensitivity on par with bulk Si (Fig. 3c).[51]

In addition, chalcogen or chalcogenide inorganic semiconductors are also ideal for optoelectronic applications within the polymer fibre platform. Selenium (Se) exhibits an anisotropic crystal structure, with the trigonal lattice being highly esteemed for its exceptional electron conductivity (Fig. 3d and 3e).[34, 54] Moreover, the intrinsic chirality, remarkable reactivity, low melting point (220 °C), and exceptional optical, electrical (8×10^4 S cm^{-1}) properties, as well as relative high intrinsic carrier concentration (9.35×10^{16} cm^{-3}) make Se a highly attractive candidate for the development of advanced optoelectronic fibres.[55, 56] However, it remains a challenge to fabricate single-crystal Se within the optoelectronic fibre due to the difficulty of control over the crystal nucleation and growth of in-fibre Se. Additionally, the precise interfacing electrodes with semiconductor domains within the fibre proves to be difficult. These prevailing challenges have been addressed *via* an innovative combination of the thermal drawing technique with a sonochemical synthesis. The as-drawn amorphous Se in the fibre transforms into an array of single-crystal nanowires that directly and intimately contact the built-in electrodes. The monocrystalline feature of Se is attributed to the anisotropic interfacial

energy of crystal planes of Se that processed in a solution. Such a fibre demonstrates an outstanding optical response (0.06 A W^{-1} at 200 nW) and response speed (5.5 μs) (Fig. 3f).[34] Furthermore, double-element semiconductors have been become one of the most intrigue candidates for the next-generation photoelectrical fibres. A typical example is Selenium-Tellurium (Se-Te) chalcogenide compound, which displays a highly anisotropic crystal structure composed of helical chains of covalently bound atoms. [57, 58] By varying the ratio of Se and Te elements, the structure can be effectively manipulated to obtain better electrical conductivity.[59] The study of phosphate glass clad fibres with $Se_{0.5}Te_{0.8}$ crystalline cores shows that the electrical conductivity can reach up to 2.0×10^{-7} Ω^{-1} cm^{-1}.[57] Furthermore, introducing a third element to the semiconductors can lower processing temperatures and/or alter the electronic band structure, leading to superb photoelectric properties.[60] For example, amorphous $As_{40}Se_{50}Te_{10}Sn_5$ and $As_{40}Se_{49}Te_{11}Sn_5$, can be integrated into the fibre and interface with metallic electrodes to produce fibre devices with excellent optoelectrical performance.

2.1.1.2 Inorganic Semiconductors for Thermoelectric Fibres

Since the Seebeck effect was discovered in 1821, a wealth of inorganic thermoelectric semiconductors such as SiGe,[61] CoSb3,[62] SnTe,[63] PbSe,[64] Cu_2S,[65] CeTe,[66] MgAgSb,[67] have been developed for various energy saving and energy management applications.[68-70] Before turning to the discussion of inorganic semiconductors employed in thermoelectric fibres, it's worthwhile to understand the "thermoelectric figure of merit", $ZT = \alpha^2 \sigma T/\kappa$, where α is the Seebeck coefficient, σ is the electrical conductivity, T is the absolute temperature, and κ is the thermal conductivity. To maximize ZT, an ideal material should have a high σ, high α, and low κ. Bi_2Te_3 is a widely recognized high-quality thermoelectric material according to this design principle (Fig. 3g).[71] With a triangular crystal structure, the narrow-gap semiconductor has an energy gap of approximately 0.16 eV, as depicted in Fig. 3h.[72] Furthermore, Bi_2Te_3 exhibits a ZT value of approximately 1, which represents the upper limit for room-temperature applications among the best inorganic thermoelectric semiconductors currently available. However, conventional Bi_2Te_3 fibres exhibit limited flexibility and a weak ZT value compared to their bulky counterparts. As showed in Fig. 3i, micro-nano polycrystalline Bi_2Te_3

thermoelectric fibres are fabricated by a two-step thermally drawing bulky Bi_2Te_3 encapsulated in a borosilicate-fibre template. Interestingly, the stress during thermal drawing induced a unique orientation in the Bi_2Te_3 nanocrystals, leading to a notable increase in electrical conductivity and decrease in thermal conductivity. This results in a significant improvement of thermoelectric performance with a 40% higher ZT (~1.4 at 300 K) compared with its bulky counterpart.[73] The advancements in thermoelectric fabric utilizing Bi_2Te_3 are notably impressive, showing excellent flexibility, bendability, and wearability. Zheng et al. engineered machine-weavable Bi_2Te_3-based thermoelectric strings, creating a thermoelectric textile with superior properties, including high stretchability, flexibility, washability, and an impressive 0.58 W m^{-2} power density at a 25 K temperature difference.[74]

SnSe is an uncomplicated and remarkably stable compound that is composed of readily available elements. The layered orthorhombic crystal structure endows the SnSe with one of the lowest lattice thermal conductivities (<0.4 W m^{-1} K^{-1} at 923 K) (Fig. 3j and 3k).[75, 76] Similar to Bi_2Te_3, the formation of single crystals in SnSe, particularly in the context of shaping them into fibres, is a crucial factor for their implementation within thermoelectric fibre technologies. In addition, addressing challenges associated with the scalability, stability, and optimization of thermoelectric properties in SnSe fibres are crucial obstacles that must be overcome. Driven by the dilemma, a thermoelectric fibre derived from single crystal SnSe was fabricated using a novel method that combined thermal drawing with subsequent laser-induced directional crystallization. The single-crystal SnSe fibre with a rock-salt phase exhibited a remarkably high ZT value of 1.94 at 862 K, surpassing that of polycrystalline SnSe fibre and comparable to single-crystal SnSe. (Fig. 3l).[77]

While researchers have long aimed to maximize ZT values, the inherent conflict within thermoelectric materials still has posed challenges in the pursuit of the highest ZT values. Specifically, high electrical conductivity often results in a diminished Seebeck coefficient and high thermal conductivity. Therefore, optimizing material properties requires adjustments in crystal structure, nano-morphology, or size to achieve the ideal balance and maximize ZT values. Furthermore, because of the high cost, toxicity, and limited availability of the inorganic thermoelectric semiconductors used, they fall short of meeting the requirements for large-scale commercialization and electricity generation. Consequently, scientists are redirecting their

focus towards advancing inorganic/polymer thermoelectric composites. CuTe, characterized by 1D nanostructure, is a promising semiconductor for thermoelectric fabrics. The synergistic use of CuTe as the building block and PVDF as the flexible substrate has proven to be an effective strategy for fabricating thermoelectric fabrics. The three-dimensional (3D) interwoven nanowires within PVDF polymers enhanced both of electrical conductivity and surface coverage, resulting a thermoelectric fabric with impressive Seebeck coefficient of 9.6 μV K^{-1}, electric conductivity of 2490 S/cm, and comparable power factor of 23 μW $(mK^2)^{-1}$ to its bulk counterpart.[78]

2.1.2 Organic Semiconductors

Organic semiconductors consist mainly of conjugated polymers that possess a backbone comprising alternating double and single bonds, along with aromatic moieties that enable the delocalization of π-electrons and supramolecular π–π interaction.[79-81] This structural characteristic provides these materials with a remarkable combination of attributes, including tunable structure, solution processability, flexibility, mechanical properties, and semiconducting behavior.[82] As a result, they hold great promise for integration into soft fibre electronic devices and serve as potential candidates for the advancement of cutting-edge fabrics.

2.1.2.1 Organic Semiconductors for Photo-detecting and Photovoltaic Fibres

Organic semiconductors display superior light-absorbing properties compared to their inorganic counterparts due to some intriguing factors. Firstly, organic semiconductors have a wider range of tunable electronic properties, allowing for precise control over their absorption spectra. Additionally, organic molecules' strong π-conjugation leads to efficient absorption of light across a broad range of wavelengths. As a result, organic semiconductors prove highly suitable for creating optoelectronic fibrous devices, including photodetector fibres and photovoltaic fibres.[83-86] Poly(3-hexylthiophene) (P3HT) has emerged as a highly promising semi-conducting polymer in recent years, owing to its excllent processability, environmental stability, and the ease with which its electronic and optical properties can be finely tuned (Fig. 3m and 3n).[87, 88] However, ensuring the efficient processing of P3HT into fibre while preserving its structural integrity, alignment, and conductivity poses a significant challenge. The

development of specialized techniques tailored for the formation of P3HT fibres may be a promising avenue for addressing this challenge. For example, a novel type of flexible UV-visible fibrous photodetector based on P3HT was fabricated using a vacuumed dip-coating method. This resultant device exhibited a 700% improvement in responsivity under UV light illumination, and a 1700% higher UV-visible rejection ratio (R350/R400), when compared to conventional counterparts. Furthermore, this smart fibre demonstrated remarkable stability of photoelectric detection even under bending conditions (Fig. 3o).[89] Despite the remarkable progress has been made in recent years, optoelectronic devices continue to struggle with achieving optimal sensitivity, often lagging behind their conventional counterparts. The implementation of Poly(3,4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT:PSS) has emerged as a promising solution to address this limitation. PEDOT:PSS is a composite material composed of positively charged conjugated PEDOT chains and negatively charged PSS chains, which are bound together by Coulombic interactions. (Fig. 3p and 3q).[88, 90] PEDOT:PSS offers remarkable optical transparency within the visible range, tunable electrical conductivity, high flexibility, and stretchability, making it a highly desirable material for the fabrication of a wide range of photo-detecting devices. However, the successful incorporation of PEDOT:PSS into the fibre structure needs the simultaneous optimization of its electrical conductivity, photosensitivity, light absorption efficiency, and charge carrier generation. Modification of the molecular structure of PEDOT:PSS within fibres is a well adopted strategy in addressing this fundamental issue. The selective connection or removal of atoms and groups within the PEDOT:PSS's molecular chain is the most common. For example, a novel fibrous photodetector based on PEDOT:PSS was developed, exhibiting an impressive sensitivity, responsivity, large external quantum efficiency, and rapid response speed at 3 V bias. Moreover, the concentrated H_2SO_4 post-treatment partially eliminated the insulating PSS component, resulting in improved conductivity and enhanced charge transportability. [91-93] However, on the whole, organic fibre photodetectors typically exhibit lower performance compared to their inorganic counterparts. This disparity can be attributed to the susceptibility of most organic semiconductor materials to deterioration when exposed to factors like water vapor, oxygen, and various contaminants. Furthermore, the purity of organic materials is notably inferior to that of inorganic materials.

Organic semiconductors also have significant potential for photoconversion due to their versatile synthesis options, suitability for low-temperature processing, and the potential to create cost-effective, lightweight, and flexible solar cells. The organic semiconductors can eventually replace inorganic counterparts in photovoltaic cells. However, the central challenge in the development of photovoltaic fibres utilizing organic semiconductors is optimal energy conversion efficiency within the constrained architecture of the fibre. The key is to balance light absorption, charge carrier mobility, and stability within the fibre. A classic example of this is use of PEDOT:PSS to design fibre solar cell electrodes. As depicted in Fig. 3r, a counter electrode fibre, that was directly infused a readily available cotton wire with PEDOT:PSS, enabled fibrous solar cells that showed an impressive power conversion efficiency of 4.8%.[94] Additionally, small molecule semiconductors have attracted much attention because of distinct electron affinity and carrier mobility. However, most research advances are still limited to the laboratory scale: small areas, small power output, low yields, and short lifetime.

2.1.2.2 Organic Semiconductors for Thermoelectrical Fibres

Due to their lower cost, relative abundance, and inherently low thermal conductivity, there has been a remarkable surge of interest in organic thermoelectric semiconductors over the past two decades. Meanwhile, there have been significant advancements in the development of personal, portable, and flexible thermoelectric modules with a fibrous structure.[95-99] However, organic semiconductors suffer from low charge carrier mobilities due to weak intermolecular interactions, which lower their efficiency in converting heat to electricity. This is the core challenges in making organic semiconductors viable for thermoelectric fibres. The incorporation of conductive nanomaterials into polymer matrix of organic semiconductors has been proved to be one of the most effective approaches for addressing this issue. An exemplary instance is an integrated p-n segmented thermoelectric fibre, in which the p-type units of carbon nanotubes (CNTs) were hybridized with PEDOT:PSS, while the n-type units were formed through oleamine doping. This fibrous thermoelectric device exhibited stretchability of approximately 80% strain, as well as high power density of 70 $mW\,m^{-2}$ at a temperature differential of 44 K.[97] Additionally, the combination of PEDOT with Te nanowires (NWs) demonstrated its effectiveness in improving both the Seebeck coefficient and electrical

conductivity.[100] Nevertheless, PEDOT:PSS tends to form delicate films on fibrous substrates, rendering them susceptible to the various stresses and strains that fabrics commonly endure. The use of P3HT as a p-type thermoelectric material for fibre-shaped devices may be a promising alternative.[101] Furthermore, there is a growing interest in enhancing the conductivity of organic semiconductors by incorporating organic molecules through doping method. To maximize the thermoelectric performance, it is imperative to gain a comprehensive understanding of the solid-state microstructure of these binary mixtures, including conformational order and orientation. Research in this field has made significant progress. Moreover, the processing techniques, such as the utilization of solvents and post-deposition procedures like thermal or solvent annealing, significantly influence the polymer structure, which subsequently impacts fibres' thermoelectric properties. This aspect needs to be further explored to gain more insights. At the end of the discussion, we compare the thermoelectric properties of different semiconductor-based thermoelectric fibres and fabrics (Table S2). We hope that this comparison can serve as a reference for researchers involved in the advancement of semiconductor thermoelectric materials.

2.1.2.3 Organic Semiconductors for Transistor Fibres

Real-time signal processing using smart fibres and fabrics has gained widespread attention in both the scientific and engineering fields. A critical aspect of this endeavor is the seamless integration of electronic components necessary for logical calculations into fibres and fabrics.[102, 103] In this regard, the development of fibre transistors with logical response has emerged as a critical area of research. Organic semiconductors offer several advantages, primarily including their ability to be processed at low temperatures and their compatibility with fibrous substrates. Furthermore, these semiconductors are adaptable to solution-based techniques, including spin coating and screen printing, which facilitates large-scale production.[104, 105] Additionally, the option of chemically modifying their molecular structures provides an effective way of tailoring the performance of fibre transistors.[106] Numerous organic semiconductors have been employed in the production of transistors. Despite the inherent advantages, the preservation of organic semiconductors' structural integrity within a fibrous configuration, while the realization of reliable electrical conductivity and stability pose a

significant challenge to obtaining excellent transistor performance.

Fibre transistors rely on organic semiconductors as their active materials, which effectively govern the flow of electrical current. Polymer semiconductors such as P3HT and PEDOT: PSS have gained widespread recognition as active materials.[107-109] A prime example is the development of a twist-type fibrous organic transistor by using PEDOT:PSS as the active layer. This transistor demonstrated excellent electrochemical stability, with a normalized drain current change of less than 1% after 2,500 cycles of repeated potential pulses.[110] In a recent example, the source and drain electrode micro fibres were twisted and coated with a P3HT layer. Operating at less than 1 V, this fibre transistor delivered substantial current densities.[107] Interestingly, poly-pyrrole is another organic semiconductor that can be synthesized in fibre shaped transistors. Notably, small molecule organic semiconductors are also alternative for fibre transistors.[111] In general, organic semiconductors used in fibre transistors all need to follow the same principle: solution processability. This is the key to fabricating fibre transistors with high charge-carrier mobility, low threshold voltage, high on/off ratio. Currently, approaches aimed at enhancing the solubility of organic semiconductors can be categorized into two primary methods. One approach involves employing soluble precursors of the actual insoluble materials. The other method is introducing solubilizing substituents into their molecular structure. Notably, the latter approach needs to be ensured that the solubilizing side chains does not disrupt an ordered solid-state structure with optimal intermolecular interaction, which plays a pivotal role in the charge-carrier transport of fibre transistors.

2.2. Inorganic and Organic Conductors

The selection of conductive materials is crucial for the development of smart fibres with high conductivity, flexibility, stretchability, and mechanical stability.[112] This section focuses on the most used conductive materials, providing insight into their versatility, improved performance, and potential for novel applications of smart fibres.

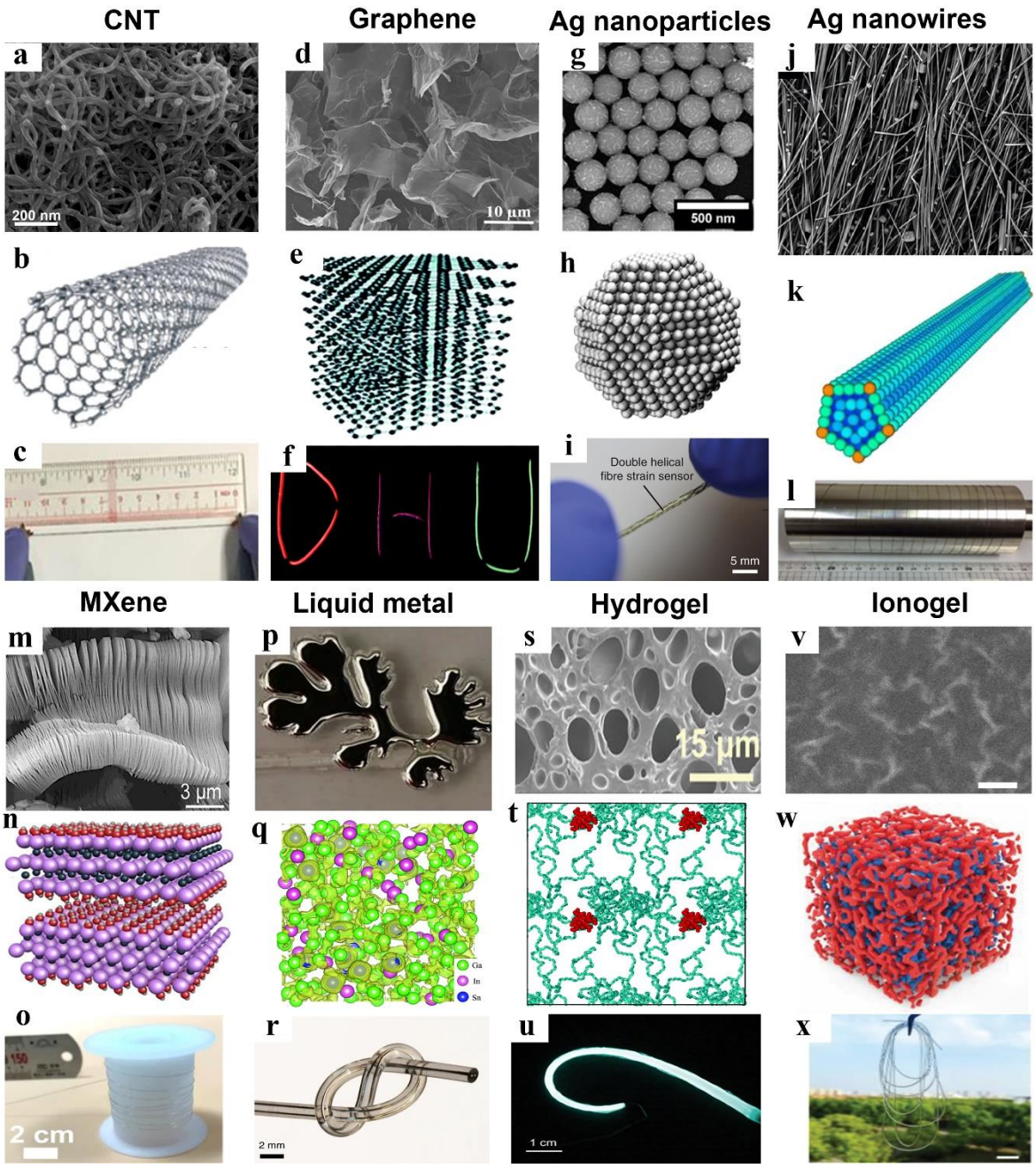

Fig. 4 Inorganic and organic fibre conductors: (a) SEM image of CNTs. Scale bar: 200 nm. Reproduced from ref. 120 with permission from American Chemical Society, copyright 2009. (b) Schematic illustration of CNT structure. Reproduced from ref. 121 with permission from Wiley-VCH, copyright 2017. (c) Photograph of a stretchable CNT-based fibre. Reproduced from ref. 122 with permission from American Chemical Society, copyright 2016. (d) SEM image of graphene nanosheets. Scale bar: 10 μm. Reproduced from ref. 123 with permission from Wiley-VCH, copyright 2018. (e) Schematic illustration of 2D graphene structure. Reproduced from ref. 124 with permission from Royal Society of Chemistry, copyright 2017. (f) Photographs of graphene-based stretchable electrothermal chromatic fibres. Reproduced from ref. 125 with permission from Royal Society of Chemistry, copyright 2017. (g) SEM image of silica particles covered with Ag NPs. Scale bar: 500 nm. Reproduced from ref. 136 with permission from Royal Society of Chemistry, copyright 2012. (h) A silver nanoparticle with an average diameter of 3.9 nm. (h) is reproduced from ref. 138 with permission from AIP

Publishing, copyright 2020. (i) Photographs of the Ag NPs-based fibre that is used as strain sensor. Reproduced from ref. 137 with permission from Springer Nature, copyright 2021. (j) SEM image of Ag NWs. Scale bar: 5 μm. Reproduced from ref. 139 with permission from American Chemical Society, copyright 2011. (k) Equilibrium atomic positions of pentagonal Ag nanowire. Reproduced from ref. 140 with permission from American Chemical Society, copyright 2015. (l) Photograph of a AgNWs-based fibre. Reproduced from ref. 141 with permission from American Chemical Society, copyright 2017. (m) SEM micrograph of Ti_3AlC_2 after HF treatment. Scale bar: 3 μm. Reproduced from ref. 146 with permission from American Chemical Society, copyright 2012. (n) Schematic illustration of the Ti_3C_2 MXenes structure. Reproduced from ref. 147 with permission from Elsevier Ltd, copyright 2019. (o) Photograph of several meters long Mxene-based fibre. Reproduced from ref. 148 with permission from Springer Nature, copyright 2022. (p) Photograph of liquid metal. Scale bar: 1 mm. Reproduced from ref. 152 with permission from PNAS, copyright 2014. (q) Atomic distributions inside eutectic GaInSn determined via density functional theory (DFT) calculations. (q) reproduced from ref. 155 with permission from the AIP Publishing LLC, copyright 2014. (r) Photographs of soft transmission fibres filled with liquid metal. (r) Reproduced from ref. 154 with permission from Springer Nature, copyright 2014. (s) SEM image (Scale bar: 15 μm.) and schematic illustration of hydrogel polymer structure. (s) Reproduced from ref. 167 with permission from Wiley-VCH, copyright 2022. (t) An atomistic hydrogel model simulation cell with PEG chains (blue) and diacrylate crosslink junctions (red) (t) Reproduced from ref. 168 with permission from Royal Society of Chemistry, copyright 2022. (u) Photograph of a bending hydrogel fibre under an alternating electric field. Reproduced from ref. 170 with permission from Wiley-VCH, copyright 2020. (v) SEM image of ionogel surface. Scale bar: 10 mm. Reproduced from ref. 172 with permission from Springer Nature, copyright 2022. (w) Schematic illustration of the polymer structure of ionogel. Reproduced from ref. 173 with permission from Wiley-VCH, copyright 2019. (x) Photograph of ionogel fibres. Reproduced from ref. 174 with permission from Wiley-VCH, copyright 2021.

2.2.1 Inorganic Conductors

2.2.1.1 Carbonaceous Conductors

Electrical conductors based on carbons have recently attracted a growing interest for the creation of smart fibres,[16, 113-116] due to their high surface area, remarkable electrical conductivity ($\approx 10^4$ S cm^{-1}), outstanding intrinsic carrier mobility (10^6 cm^2 V^{-1} S^{-1}), and superior mechanical properties .[117] It's important to note that the electrical conductivity quality of fibres is typically linked to the concentration of carbon materials within the fibre substrates. The creation of percolation networks is essential for function of these fibres. Research on smart fibres has primarily focused on establishing an empirical relationship between morphology, structure, composition, and their electrical properties.[118, 119] For example, carbon materials with

high aspect ratio and large surface area stand out, because they can be easily assembled into percolation networks with a low percolation threshold. From this viewpoint, carbon nanotubes (CNTs) have proven to be successful in satisfying the specified criteria. As shown in Fig 4a and 4b, CNTs exhibit tubular shape, high aspect ratio, ballistic electron transport, current carrying capacity that exceeds superconductors, and mechanical strength/stiffness.[120, 121] A flexible and conductive fibre was created by dip-coating elastic fibrous substrates with CNTs. The percolation networks of CNTs enabled it to achieve electrical conductivity (11.2 kΩ cm^{-1}) and high stretchability (300%), as depicted in Fig. 4c.[122]

Graphene has also gained considerable attention due to its remarkable morphological, chemical, mechanical, thermal, electrical, and electronic properties (Fig. 4d and 4e).[123, 124] To use graphene in fibre electronics, the first challenge is finding efficient techniques for mass-producing graphene. A potential solution is to synthesize graphene oxide (GO) sheets and then completely reduce them *via* thermal and chemical reduction methods. An exemplary instance of this is the successful incorporation of reduced graphene oxide (rGO) as a conducting element in the production of stretchable and multicolor electrothermal chromatic fibres (Fig. 4f). The multi-layered and electrothermally stable structure of rGO granted long-term mechanical and color-stabilizing properties to the conductive fibres.[125] rGO's carbon network, while useful, exhibits irreversible defects compared to graphene, resulting in limited applications. Additionally, a major concern with graphene-coated fibres is poor surface adhesion, making it difficult to preserve their integrity in practical use.

In addition to electrical and mechanical properties, other features, such as thermal conductivity is another important feature that adds merit to devices construction. A pure CNT fibre with ultra-high electrical conductivity (> 10^7 S m^{-1}) and large thermal conductivity (14 ± 5 mW m^{-1} K^{-2}) was successfully produced by solution spinning.[126] However, CNTs' high aspect ratio and strong Van der Waals forces frequently cause significant agglomeration during production, compromising precise controlling of fibre size and functional stability. Research on suitable solvents facilitating uniform CNT dispersion offers a promising avenue for future exploration.[127-129] In general, the creation of high-performance carbonaceous conductor fibres is hindered by the difficulty of arranging these materials into efficient and robust structures. To address this challenge, it is crucial to precisely control how carbon materials align and interact

within the fibre to create optimal interfaces.

2.2.1.2 Metallic Conductors

Replacing carbon nanomaterials with metals is a promising approach for creating smart fibres and fabrics. One intriguing example is the utilization of arrays of discrete, anisotropic planar coils made of aluminum and/or copper foils in the production of metamaterial fabrics.[130] Bulk metallic materials however face challenges in stretchable and deformable fibre electronics due to their rigidity and vulnerability to corrosion. Nanotechnology enables the transformation of bulky metallic materials into low-dimensional nanostructures, like zero-dimensional (0D) nanoparticles and one-dimensional (1D) nanowires. These metallic nanomaterials exhibit unique physical and chemical properties due to their small size, distinct from bulk materials.[131-135] An excellent example is silver (Ag) nanoparticles (NPS) (Fig. 4g).[136, 137] They have superior electrical, thermal and optical properties, and also displays a distinct ability of self-alignment property in response to mechanical strain or electrical fields. Based on these features, a smart fibre embedded with Ag nanoparticles was developed, as illustrated in Fig. 4h and 4i.[137, 138] This fibre displayed outstanding electrical conductivity and an impressive sensitivity level of 12. Consequently, it enabled the establishment of a wireless fibre sensing system for incessantly monitoring tensile strains during porcine leg movements. Notably, the size and shape of Ag NPs significantly impact their properties, which can alter the surface-to-volume ratio and surface energy. These attributes can be controlled through selecting various precursors, stabilizers, adjusting pH and temperature. Apart from Ag NPs, 1D Ag NWs are also recognized as an outstanding conductive material, which are employed in smart fibres due to their high aspect ratio, chemical inertness, and low percolation threshold (Fig. 4j).[139] The challenge of using Ag NWs is their poor dispersibility on hydrophobic polymer substrates. Surface modification of Ag NWs is often necessary to improve their compatibility with insulating matrices. By modifying the surface of Ag NWs with a polyethylene glycol derivative, the compatibility of polyurethane and Ag NWs was enhanced, enabling the nanowires to disperse uniformly in the elastomeric matrix. This created efficient percolation networks, resulting in a composite fibre with remarkable electrical conductivity, reaching 14205 S cm^{-1}. Furthermore, this conductivity remained stable even when stretched to a strain of 140% (Fig. 4k and 4l).[140, 141] However, Ag

NWs are known to suffer from gradual oxidation, which leads to a decline in their electrical conductivity. In addition, their limited biocompatibility presents a significant challenge for their application in the field of biomedicine.[142] Nonetheless, we envision that Ag NWs are the most promising option due to their best overall performance, scalability, low production costs, and compatibility with existing production lines.

Based on above discussion, the pursuit to integrate metal conductors, notably metal nanowires or nanoparticles, into functional fibres relies on addressing three pivotal issues: ensuring uniform dispersion within the fibrous substrate, and achieving a well-balanced combination of mechanical and electrical properties.

2.2.1.3 Inorganic Nonmetallic Conductors and Liquid Conductor

In recent years, a new class of two-dimensional (2D) metal carbides, named MXenes, has emerged as conductive materials, showing unique properties derived from transition-metal carbides, nitrides, and carbonitrides as building blocks.[143-145] They demonstrate distinct structural, electronic, and chemical properties, as depicted in Fig. 4m and 4n.[146, 147] However, structure defects like voids and wrinkles of MXene nanosheets, along with weak interlayer interactions are primary challenge of utilizing MXenes for fabricating functional fibres.[148] Enhancement of the interfacial interactions between MXene sheets by applying external force is an effective solution. A highly oriented, low-porosity MXene fibre was created through thermal drawing-induced stresses (Fig. 4o). Such fibre showed excellent tensile strength (585.5 MPa), remarkable toughness (66.7 MJ m^{-3}), and a high electrical conductivity (8802.4 ± 30.8 S cm^{-1}).[148] However, the preparation of MXene fibres typically requires stringent conditions, such as high-temperature treatment, strong acid or base etching, and the use of toxic chemicals. Further, the fibres are susceptible to oxidation in air.[149, 150]

Liquid metal is the general term for low-melting-temperature metals and alloys based on post-transition metals.[151] The unique characteristics of liquid metals, such as fluidity, flexibility, and alloyability, that are not found in other conductive material (Fig. 4p).[152] However, the high surface tension of liquid metals presents a challenge in maintaining the desired shape and properties when fabricating electrical fibres. Additionally, the susceptibility to oxidation or degradation further complicates the utilization of liquid metals for conductive fibre

development. For solving these problems, an ultra-stretchable conductive fibre was fabricated by injecting liquid metal (EGaIn) into hollow poly[styrene-(ethylene-co-butylene)-styrene (SEBS) fibres. This conductive fibre exhibited electrical conductivity comparable to traditional metallic wires (3×10^{-5} Ω cm^{-1}), while possessing the ability to be stretched up to 800% further while maintaining electrical conductivity. The fibre's tactile properties, based on its change in electrical resistance, made it suitable for serving as stretchable wires for earphones, battery chargers, and smart garments.[153] Notably, the liquid metal core might collapse under pressure or strain, limiting its ability to sense dynamic deformations. To solve this problem, researchers created microstructured elastomeric fibres with multiple liquid metal conductors.[154] As displayed in Fig. 4q and 4r, these fibres provided remarkable force resolution (0.2 N), spatial resolution (< 6 cm), and strain resolution (0.25%), paving the way for highly precise electronic fabrics for continuous pressure and stretch monitoring.[154, 155]

2.2.2 Organic Conductors

While inorganic conductive materials in functional fibres have made remarkable advancements, challenges remain. These include interface failures during stretching, limited transparency in the visible range of soft display fabrics, and relatively high fabrication costs.

Hydrogels and ionogels represent novel classes of functional organic conductors that have captured the attention of the flexible electronics community.[156, 157] These gel materials feature uniformly distributed solvated ions of ionic liquids and electrolyte salts within polymer matrices, which endow them with sufficient ionic conductivity, high transparency, high stretchability, and desirable biocompatibility.[158-161] The mechanical strength of hydrogel conductors can be efficiently tailored through polymer network structural design, such as the single network and double network design strategies,[162-164] or supramolecular design,[165, 166] to meet the physical toughness requirements of various wearable applications (Fig. 4s and 4t).[167, 168] A hydrogel made of polyvinyl alcohol (PVA), combined with lithium chloride, was used to create artificial ionic nerve fibres. These fibres showed outstanding traits: rapid self-healing, exceptional stretchability over 7000%, stable conductivity at 11.76 S cm^{-1}, and excellent resistance to freezing down to -80°C.[169] In addition, the emergence of stretchable ionotronic luminescent fibre based on polyacrylamide (PAAm) hydrogels posed a solution of poor

adhesion between hydrogel ionic conductors and other target materials (Fig. 4u).[170] Nevertheless, hydrogels have long been challenged by the issue of water evaporation. [158, 171] Although certain studies revealed the incorporation of moisturizers into hydrogel matrices or the utilization of elastomers as an encapsulation layer to prevent it, these measures cannot eliminate it completely. Ionic liquids, which are room-temperature molten salts composed primarily of organic ions that can undergo almost unlimited structural variations, can be used to create ionogel conductors and entirely resolve the issue of water evaporation that observed in hydrogels (Fig. 4v and 4w).[172, 173] Common strategies for producing ionogels involve incorporating various ionic liquids into elastomeric networks. For example, Wu et al. fabricated ionogel fibres by integrating ionic liquids (BMIM PF_6) into liquid crystal elastomers (Fig. 4x).[174] The ionogel fibres exhibited high conductivity of 0.14 mS m^{-1}, excellent transparency of 92%, remarkable stretchability of 2700%, and superior toughness of 56.9 MJ m^{-3}. However, the toxicity of ionic liquids is a major drawback for their use in bioelectronics. Moreover, the problems of hygroscopicity and low ionic conductivity need to be addressed in ionogel fibres.[158, 175] The current challenge within the domain of organic conductors is achieving a balance among the fundamental attributes of stretchability, conductivity, self-healing capabilities, transparency, and other desirable properties. The pursuit of such comprehensive properties can maximize their applicability across a variety of practical scenarios. The feasibility of constructing dynamic polymer networks at the molecular level using supramolecular chemistry has been effectively demonstrated.[176, 177] The diverse interactions, such as hydrogen bonding, metal-ligand complexation, π-π stacking, host-guest interactions, collectively drive the assembly of dynamic and adaptable polymer networks. Through precise regulation of molecular structures, functional group positions, and non-covalent interactions, components of polymer network (cross-linking density, molecular chain mobility, and the degree of order-disorder) can be systematically engineered to achieve an integration and balance among diverse properties. It is foreseeable that forthcoming advancements in functional fibres derived from organic conductors will evolve significantly toward multifunction and versatile applicability across various scenarios.

2.3. Inorganic and Organic Dielectrics

A dielectric is the material that electrically insulates but can be polarized by the application of an electric field. When a dielectric material is subjected to an electric field, the equilibrium positions of the charges within the dielectric material shifts, leading to polarization where positive charges move towards the field and negative charges move in the opposite direction, resulting in the creation of an internal electric field.[178-181]

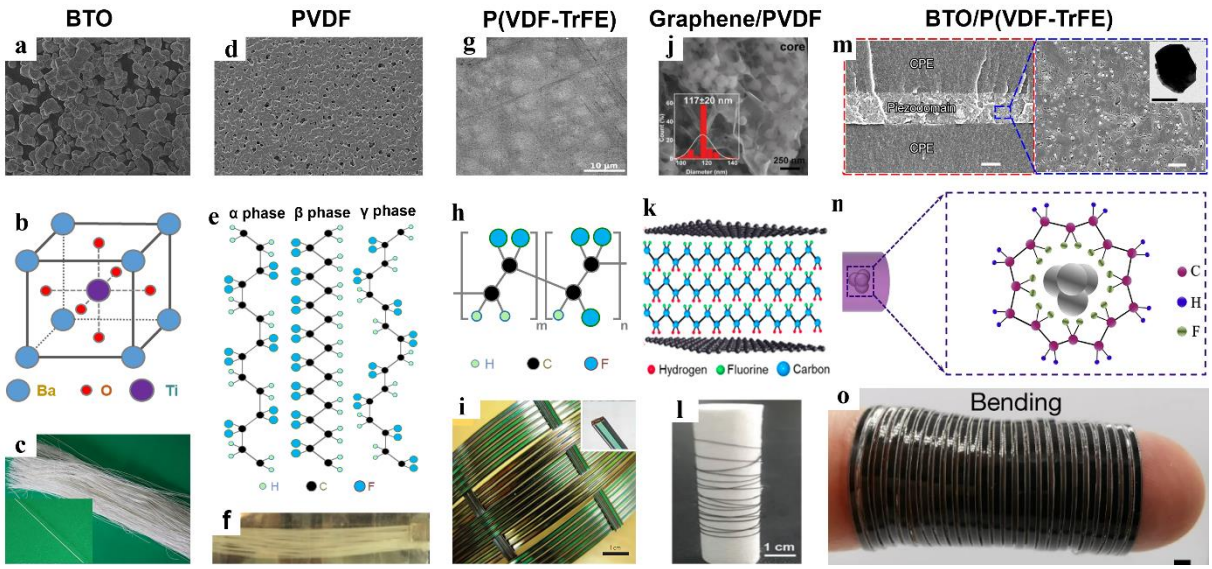

Fig 5. Inorganic and organic fibre dielectrics: (a) SEM image of BTO. Scale bar: 1 μm. Reproduced from ref. 186 with permission from Elsevier Ltd, copyright 2015. (b) Schematic illustration of crystal structure of BTO. (c) Photograph of BTO nanowire-based fibres. Reproduced from ref. 187 with permission from Elsevier Ltd, copyright 2015. (d) SEM image of PVDF. Scale bar: 1 μm. Reproduced from ref. 190 with permission from Springer, copyright 2009. (e) Schematic illustration of three crystalline forms of PVDF. (f) Photograph of PVDF fibres. Reproduced from ref. 192 with permission from IOPscience, copyright 2013. (g) SEM image of P(VDF-TrFE). Scale bar: 10 μm. Reproduced from ref. 193 with permission from Elsevier Ltd, copyright 2017. (h) Schematic illustration of chemical structure of P(VDF-TrFE). (i) Photograph of 2D fabric device knitted by piezoelectric/Fabry-Perot fibres. Reproduced from ref. 195 with permission from Springer Nature, copyright 2010. (j) SEM image of fibre core structure with graphene/PVDF balls. Scale bar: 250 nm. The inset shows the average diameter: 117 ± 20 nm. (k) Schematic molecular structure of PVDF/graphene. (l) Photograph of porous graphene fibres. (j and l) Reproduced from ref. 198 with permission from Wiley-VCH, copyright 2019. (k) Reproduced from ref. 199 with permission from American Chemical Society, copyright 2020. (m) SEM micrograph of BTO/P(VDF-TrFE) composite. Scale bar: 20 μm and 2 μm. (n) Schematic diagram of the BTO/P(VDF-TrFE) nanocomposite. (o) Photograph of a piece of acoustic fibre wrapped around a finger. (m and o) Reproduced from ref. 4 with permission from Springer Nature, copyright 2012. (n) Reproduced from ref. 200 with permission from Springer, copyright 2020.

2.3.1 Inorganic Dielectrics

In the domain of smart fibres, the inorganic dielectric materials used include but are not restricted to titanium dioxide (TiO_2),[182] barium strontium titanate (BST),[183] ceramic barium titanate ($BaTiO_3$ (BTO)),[184] and lead zirconate titanate ($PbZr_1$-$xTixO_3$ (PZT))[185].These materials exhibit a high dielectric constant (k) in the range of hundreds or higher. Inorganic dielectric materials, however, typically exhibit a rigid nature in contrast to the greater flexibility observed in organic counterparts. They exhibit a limited capacity to endure frequent bending without affecting functionality. Hence, the challenge of enhancing the flexibility of inorganic dielectric materials while preserving their dielectric properties remains a critical concern in advancing the domain of dielectric functional fibres. BTO is a commonly used inorganic dielectric, which possesses a tetragonal crystal structure below the Curie temperature (T_c) (Fig. 5a and 5b).[186] Once beyond the Curie temperature, BTO undergoes phase changes. As mentioned above, the intrinsically rigid nature prevents BTO to fabricate functional fibres. The advent of composite structures methodologies has presented promising avenues for addressing this challenge. As shown in Fig. 5c, smart fibres that were fabricated by spinning method. The high-aspect-ratio BTO nanowires were successfully assembled into polyvinyl chloride (PVC) matrices, leading to an impressive electrical output characteristic, including an output voltage of up to 0.9 V and an output current of up to 10.5 nA.[187] Nevertheless, enhancing nanoparticle dispersion and establishing a strong bond between particles and polymers are vital. The synthesis and functionalization of inorganic dielectric nanoparticles mark a significant breakthrough avenue. Moreover, employing in-situ polymerization holds promise as a valuable approach in this regard.

2.3.2 Organic Dielectrics

Organic dielectric polymers have attracted significant interest from the chemical, materials science, and engineering communities owing to their inherent flexibility, ease of processing, adequate mechanical strength, biocompatibility, and remarkable sensitivity to even minor mechanical stresses.[188, 189] Among these polymers, polymeric polyvinylidene difluoride (PVDF) is a widely used dielectric material for the fabrication of smart fibre devices (Fig. 5d).[190] The dielectric properties of PVDF are intricately linked to its molecular architecture, comprising a repeating unit of $(CH_2\text{-}CF_2)_n$. The piezoelectric properties of PVDF are heavily influenced by

the orientation of its C-F bonds. PVDF exist in three distinct crystalline phases, namely α (form II), β (form I), and γ (form III) (Fig. 5e). The β phase of PVDF exhibits superior piezoelectric characteristics, displaying significant polarization and high sensitivity to mechanical stress. The piezoelectric performance of PVDF is correlated with the proportion of its β-phase content.[191] Nevertheless, the functions of PVDF are notably depended on its molecular configuration. Thus, achieving the desired molecular arrangement during fibre processing becomes imperative for optimal performance. Melt extrusion is a low-cost, continuous process that produces high-quality PVDF fibres with desired alignment (Fig. 5f).[192] The β-phase content can reach approximately 80%. Moreover, modifying PVDF molecular chains with polar groups has been proved to be feasible for enhancing the dielectric and mechanical characteristics of dielectric polymer-based fibres.

Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) is a commonly utilized piezoelectric material that exhibits immense potential in smart fibre applications (Fig. 5g).[193] The compound exclusively comprises of one crystalline phase variant, primarily due to the steric hindrance that arises from the rotation of the C-C bond, induced by the extra F atom (Fig. 5h). Thus, the optimization of the configuration of polymer chains is a key factor in enhancing the crystallinity of P(VDF-TrFE). This is a fundamental prerequisite for the fabrication of fibres with excellent piezoelectric properties. Stretching techniques are frequently employed to align polymer chains. Fortunately, because of desirable melting temperature, suitable electromechanical coupling coefficient, and excellent piezoelectricity, P(VDF-TrFE) is an ideal material for thermally-drawn fibres.[194] The production of a piezoelectric fibre device with a length of ten meters can be realized *via* thermal drawing of a preform containing P(VDF-TrFE), metal electrodes, and insulating polymers (Fig. 5i).[195] However, employing P(VDF-TrFE), which is more expensive than PVDF, will inevitably increase the cost of fabricating fibre-based devices. Additionally, for organic dielectric-based fibres, addressing surface defects such as pits, roughness, and variable thickness is crucial, as they can lead to a wide distribution of breakdown strength. Overall, researchers are striving to achieve purely organic dielectric fibres with high dielectric constant, high breakdown strength, low dielectric loss, and high mechanical and functional properties.

2.3.4 Hybrid Dielectrics

To improve the dielectric constant, ferroelectricity, and piezoelectric coefficient of smart fibre devices, the addition of carbon materials (such as graphene and CNTs) or inorganic dielectric materials (including BTO and PZT) to organic dielectrics such as PVDF and P(VDF-TrFE) is a commonly employed strategy.[196, 197] It is essential to note that achieving a well-balanced combination of electrical and mechanical properties when integrating hybrid dielectrics into the fibre matrix is a significant challenge. In light of this, Huang et al. developed porous fibres based on graphene, PVDF, and polyurethane, showing excellent performance with a low detection limit (0.01% strain), durability (over 6000 cycles), and high gauge factors (51 in 0-5% and 87 in 5-8%), as shown in Fig. 5j and 5k.[198, 199] These porous fibres were also integrated into commercially available fabrics for spatially mapping tactile stimuli, as shown in Fig. 5l.[198] In addition to highlighting the balance of properties, there is an increasing focus on the role and innovative engineering of filler-polymer interfaces. Such considerations have a significant influence on the overall functionality of nanocomposites and their fibre devices. A new acoustic fabric with hear and speak capabilities was developed using innovative piezoelectric fibres, which included an active layer of P(VDF-TrFE) loaded with BTO ceramic particles (Fig. 5m and 5n).[4, 200] Fibres containing 20 wt% $BaTiO_3$ nanoparticles showed enhanced ferroelectric properties with up to 10 μC cm^{-2} remanent polarization. The interaction between BTO particles and the P(VDF-TrFE) matrix caused cavitation at the interface, leading to the formation of a porous ferroelectric structure. As result, the piezoelectric fibre gained the ability to detect acoustic waves in the audible range, and its performance was comparable to that of commercial microphones (Fig. 5o).[4] We anticipate that controlling the microstructure of hybrid dielectrics at the nanoscale can offer a unique and impactful method for creating intelligent fibres, enabling a wide range of novel applications in smart sensing, healthcare, space security, actuation, and energy-related fields.

3. Chemical and Physical Mechanisms of Smart Fibres Enabled Fabrics

In this section, the physical and chemical mechanisms of smart fibre enabled fabrics, as shown in Fig.6, will be examined and discussed. In particular, we will elaborate on how these

mechanisms enable diverse functions.

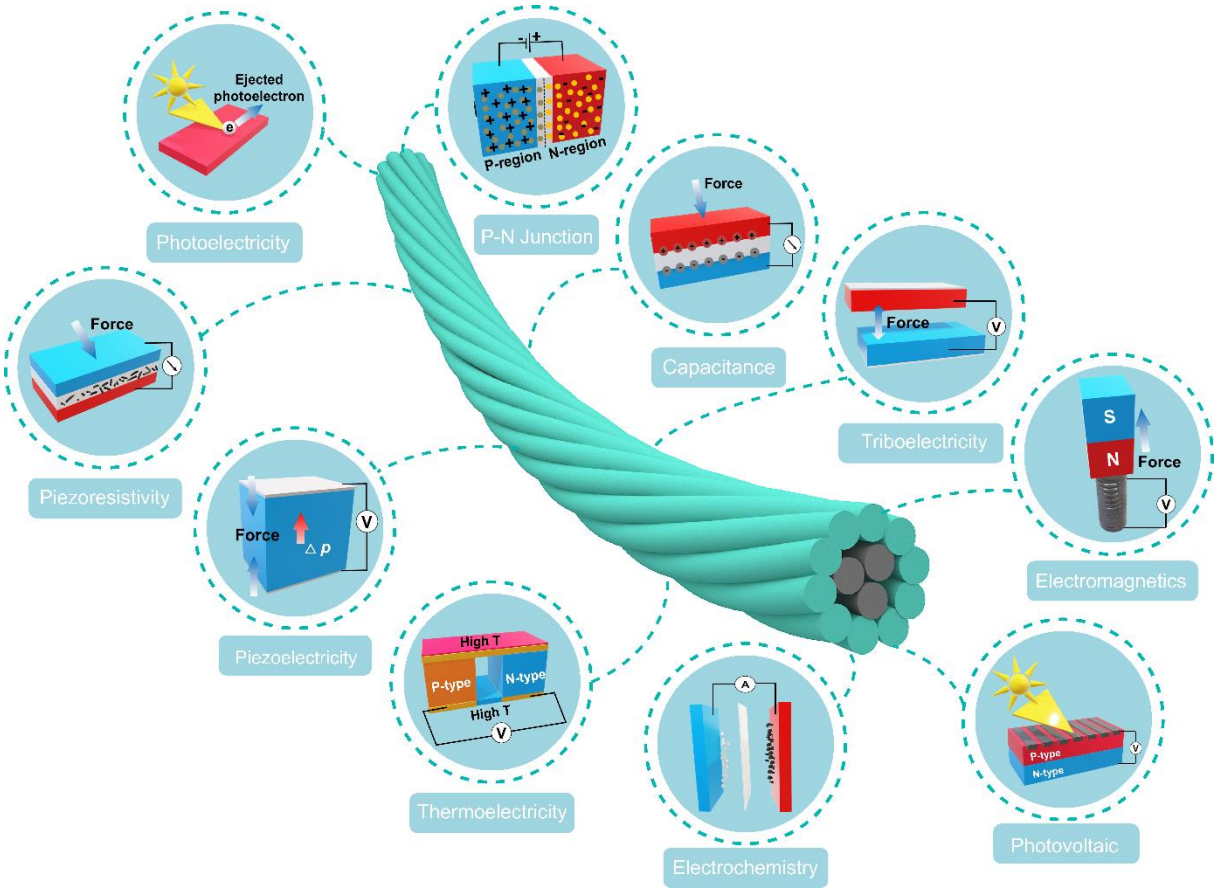

Fig 6. Schematic illustration of chemical and physical mechanisms of functional fibre enabled smart fabrics.

3.1. Photoelectricity Mechanism

The photoelectric effect is a phenomenon of physics where the emission of electrons from a material happens when it is exposed to light or other electromagnetic radiation. Consider a material (e.g. Si single crystal) with a band gap E_g; when an incident light with photon energy bigger than E_g hits the material, the electron of the material would be excited and leap from the valence band to the conduction band, and would thus be able to move freely. When an external voltage is applied to the material, a photocurrent flow will come into being.

Chalcogenide semiconductor glasses based on S, Se and Te have been adopted as the functional part of optoelectronic fibres quite frequently, because of their unique structures and variable compositions.[201] Chalcogenide semiconductors are typically amorphous or polycrystalline, making them different from traditional crystalline semiconductors, such as Si. By tuning the composition and structure, chalcogenide semiconductors could show various

electrical and optical properties. The integration of metal electrodes in contact with the chalcogenide functional component enables photodetection through the measurement of the photocurrent generated at the electrodes.[202] An example of this is the integration of a chalcogenide glass core ($As_{40}Se_{50}Te_{10}Sn_5$) with four Sn metallic electrodes into a single fibre, which enables the localization of an illuminated point.[203] Another study enhances the photo-detecting performance by utilizing a thin semiconductor photo-detecting layer instead of a thick one, aiming to minimize absorption and let through more high-frequency photons.[204]

3.2. P-N Junction Mechanism

A P-N junction is a type of semiconductor junction formed by the joining of a p-type semiconductor and an n-type semiconductor. When a p-type and n-type semiconductor are brought together to form a P-N junction, a depletion region is created at the junction, where the mobile charge carriers from each side diffuse and recombine. The depletion region has no free mobile carriers and behaves like an insulator, creating a potential barrier that opposes the flow of current across the junction. Many important electronic devices such as diodes, transistors, and LEDs are based on the P-N junction and by integrating those devices into fibres, “smarter” fabrics with unique functions can be fabricated.[205] For example, the diodes can be integrated into fibres to enable novel light-emitting and photo-detecting fibres. By weaving those fibres into normal fabrics, inter-person optical communication link can be established between individuals wearing such fabrics.[206] Besides feeding P-N junction based microelectronic device into the fibres, the P-N junction could also be constructed in-situ using laser-induced Plateau-Rayleigh instability, followed by the laser-induced thermocapillary convection to achieve a P-N particle assembly.[207]

In addition to normal P-N junctions, more sophisticated P-I-N heterojunctions are also widely used. A P-I-N diode is a type of diode that consists of a P-type semiconductor region, an intrinsic semiconductor region, and an N-type semiconductor region. The P-I-N diode has a wider depletion region compared to a standard p-n junction diode due to the intrinsic layer, which makes it useful for applications where a high voltage rating and low leakage current are required. P-I-N diodes are also used as rectifiers in high-frequency applications, where they can handle high voltages and have low capacitance due to the intrinsic layer.[208]

3.3. Piezoresistivity Mechanism

Piezoresistivity is a phenomenon in which the electrical resistance of a material changes

when it is subjected to mechanical stress or strain.[116] This effect is observed in certain materials, such as semiconductors, metals, and polymers, and can be utilized for various applications in sensors and electronic devices. When a material is subjected to mechanical stress or strain, the atoms in the material shift their positions slightly, which can change the spacing between the atoms and the movement of electrons in the material. This change in the atomic arrangement can cause a change in the electrical resistance of the material, as the flow of electrons through the material is affected. Semiconductor piezo-resistors have been investigated widely and have been integrated into fibres to enable fibre strain sensors.[209]

Aside from semiconductor materials, carbon-based conductors (CNTs, graphene) are another important group of piezoresistive materials. Typically, the carbon-based conductors form a loose aggregate, and external mechanical strain would separate or pull together the conductors within the aggregate so that the contacting area between conductors would decrease or increase, thus changing the number of possible conductive paths and affecting the electrical resistance. A study has shown that a yarn coated with graphene nanoplatelets could exhibit a piezoresistive responses while maintaining stretchability and flexibility.[210]

3.4. Capacitance Mechanism

A capacitor is a passive electronic component that stores energy in an electric field. A typical capacitor consists of two electrode plates with a dielectric layer in between. When a voltage is applied across the plates, an electric field is created in the dielectric layer, and electrons accumulate on one electrode plate while an equal number of electrons are removed from the other electrode plate. This separation of charge creates an electric potential difference between the plates. The amount of charge stored on the plates is proportional to the voltage applied and the capacitance of the capacitor.

The most important function of capacitors is energy storage. Combining the capacitive function and the fibre shape, fibre capacitors have been developed and demonstrate unique applications in wearable energy storage. For example, a PVDF-based fibre capacitor can be fabricated through thermal drawing and the length of the fibre could be ultra-long (100m).[211] Besides energy storage, the capacitance mechanism can be harnessed to fabricate mechanical sensors as well. Regarding the capacitors as a simple two-plate capacitors, the external force applied onto the capacitor would cause the distance between the two conductive plates to change and this would lead to a change in the capacitance. Therefore, capacitance can be measured to detect changes in mechanical pressure. One study showed the fibre capacitors can be woven to obtain a 2D touchpad sensor which is capable of detecting the location of

mechanical pressing.[212]

3.5. Piezoelectricity Mechanism

The piezoelectric effect is a physics phenomenon in which certain materials generate an electric charge in response to an applied mechanical stress or strain, or conversely, undergo mechanical deformation when an electric field is applied to them. This effect is found in various materials such as quartz, ceramics, and certain types of crystals and polymers. The piezoelectric effect is based on the symmetry of the crystal structure of the material. When the crystal structure is deformed or subjected to stress, the positive and negative charges in the crystal are separated, creating an electric potential difference across the material. Conversely, when an electric field is applied, the charges are displaced, causing a deformation of the crystal.[181] Regarding piezoelectric materials, piezoelectric polymers such as polyvinylidene difluoride (PVDF) and its co-polymer P(VDF-TrFE) have been frequently adopted in the fabrication of flexible piezoelectric devices including piezoelectric fibres, due to the low processing temperature and flexibility.[213] Yet polymeric piezoelectric materials have a relatively low d_{33} coefficient, therefore piezoelectric ceramic particles, such as BTO ($BaTiO_3$) and PZT ($PbZrxTi1\text{-}xO_3$), are embedded into polymers to enhance their performance.[214, 215]

If the piezoelectric materials are connected to an external circuit, the piezoelectric charges can be collected and measured, therefore enabling piezoelectricity-based transducer and energy harvester. Many studies have reported the fabrication of piezoelectric fibres and their use in energy harvesting, sound emission and detection. For example, one study has reported a single fibre capable of receiving and emitting audible sound,[4] another study fabricated a spirally-structured piezoelectric fibre and used it to collect the vibration energy from human body.[216]

3.6. Triboelectricity Mechanism

The triboelectric effect is a phenomenon where electric charges are transferred between two materials upon contact, resulting in the generation of electrical energy from mechanical energy. During this process, the surfaces of the two materials become charged with opposite electrostatic charges when they contact. Subsequently, when the materials are separated, a potential difference arises between the charged surfaces, which drives the movement of charges across conductive materials from one surface to the other. Repeating such a process can result in an alternating current flow in the external circuits. Based on this mechanism, triboelectric nanogenerators (TENGs) have been created for energy harvesting.[217, 218]

The surface characteristics of the materials are the leading factors that determine the surface properties of the tribo-systems, which affect the performance of TENGs.[219] Compared to traditional 2D plane TENGs, the fibre-based TENG exhibits a larger surface-to-volume ratio and can be woven; these properties make it suitable for energy harvesting during daily activities.[39] Furthermore, the microstructure and pattern of the fibres are also crucial in enhancing TENG performance. Surface roughness and microstructures can significantly affect the electrical charges generated during the material sliding process.

Daily activities of humans create the necessary movement conditions for TENGs to function. Fibre-like TENGs, which can be easily incorporated with regular fabrics, can offer a comfortable and compact platform for energy harvesting, and have become a popular form factor of TENGs.

3.7. Thermoelectricity Mechanism

The thermoelectric effect refers to the phenomenon whereby energy is converted between thermal and electrical forms. The Peltier and Seebeck effect are the two main thermoelectric effects.[220] The Seebeck effect describes a thermal-to-electrical energy conversion phenomenon in which a temperature gradient across two dissimilar conductors in a closed circuit generates a potential difference between the two ends of the conductors. This potential difference can drive an electrical current in the circuit, allowing for the conversion of thermal energy into electrical energy. In contrast, the Peltier effect is an electrical-to-thermal energy conversion phenomenon that occurs when an electrical current is passed through a junction of two dissimilar conductors. The electrical current causes heat to be absorbed or released at the junction, depending on the direction of the current flow. This results in a temperature gradient across the junction and can lead to the generation of a cooling or heating effect, depending on the direction of the current flow. The Peltier effect is commonly used in thermoelectric coolers, which are solid-state cooling devices that use the phenomenon to create a temperature differential across a thermoelectric module.[221]

Thermoelectric performance is usually evaluated by a dimensionless figure-of-merit, ZT.[222-224]

$$ZT = \frac{S^2\sigma}{\kappa}T$$

where S is the Seebeck coefficient, σ is the electrical conductivity, κ is the thermal conductivity, and T is the absolute temperature. Ideal thermoelectric materials should exhibit high electrical conductivity but low thermal conductivity. Inorganic semiconductor-based alloys including Si-

Ge alloy and Sn-Se compounds show high thermoelectric performance when compared to other thermoelectric materials. In addition, their thermoelectric performance can be further improved through microstructure manipulation.[77, 225] Interestingly, computational theoretical findings reveal that confining an electron within a 1D structure smaller than its wave function space results in distinctive movement traits. These traits can induce the quantum confinement effect, potentially expanding material bandgaps. Such an effect contributes significantly to the enhancement of thermoelectric performance.[226, 227] Therefore, compared with their bulk counterparts, fibre-based 1D thermoelectric materials show a significant thermoelectric effect due to their special microstructure and interface.

3.8. Electromagnetics Mechanism

Electromagnetic generators (EMGs) are widely used in various large-scale power plants, including those based on fossil fuels, hydrodynamic and wind power generators.[228] Faraday's law of induction describes the basic working principle of EMGs, which involves the generation of an electromotive force (potential difference) in a wire loop by a changing magnetic flux.[229] Electromotive force (V_{emf}) can be calculated through Lenz's law:

$$V_{emf} = -N\frac{d}{dt}\iint_{S} BdS$$

where *N* is the number of turns in a coil, *B* is the magnetic flux density passing through an area of *dS*, and t is time. This EMF induces a current in the conductor that produces a magnetic field that opposes the change in the original magnetic field:

$$I = \frac{V_{emf}}{R + r}$$

where *I* is the induced current, *R* is the resistance of the external circuit and *r* is the resistance of the coils.

Typically, EMGs are composed of a fixed part and a moving part, with coils and/or permanent magnets included in either part. Rotational, oscillatory, or linear movement relative to the magnetic field lines can result in an electromotive force in the coil, thus converting magneto-mechanical energy into electricity. Human movements during normal daily activities provide ideal relative movements for EMGs.[230] The utilization of the abundant mechanical energy generated by human motion presents a viable option for harnessing waste energy and developing sustainable energy sources. Subsequent sections will examine the development of flexible, compact, and high-efficiency fibre-based wearable EMGs.

3.9. Electrochemistry Mechanism

The electrochemical mechanism is a concept that describes the process by which chemical reactions occur through the transfer of electrons between molecules or atoms.[231] The mechanism involves the use of an electrochemical cell, which consists of two electrodes (an anode and a cathode) immersed in an electrolyte solution. During the process, the flow of electrons from the anode to the cathode generates an electric potential difference, which causes the movement of ions in the electrolyte solution. There are two types of electrochemical cells (galvanic and electrolytic cells).[231] In galvanic cells, chemical energy released by spontaneous chemical reactions is converted into electrical energy. In electrolytic cells, electrical energy is used to drive non-spontaneous reactions, storing electric energy in chemical forms.

Through making use of this reversible energy conversion between chemical and electric energy, important energy storage solutions such as batteries have been developed.[232, 233] Compared with traditional bulky energy storage devices, fibre-shaped energy storage devices offer a flexible and compact form factor, which can be sewn into fabrics or made into non-planar soft 3D objects, thus drastically broadening the application range.

3.10 Photovoltaic Mechanism

The photovoltaic effect converts solar energy into electrical energy by generating electrons and holes through photon excitation. P-N junction semiconductor photovoltaic device is the well-studied mechanisms for creating solar cells.[234] When photons of light with sufficient energy are absorbed by the semiconductor material, it can excite electrons from the valence band to the conduction band, creating electron-hole pairs. In the P-N junction, the built-in electric field can separate the electron-hole pairs, causing electrons and holes to move in opposite directions toward the positive and negative contacts on either side of the solar cell. Both electrons and holes are then collected by the respective electrodes, resulting in a photocurrent and photovoltage.

The concentration of photogenerated carriers is affected by the bandgap energy of the material, and the open-circuit voltage is often related to the material's forbidden region width. Therefore, the photocurrent and photovoltage are directly affected by the band structure of P-N junction.[234, 235] Nanoconfinement is an effective method to engineer the bandgap of the semiconductor.[236] By reducing the dimension of the bulk semiconductors into 1D

semiconductor nanofibers, the band structure of the semiconductors can be modulated, providing possibilities to promote the photovoltaic effect.[237] Furthermore, highly flexible fibre-based photovoltaic solar cells can be incorporated into fabrics, allowing for the creation of solar energy harvesting textiles that can power other wearable devices.[238]

4. Fabrication Technologies of Smart Fibres Enabled Fabrics

Even though attaching silicon-based electronic and optoelectronic devices onto fabrics constitutes an interesting avenue for the construction of smart fabrics, a well-received strategy is to revolutionize materials and structure, and to impart functionality at the fibre level. In this section, all strategies for fabricating intelligent fibres and fabrics, along with their related fundamental principles, advantages and disadvantages, technological breakthroughs, will be comprehensively examined. In addition, we discuss the common scientific problems with these approaches.

4.1. Fabrication Technologies

4.4.1 Wet Spinning

The wet spinning is a gentle process of forcing the polymer solution through fine spinneret orifices into a coagulating bath, where continuous filaments are drawn out using take-up rollers. This technique involves the phase-change properties of highly concentrated polymer dope to create solid fibres in the coagulation bath.[160, 239] Hence, the fundamental physical mechanism of this technique is phase separation, wherein the polymer undergoes a transformative phase shifting from a dissolved state to a solid state, thereby forming fibrous structures. Fibre formation in the coagulation bath is a multifaceted process. It is influenced by many parameters such as bath composition, temperature, extrusion rate, and take-up velocity.[240] Moreover, the difference in mass transfer rates plays a pivotal role in coagulating the outer layer of the polymer solution, ultimately shaping the resulting properties and microstructure of the as-spun fibres. Compared to dry spinning and melt spinning, wet spinning operates at a slower speed due to the high tension caused by the viscous liquid used. The wet spinning method has been exploited for large-scale production of continuous fibre batteries (Fig. 7a-i).[241] This high-speed process

extruded and combined the cathode, anode, and electrolyte into a single fibre at rates exceeding 250 m h^{-1} (Fig. 7a-ii). To ensure smooth extrusion, a tapered channel was vital for the polymeric electrode fibres before they enter the coagulating bath containing a 1.75 M NaOH and 2 M Li_2SO_4 solution.

4.4.2 Dry Spinning

Dry spinning is a method used to transform a high-vapor-pressure polymer solution into a solid fibre by carefully controlling the process of evaporation during spinning.[242] The core physical mechanism involved in this process is the evaporation and solidification of the spinning solution. During this process, polymer molecules assemble and form a solid structure as the solvent progressively evaporates. Achieving precise control over heat transfer, mass transfer, and filament stress is essential in ensuring the success of this process.[243] This technique is particularly applicable to polymers that are susceptible to thermal degradation and cannot form thermally stable or viscous melts. Additionally, these polymers must also be soluble in volatile solvents like ether and acetone, which are typically recovered *via* gas absorption, condensation, and distillation for cost-effectiveness and environmental considerations.[242] From a microstructural perspective, high pressure enhances molecular alignment within the polymer solution, resulting in dry-spun fibres with excellent tensile strength and toughness. Notably, an ionic fibre sourced from silk with a remarkable 250% stretchability was produced by dry spinning (Fig. 7b-i).[244] The silk/Li^+ solution was loaded into a syringe and extruded through a 14 G spinning nozzle with a speed of 20 ml/min. The resulting high-viscosity fibre was collected using a PTFE plate, which was systematically moved along a linear path at a controlled speed of 300 mm/min. The obtained fibre exhibited remarkable resilience, reaching 87.2% at a maximum tensile strain of 100% (Fig. 7b-ii). In general, the preparation of dry-spun fibres is intricately linked to factors such as temperature and polymer solution concentration. Additionally, the mass transfer mechanisms associated with solvent evaporation and diffusion significantly impact fabrication efficiency. Therefore, wet spinning and melt spinning are more widely adopted techniques.

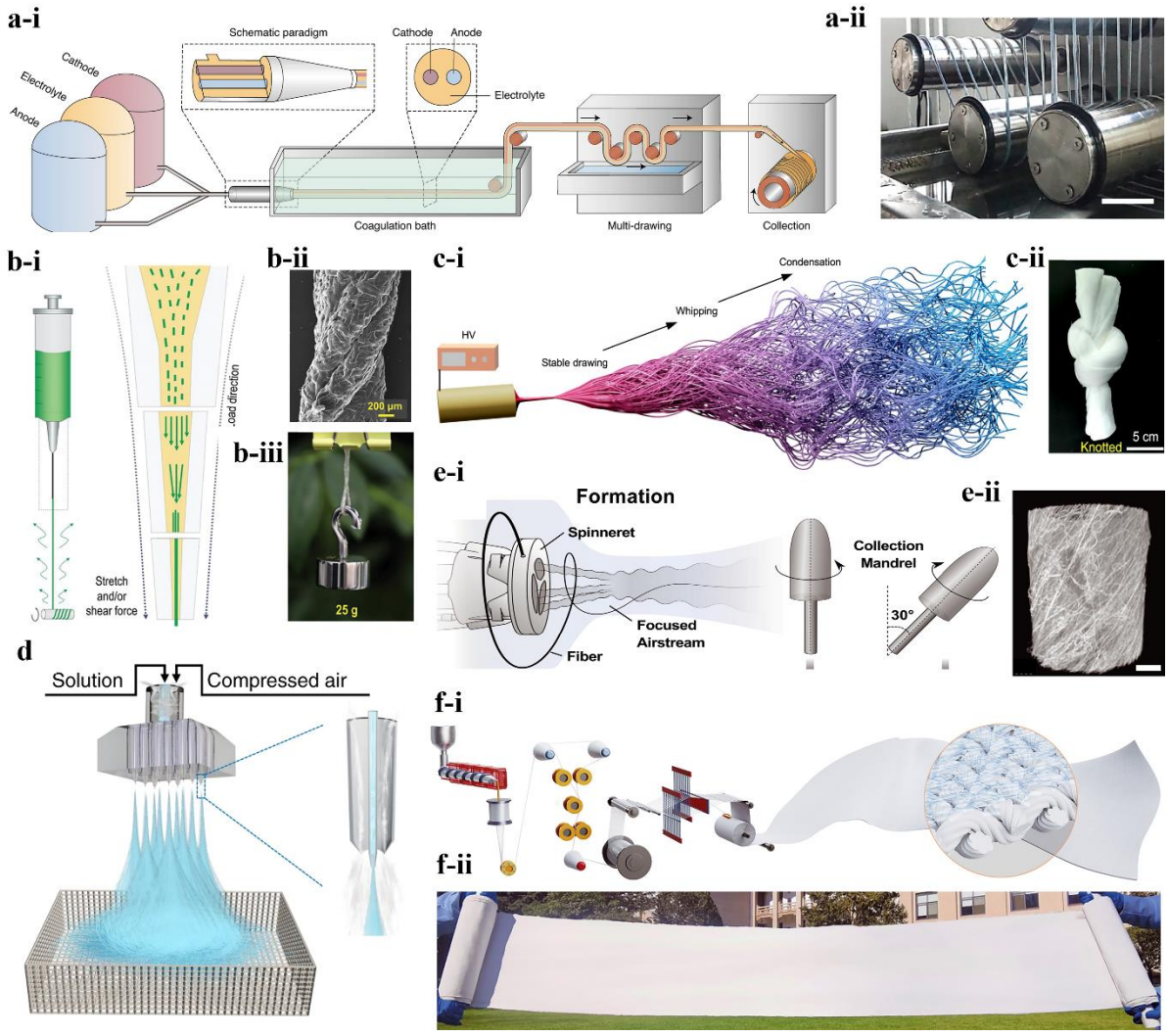

Fig 7. Spinning techniques used in design and fabrication of functional fibres: (a-i) Schematic illustrating the process of wet spinning used to produce fibre batteries. (a-ii) The correlation between extrusion distance and flow velocity. (a-iii) Photographs of the fibre batteries. (a) Reproduced from ref. 241 with permission from Springer Nature, copyright 2022. (b-i) Schematically illustrating the process of dry spinning used to fabricate silk-sourced ionotronic fibres (SSIFs). (b-ii) SEM image of the SSIF twisted yarn. (b-iii) Optical microscope image showing an SSIF fibre with a length of 30 mm can bear an object over 33 times its weight. (b) Reproduced from ref. 244 with permission from Wiley-VCH, copyright 2023. (c-i) Illustration of electrospinning for directly fabricating ceramic nanofibrous aerogels. (c-ii) Ceramic aerogel can be knotted without pulverization. (c) Reproduced from ref. 248 with permission from Springer Nature, copyright 2022. (d) Schematic illustrating the blow spinning procedure of ceramic sponges. (d) Reproduced from ref. 249 with permission from Springer Nature, copyright 2020. (e-i) Schematic illustration of the rotary jet spinning process. (e-ii) Photograph of the representative fibre-coated rod. (e) Reproduced from ref. 254 with permission from American Association for the Advancement of Science, copyright 2022. (f-i) Schematic illustration of the melt spinning process. (f-ii) Photographof the metafabric (0.3 m by 15 m). (f) Reproduced from ref. 257 with permission from American Association for the Advancement of Science, copyright 2021.

4.4.3 Electro Spinning

Electro-spinning has been used to produce fibres with controlled structures, porosity, orientations, and dimension.[245] In contrast to wet, dry, and melt spinning, which yield fibres with micrometer-scale diameters, electrospinning offers a facile method for generating continuous fibres with nanometer-scale diameters. The fundamental physical principle of this technology is utilization of an electric field to induce the migration of charged polymers into nanometer-scale fibre. The electro-spinning equipment typically consists of a high-voltage power supply, a syringe pump, a spinneret and a collector.[246] By employing specialized collector and spinneret designs, electro-spun fibre microstructures can be precisely tailored to meet specific requirements, thereby significantly advancing the field of nanofiber devices. Electrospinning accommodates natural polymers, synthetic polymers, nanoparticles, metals, and ceramics. These materials are commonly processed into spinning solutions, enabling the production of fibres by manipulation of electrostatic forces. When the structural attributes of nanofibers are combined with the unique physical, chemical, and mechanical properties of additional components, a series of advanced fibres with unique functionalities emerge.[247] For example, Cheng et al. created a resilient ceramic aerogel with interwoven crimped nanofiber structures using 3D reaction electrospinning, which was controlled through a sol-gel reaction within the jet flow (Fig. 7c-i).[248] The ejection mode of the conical droplet shifted to a multi-jet form with the addition of a small amount of high-molecular-weight polymers. Condensation between colloidal particles remained unchanged. Precise regulation of sol jet gelation, within milliseconds, was achieved by adjusting colloidal particle protonation. The resulting fibres exhibited ultralow thermal conductivity and can be used in space vehicle thermal protection systems (Fig. 7c-ii). Despite their potential applications in ultrafiltration, ultrasensitive sensors, and catalysts, common electro-spun fibres, with diameters typically ranging from 100 to 500 nm, have limitations. Various methods, including reducing polymer concentration, increasing solution temperature, and enhancing solution charge density, have been employed to decrease the diameter of electro-spun nanofibers. However, these approaches often result in nonuniform fibres with poorly defined structures.

4.4.4 Blow Spinning

Blow spinning is an economical technique that utilizes the shearing force generated by a high-speed gas to create fibres. The fundamental physical mechanism involves the utilization of a high-velocity air stream to greatly stretch the extruded polymer solution (Fig. 7d).[249] Specifically, the process begins with the extrusion of a polymer solution from a needle tip, refining it into a liquid jet at the gas-liquid interface due to the shearing force induced by gas flow. Subsequently, solvent evaporation is facilitated by gas flow, resulting in high-quality dry fibres.[250] This technique can deposit conformal fibres on both planar and nonplanar substrates at a deposition rate approximately 10 times faster than traditional electrospinning technique. Furthermore, blow spinning eliminates the need for an electric field and utilizes solvents with relatively low toxicity, such as acetone.[251] These features facilitate the commercial applicability of blow-spun fibres. Unlike melt spinning and dry spinning that require additional steps such as gas cooling and solvent evaporation, blow spinning efficiently achieves both polymer extrusion and solvent evaporation through the pressurized gas, simplifying the production process. The quality of blow-spun fibres can be tailed through the precise adjustment of polymer molecular weight, concentration, viscosity, gas pressure and polymer solution flow rate. Selecting the appropriate polymer and solvent system is of importance. The solvent should have excellent solubility to enable the maximum solution concentration. Moreover, the polymer should possess a substantial molecular weight to facilitate the entanglement of polymer chains, ensuring a sufficiently high polymer relaxation time for the successful production of polymer fibres.[252] Blow spinning technology can produce fibres ranging in diameter from around 100 nm to over 1 μm. Through adjustment of the polymer-solvent system, polymer fibres exhibiting beaded and particulate morphologies can be obtained. Similar to other spinning techniques, multicomponent polymer mixtures can be used in blow spinning to create diverse polymer fibres, including heterogeneous fibres and core-shell amorphous polymer fibres.[253] These fibres demonstrate remarkable properties such as high fatigue strength and inherent self-healing abilities. While the potential for producing micro/nanofibers using blow spinning has been demonstrated, this technique still faces challenges related to limited preparation precision, constrained dimensional accuracy, and an incapacity to fabricate 3D structures.[254]

Rotary jet spinning represents a significant breakthrough, enabling the construction of intricate 3D configurations due to the ability of creating fine structures and hierarchies through

the control of fibre arrangements in 3D.[254] The underlying physical mechanism of this technique involves the extrusion and elongation of polymer solutions into nanofibers under centrifugal force. As demonstrated in Fig. 7e-i, rotary spinning used a small orifice in the spinneret to produce single-micrometer fibres through the application of centrifugal force. The polymer solution was pushed through the orifice to create a cloud of fibres that formed independently. The fibres were then drawn into a jet stream, which aligned and confined them in a small area, allowing for patterning (Fig. 7e-ii). This innovative spinning technique opens the possibility of constructing complex anatomical structures previously unachievable with other conventional biofabrication methods.

4.4.5 Melt Spinning

Currently, the melt spinning technique is the predominant method for producing commercial fibres from thermoplastics, including nylon, polyethylene, polyester, cellulose diacetate, and polylactic acid., owing to its simple production process, high spinning speeds, cost-effectiveness, and environmentally friendly features.[7] The physical mechanism of this technology is to use rapid cooling processes to induce the solidification of molten polymer solutions. The molecular chains of molten polymer orient into more ordered and stable solid phase features. The production process can be summarized as follows: A continuous flow of viscous, molten thermoplastic polymer is extruded through a spinneret. After that, cold air or gas is utilized to rapidly cool and solidify the polymer fibres. These solidified fibres are then collected and further processed to produce the end products.

The physical properties of melt-spun fibres mainly depend on melt flow velocity, solidification speed and take-up speed. They are basically indirectly determined by the molecular weight of the polymer and the arrangement of the polymer molecular chains. The high molecular weight facilitates the formation of highly oriented fibres, resulting in tensile strength that is significantly higher than when spun.[255, 256] Bicomponent melt spinning offers the possibility to obtain polymer fibres with extraordinary properties such as ultra fineness, photoconductivity or electrical conductivity. Polymers suitable for this technology need to have a well-balanced processing temperature and viscosity. Therefore, a good understanding of adhesion and bonding between two components is required. A radiative cooling fabric made of

titanium oxide/polylactic acid (TiO_2/PLA) fibres was created through melt spinning technique (Fig. 7f-i).[257] The composite metafibres of ~30 μm diameter that were flexible, strong, and can be woven into a fabric that boasted passive radiative cooling properties while retaining its mechanical strength and scalability (Fig. 7f-ii). Although the melt spinning technique offers numerous advantages, it still has distinctive limitations. For instance, the range of raw materials suitable for this technique is restricted, particularly those with high decomposition temperatures and low melting viscosities, which can be challenging to process using this approach. Additionally, the extrusion step in the process limits the size of the melt-spun fibres to above 10-12 μm, making it unsuitable for scenarios where finer fibre sizes are required.[256] These challenges may be addressed by combining two or more spinning techniques. In addition, melt-spun fibres are increasingly perceived as a global challenge in terms of resources, sustainability and waste management. Continuous efforts to develop new types of sustainable fibres are definitely necessary for a prosperous future.

4.4.6 Thermal Drawing

Conventional fibre fabrication techniques often produce functional fibre devices with limited and simple functionalities. In contrast, thermal drawing is a powerful technique for fabricating electronic and optoelectronic fibres featured with sophisticated architecture and complex functionality by a single draw step.[30] This can be achieve by co-drawing a diverse array of materials, ranging from glasses, polymers, composites, metals, semiconductors, dielectrics to even chips, in a macroscopic preform into a fibre device.[256, 258] The operational principle of this technology involves using the viscous flow phenomenon induced by the material's softening at high temperatures. This facilitates the elongation and thinning of the preform, ultimately resulting in the formation of fibres. Specifically, diverse material components can be integrated cohesively to create preforms using techniques like additive manufacturing or hot pressing. The preform undergoes a transformation in a furnace, where materials are softened or melted. A capstan, providing an external force, draws the softened preform into fibres.[259] The size of these fibres can be regulated by the drawing temperature within the hottest zone of the furnace, the feed rate of the preform, and the applied drawing tension. Thermal-drawn fibres usually show translational symmetry, wherein both the fibre materials and geometries precisely mirror those

found in the fibre preform.[148] As shown in Fig. 8a-i, an artificial muscle fibre with a dimension spanning three orders of magnitude was developed using thermal drawing of a polymeric composite preform based on an elastic cyclic olefin copolymer elastomer.[260] In the initial draw, fibres were generated, exhibiting features spanning from a few millimeters to tens of micrometers. Subsequently, by arranging these first-drawn fibres into a second preform and subjecting them to another drawing process, the feature size can be further reduced to a few micrometers (Fig. 8a-ii). The fibre served as a high-performance artificial muscle that enabled rapid and reversible actuation in response to external thermal stimulation (Fig. 8a-iii). Recent studies on thermally drawn fibres show a growing interest in making their structures asymmetric. Strategies like introducing chemical reactions during drawing, in-situ convergence of materials or devices into the fibre channels, or using techniques like laser heat treatment and solvent soaking have been explored.[6, 261] These changes in structure make thermally drawn fibres more diverse and powerful in their functions.

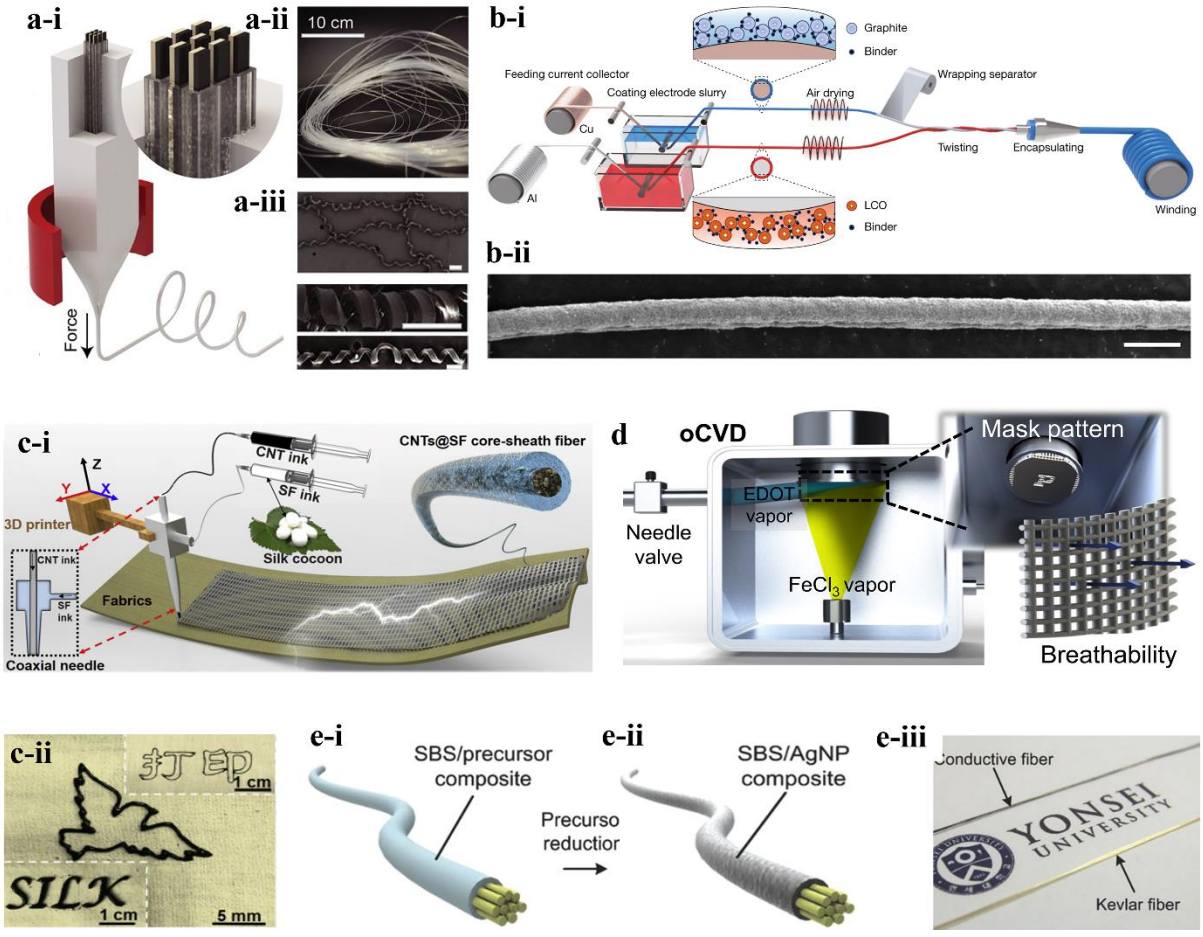

Fig 8. Design and fabrication techniques used for producing functional fibres: (a-i) Schematic illustration of thermal drawing process used to produce artificial muscle fibres. (a-ii)

Photograph of ~60 m artificial muscle fibres. (a-iii) Micrographs and photographs of the artificial muscle fibres. (a) Reproduced from ref. 260 with permission from American Association for the Advancement of Science, copyright 2022. (b-i) Schematic of the dip-coating process used to produce continuous fibre battery. (b-ii) SEM image of FLIB. Scale bar, 10 cm. (b) Reproduced from ref. 232 with permission from Springer Nature, copyright 2021. (c-i) Schematic illustration of the 3D printing process. (c-ii) Photographs of customer-designed fibre patterns on smart fabric. (c) Reproduced from ref. 273 with permission from Elsevier Ltd, copyright 2019. (d) Schematic illustration of the OCVD process. (d) Reproduced from ref. 278 with permission from American Association for the Advancement of Science, copyright 2021. (e-i) Schematic illustration of chemical reduction process used to fabricate conductive fibre. (e-ii) Photograph of the conductive fibre. (e) Reproduced from ref. 279 with permission from Wiley-VCH, copyright 2015.

4.4.7 Coating

Coating techniques, especially dip coating, offer a simple, efficient, and cost-effective method for enhancing the performance of fibres and fabrics while largely preserving their flexibility.[262] The process's physical mechanism is the evaporation of a solvent, which causes the solute, including metal nanoparticles, conductive polymers, graphene, or others, to precipitate and form a functional layer on the surface of fibres and fabrics through capillary action and viscous forces.[263] In order to prevent the coating material from delaminating from the fibrous matrix, it is necessary to establish chemical bonding, physical entrapment, or a combination of both. In addition, the viscosity of the solution, the speed at which the fibre matrix is drawn, and the drying conditions, are also important factors that need to be considered to guarantee the coating uniformity.[264] Nevertheless, achieving this uniformity poses a significant challenge, especially concerning the maintenance of high loading levels and the stability of coatings on lengthy fibrous substrates of diverse diameters. An improved dip coating method was successfully developed recently as shown in Fig. 8b-i and b-ii.[232] Utilizing adhesives like polyvinylidene fluoride, sodium carboxymethyl cellulose, and butadiene styrene rubber emulsion, an even coating and wrapping of active materials and separators onto the fibre matrix were achieved. This process significantly enhanced interfacial adhesion, thus addressing common issues such as low load, material peeling, and uneven distribution that frequently limit fibre batteries. In addition to coating uniformity, the control of coating accuracy is critical to the cost, function and use case of the fibre. Electrospray coating may be an alternative. In this technique, an electric field is utilized to propel liquid expelled through a nozzle, generating charged

droplets.[97] These charged droplets are subsequently directed onto a surface, facilitating the creation of a uniform and fine film. In addition, the compression coating has garnered significant interest for its application of materials such as polymers, metals, and ceramics onto fabric substrates at high pressure. This process also generates a robust and uniform layer, endowing the material with diverse properties such as ultrahigh conductivity and strength.[265]

4.4.8 Printing

Advanced printing technique capable of depositing electronic components onto fibrous substrates, represent a new frontier in fibre and fabric technology. Screen printing is a powerful manufacturing technology for achieving scalable and rapid production of fibre and fabric devices with millimeter-level spatial resolution.[266] The core mechanism of the technique involves the utilization of pressure to allow ink to pass through the open areas onto the fabric surface. The cost-effectiveness, user-friendly operation, and scalability make screen printing a highly competitive choice in the fabrication techniques.[266-268] Nevertheless, the widespread implementation of such fibres and fabrics faces certain challenges. Specifically, the challenges towards printability and electrical performance are related to the surface roughness, absorption capacity, barrier properties, thermal stability, and surface energy of fibre-based substrates. Moreover, the inherent properties of functional ink materials applied in screen printing, along with their immobilization chemistry within the fibre matrix, offer a foundation for optimizing the ultimate performance of fibre-based electronics. The viscosity and rheological characteristics of ink are significantly influenced by the binder. An appropriate binder guarantees robust adhesion of the ink to the substrate, thereby optimizing its functionality. For instance, when employing nanomaterials like graphene and carbon nanotubes, the choice of binder is crucial to mitigate electrostatic interactions and prevent them aggregation during application.[269] Besides, the irregular surface of fibres and fabrics can compromise the adhesion of ink components during printing, leading to inconsistent electrical performance under high deformability.[270] This issue could potentially be addressed through a pre-treatment approach applied to the fibre or fabric matrix.

With digital design coupled with layer-by-layer assembly, 3D printing is capable of creating intricate 3D structures quickly and precisely. This method enables on-demand

production in a broad range of scales from a few microns to meters, offering an ideal avenue for cost-effective manufacturing functional fibres and fabrics.[271, 272] Like in screen printing, the effects of the 3D printing are intricately associated with the quality of the ink employed. The introduction of nanofillers is a common protocol that serves a dual purpose, allowing for dynamic control over the ink's rheological properties while also imparting additional functionalities. Such inks are frequently employed in 3D printing technology, particularly in ink direct writing, for producing stretchable electronics based on fibre structures. From a technical standpoint, however the use of a single-axial spinneret in this 3D printing limits material performances and design flexibility for printed structures. The advent of 3D printers with coaxial spinnerets presents a viable solution to these difficulties.[273] As illustrated in Fig. 8c-i, a coaxial spinneret was affixed to a 3D printer and connected to two syringes containing CNT ink and silk fibroin (SF) ink, respectively. The CNT ink and SF ink were injected from the inner spinneret and the outer spinneret, respectively, to form core-sheath structured fibres. The coaxial spinneret can be programmed to create various flexible and custom-designed core-sheath functional fibre patterns (Fig. 8c-ii). It is evident from the above discussion that, in current 3D printing techniques, the simple extrusion of polymers is unlikely to produce fabric structures compared to conventional fabric manufacturing methods. The reason is that the basic structural characteristics of fabric are very complex (Section 5 for a detailed discussion). Small dimension of the fibres, high porosity of the structure, and the necessary discontinuities within the fabrics represent a collective challenge that current 3D printing technologies are unable to address simultaneously. Printing with fibres (PWF) is a pioneering concept involving the real-time dispensation of fibres through a carefully engineered fibre formation process. This innovative approach represents a pathway towards addressing the existing challenge.[274]

4.4.9 Chemical Vapor Deposition and Chemical Reduction

Chemical Vapor Deposition (CVD) is a method in which a solid material is deposited from a vapor by a chemical reaction occurring on or near a heated substrate surface.[275, 276] It has two distinct advantages. Firstly, outstanding spray ability ensures uniform coating thickness even on intricately configured fibre or fabric substrate. Secondly, it enables selection and personalization of functional areas on the fibre or fabric substrate. The features of the fabric

substrates, surface temperature, composition of the reaction gas, pressure, and flow rate collectively influence the quality of the deposited film. Consequently, a range of innovative CVD technologies have emerged in response to these intricate factors. For example, the utilization of advanced precursor materials coupled with innovative plasma enhancement techniques can notably lower the deposition temperatures.[277] Furthermore, the decrease of vapor pressure can enhance deposition rates and reduce deposition times. After various research endeavors, oxidative chemical vapor deposition (oCVD) has been developed and emerged as a prominent and innovative technique.[278] This method is distinctive and offers a unique approach to synthesize conductive polymer films with excellent electrical conductivity. The conductive polymer film demonstrates outstanding uniformity that can cover the substrate surface without considering the surface morphology and wettability. As shown in Fig. 8d, a highly conductive PEDOT film was created through the polymerization of the vaporized monomer, EDOT, and the oxidizing agent $FeCl_3$, in the chamber. No pre-treatments or binders were required because the reagents uniformly coated the surface of any substrate to form a highly uniform layer. The thickness of the PEDOT polymer can be easily controlled by adjusting the deposition time, ranging from 10 nm to over 1 μm, without compromising the mechanical properties and strength of the fabric substrate.

For chemical reduction processes, the typical approach involves reducing graphene oxide and metal ions in a solvent using a separate reducing agent for synthesizing graphene and metal nanoparticles, respectively. This approach has been further expanded to the development and integration of functional fibres and fabrics. A stretchable conductive fibre made of AgNWs and AgNPs embedded in an elastomeric matrix of styrene-butadiene-styrene (SBS) was created through a series of silver precursor absorption and reduction processes (Fig 8e-i and e-ii).[279] This unique combination of AgNPs and AgNWs resulted in a conductive fibre that maintained excellent electrical connections even under 220% stretching (Fig. 8e-iii). To enable this liquid-phase-dependent approach within the fabric substrates, the presence of specific functional groups is imperative. These groups facilitate the compatibility of the precursor and reducing agent, ensuring a homogeneous distribution of reduced functional materials throughout the fabric. Furthermore, preserving the inherent fabric advantages, such as breathability and skin compatibility, remains a key consideration in the application of this strategy. Presently, the

feasibility of this method is restricted by strict requirements, notably the need for expensive precursors, utilization of hazardous solvents and chemical reducing agents, and the imperative use of stabilizers to prevent aggregation. The use of mild and environmentally friendly bio-reducing agents represents the future evolution of chemical reduction method.

4.4.10 Critical Analysis and Comparison of Different Techniques

The discussed fabrication techniques in previous sections exhibit distinct characteristics that can be used to produce advanced smart fibres tailored to specific forms and application scenarios, as detailed in Table S3. Wet spinning technology is a compelling option due to its cost-effectiveness, broad material selectivity, and facile control over fibre sizes, making it particularly suitable for fabricating conductive fibres. However, it involves complex procedures and operates at lower spinning speeds. Furthermore, the resultant fibre size is constrained to the micron scale, limiting the realization of nanoscale effects. Dry spinning offers a rapid production method. The high-pressure shear force induces an ordered arrangement of polymer molecular chains, yielding fibres with excellent tensile strength and toughness. However, the solvent used in this process is both toxic and volatile, meanwhile presenting challenges in controlling the cross-sectional structure of the fibre. Electrospinning is a versatile technique capable of producing nanoscale fibres with controlled porosity and morphology. Materials such as cellulose, P(VDF-TrFE), and ceramics find applicability in the creation of functional fibre aerogels via electrospinning. Despite its advantages, conventional electro-spun fibres typically exhibit an average diameter ranging between 100 and 500 nanometers, limiting their potential in applications such as ultrafiltration, ultra-sensitive sensors, and catalysts. Blow spinning technology demonstrates a remarkable tenfold increase in fibre production speed compared to traditional electrospinning and it does so without relying on electric fields. Nevertheless, challenges still exist in controlling dimensional accuracy and achieving intricate fine structures and hierarchies. In contrast, rotary jet spinning can provide precise control over nano-fibres, enabling the creation of complex geometric shapes and patterns. It is the preferred method for applications demanding the precise manufacture of complex biological anatomical structures. Melt spinning is a primary method for producing thermoplastic fibres due to its notable speed and cost efficiency. The adoption of two-component melt spinning is a common strategy for

creating smart intelligent conductive fibres, optical conductive fibres, and photothermal fibres. Nevertheless, this technology faces limitations in terms of the range of suitable raw materials, resulting in a single-fibre structure. Thermal drawing technology is an ideal choice for producing fibre electronic devices endowed with intricate internal structures and diverse functionalities. The distinctive attributes of thermal drawing, such as customizable structures, scalable preparation processes, and seamless integration with other technologies, distinguish it as a superior strategy among various preparation methodologies. It can be served as powerful approach for fabricating intelligent fibre devices with sophisticated functionalities. In contrast, coating technologies such as dip coating, electrospray coating, and compression coating offer distinct advantages in situations where simplicity and cost-effectiveness are critical. These techniques facilitate direct material deposition, although the risk of introducing defects and impurities into the material exists. Key considerations in these processes include ensuring uniform dispersion and strong adhesion between the coating and the substrate. Screen printing technology emerged in response to the demand for selectively depositing functional materials, such as electronic components, onto fibre substrates. This method offers the capability to design electronic fabrics with millimeter-level spatial resolution and a versatile selection of substrates. Additionally, the adaptability of 3D printing enables the fabrication of fibre structures using conductive polymer composites. Despite these advantages, challenges like slow printing speed, limited material options, and high costs still exists.

5. Integration Methods of Smart Fibres Enabled Fabrics

Textiles with electronic functionality and smart fabrics can be realised in a variety of ways, however all employ a textile, or textile concepts at their core. This section will overview the fundamentals of textile construction, discuss methods for integrating electronics with textiles, and provide examples of different textile construction techniques being employed to integrate fibre and yarn type electronics into textile structures.

5.1 Textile Construction

Textile fabrics typically take one of three forms: knitted fabrics, woven fabrics, and bonded

fabrics. Knitted fabrics are formed through the interloping of yarns while woven fabrics are formed through the interlacing of yarns. Bonded fabrics are a type of non-woven fabric, in which fibres are bonded together mechanically, chemically, or thermally rather than being woven together like traditional fabrics. Once a textile is constructed it can undergo post-processes to further alter its appearance and structure. We think fabric electronic devices based on fibre route offer several benefits: (1) Functional fibre units ensure the attainment of required functions within the fabric at both micro and macro scales. They can be customized for specific applications through the optimization of electrical, mechanical, and chemical attributes using bottom-up and top-down multi-scale design strategies. (2) The inherent toughness of the fibre renders it suitable for conventional weaving, knitting, and bonding techniques for fabric integration, thereby facilitating seamless adaptation to intricate three-dimensional surfaces. This feature ensures the robust functionality of the resulting fabric electronic devices while preserving the user's comfort experience. (3) The fibrous structure is highly compatibility with contemporary manufacturing methodologies of the textile industry. From a commercial perspective, this excellent compatibility lays the foundation for the mass production and integration of fabric electronic devices in forthcoming endeavors.

5.1.1 Weaving

Weaving is the process of interlacing two sets of yarns which are referred to as the warp and the weft. Weaving is conducted using a loom and these can range significantly in their size and complexity from a simple hand frame to large, computerised, industrial machines.[280] Woven structures are fundamentally non-stretchable and will only be stretchable if a stretchable yarn is used in their construction. There are three fundamental types of weaves. A simple plain weave sees the warp and weft yarns perpendicular to one another, with the weft yarn going over a warp yarn, then under another warp yarn, then over a warp yarn again and so on. In a balanced plain weave, the yarns are of equal (or similar) thickness (weight) and are equally spaced. This will produce a durable and flat fabric. The second weave structure is a twill weave; this is achieved by passing the weft yarn over multiple warp yarns (known as a float) with an offset between the rows creating a diagonal pattern. The twill weave structure is known to have good drape characteristics and is often used for furnishings and clothing. The final weave structure is a stain

structure where several weft yarns cross over a warp yarn (or vice versa) and then interlace with one warp yarn, creating a very flexible fabric. Stain weaves are often described by their harness. In addition to weaving a single layer of material (single cloth), double cloth (or double weave) structures can also be constructed where two or more sets of warp yarns are used. This will result in a thicker fabric.

5.1.2 Knitting

Knitting describes the interlacing of yarn loops to create a structure that is stretchable in all dimensions.[281] There are two main types of knitting, weft knitting and warp knitting. In warp knitting latch or compound needles are arranged on a flat plane and the stitches are formed parallel to this needle plane where each needle is provided with an individual yarn to form columns of stitches known as seam. In weft knitting the needles can be arranged either in a circular fashion (circular knitting) or on a flat plane (flat knitting) and all of the stitches are formed by individual yarns row by row (courses). The needle plane will have a fixed width, but can produce a fabric in any length parallel to the needle plane. Warp knitting can be used to produce fabrics at high speeds and is used for many industrial applications (ranging from fabrics for the automotive and aerospace industries, to sportswear). Warp knitting machines have a large footprint and are expensive so see limited use in academic research.

For weft knitting, loops are formed in the horizontal direction (courses) with the stiches in each course generally being formed from the same yarn. While a slower process, weft knitting (flat-bed knitting) allows significant control over the geometry of the final product allowing for 3D-structures to be created. Weft knitting machines use less floor space than their warp knitting counterparts and flat-bed knitting machines can be found at many academic institutions, leading to this type of knitting being employed to incorporate functional fibres and yarns into fabric structures in some instances.

Knitting is a versatile technology, and many factors can affect the final fabric structure and its properties including the stich length, machine guage (affecting stich density) and architecture.

5.1.3 Bonded Fabrics

Bonded fabrics are created using fibres that are bonded together using a chemical, mechanical, or thermal processes.[282] An advantage of this technology is that the fibres are used directly, and yarns do not need to be formed (as is the case for knitting and weaving); However, they demonstrate poor bending characteristic due to poor shear properties.

Thermal bonding can occur when either thermoplastic fibres or a mix of thermoplastic fibres and other fibres are employed. Mechanisms include calendar bonding (pressing the fibres between heated rollers), through air bonding (the fibre mesh passes through an oven), radiant heat bonding (where an infra-red heat source is applied), and ultrasonic bonding (where high-frequency vibrations are applied, which convert into thermal energy). Powder bonding is also a variant of thermal bonding where thermoplastic powders are applied as a bonding agent. Mechanical bonding requires the entanglement of the constituent fibres. Stich bonding sees the fibres held together by stitching a continuous filament throughout the structure.

5.1.4 Common Forms of Textile Post-Processes

Once fabricated textiles commonly undergo post-processes to achieve different appearances and functionality. Most finishing techniques hold limited importance to current E-textile innovations and their discussion is well beyond the scope of this review. An exception is printing: printing is a common finishing method used by the textiles industry to apply a colour or patterns to a fabric. At present, the common printing strategies include stamp printing, stencil printing, screen printing, and digital textile printing. It should be emphasized that the surface roughness and hydrophobic properties of the textiles have a profound influence on both the printing process and the print quality. Specifically, a smooth surface typically facilitates superior ink adhesion, enabling more accurate printing. Conversely, a rough surface tends to unevenly absorb ink, leading to potential spreading of the printed image; Hydrophobic surfaces present inherent challenges for the setting and adherence of water-based inks.[283] The enhancement of textile roughness or hydrophobicity can be achieved through surface treatment engineering or functional coating.

Other post processes see the textile used as the base onto which other materials are applied. In the area of electronic textiles, the application of lamination, coatings, and conversion into composite materials hold some relevance. Embroidery and couching have also been employed.

Lamination is a technique where different layers are bound together, normally a textile and a polymer film. This can improve the durability of the fabric. Depending on the materials laminated other properties can be introduced to the textile using this method such as water resistance. Materials are typically bound together using a thermal process or an adhesive. Coatings can also be applied to textiles, again this is often used to enhance durability and to instill new properties. Chemical and polymer coatings can be applied in a variety of ways making this an expansive topic, the simplest coating technique being spreading the coating over the textile. Textiles can also be used as pre-forms for composite materials; here a textile is infused with a material (often a polymer resin) to create a structure that is strong and light-weight. Fibre-glass is a common example of a textile composite. Couching is a type of embroidery where embroidery stiches are laid across another material to hold it to the textile.

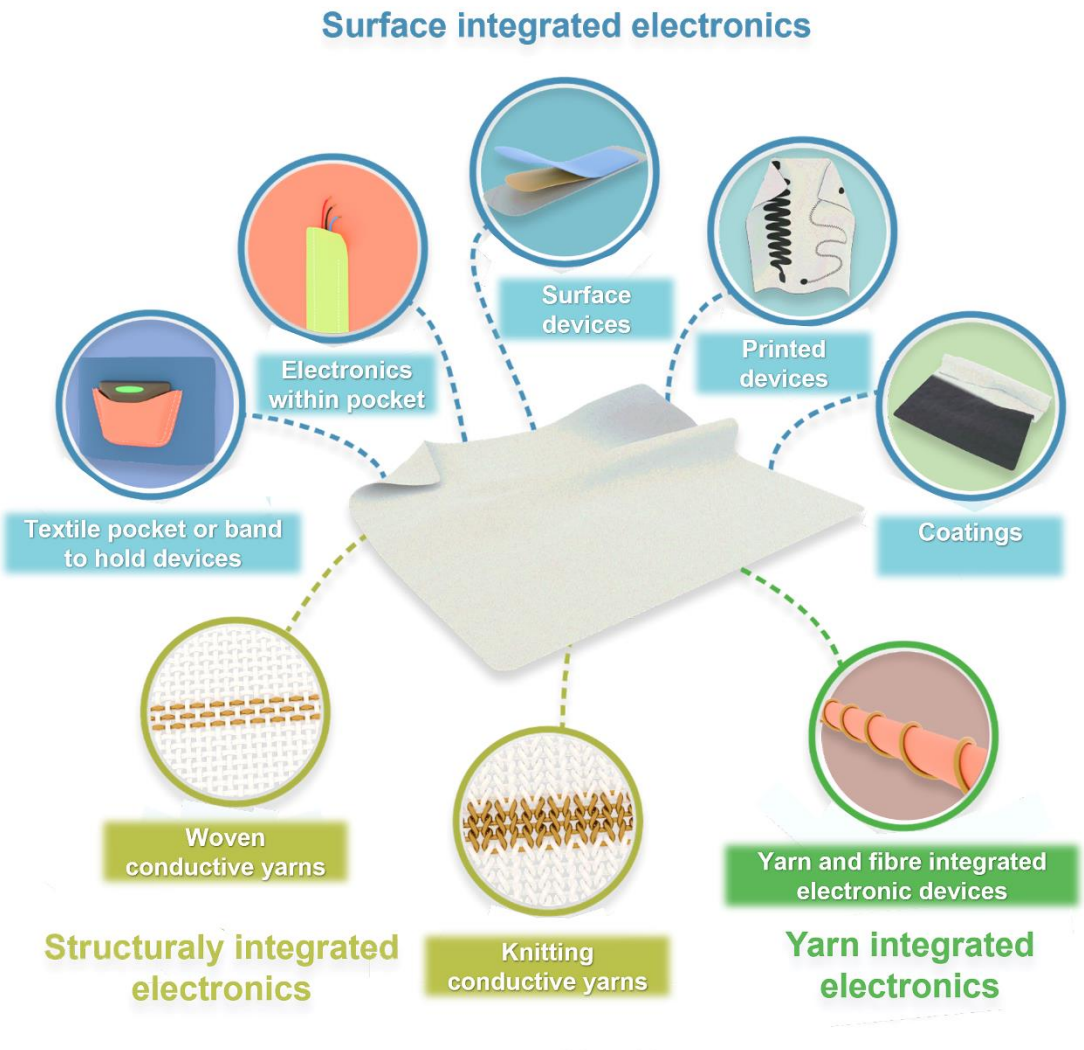

Fig 9. Schematic illustration of key methods used to create electronic fabrics and textiles.

5.2 Key Methods for Creating Electronic Fabrics and Textiles

Fundamentally an electronic textile is a textile where electronic functionality has been incorporated either through the attachment of electronics or integration of electronics during the production process. The method for integrating the electronics will affect the appearance and properties of the resultant textile, so the suitability of using different technique will depend on the intended application. While this review is focused on the integration of fibre- and yarn-based devices to create electronic textiles only, a brief overview of other means of integrating electronics into textiles will be provided for completeness. More extensive reviews on the historic development of electronic textile,[284] and electronic textiles more generall,[285-287] are available elsewhere.

Integration methods for electronics with textiles can be separated into three broad categories, with various key sub-categories, as depicted in Fig. 9. Surface integrated electronics represent the earliest development of electronic textiles, where the textile is used as a scaffolding on which electronics are mounted. This represents an electronic textile where a textile has electronics mounted onto it to create a wearable device. Many modern wearables use a textile band or pocket to hold a device. The invention of heated garments represented a large developmental step in the field. Most heated textiles have a resistive heating element sandwiched between two textile layers (essentially a pocket). E-textiles that use this integration technique include some concept garments, such as the Levi's ICD+ jacket by Philips and Levis, where rigid electronics were held within pockets in the jacket, with cabling hidden within the jacket's structure.

Mounting devices on the garments surface is a typical methodology utilized by the hobbyist community with companies such as Adafruit and Electro Fashion selling small electronic boards that can be sewn onto garments to add electronic functionality. In a commercial space these textiles are more sophisticated with (typically) flexible electronics being attached to the textiles. Typical commercial products of this type include t-shirts with illuminated panels and heart rate monitors (typically bras or straps) where conductive polymer electrodes are bonded to the fabric. These attached electronics can be fabricated using any electronics fabrication technique; however, some products have been developed specifically for

use with textiles. The DUPONT™ INTEXAR™ was developed as a highly stretchable conductive paste to allow for the screen-printing of electronics to laminate onto fabric. For example, this has been employed to create piezoresistive breathing sensors and sEMG electrode in the academy.[288, 289]

Coating textiles to achieve electronic functionality has seen an increase in interest in recent years given the rise in graphene technology. Examples include textiles coated in reduced graphene oxide being used for activity monitoring as shown by Karim et al,[290] and strain sensing and as a component of supercapacitor as demonstrated by Afroj et al.[265] These textiles have fairly normal properties and have been demonstrated to be washabl.[265]

Modern advances have also seen electronics printed directly onto textiles using both screen-printing and ink jet printin.[291, 292] Electronic functionally can also be accomplished through the knitting and weaving of conductive elements. Starting with innovations by the Massachusetts Institute of Technology (MIT) and the Georgia Institute Technology,[293, 294] electronic fabrics where functionality was achieved through the incorporation of conductive fibres (normally metal, conductive polymer, or carbon nanotube based) as part of the fabric fabrication process have grown in traction. This type of technology can be used to construct devices that only require a conductive area to function and is largely limited to electrodes; for example for electrocardiogram measurements,[295] switches and pressure sensors,[295] stretch sensors,[296] and for heating.[297] The type of fabric employed is normally dependent on the functionality sort. For example, knitted fabrics are often preferred for stretch sensors (given the inherent stretchability of knit), however examples of both weaving and knitting being used for the other sensors, devices or electrode types are present in the literature.[298, 299]

The final method of electronics integration is the incorporation of yarn or fibre-based electronics, which is the focus of this review. These fall into two categories, where the electronics are completely integrated within a single yarn or fibre or when yarns and fibres with electronic functionality are brought together during the fabric fabrication process to create a final, functional device (for example for some fabric solar panels).[206, 300] In the former case, the technology should be fabric agnostic however weaving is predominantly used as these yarns and fibres are often too thick or brittle to form tight loops. In the latter case weaving is also most common, in part likely due to the difficulties in knitting some of these devices but also as

the weave is often used to introduce a counter-electrode and the functionality of the device would change if large relative deformations were possible. Electronics textiles have also seen limited use in composites. For example, Irfan et al. demonstrated an electronic textile in cement structures in 2022 for monitoring mechanical loading.[301]

In the cases where the electronics are integrated as a post-process and not during the physical textile construction (which involves knitting or weaving) the inherent textile properties of the relevant material will change, such as the breathability and drapability. In examples where pre-made electronics are added to the textile, such as through the insertion of electronics into a pocket, or the lamination of a device onto the surface of a textile, the presence of the electronics will intrinsically change the feel of the textile, and often the appearance. Some extent this is also true for printed devices depending on the materials used or encapsulation employed. Coated textiles, and electronic textiles formed through the knitting or weaving of conductive materials can result in textiles with fairly normal properties; however not a normal appearance. Fundamentally however this type of electronics integration technique on it's own can only be used to create electrode-based devices (heaters, electrodes, strain sensors, etc.).

The key advantage of using yarn and fibre type electronics to create E-textiles is that they can be given a wide range of functionality and that they can be incorporated into the textile during the physical textile construction process, resulting in a textile with largely normal properties. This review therefore focusses on yarn and fibre-based electronics exclusively.

5.3 Examples of Integrating Fibre-Based Electronics into Textiles

At the fibre level, employment of carefully selected functional materials facilitates the creation of smart electronic fibres. Through tailored configurations and subsequent integration, these fibres endow fabrics with intelligent electronic capabilities, establishing a promising wearable platform for diverse applications in multi-mode sensing, human-machine interaction, machine learning, and other interdisciplinary fields. A comprehensive summary and analysis of the selection of functional materials, and corresponding fabrication techniques, is presented in Section 2 and 4 of this review. Within this section, our primary emphasis is on how electronic fibres enable intricate functionalization in smart electronic fabrics through the evolution of architectural structures.

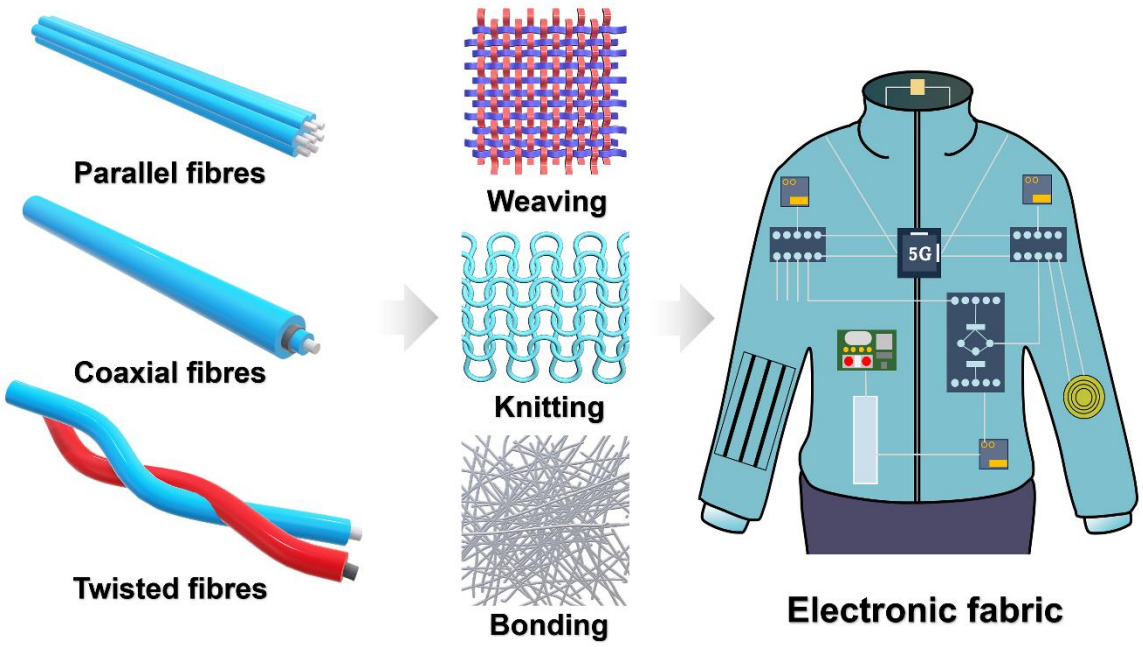

Fig 10. Schematic illustration of the ways of integrating functional fibres into smart and electronic fabrics: weaving, knitting, and bonding.

Currently, the fibre configurations categorically include parallel, coaxial, and twisted configurations, as illustrated in Fig. 10. The parallel configurations are notably common within thermally drawn fibres targeted for sensing and actuation, and the domain of energy storage fibres or textiles.[33, 302, 303] Supercapacitors store energy through a dual electrode layer, making a parallel structure ideal for designing supercapacitor fibres.[304] Nevertheless, the necessary packaging and the limited interfacial area between the electrolyte and electrode present obstacles to further enhancing the capacitance. The strategy of twisting two fibre electrodes has demonstrated to be effective for enhancing electrochemical performances of supercapacitor fibre.[305] It is contributed to a significant increment in the effective contact surface area at the interfaces, and enhancing the interaction of active materials. Unfortunately, the interface contact area is still limited. In addition, the interface is prone to separation failure under continuous bending, which will significantly reduce the energy storage capacity of the fibre. This dilemma gave birth to the third fibre configuration, that is, the coaxial configuration. For battery fibres, the construction involves the sequential assembly of the core fibre electrode, electrolyte, and outer electrode in a layered fashion. It can optimize the interfacial interaction area, thereby enhancing the electrochemical performance exhibited by the system. The coaxial configuration strategy is also effective for fabricating high-performance supercapacitor fibres. In addition, the

coaxial core-shell structure also brings inspiration to the design of high-performance energy harvesting fibres. This design is also prevalent in the design of electronic and optoelectronic fibres due to its ease of fabrication and effectiveness in encapsulation. In general, a paramount challenge of coaxial configuration strategies is the precise assembly on fibrous substrates with high aspect ratios. By precisely controlling the dimensions and materials of different layers in the fibre, it is possible to optimize the interaction between active materials, leading to improved performance in energy storage, sensing, optical or optoelectronic applications.[24, 33]

In fact, the electronic fibres aforementioned are seldom employed individually; rather, they are frequently incorporated into textiles through textile construction techniques, thereby actualizing the conceptualization of smart electronic fabrics. As shown in Fig 10, the three core textile construction methods can be used to integrate functional fibres into textiles, with the literature showing knitting and weaving being used to accomplish this.

Weaving has been the most commonly used method for incorporating functional yarns and fibres into textiles. All three fundamental types of weaving have been employed to create electronic fabrics using functional fibres or yarns. An example of different weave types being used in the construction of an electronic fabric device includes a solar and mechanical energy harvesting fabric. Plain, stain, and twill weave structures are all explored and the function of the device evaluated for each structure.[306] A further example is an acoustic sensing fabric, where a fibre-based microphone was integrated into a fabrics as a weft yarn in a plain weave structure.[4] An example of a double-cloth structure being used to integrate functional fibres into a fabric, creating a fabric with temperature and pressure sensing capabilities. Here the weave structure is intrinsic to the function of the pressure sensing element of the fabric.[307]

An example of electronic functional fibres being incorporated into a fabric through knitting includes a fabric. that integrated both a triboelectric nanogenerator and supercapacitors into a knitted fabrics where the functional fibres were used to form the knitted stitches.[308] As opposed to directly using a functional fibre to form loops, fibres have also been incorporated into a rib or interlock knitted structures using an inlay technique; this is where the functional fibre is essentially held between two layers of the knitted structure. An example of this is shown in work that developed knitted fabrics integrated with piezoresistive fibres for pressure sensing.[309] The incorporation of functional fibres in this way will subject the fibres to less server

mechanical stresses than using them to form loops. A similar concept to inlaying is to knit miniature tubes within a structure and incorporate a functional fibre as a post-production process. This concept has been utilized to integrate various types of electronic yarns into knitted structures, including electronic yarns with embedded microphones.[310] While some examples do exist, overall knitting has seen limited use in the construction of fabrics using electronically functional fibres and yarns.

Non-woven fabrics have seen use for creating electronically functional devices particular for energy harvesting applications. An example includes a solar cloth, where electrospinning was utilized to create a non-woven cloth solar cell.[311] A further example is a piezoelectric–pyroelectric nanogenerator that is comprised of a PDVF membrane (electrospun), a thermoplastic polyurethane (TPU) layer (also electrospun), a carbon nanofiber membrane (electrospun), and a further carbon nanotube layer.[312] The authors are not aware of any examples of complete functional fibre devices being integrated into fabrics using bonding techniques.

Beyond knitting and weaving other techniques have been employed to integrate functional fibres and yarns within fabrics. Embroidery techniques where the functional device has either been used as the embroidery yarn or embroidery yarn has been used to affix a functional yarn in place on the surface of a fabric can be used. An example includes the attachment of an electronic yarn with embedded LEDs onto a stretchable unitard.[313] Here the electronic yarn itself is not embroidered but embroidery is used to fix the yarn in place.

Although the evolutionary integration of functional fibres endows fabrics with complex functionalities, it is insufficient for achieving high-performance electronic fabrics and textiles. Additional post-processes and component integrations are crucial. For instance, though thermoelectric fibres convert temperature differences into voltage, the performances of resultant thermoelectric fibres and fabrics are typically poor without further modifications. Post-processing technology is essential for achieving wearable systems with efficient thermoelectric conversion, including the incorporation of heat sinks and proper electrical connections (Table S2). Specifically, (1) heat sinks manage heat flow and maintain temperature gradients; (2) series connections of p-type and n-type semiconductor fibres maximizes voltage output; (3) proper electrical connections require the use of highly conductive threads or coatings; (4) annealing eliminates defects and enhances carrier mobility; and (5) densification reduces

porosity and increases density. Collectively, these additional post processes are crucial for effective heat-electricity transfer. Therefore, while the fabrication of modern fabric electronics can highly rely on functional fibre integration, substantive post-processing also deserves significant attention.

5.4 Critical Analysis and Comparison of Current Integration Techniques

As described above, beyond the fibre route, there are post-processing methodologies such as printing, coating, laminating or embedding of electronic elements. Screen printing and inkjet printing allow conductive ink to be printed directly onto fabric substrates, offering high-resolution and intricate patterns. However, conductive inks exhibit limited adhesion and durability, particularly under repetitive mechanical bending and scrubbing. The surface coating technique is a straightforward approach that applies functional materials to traditional fabric surfaces and is versatile across substrates. While offering ease for mass production, it has a drawback similar with printing methodologies, wherein the functional layer is susceptible to flaking or degradation upon mechanical deformation, washing, or long-term usage. Laminating and embedding techniques enable the direct integration of diverse electronic components onto or within fabric substrates to create intricate circuits capable of executing specific functions. While this avoids flaking, it significantly reduces air permeability and flexibility. In contrast, the fibre route can seamlessly integrate functional fibre units into the fabric structure without compromising flexibility and breathability of the textile. Moreover, the fibre unit is highly designable, allowing for tailored adjustments to its mechanical properties, electrical conductivity, and even self-healing capabilities to adapt with diverse application scenarios. The fibre route's versatility supports a range of functions, including sensing, data processing, energy harvesting, energy supply, and actuation, enabling multifunctional fabric electronic devices. Nevertheless, like above fabrication techniques, reliability remains a concern, as damage and failure of electronic components are challenges. The production of high-performance electronic fibres remains complex and costly, and daily maintenance and power management are additional issues. Combining the advantages of fibre route with other integration methods may be a crucial for advancing future electronic fabrics and textiles.

6. Functions and Applications of Smart Fibres Enabled Fabrics

Groundbreaking discoveries over the course of the 20th and 21st centuries in multiple fields such as materials, advanced manufacturing and microelectronics have led to the quick development of the interdisciplinary research in functional fibres. It has facilitated the iterative and dynamic evolution of fabrics. Fibres or fabrics, yet involved in civilization long ago, remain less-developed in terms of functionality. The study in functional fibres has bring up the concept of smart fibres and fabrics which are the types with functions from sensing, communication, display to energy harvesting, and take a step further, from having a single function to fabrics with systematic attributes that integrated of multiple modules. Smart fibres and fabrics can be seen as 1D miniature of conventional devices and may open up to a new generation of smart devices and systems that seamlessly integrated into daily life. Proactive sensors, interactive communicators, data processors, executors and power supplies are the five major perspectives of the new form devices. In this section, we highlight the smart fibres enabled fabrics from these five major perspectives.

6.1. Environmental Sensing

Fabrics are the first and usually the only barrier for human body to the environment. Machines and robots can be dressed as well. The fabrics are commonly expose directly to the environment, making them suitable media for sensing various stimuli, including light, sound, touch, temperature, humidity and more. Fibres and fabric sensors targeting different stimuli are introduced below.

Fig 11. Environmental sensing: (a) Thermally-drawn light-emitting and light-detecting fibres. (a-i) Commercial chips are integrated into a single fibre via convergence thermal drawing technique. (a-ii) Schematic of the working mechanism of light-emitting and light-detecting fibres and (a-iii) The image of a light-emitting fibre. (a) Reproduced from ref. 206 with permission from Springer Nature, copyright 2018 and 2019. (b-i) Acoustic fabric woven from cotton and acoustic fibres made of piezoelectric materials. (b-ii) The human ear-inspired acoustic fibric detects vibrations as low as 40 dB (a quite library environment). (b-iii) A photograph of the Twaron-weft acoustic fibre containing one fibre transducer (6.7 cm in length) woven in the weft. (b) Reproduced from ref. 4 with permission from Springer Nature, copyright 2022. (c) A core-shell fibre consisting of a liquid metal core and elastomer cladding. (c-i) The core-shell fibre is capable of sensing touch, in terms of pressure and position by time-domain reflectometry and been monitored in real time (c-ii). (c) Reproduced from ref. 154 with

permission from Springer Nature, copyright 2020. (d) While the liquid metal core fibre needs a power supply to sense touch, a self-powered nano- or micro-patterned fibrics sense touching in the absence of a power supply (d-i). The surface pattern enhances the triboelectric effect and thus enlarge the electrical signal generated from touching a fabric and turn the fabric a self-driven touching sense (d-ii, d iii). (d) Reproduced from ref. 258 with permission from Springer Nature, copyright 2020. (e) A polymer fibre consisting of aggregation-induced emission (AIE) molecules that is used as humidity sensor. Swelling of the fibre is induced by environmental moisture and thus activating intramolecular motions of AIE molecules to result in fluorescence, which has a linear response in emission wavelength to humidity. (e) Reproduced from ref. 318 with permission from China Science Publishing and MediaLtd. copyright 2021. (f) A fibre temperature sensor utilizes the thermochromic effect. The fibre color straightly reflects the environmental temperature changes. (f) Reproduced from ref. 319 with permission from Springer Nature, copyright 2023. (g) A colorimetric gas-sensing yarn that senses toxic gaseous substances and result in eye-readable outputs. (g) Reproduced from ref. 320 with permission from American Chemical Society, copyright 2020. (h-i) The embedding of fibre optics within fabrics for strain sensing. (h-ii) Optical fibres-embedded fabric for human respiration monitoring. (h) Reproduced from ref. 321 with permission from Springer Nature, copyright 2020.

6.1.1 Light Sensing

Fibre photodetectors, whether used independently or woven into fabrics, can be employed for applications that require the detection of light. For example, they can be utilized to observe surroundings, measure light conditions, capture images, and more. Challenges of constructing light-sensing fibres remain in integrating semiconducting, conducting, and insulating materials into a single fibre with intimate interfaces. Various techniques including film attachment, coating and hydrothermal growth have been studied to achieve the fabrication of fibre photodetectors but with limited fibre lengt.[314-316] Thermal drawing method, utilize the preform-to-fibre process, produces kilometer-level ultralong fibre in a single draw. Due to the viscous state of materials during the fibre formation, intimate interfaces between each material are achieved in resulting fibre photodetectors. However, similar rheological characteristics of each material are required to enable co-drawing. This requirement limits the selection of materials. Due to the low softening points of polymer materials, Sn, In, or low melting-point metallic alloys are the options for electrodes. The selection of semiconductors is highly limited. Chalcogenide glasses are one of the few options as the semiconductor due to their low processing temperature.[34, 202, 203] Another strategy was reported by Michael et al. in 2018,[206] which incorporated commercial planar-type microchips into single fibre. This strategy

commenced with the preparation of a macroscopic preform, which was a polymer slabs with machined grooves to place discrete planar-type microchips in addition to the hollow channels prepared for metal wires insertion. Two metal wires were continuously fed into the preform along the hollow channels during the thermal drawing. At necking region where the preform experiences elongation, the metal wires moved towards the embedded microchips due to the displacement caused by the transverse contraction. Although in preform a layer of polymer separates the metal wires and the microchips in the preform, the contractive forces at necking region help the metal wires squeezes out the separating polymer layer and establish the electrical contacts to the microchips. A ladder-like in-fibre structure consisting of two wire electrodes connected by a series of parallel microchips located in the center can be achieved in a single fibre through this process (Fig. 11a-i and a-ii). Various microchips can be incorporated into a fibre form factor via this method, including light-emitting fibre and light-detecting fibres. Spontaneously, the fibre photodetectors inherited the sensitivity of planar-type photodetectors. Identical rectifying behaviors were observed on the fibre photodetectors. With reverse bias applied, the photocurrent of the fibre photodetectors raised for approximately four orders of magnitude when subjected to illumination. A significant enhancement in photosensitivity by orders of magnitude was observed on these microchips-embedded fibres, compared to the fibre photodetectors with chalcogenide glasses as semiconducting components. Notably, the fibre photodetectors were mechanically robust. They maintained stable performance on curved surfaces, bending at various radii, and survived multiple laundry cycles in a commercial washing machine, highlighting the capability of this fabrication method for fabric-oriented applications.

6.1.2 Sound Sensing

Vibration or sound is another significant source of environmental stimuli. As a source, it can contain abundant information including human activities, machinery, moving objects and more. As a tool, it can be used to detect the integrity and performance of structures, machines, and living organisms. An acoustic sensor in fibre form factor offers the adaptability to various surfaces by conforming to irregular-shaped objects and surfaces, and the potential for large-scale coverage while maintaining desired features like lightweight and permeability. Acoustic

fabric may pick up vibration signals from the sources that are inaccessible to their traditional rigid counterparts, opening up new avenues for innovation in multiple applications including environmental monitoring, construction maintenance and wearable electronics. PVDF and its copolymers such as P(VDF-TrFE) are the most commonly used piezoelectric material in the fabrication of acoustic fabrics. For example, Su et al. in 2021 introduced a method of fabricating non-woven acoustic fabrics electrospinning.[317] PVDF polymer and piezoelectric barium titanate particles were mixed to form a polymer-based precursor for the electrospinning. The authors conducted a comprehensive analysis on the PVDF-barium titanate mixture *via* phase-field simulation and experimental study to guide the performance-enhancing strategy for the electrospun fabrics. PVDF-based acoustic fibres were also fabricated *via* the thermal drawing method. Yan et al. in 2022 reported a new strategy, inspired by human ear, for designing high-performance acoustic fabric (Fig. 11b-i).[4] A simple sandwich structure of electrode-piezoelectric composite-electrode was established in a soft elastomer cladding *via* fibre thermal drawing. There were three features in the designing for the acoustic fibre: i) the fibre cladding was much softer than the piezoelectric domain. This combination turned out to be helpful in stress concentration at the piezoelectric domain, which efficiently convertd vibrations into electrical signals. ii) the piezoelectric domain was placed off center, which again enhanced the sensitivity for vibrations as the sensing domain was away from the neutral axis. iii) Pores were induced around the rigid $BaTiO_3$ nanoparticles as only P(VDF-TrFE) deformed during the thermal drawing. These pores in the subsequent poling process improved the numbers of dipoles and thus increased the electrical outputs that were formed through vibrations. Woven into a shirt, the acoustic fibres can turn a passive shirt to a functional shirt that detected environmental vibrations, including wind, sound and claps (Fig. 11b-ii and b-iii). Dias's team created an acoustic sensing yarn by integrating commercial microelectromechanical system microphones into yarn.[310] The close proximity of the sensing elements to the ears provides an accurate measure of sound levels someone is exposed to. The yarns are integrated into a knitted helmet cover to create a functional acoustic sensing prototype.

6.1.3 Mechanical Sensing

The sense of mechanical stimuli is one of the five senses crucial not only for humans but

also for all living creatures. In the future, this ability will play a critical role in the development of smart robotics. While electronic skins are typically two-dimensional, the development of a one-dimensional fibre capable of mechanical sensation is essential for enabling novel applications. Moreover, such fibres can be utilized as raw materials for manufacturing two- or three-dimensional fabrics. Various types of mechanical-sensing fabrics, including resistive, capacitive, piezoelectric, and others, have been reported. [154, 259] It is worth nothing that such fibrics can be fabricated with liquid metal transmission lines, which are capable of detecting multimodal deformations of complex moving patterns *via* time-domain reflectometry. As distributed probes of multimodal deformations, the liquid metal transmission line is prepared *via* thermal drawing. An ultralong and uniform elastomer fibre with complex cross-sectional architectures has been fabricated for use as transmission lines (Fig. 11c-i). Through the time-domain reflectometry analysis, multimodal deformations, including pressing, stretching, and multi-point pressure, could be precisely detected and visualized in real-time (Fig. 11c-ii). This transmission line achieved a force resolution of 0.2 N, a spatial resolution of < 6 cm, and a strain resolution of 0.25%, realizing electronic fabrics capable of sensing touch.

The efficiency of picking piezoelectric signals up by fabrics is largely affected by contacting area and morphology of the fibre surface. As soft and conformal bases, fabrics have the advantage of receiving large contact area on the monitored object. However, single fibres, as the base unit of the sensing fabric, especially for thermally drawn fibres, are usually smooth on the surface and weak in surface morphology tailoring. Wang et al. reported an *in-situ* imprinting method targeting at thermally drawn fibres.[258] Various designed patterns with submicron resolution were directly printed on the fibre surface during the fabrication process (Fig.11 d-i and d-ii). The scalability of this method was demonstrated through the fabrication of a 300-meter-long fibre with fully printed patterns. Additionally, the versatility of this method was showcased through its application to several materials. Fabrics consisting of micropatterned fibres have exhibited improved piezoelectric signals (Fig.11 d-iii).

6.1.4 Moisture Sensing

Sensing environmental water vapor, which is ubiquitous, is essential for maintaining industrial systems and sustaining living organisms. A desired method to develop a sensitive

humidity sensor involves mixing aggregation-induced emission (AIE) molecules with a water-capturing polymer. Jiang et al. reported a fibre humidity sensor prepared by solution-spinning (Fig. 11e), taking the advantage of intramolecular motion of donor-acceptor based AIE molecules, a fibre which was sensitive to moisture was fabricated.[318] The fibre absorbed water vapor and by polymer swelling, the binary effect of AIE and the twisted intramolecular charge-transfer (TICT) was triggered *via* the regulation of intramolecular motions. Emissions in different wavelengths were generated, which was related to local humidity and can be used to quantify and map variations of it. The micro-/nano-fibrous structure of the fibre sensor brought it favorable features like mechanical robustness, flexibility, and high surface-to-volume ratio, which were beneficial for high and fast response to environmental moisture. Assembly of the spun fibre sensor could form various structure, including coils, meshes and fabrics, which was adaptive to diverse configurations.

6.1.5 Temperature Sensing

Another critical environmental signal is temperature. From enzymes activities to machine reliability, temperature plays a pivotal role in a myriad of biological and artificial systems. Traditional temperature sensors meet the difficulty in complex situations and for large-scale monitoring with high spatial resolution. Robert et al. in 2023 reported a fibre temperature sensor that consisting of patterned elastomer doped with functional dye.[319] Temperature shifted augment the light chromaticity and intensity as it traveled through the fibre, resulting in a directly readable sensor output revealing the environmental temperature (Fig. 11f).

6.1.6 Gas Sensing

A visually readable sensor is favored for applications that needs a simple and rapid detection of signals. Such a sensor can be used for the detection of toxic gaseous substances in environment. A fabric colorimetric gas sensor could warn the user in a quick manner. The application of conventional colorimetric sensors is limited by the low-sensitivity, poor selectivity and detection for trace toxic gaseous substances. A meter-scale synthesis of a fabric colorimetric sensor was reported by Kim et al. in 2020.[320] The authors prepared the sensor with ionic liquid-functionalized composite nanofiber yarn (Fig. 11g). Being used as a single fibre sensor, it showed enhanced sensitivity that detected H_2S as low as 1 ppm, which was attributed

to the high surface area and porosity. It can be sewn into patterned fabrics for a wearable toxic gas alarm.

6.1.7 Strain Sensing

One fibre optic sensing scheme applicable in strain monitoring involves a notched polymer optical fibre (POF), as depicted in Fig. 11h-i, where the POF is bent to form a loop.[321] The POF itself serves as an intensity-based strain sensor, eliminating the need for complex measurement equipment. Enhancing bending sensitivity in POF strain sensors has been achieved by selectively removing the cladding layer adjacent to the fibre core. The notched surface alters light reflection, thereby increasing strain sensitivity. Additionally, applying pretension to the POF further improves the sensitivity. Placing the loop top at the notched section further enhances the POF's sensitivity.

A strain-sensitive fabric can be woven with embedded POF strain sensors and conventional threads (Fig. 11 h-ii). The fabric was used to create a flexible belt capable of monitoring of human respiration. Respiratory curves obtained from the breath belt showed strong correlation with clinical monitor measurements. The breath belt shows potential for monitoring human respiration in MRI environments due to its immunity to electromagnetic interference. Interestingly, fibre optic sensing scheme has found applicability in the construction industry, particularly for concrete, which stands as one of the most used structural materials, yet remains opaque to visible light range.[322] The use of optical fibres for strain sensing enables large-scale sensing capabilities, allowing for the monitoring of entire construction blocks or segments.

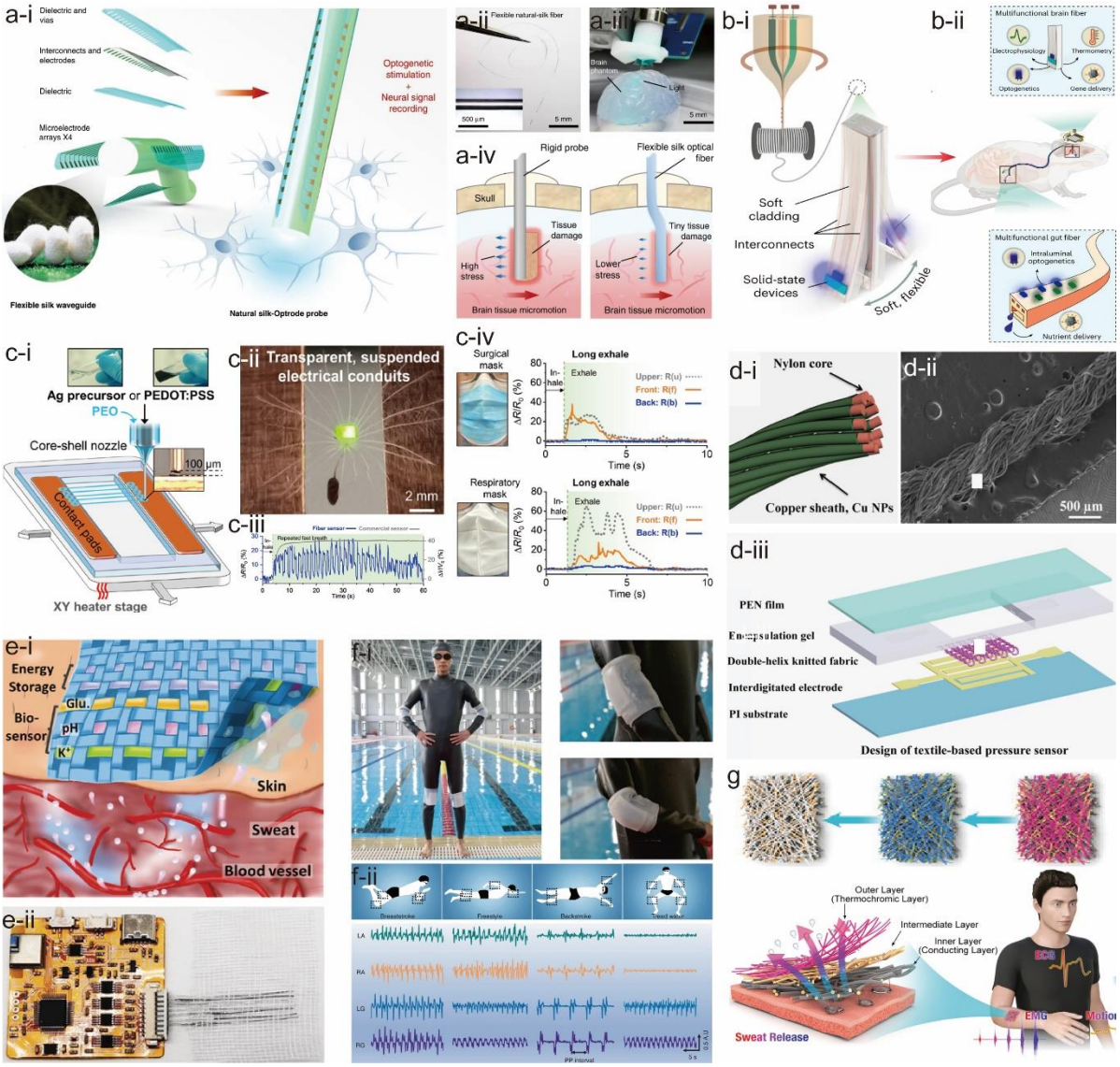

Fig 12. Physiological sensing. (a) A silk-based fibre for neural recording. (a-i) The fibre is prepared with silk protein and integrated with multiple electronic components. (a-ii, iii) The flexibility of the neural fibre allows recording in freely behaving animals. (a-iv) The neural fibre actively adapts to the brain after implantation by reducing its own mechanical stiffness with high fidelity. (a) Reproduced from ref. 325 with permission from Springer Nature, copyright 2022. (b) A thermally drawn fibre probe with multiple solid-state devices for the modulation of neural circuits. (b-i) Fabrication and (b-ii) functions of the fibre probe. (b) Reproduced from ref. 326 with permission from Springer Nature, copyright 2023. (c) Functional mask for breath monitoring via inflight fibre printing. (c-i) The printing process and (c-ii) the printed fibre mesh. (c-iii, iv) Commercial masks integrated with printed fibres are used to monitor breath. (c) Reproduced from ref. 327 with permission from American Association for the Advancement of Science, copyright 2020. (d) Pulse monitoring by fabric sensors. (d-i) Schematic illustration of the fabric made by the fibre with a core-sheath structure. (d-ii) SEM images showing the surface morphology of the fibre. (d-iii) The design of sandwiched textile-based pressure sensor. (d) Reproduced from ref. 328 with permission from Wiley-VCH, copyright 2022. (e) A fabric integrated with reduced graphene oxide/tetra-aniline fibre for continuous monitoring of human sweat. (e-i) The fabric sensor works as a patch attaching to

the skin and (e-ii) connected to an interface board. (e) Reproduced from ref. 329 with permission from Wiley-VCH, copyright 2023. (f) A fabric nanogenerator that can be stitched onto daily wearing such as swimming suit (f-i) and monitoring human body multi-position motion both on the ground and underwater (f-ii). (f) Reproduced from ref. 330 with permission from Springer Nature, copyright 2019. (g) Skin electrodermal activity monitoring via functional fabric. (g) Reproduced from ref. 331 with permission from Wiley-VCH, copyright 2023.

6.2. Physiological Sensing

Fabrics are in direct contact with the skin, which makes them suitable media for monitoring physiological signals. Continuous sensing and recording of various physiological activities are important for health assessment, disease diagnosis, preventive care, and many more. Multiple physiological information can be collected *via* fabrics, including neural activities, respiratory rate, heart rate, sweat content, muscle activity and more.

Fibre structures are preferred for neural probes for several reasons. First, fibres are typically more flexible and less invasive, compared to their counterparts. This is an importance feature for neural probes, as it allows the fibres to move with the neural tissue, reducing the relative displacement between the probe and the brain for less damage to the neural tissue. This leads to an improved long-term reliability and less inflammatory response. Second, the fibre form factor allows the fibre sensors to integrate with multiple channels while maintaining a thin thickness. This high-density capability enables fibre neural probes to be used in a single strand or in a bundle for simultaneous recording for a large number of neurons. Further, fibre neural probe is suitable for the integration of waveguide, allowing for the study of optogenetics on neural activities modulation. Pioneering work demonstrate the multifunctionality of thermally drawn fibre probes made out synthetical polymers and metals. [323, 324] Natural materials can offer biocompatibility and environmentally friendly characteristics. Zhou et al. fabricated high-quality silk fibre from preconcentrated silk solution, addressing the long-lasting air bubble issue in silk fibres.[325] The microelectrode arrays were fabricated on the fibre surface using standard microfabrication processes (Fig. 12a-i). The resulting silk fibre neural probe is both flexible and biocompatible to align with the soft nature of brain tissue (Fig. 12a-ii-iv). It can be precisely placed into the brain for multichannel neural recording. The silk component was crucial for the assembling of the probe, as it offered high light transparency, outstanding biocompatibility, and adjustable mechanical properties. The mechanical compatibility of the silk-based fibre neural

probe stemmed from the hydration of silk, which reduced its stiffness to match the brain tissue micromotion. This property minimized stress and reduced the likelihood of damage to the brain tissue, ensuring stable long-term neural recording by the silk fibre neural probe.

One step further than recording the neural activities, fibre neural probe can be also used in the modulation of neural circuits. In 2023, Polina et al. reported a thermally drawn fibre probe that allowed the wireless modulation of gut and brain neural circuits (Fig. 12b-i).[326] Taking the scalability and mechanical versatility of thermally drawn fibres, the authors combined multiple microelectronic chips and optical waveguide into a single strand of fibre, to deliver light for optogenetics. The modulation of neural activities by this fibre neural probe was validated by modulation of mesolimbic reward pathway in the mouse brain. In addition, the wireless control of sensory epithelial cells was also demonstrated by applying the fibre probes in intestinal lumen, a region that poses anatomical challenges for access. The wireless modulation of gut and brain neural circuit was shown by the evocation of reward phenotype *via* optogenetic stimulation of vagal afferents from the intestinal lumen in untethered mice (Fig. 12b-ii).

Face mask is usually made of non-woven fabrics and plays an important role in the periods of globally outbreak of acute respiratory disease. Except the protection from microbes and dusts, masks are also a suitable candidate to monitor breathing. The breath rate, breath content reveals one's health conditions. To integrate sensors onto a mask, the sensors must be mechanically compatible, requiring them to be soft and flexible, as mounted rigid sensors affects the respiratory by limiting the movement of the mask. Also, for the comfort of users, the sensor should be lightweight and permeable. Thus, fibre-shaped sensors are naturally desired for integrating into functionalized masks. Zhou et al. reported an inflight fibre printing method to fabricate high-sensitivity, low-cost functional masks to monitor respiration rate and moisture in breathing (Fig. 12 ci-ii).[327] The printed fibre sensor can be readily attached to any type of disposable masks and showed a high sensitivity on par with commercial humidity sensor (Fig 12. ciii-iv).

Pulse rate is a critical indicator of heart health. Abnormal pulse rate, for example, bradycardia (too slow) or tachycardia (too fast), is a potential warning for underlying heart conditions or other health issues. Functional fabrics that sense pulse rate can be seen as a miniature of the pulse monitoring system and can be worn on patients to achieve 24 hours

monitoring without the need for hospitalization. Zhang et al. reported an ultrafast-response/recovery pulse sensing fabric made of DNA-like twisted piezoresistive yarn structures (Fig. 12d-i and d-ii).[328] A fabric patch was assembled with piezoresistive yarn for pulse monitoring (Fig. 12d-iii). The fabric pulse sensor had a balanced performance on the sensitivity (0.57 kPa^{-1}), response time (2 ms), relaxation time (2 ms), linearity (4.9%), variation (7.8%), durability (6000 cycles), and hysteresis (5.3%). The unique twisted structure of this fabric sensor offered fast response and recovery compared to other fabric-based sensors.

Sweat is a bountiful source of health status, providing biomarkers nearly as plentiful as those found in the blood. It contains a variety of chemical substances such as inorganic ions, organic molecules, amino acids, hormones, proteins, peptides, and other secretions. The readout of sweat content can be used as a non-invasive measurement for health monitoring through the analysis of sweat content, electrolyte imbalance, lactate index, sweat glucose level, and more. As displayed in Fig. 12e-i, an integrated electrochemical fabric based on different kinds of sensing fibres was developed for real-time monitoring of swea.[329] The fabric readily absorbed sweat and could monitor glucose, K^+ and pH continuously and withstand numerous bending cycles while maintaining high sensitivity. The fibres were woven into a fabric patch that can be worn while an interface board is used to collect, process and transfer the captured physiological signals (Fig. 12e-ii).

Joints serve as bone levers, enabling intricate limb movements by providing a fulcrum. The level of joint health significantly determines the quality of one's living. Utilizing smart fabrics for real-time monitoring of joint motion not only aids athletes in evaluating bone and joint-related health status but also provides medical professionals with a robust foundation for analyzing and resolving motion issues from multiple perspectives, ensuring comprehensive health diagnosis and protection. As shown in Fig. 12f-i, a bionic stretchable nanogenerator fabric consisted of a PDMS-silicone two layered structure inspired by electric eel, was reported to be able to continuously monitor the joint motion on the ground and underwater (Fig. 12f-ii).[330] It can be readily stitches onto commercial apparel to enable the passive clothing functions. The mechanical robustness of the smart fabric allowed it to withstand harsh environment for the long term.

Smart fabrics are suitable media for collecting signals from skin electrodermal activity.

Skin electrodermal activity is particularly important in physiological studies as it is sensitive to emotional changes, including pressure, anxiety or excitement. By monitoring skin electrodermal activities one can understand the link between emotional responses to electrical signals and potentially develop techniques to improve one's mental health. Efficiently collecting signals from skin electrodermal activity via fabrics poses a challenge. In Fig. 12g, it showed a hierarchical nonwoven electronic fabric that inspired by the transpiration system of vascular plants and the water diode phenomenon. A porosity-hydrophilicity dual-gradient was created by layer-by-layer electro-airflow spinning method and selective oxygen plasma treatment, which led to the unidirectional, nonreversible, and anti-gravity water transporting performance of the fabric. When worn on the skin, the fabric functions as an on-skin bioelectrode, enabling stable detection of skin electrodermal activity over extended periods of operation.[331]

6.3. Interactive Communication

Fabrics communication refers to the utilization of different types of electronic fabric that incorporate intelligent fibres capable of conveying various messages, including the words, voice, physiological signals, and even feelings, through diverse manners ranging of displaying, optics, optronics, near-field communication, and radiofrequency identification. With the continuous advancement of novel materials, wireless communication, flexible electronics, and innovative storage technologies, smart fibres that can actively communicate have become a reality.[332, 333] This breakthrough has paved the way for the development of wearable fabric communication systems, marking a significant milestone in wearable technology. Equipped with diverse communication capabilities, these smart fibre-enabled fabrics hold the potential to revolutionize human-to-human, human-to-machine, and machine-to-machine communications.

Display plays a crucial role in presenting information and facilitating communication. Currently, displays are evolving towards high flexibility and wearability. The seamless integration of display into fibres or fabrics is one of the research directions actively explored by the scientific community. However, the realization of fibres and fabrics with functional, large-area displays has remained challenging due to the difficulty of acquiring durable and easily assembled small illuminating units over a wide area. After over a decade of dedicated

effort, a breakthrough has been achieved: a piece of fabric that doubles as a soft display (Fig. 13a).[334] This fabric was woven from polyurethane gel fibres doped with ionic liquid and conductive fibres coated with ZnS phosphor (Fig. 13a-i). The fibre crossbar structure of electroluminescent units allowed the large-scale assembly of the fabric display (Fig. 13a-ii). A fabric display-based communication shirt capable of transmitting, receiving, and displaying messages was demonstrated for use as an assistive device for individuals with hearing or speaking disabilities. (Fig. 13a-iii). Despite human-to-human communication, smart fibre-based communication systems could also improve the efficiency and security of human-to-machine interactions. Such system aims to design interfaces and systems for effective communication between humans and machines, including user interfaces, input devices, and feedback device. Based on the principle, a self-powered fabric was developed, offering a new perspective on biometric authentication systems. This fabric was created by constructing a triboelectric nanogenerator (TENG) from a silver-plated cloth combined with CNT- and Polytetrafluoroethylene (PTFE)-coated fabric (Fig. 13b-i).[335] Benefiting from the flexibility, contact electrification performance, and self-power supply, a self-powered wearable keyboard (SPWK) was fabricated by integrating large-area fabric-based TENG sensors, which can dynamically identify individuals' typing characteristics, showing the practical applications in human-computer interactive communication (Fig. 13b-ii).

In the information age, optical communication is indispensable to meet the long-distance transmission demands of vast amounts of data in modern society. Integrating semiconductor diodes, a crucial component of optical communication, into fabrics is expected to enhance their functionality and performance, potentially enabling wearable optical communication. A noteworthy example is the use of thermal drawing techniques to integrate hundreds of semiconductor diodes in parallel within a single fibre.[206] Consequently, light-emitting and photo-detecting diode fibres were obtained, enabling the setup of a bi-directional optical communication system operating at three megahertz between two fabrics composed of light-emitting and photo-detecting fibres (Fig. 13c).

Fig 13. Interactive communication: (a) Luminescent fibres for large-area display. (a-i) Photograph showing a multicolor display textile under complex deformations, such as bending and twisting. (a-ii) A magnified photograph of the multicolor display textile shows that the EL units are uniformly distributed with a spacing of ~800 μm. (a-iii) Future clothing communication could be enabled by display textile. (a) Reproduced from ref. 334 with permission from Springer Nature, copyright 2021. (b) TENG fibres for human-machine communication. (b-i) Schematic diagram of the F-TENG. (b-ii) A photograph illustrates the self-powered wearable keyboard system designed for real-time keystroke tracing and recording. (b) Reproduced from ref. 335 with permission from Springer, copyright 2021. (c) Diode fibres for optical communication. Schematic illustration of bi-directional communication system concept. A garment is composed of a fabric that contains both light-emitting and photo-

detecting fibres. (c) Reproduced from ref. 206 with permission from Springer Nature, copyright 2018. (d-i) Schematics of a fibre-shaped artificial optoelectronic synapse (FAOS). (d-ii) Schematics of "learning-forgetting-relearning" behavior. (d) Reproduced from ref. 332 with permission from Cell Press, copyright 2023. (e) Metamaterial fabrics for near-field communication. (e-i) Wearable modular network integrated into the clothing and covered by transparent heat-transfer vinyl. (e-ii) NFC reader on shirt and pants receives information. (e) Reproduced from ref. 130 with permission from Springer Nature, copyright 2021. (f) Metamaterial fabrics for safety radiofrequency identification. (f-i) Structure of the metamaterial textile. (f- ii) Electric field distribution |Ez| emitted by a dipole above a metamaterial textile. (f-iii) Full-wave simulations of wireless transmission in a computational human body model. (f) Reproduced from ref. 337 with permission from Springer Nature, copyright 2019.

Furthermore, optoelectronic communication paves the way for biomimetic visual systems with receptor-like sensing and synapse-like learning/memory functions, presenting promising avenues for the future of wearable electronics. Illustrated in Fig. 13d-i, a fibre-shaped artificial optoelectronic synapse (FAOS) exhibited a double-twisted architecture comprising high-density TiO_2-x and MoS_2 arrays.[336] By applying electronic and light stimuli to the FAOS, two sensory inputs demonstrated the ability to induce synaptic functions, including excitatory postsynaptic current and "learning-forgetting-relearning" behavior (Fig. 13d-ii). Notably, the FAOS exhibited remarkable flexibility, with no significant degradation in optoelectronic synaptic performance observed during bending. Consequently, the integration of several FAOSs into commercial textiles gave rise to optoelectronic synaptic arrays, culminating in the development of wearable fabric capable of interactively perceiving, retaining, and transmitting information.

Near-field communication (NFC) operates as the conduit for short-range wireless data exchange between close-proximity devices, with ongoing research endeavors focusing on the integration of NFC tags or antennas into fibres. This integration paves the way for smart fabrics endowed with communication capabilities suitable for various applications like interactive clothing, wearable technology, and healthcare monitoring. Metamaterial fabrics emerge as a solution to seamlessly integrate with conventional clothing, forming secure and adaptable communication networks over the human body. Thus, the utilization of textile-integrated metamaterials drives the expansion of long-distance NFC.[130] These metamaterials, constructed using arrays of discrete, anisotropic magneto-inductive elements comprising metal foils, adorn shirts and pants, enabled the secure transfer of NFC data and supported the direct body-to-body

communication without external terminals (Fig. 13e-i). Furthermore, beyond NFC, radiofrequency identification (RFID) serves as another technology for capturing and storing data, enhancing our capability to perceive and interact with the surrounding environment (Fig. 13e-ii). Tian et al. demonstrated the fabrication of a garment utilizing metamaterial textiles capable of facilitating surface-plasmon-like modes at communication frequencies, achieving efficiencies three orders of magnitude higher than conventional radiative networks (Fig. 13f-i).[337] Surprisingly, this garment exhibited the ability to robustly propagate wireless signals, even across discontinuities in the conductive structure (Fig. 13f-ii), thereby unlocking novel capabilities in wireless power transfer of personal health data. Notably, metamaterial textiles effectively confined the wireless signal within 10 cm of the body, enabling efficient transmission around the body while mitigating the risk of eavesdropping (Fig. 13f-iii).

6.4. Data Storage and Processing

The pursuit of smart fibres, capable of gathering, storing, and analyzing data, stands as a frontier in cutting-edge research.[338, 339] Yet, this capacity transcends mere data management, aspiring to novel wearable fabrics with sensory, memory, learning, and decision-making capabilities. Particularly, a fabric computing platform empowered by smart fibres could benefit from a brain-inspired architecture, adept at processing vast volumes of unstructured sensory data from the human body or its surroundings. Crossbar-type electronic fabrics, woven using 1D fibre devices, offer an ideal platform for deploying artificial neural networks (ANNs), enabling rapid parallel signal processing and identification of critical features. For instance, Fig. 14a illustrates the development of multiple ferroelectric organic transistors on a 1D Ag wire, utilizing P(VDF-TrFE) as a fibre-shaped multi-synaptic device platform for an electronic fabric neural network.[340] These 1D multi-fibre synapses, with their ease of extension into a NOR-type synaptic array, promised a fundamental element for an e-fabric neural network. Demonstrating remarkable recognition accuracy of around 70% for electrocardiogram patterns, even in a single-layer neural network, these multi-synapses hold great potential regardless of bending conditions.

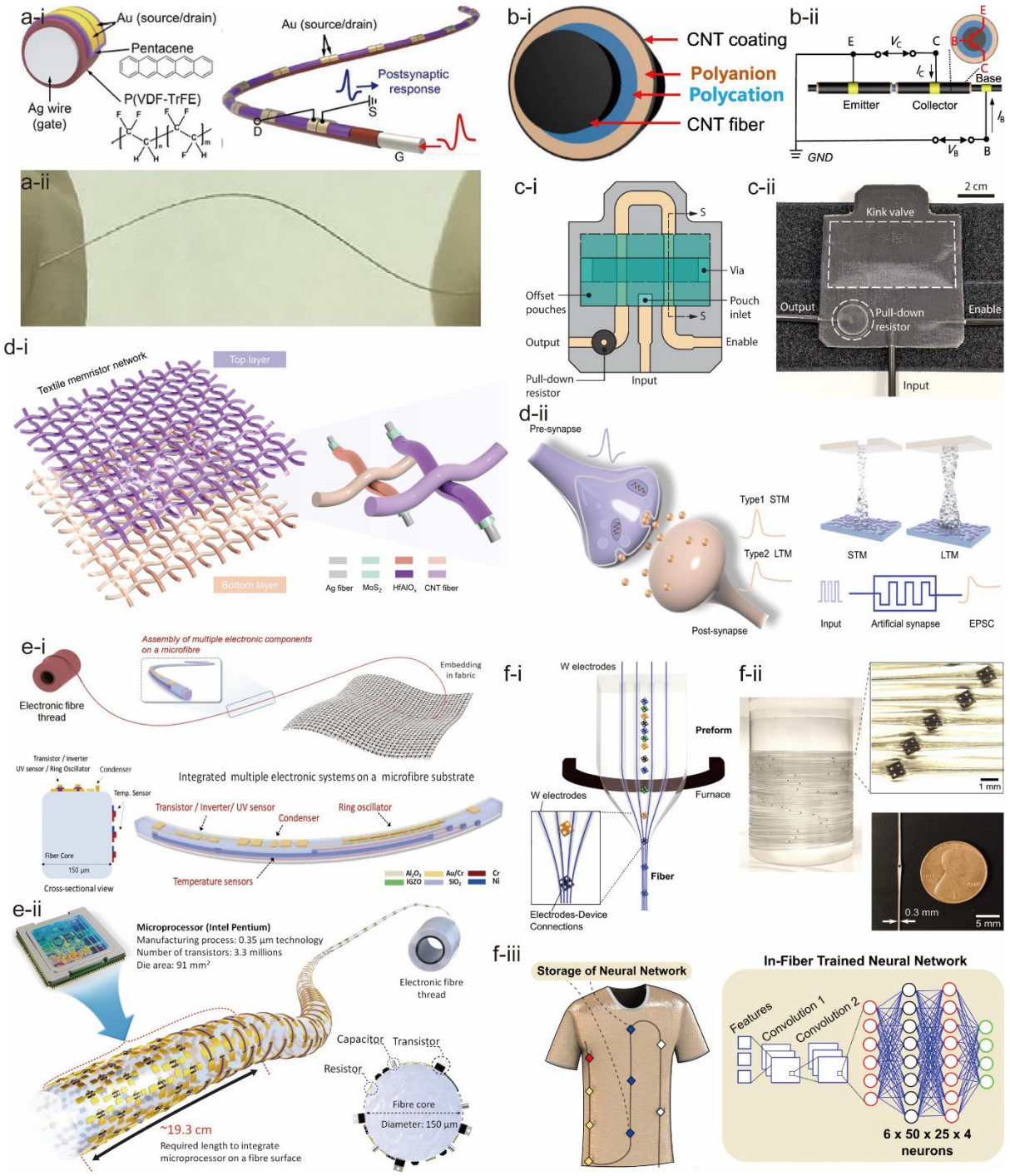

Fig 14. Data storage and processing: (a-i) Schematics of the fibre-shaped organic artificial multi-synapses. (a-ii) Optical photograph of the completed fibre-shaped synaptic device. (b-i) Illustration of the cross-sectional structure of ionic-junction fibres. (a) Reproduced from ref. 340 with permission from American Association for the Advancement of Science, copyright 2020. (b-ii) Circuit diagram of a fibre-shaped ionic diode and the equivalent circuit model for a SEBS-IM/SEBS-SN junction under direct current bias of +3.0 V. (b) Reproduced from ref. 341 with permission from Springer Nature, copyright 2023. (c-i) Schematics of the textile-based electricity-free pneumatic computers. (c-ii) Image of a garment containing fluidic logic element. (c) Reproduced from ref. 342 with permission from NATL ACAD SCIENCES, copyright 2022. (d-i) Schematic image of textile memristor network, incorporating an upper-layer device characterized by synaptic plasticity and a lower-layer device endowed with neural

functionalities. (d-ii) Schematic of biological synapse, which could be emulated by artificial synapses with short-term memory and long-term memory. (d) Reproduced from ref. 343 with permission from Springer Nature, copyright 2022. (e-i) Schematic illustrations of e-textile integrated from a multifunctional electronic fibre and embedded in a fabric. (e-ii) Schematics of the implementation of the microprocessor on a microfiber. (e) Reproduced from ref. 344 with permission from Springer Nature, copyright 2022. (f-i) Thermal drawing of the digital fibre preform. (f-ii) Photograph of a spool containing a continuous digital fibre with 100 embedded devices (left); Magnified optical image of the fibre array with rotated digital devices (right); Photograph showing size comparison between the fibre and a coin (bottom). (f-iii) Digital fabric with incorporated neural network capabilities. (f) Reproduced from ref. 345 with permission from Springer Nature, copyright 2021.

The surge in interest surrounding fibre-shaped ionic-junction devices stems from their potential as mediators for signal transmission and logic operations between electronic devices and biological systems. This led to the development of an ionic-junction fibre, utilizing Poly(styrene-b-(ethylene-co-butylene)-b-styrene) (SEBS) and Na^+/Cl^- as the polymer backbone and free-moving ions, respectively (Fig. 14b-i).[341] This fibre, scalable to kilometer lengths, was integrated into functionalities such as ionic diodes and ionic bipolar junction transistors, facilitating synaptic characteristics and neural signal transmission. Furthermore, circuit design enabled the successful implementation of two distinct types of ionic-junction logic gates ("AND" gate and "OR" gate), paving the way for electrical stimulation signal transmission in vivo and the design of biomimetic neuron computer interfaces (Fig. 14b-ii).
From the above examples, it becomes evident that extensive efforts have been directed towards functional clothing with computational capabilities, yet the realization of such capabilities must rely on external power supplies. Notably, mechanical engineers at Rice University pioneered the development of fabric-based electricity-free pneumatic computers, leveraging "fluidic digital logic".[342] This innovation facilitated combinational and sequential logic functions, onboard memory storage, and user interaction *via* pneumatic actuators (Fig. 14c-i and c-ii). In contrast to electronic circuits where gates were either on or off (1 or 0), pneumatic gates substituted these states with "high" or "low" air pressure. Consequently, logic-enabled textiles offered the potential to aid users in physical motion without electricity. Specifically, a textile computer demonstrated the capability of input-driven digital logic to control untethered wearable robots, assisting users with functional limitations.

Despite significant advancements in ANNs, as shown in Fig. 14a, the persistent challenge

lies in the performance gap between synaptic devices and neurons. Additionally, the complexity and redundancy of circuits result in high-power neuron functionality in complex memristor circuits and inefficient data processing in electronic fabrics. Addressing these issues, a reconfigurable memristor fabric network based on Ag/MoS_2/$HfAlO_x$/CNT structure was fabricated, serving as both an artificial synapse and neuron with ultralow energy consumption (Fig. 14d-i).[343] This system demonstrated continuous modulation of synaptic weights in the nonvolatile mode and action potential inspiration in the volatile mode (Fig. 14d-ii), integrated into a heating fabric system for intelligent temperature modulation.

While current smart fibres shown the capabilities in sequential data recording, detection, and readout, they predominantly feature single-function electronic components on a single fibre. The aspiration remains the assembly of multiple electronic systems into a single fibre, achieving multifunctionality, including computing capability. A one-dimensional microfiber, with a diameter of 150 μm, served as a substrate for an electronic fibre platform, integrating various electronic components using high-resolution maskless photolithography.[344] This multifunctional electronic textile platform showcased exceptional electronic properties during testing, with large-scale preparation remaining a pivotal challenge for future commercialization (Fig. 14e-i and e-ii). In 2021, a notable breakthrough emerged in the storage, processing, and analysis of physiological monitoring data by directly integrating hundreds of interspersed digital chips and memory devices into a thermally drawn PMMA fibre (Fig. 14f-i). [345] Illustrated in Fig. 14f-ii, these microchips were interconnected using wires to form a ten-meter flexible fibre. Noteworthy is the collection and storage of sensory data facilitated by a connection port for all digital chips, avoiding the reliance on traditional machine learning algorithms necessitating a separate computing device. Upon integration into a garment, this digital fibre effectively captured and retained body temperature data over extended periods, enabling real-time inference of wearer activity with an impressive precision of 96% *via* a trained neural network boasting 1650 neuronal connections stored within the fibre (Fig. 14f-iii).

6.5. Feedback and Actuation

In recent years, there has been a significant focus on smart fabrics capable of executing operations in response to environmental or physiological changes, finding applications in

healthcare, sports, and military domains. For instance, while clothing plays a vital role in maintaining thermal comfort, its inability to adapt to ambient temperature fluctuations can lead to discomfort or even fever due to excessive body heat loss. Addressing this issue, an economical and effective solution enabling clothing with self-regulating temperature capabilities is important.[346, 347] Given that the human body dissipates 50% of its heat through infrared radiation (IR), manipulating the IR radiation characteristics of materials can aid in managing localized heating. To achieve this, an intelligent fabric with a bilayer nanophotonic structure was developed, featuring low IR emissivity on the outer surface and high IR emissivity on the inner surface (Fig. 15a-i).[348] This fabric effectively reduced IR heat dissipation from the human body, as confirmed by thermal imaging (Fig. 15a-ii). Additionally, a highly porous and mechanically strong encapsulated aerogel fibre was developed, inspired by the core-shell structure of polar bear hair, offering exceptional thermal insulation and durability (Fig. 15b-i).[349] Such fibres, when integrated into garments, provided warmth equivalent to down jackets while being significantly thinner, suitable for extreme cold environments (Fig. 15b-ii and b-iii). In addition, recent scientific research has highlighted the importance of cooling the human body through clothing, employing various design strategies to regulate the heat dissipation process. Notably, the introduction of infrared (IR) transparent fabrics has emerged as a key approach to facilitate the complete dissipation of human radiation.[350] An innovative concept, the metafabric was introduced to achieve enhanced passive cooling alongside exceptional mechanical strength, wettability, permeability, and wearability.[257] Illustrated in Fig. 15c-i, metafabrics featured a hierarchical structure of scatterers, including a titanium oxide-polylactic acid (TiO_2-PLA) composite woven fabric laminated with a thin polytetrafluoroethylene (PTFE) layer. These metafabrics exhibited an extensive spectroscopic response spanning two orders of magnitude in wavelength, effectively rejecting solar power and emitting strongly in the mid-infrared range. With the scalability of production, metafabrics offered a viable option for large-scale manufacturing. Thermal imaging and thermocouple measurements demonstrated that metafabrics effectively lowered the human body temperature by approximately 4.8°C (Fig. 15c-ii).

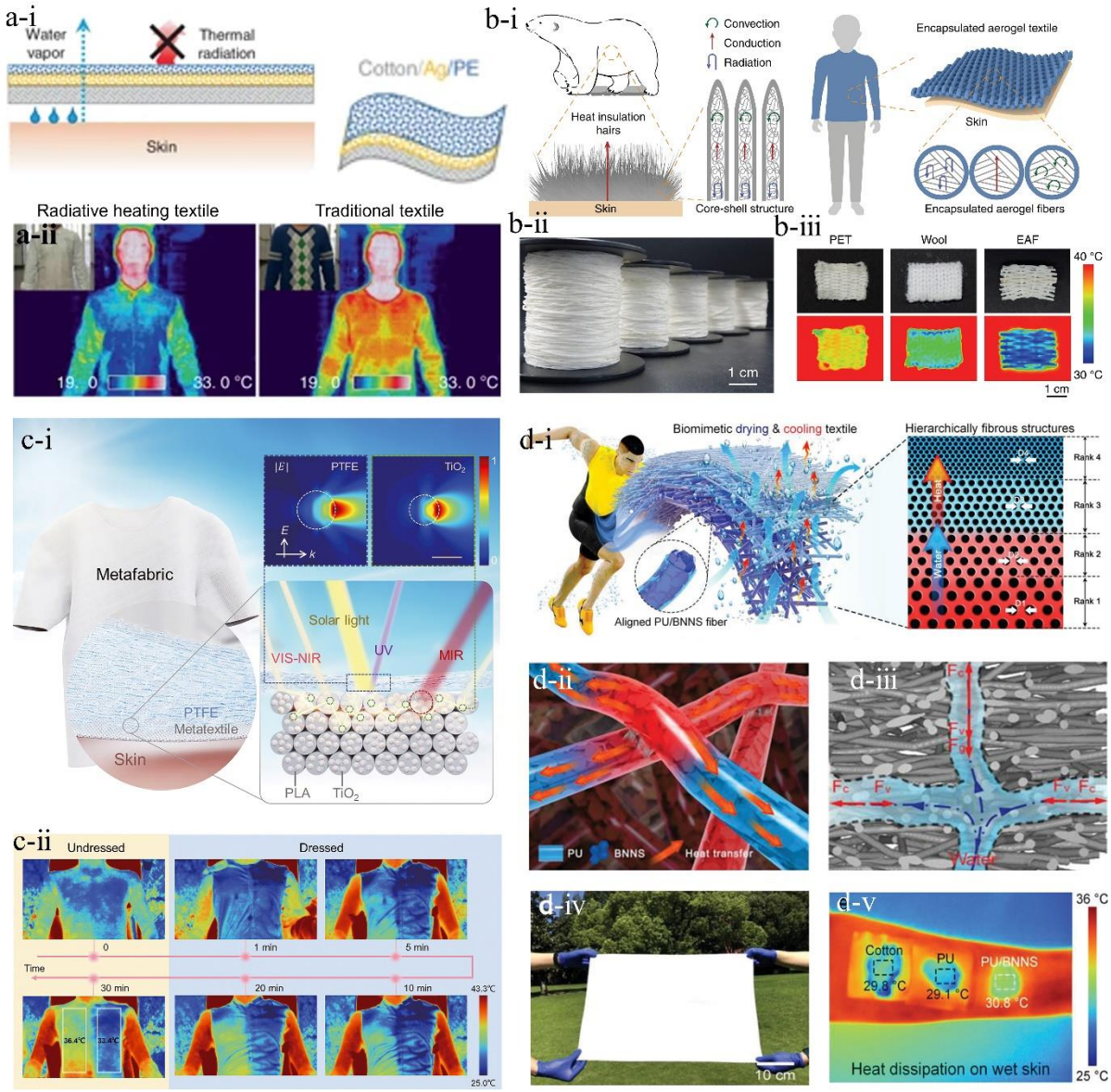

Fig 15. Feedback and actuation: (a-i) A textile with nanophotonic structure uses an IR-transparent layer, an IR-reflective layer, and embedded nanopores in both layers for low IR emissivity and excellent breathability simultaneously. (a-ii) Thermal images of human bodies wearing garments made from radiative heating cotton/Ag/PE textile and traditional textile. (a) Reproduced from ref. 348 with permission from Springer Nature, copyright 2017. (b-i) Schematic illustration of thermal insulation principles of the polar bear hairs and encapsulated aerogel fibres. (b-ii) Optical images of as-prepared fibre reels. (b-iii) Optical and IR images of nylon, PET, wool, and encapsulated aerogel fibre textiles at a stage of 40°C, respectively. (b) Reproduced from ref. 349 with permission from American Association for the Advancement of Science, copyright 2023. (c-i) Schematic illustration of a metafabric for daytime radiative cooling. (c-ii) Infrared images of the volunteer under direct sunlight. (c) Reproduced from ref. 257 with permission from American Association for the Advancement of Science, copyright 2021. (d-i) The schematic diagram depicts the biomimetic multilayer fibrous membrane functions as a practical fabric for personal cooling by releasing sweat and dissipating heat. (d-ii) Schematic of heat transfer among the interconnected PU/BNNS fibres along the in-plane and through-plane direction. (d-iii) Schematic illustration of the spontaneous wicking in the fibrous

membrane along with the vertical and horizontal directions. (d-iv) Photograph of the large-sized biomimetic multilayer fibrous membrane. (d-v) Infrared thermal images of the heat dissipation performance of the PU/BNNS multilayers under wetted. (d) Reproduced from ref. 351 with permission from Wiley-VCH, copyright 2021.

It is important to acknowledge that clothing adhering to the skin due to excessive perspiration can hinder the effectiveness of cooling fabrics. Therefore, it is crucial to develop intelligent fabrics that not only promote sweat evaporation but also facilitate efficient heat dissipation. Fig. 15d-i illustrates the efficacy of personal drying and cooling fabrics featuring a hierarchical and interconnected network designed for antigravity directional water transport and unimpeded heat dissipation .[351] The innermost layer, consisting of the thickest fibres and largest capillary pores, functioned as the contact layer against the skin, effectively extracting excess sweat (Fig. 15d-ii and d-iii). The utilization of aligned polyurethane (PU)/boron nitride nanosheet (BNNS) created ample heat transfer pathways with minimal interfacial thermal resistance. Consequently, the PU/BNNS fabric exhibited a higher surface temperature compared to the other two fabrics under both dry and wet conditions, thereby ensuring superior and efficient heat dissipation (Fig. 15d-iv and d-v).

Despite regulating temperature, it is also crucial for fibres and fabrics to respond in real-time to external stimuli and react accordingly. As a result, a wide array of actuating fibres and fabrics have been developed, each employing different mechanisms such as electrical actuation, ion-motion actuation, and thermal actuation. These materials have the capability to provide feedback by autonomously adjusting color, texture, or structure.

For light actuation enabled feedback, Yu et al. introduced a novel core-shell CNTs@LCE fibre soft actuator. This actuator consisted of a liquid crystal elastomer (LCE) fibre coated with a shell of carbon nanotubes (CNTs).[352] The fibre exhibited remarkable light-driven phototropic bending behavior under NIR light stimulation, attributed to the photothermal-induced temperature gradient along the thickness of the fibre and the corresponding differential contraction (Fig. 16a-i). The fibre demonstrated high load-lifting capability and served as an artificial muscle for biomimetic applications. Additionally, it showed unprecedented photo-driven phototropic locomotion, including tracking moving light sources, climbing slanted surfaces, and precise bending towards incident light from any direction (Fig. 16a-ii).

Fig 16. Feedback and actuation: (a-i) Photos of the bending actuation caused by left-side illumination. (a-ii) Photo of the phototropic movement of a sunflower, stimulated by infrared light spots from various incident directions. (a) Reproduced from ref. 352 with permission from Elsevier Ltd, copyright 2022. (b-i) Schematic of the preform-to-fibre draw process (left); An array of flexible electro-strictive fibres exhibiting colored reflections through the Bragg effect (right). (b-ii) The amplitude of oscillation is displayed for both on-resonance and off-resonance frequency points. (b) Reproduced from ref. 353 with permission from Springer Nature, copyright 2017. (c-i) Bimorph fibres produced via two-step thermal drawing. (c-ii) Photographs of the artificial fibre muscles and of them lifting 1 g mass. (c) Reproduced from ref. 260 with permission from American Association for the Advancement of Science, copyright 2019. (d-i)

Schematic illustration of a continuum robot's magnetically responsive tip, caused by the programmed magnetic polarities generated by embedded hard magnetic particles in the robot's soft polymer matrix body. (d-ii) Demonstration of the soft continuum robot passed through a 3D cerebrovascular phantom network. (d) Reproduced from ref. 354 with permission from American Association for the Advancement of Science, copyright 2019. (e-i) Schematic illustration of artificial muscle fibre actuator using nylon 6,6 monofilament sewing thread. (e-ii) Photographs of hydrothermal response of an 860-mm-diameter nylon 6 fishing line, which is coiled and capable of lifting a load of 500 g by 12%. (e) Reproduced from ref. 355 with permission from American Association for the Advancement of Science, copyright 2014. (f-i) 3D encoded sewing constraint for highly programmable soft textile robots. (f-ii) Tailored soft wearable textile robot corrects spinal posture. (f) Reproduced from ref. 356 with permission from American Association for the Advancement of Science, copyright 2024. (g-i) Schematic illustrates the shape deformation mechanism of a graphene/LCE composite fibre through reversible percolation. (g-ii) Optical microscopy of relaxed and contracted states of graphene LCE fibres. (g) Reproduced from ref. 357 with permission from Springer Nature, copyright 2022.

For electrical actuation enabled feedback, a novel thermally drawn microelectromechanical fibre device based on electro-strictive P(VDF-TrFE-CFE) ferrorelaxor terpolymer was developed (Fig. 16b-i).[353] This fibre device featured an electro-strictive terpolymer layer extending along its entire length, enabling electromechanical actuation with strain values exceeding 8%. The fibre exhibited frequency and amplitude-tunable cantilever-like resonant vibrations when subjected to AC fields (Fig. 16b-ii). This capability enabled applications such as textile optical modulation based on AC-driving schemes, allowing for the deflection of optical beams incident transverse to the fibre axis. The monolithic integration of electrodes into the fibre allowed a straightforward connection with external circuits. For thermal actuation enabled feedback, a strain-programmable bimorph fibre-based actuator was fabricated through a high-throughput iterative fibre-drawing process (Fig. 16c-i).[260] This actuator, involving polyethylene and cyclic olefin copolymer elastomer, spanned lateral dimensions from millimeters to micrometers, with arbitrary lengths. Cold drawing of these fibres resulted in the formation of springs, facilitating reversible and repeatable thermal actuation (Fig. 16c-ii). These fibre-based actuators, with thermally and optically controllable features, can lift more than 650 times their own weight and endured strains exceeding 1000%, making them applicable in fields such as robotics and prosthetic limb technologies. Furthermore, by combining magnetic microparticles with soft fibrous substrates, unique fibre actuators powered by magnetic fields can be created. Fig. 16d illustrates submillimeter-scale

ferromagnetic soft fibre robots developed by Zhao's research group.[354] These fibre robots had bodies composed of soft polymer matrices containing uniformly distributed hard magnetic microparticles, allowing for easy fabrication at the submillimeter scale using printing or injection molding methods. When exposed to a magnetic field, the fibre robot demonstrated the capability to navigate highly restricted environments, including narrow and tortuous vasculature, by employing active and omnidirectional steering *via* magnetic actuation (Fig. 16d-i). This integration of capabilities enabled successful navigation through complex and constrained scenarios, such as a cerebrovascular phantom with multiple aneurysms (Fig. 16d-ii). This accomplishment addresses the inherent challenges associated with bulky robotic catheters or passive manual instruments, as they lack the ability to navigate such environments effectively.

Another approach involved fabricating fabric actuators using thermal expansion materials directly. This method, reported by Haines et al., utilized cost-effective commercial fishing and sewing thread materials like Nylon and Polyethylene.[355] The actuator was fabricated by twisting and coiling pristine fibres. When heated, untwist due to polymer chain length contraction and diameter expansion resulted in contraction (Fig. 16e-i). These coiled fibres can lift loads over 100 times heavier than human muscle of the same length and weight, indicating their potential for large-scale applications (Fig. 16e-ii).

By integrating soft pneumatic actuation with resilient textiles, a fascinating realm of possibilities emerges- textile actuators resembling of the adaptive motions seen in mollusks and plants. This innovative concept gives rise to a unique design paradigm known as encoded sewing constraint (ESC), which revolutionizes the structuring of 3D textile shells for soft robotics.[356] As shown in Fig. 16f-i, these soft textile robots, featuring pneumatic actuation, had remarkable advantages such as high-dimensional programmability, customizable design, and streamlined manufacturing processes. Through strategic integration of heterogeneous stretching properties into the seams of the textile shells, the inner bladder's inflation can be precisely controlled, enabling complex shape morphing and locomotion sequences inspired by nature's ingenious designs, such as tendril-like movements (Fig. 16f-ii).

Different from the single variable actuating parameters, a novel approach centered around fibre feedback materials was developed, seeking the optimal combination of strain, stress,

energy density, and mechanical strength through a conformational transformation mechanism (Fig. 16g). Drawing inspiration from the intricate architecture of mammalian skeletal muscles, a single fibre actuator was engineered, leveraging reversible percolation dynamics driven by liquid crystal elastomers (LCEs) and exfoliated graphene fillers.[357] This design not only facilitated photothermal actuation with impressive work capacity and responsiveness but also enhanced the actuator's mechanical reliability and thermal conductivity, setting the stage for seamless integration into high-powered soft robotics applications (Fig. 16g-i and g-ii).

6.6. Energy Storage and Harvesting

Smart fibre-enabled fabrics with energy storage capabilities are a cutting-edge field in textile technology, allowing the harnessing and storage of energy for powering electronic devices or serving as a portable energy source. At present, the most promising approach is to transform traditional energy storage devices into single-fibre structures, which can then be integrated into electrochemical energy storage fabrics. This not only preserves their electrochemical properties, but also retains their necessary mechanical flexibility and wearability.[554-557]

Currently, research and study in energy storage fabrics centers around batteries and supercapacitors. Despite their similar elemental compositions, they exhibit distinct functional characteristics. Notably, fibre lithium-ion batteries (FLIBs) have gained considerable attention due to their remarkable properties, including high energy density and low self-discharge rates.[358, 359] Interestingly, it has been demonstrated that the internal resistance of FLIBs decreases with length, paving the way for the production of high-performing, meters-long FLIBs through scalable industrial processes (Fig. 17a-i).[232] These batteries had a notable energy density of close to 86 Wh Kg^{-1} and a volumetric energy density of 182 Wh L^{-1}. With a capacity of 25 mAh and energy of 95 mWh per meter at a current density of 17 mA g^{-1}, they were well-suited for powering wearable electronics, such as heart rate monitors. Demonstrating their versatility, a jacket woven with fibre batteries showed the ability to wirelessly charge a phone placed in a pocket (Fig. 17a-ii and a-iii). Furthermore, these fibre batteries can be seamlessly integrated into a full fabric system powering fibre sensor and a fabric display, providing real-time health monitoring for the user at exercising. However, with the escalating energy demands

of flexible electronics, FLIBs with such energy densities may prove insufficient, necessitating alternative solutions.

Fig 17. Energy storage and harvesting: (a-i) Reels of fibre lithium-ion batteries are obtained. (a-ii) Magnified photograph of fibre lithium-ion batteries with a length of 1 m. (a-iii) Illustration demonstrates how integrating FLIB textile and a wireless transmitting coil into everyday clothes enables wireless charging of a mobile phone. (a) Reproduced from ref. 232 with permission from Springer Nature, copyright 2021. (b-i) Image of 100 m of supercapacitor fibre on a spool. (b-ii) Image of fully machine-woven supercapacitor textile. (b-iii) Image of 100 ×

15.2 cm2 multifunctional textile consisting of twelve 1 m supercapacitors and a 3 m light emitting fibre. (b-iv) The thermally drawn supercapacitor fibre can also be used as a print filament of 3D printing. (b) Reproduced from ref. 211 with permission from Wiley-VCH, copyright 2020. (c-i) A magnetoelectrical clothing generator that could power devices while people are moving. (c-ii) The peak power generated by the magnetoelectrical clothing on the arm-swinging frequency. (c) Reproduced from ref. 360 with permission from Wiley-VCH, copyright 2022. (d-i) A photograph of the hybrid power textile mixed with colored wool wires. (d-ii) In natural daylight with mechanical excitation, a small hybrid power textile can power a wearable electronic watch. (d) Reproduced from ref. 306 with permission from Springer Nature, copyright 2016. (e-i) Schematic illustration of fibre-shaped aqueous Zn ion batteries that could be charged under various light conditions. (e-ii) Photographs of the photo-powered energy textile. (e) Reproduced from ref. 361 with permission from Elsevier Ltd, copyright 2024. (f-i) Schematic showing energy harvesting and storing ribbon consisting of the top perovskite solar cells and bottom symmetric supercapacitor with shared copper electrode. (f-ii) A photograph of a military uniform incorporating a lightweight fabric woven with energy harvesting and storing ribbons and cotton threads. (f) Reproduced from ref. 362 with permission from Springer Nature, copyright 2016. (g) A user wearing the fully assembled system. The energy harvesting device is integrated into the insole of the right shoe. (g) Reproduced from ref. 363 with permission from American Association for the Advancement of Science, copyright 2022. (h-i) Schematic of an alternating p/n-type thermoelectric fibre. (h-ii) Photograph of a weaved thermoelectric textile with waterproof layer washed in water. (h-iii) Photograph shows a robotic arm equipped with thermoelectric textiles for temperature sensing (hand), phototaxis (wrist), and energy harvesting (arm). (h) Reproduced from ref. 364 with permission from Springer Nature, copyright 2020.

The advantage of using supercapacitors as energy storage devices lies in its rapid charging times, long cycle life, and high-power density. However, achieving high performance metrics such as capacitance, power and energy density is challenging. As a result, only short lengths of fibre supercapacitors have been reported until recently. The breakthrough in thermal drawing technique has led to the fabrication of ultralong supercapacitor fibres.[211] A macroscale preform was transformed into 100 m long energy-storage fibres, offering scalability, flexibility, cladding protection, and superior capacitor performance (Fig. 17b-i). Notably, the areal capacitance of these fibres remained stable, ranging from 244 to 220 mF cm^{-2}, even with an increase in current density from 0.5 to 4 mA cm^{-2}. A fully machine-woven 100 cm × 100 cm supercapacitor fabric, used these fibres as feedstock, exhibited stable performance through repeated machine washing, submersion, and bending (Fig. 17b-ii). Moreover, a fabric integrating twenty discrete green light-emitting diodes, powered by twelve 100 cm supercapacitor fibres, was successfully developed (Fig. 17b-iii). Intriguingly, these fibres also served as filaments for 3D printing applications (Fig. 17b-iv).

Despite fabrics storing energy, the demand for continuous power supply has spurred exploration into harnessing energy through fibre-enabled fabrics. Motion-based energy harvesting, particularly electromagnetic (EM) induction, has emerged as a promising avenue. A scalable-manufactured flexible magnetoelectrical clothing generator was engineered to generate electricity *via* arm swinging (Fig. 17c-i).[360] Employing the "particle flow spinning" (PFS) method facilitated continuous production of magnetic yarns, culminating in the creation of a magnetic fabric *via* weaving machines. Integration of magnetic fabrics and conductive wires ensured consistent voltage and current generation during arm motion (Fig. 17c-ii). Notably, these magnetic fabrics exhibited functionality across various conditions, including underwater, acidic/alkaline environments, and extreme temperatures. By strategically positioning coils and magnetic fabrics, a maximum output power of 96 mW was achievable. In practical applications, this magnetoelectrical clothing generator powered LED lights, calculators, wireless communication, and health monitoring devices. Additionally, combining two energy harvesting modes in fibres or fabrics can significantly enhance efficiency and output. A micro-cable power textile, designed to harvest energy from ambient sunlight and mechanical motion simultaneously, was developed (Fig. 17d-i).[306] This hybrid textile, integrated into colorful wool fibres, delivered an output power of 0.5 mW under sunlight with an intensity of 80 mW cm^{-2}, driving electronic watches continuously (Fig. 17d-ii).

Harnessing photons is another promising alternative toward realizing long lasting wearable devices. An "all-in-one" wearable energy textile with photo-powered capabilities under various light conditions has been developed.[361] This textile featured a photo-powered cathode based on MoS_2@TiO_2@Ti, engineered to enhance electron-hole separation during the photo-charging process (Fig. 17e-i). The resulting "all-in-one" photo-powered batteries demonstrated the ability to charge under both ambient light and sunlight, achieving a photoconversion efficiency close to 1%. Thanks to its flexibility, the fibre-shaped battery seamlessly integrated into textiles like sweaters and hats (Fig 17e-ii). On sunny or cloudy days, the wearable photo-powered hat could efficiently power bulbs and smartphones, significantly prolonging battery life. Additionally, an all-solid-state, energy harvesting and storing (ENHANS) fabric was developed, integrating a perovskite solar cell (PSC) on top of a symmetric supercapacitor (SSC) (Fig. 17f-i).[362] Through a solvent-assisted perovskite growth

technique, the thin sandwich PSC achieved a conversion efficiency of over 10%. Employing a straightforward wet processing method, copper hydroxide nanotubes (CuOHNT) were produced on the supercapacitor electrodes to enhance storage capacity. Exposed to simulated solar light, the flexible solar fabric yielded an energy density of 1.15 mWh cm^{-3} and a power density of 243 mW cm^{-3}. Moreover, the high flexibility and all-solid-state architecture of the ENHANS fabrics allowed seamless integration into daily clothing, as demonstrated in Fig. 17f-ii.

Pneumatic energy, deriving from compressed air or gases, holds potential for stored and transmitted energy. Utilizing fabrics, pneumatic energy harvesting involves flexible materials to convert such energy into electricity. A soft, unobtrusive textile-based energy harvesting system was developed for this purpose.[363] Integrating a soft textile pump directly into the user's shoe insole, the system stored the harvested energy in a wearable textile bladder as needed (Fig. 17g). Demonstrating significant conversion efficiencies, it recovered over 20% of the mechanical energy from walking. Thus, the insole textile pump achieved a peak average power output of 3 W, outperforming existing foot-strike energy harvesting systems relying on electromagnetic, piezoelectric, and triboelectric mechanisms. Unlike single-use battery packs, this system offered continuous power generation without the need for periodic replacement or refueling. Moreover, its fabrication process was straightforward, cost-effective, and easily scalable for mass production. Fabric-based pneumatic energy harvesting represents an innovative approach to generating electrical power, heralding new opportunities for sustainable and self-powered electronic devices.

Thermoelectric (TE) generators, renowned for harnessing thermal energy through the Seebeck effect, have traditionally been bulky. Yet, technological advancements have led to the creation of flexible and lightweight TE generators using fibres. For instance, a scalable gelation extrusion technique was developed to fabricate TE fibres comprising both p-type and n-type segments utilizing SWCNT/PVA.[364] These segments seamlessly integrated into a continuous fibre. Noteworthy was the hydrocolloid-based network's rheological properties, facilitating excellent confinement of heterogeneous molecular particles within the continuous matrix. This led to high homogeneity, robust interface bonding, and the desired alternation of p/n-type segments (Fig. 17h-i). Weaving these TE fibres into fabrics enabled TE textiles to serve various

functions, such as a conformal heat harvesting cloth (Fig. 17h-ii). This cloth can be worn on a robotic arm and exhibited capabilities in body heat harvesting, phototaxis, and temperature reflexivity (Fig. 17h-iii).

6.7. Closed-loop Network of Fibres Enabled Intelligent Wearable System

Smart fabrics that span from proactive sensing and communication to data storage and processing, real-time feedback and power supply form a closed-loop network of functional-fibre-based wearable system (Fig. 18). This system is akin to the human nervous system, where sensors gather information, nerves transmit data, the brain processes information, and the muscles react accordingly, all powered by metabolic energy from the body. In a similar vein, functional fibre enabled wearable system within the close-loop network are revolutionizing the way we interact with the digital and physical worlds, especially in applications like personalized healthcare surveillance, the Internet of Things, and Artificial Intelligence (AI).

Sensing is the initial phase in the closed-loop network of functional-fibre-based wearable system. Fabric sensors have the ability to adapt to detect a range of stimuli from environment changes such as temperature, and pressure to physiological activities, thereby gathering critical data about the environment or the health status of an individual. Once data is collected, communication becomes essential. Given the nature of fabrics, which are often worn or integrated with the human body, communication protocols need to be energy-efficient and reliable. They must have the capacity to handle the data transmission with minimal energy consumption to preserve the device's power for as long as possible. Fabrics using light, vibration, and microwaves to communicate with individuals or machines are developed. In addition, data storage and processing capabilities are an indispensable component of a closed-loop network. Fibre- or fabric-based memories can store the data from sensors while the fabric processors deal with the data and determine what action needs to be taken. They can be also used as a link to cloud storage and processing, especially for more complex analysis, heavy computation, and long-term data archiving. Real-time feedback fibres and fabrics are the executors for the needed actions after processing the information. Varied from changing a display, adjusting the temperature, to providing walking assistance as exoskeleton devices, smart fabrics offer prompt and accurate feedback, preserving the continuity of the user

experience, and ensuring that the system is responsive to current conditions owing to their unique features. Power supply is what closes the loop. Despite the development of some self-powering fabrics, a lightweight and flexible power supply remains arguably the most significant challenge in the closed-loop network of functional fibre enabled wearable system. High-capacity fibre batteries and supercapacitors are promising solutions. Additionally, fabrics that harvest energy from sources such as solar or body heat provide an alternative. The incorporation of novel materials and structures into fibre dimensions is also critical to improving the longevity and usability of these devices.

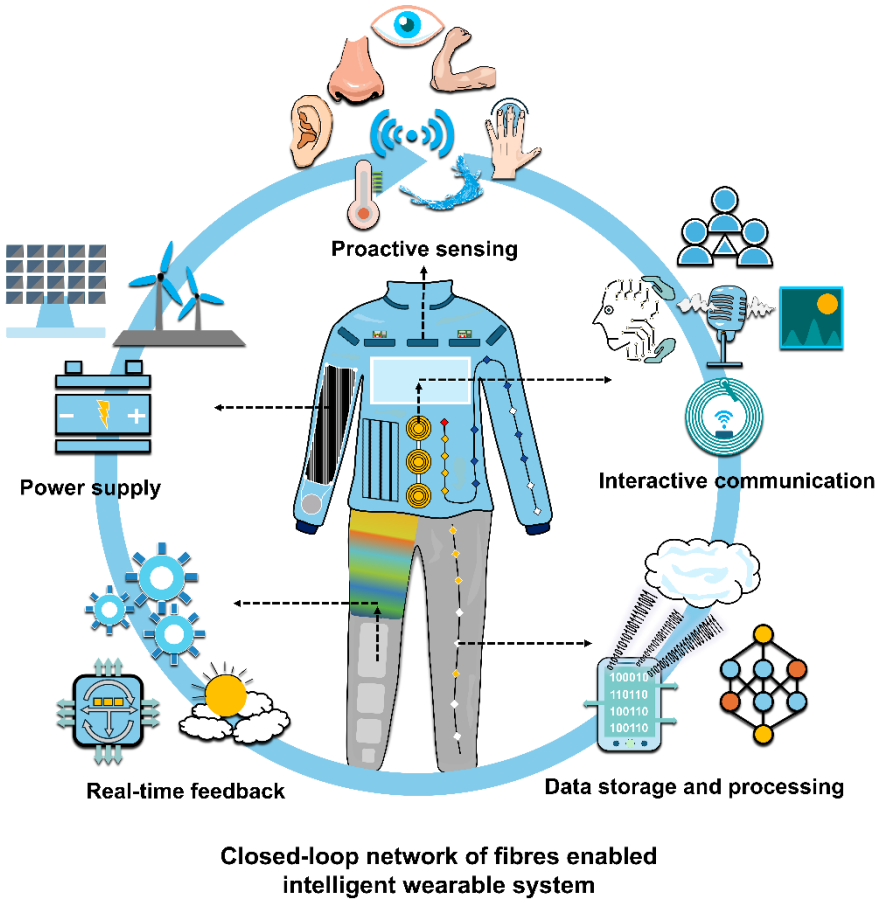

Fig 18. Schematic illustration of the closed-loop network of fibres enabled intelligent wearable system.

The future of functional fibre enabled wearable system seems promising. With continuous advances in materials science, microfabrication, and textile technology, we envision a future where intelligent fabrics become more autonomous, efficient, and comfortable, making them more suitable for human interaction and seamless integration into our everyday lives. Coupling with AI and machine learning algorithms can enable intelligent fabrics to learn and adapt over

time, thereby optimizing their function and conserving power. Furthermore, the closed-loop functional fibre-based wearable system has the potential to revolutionize various industries. In healthcare, such wearable system could provide continuous monitoring and personalized feedback for patients, while in consumer electronics, they could facilitate more intuitive and immersive user experiences.

7. Future Perspective of Intelligent Fabrics and Outlook

Smart fibre-enabled fabrics represent an exemplary topic that has emerged in the field of interdisciplinary research, engaging a combination of disciplines including physics, chemistry, mechanics, materials science, electronics and optoelectronics, textile engineering, biomedicine, data science, and etc. Innovations in materials selection, in-fibre structure design, fabric architecture arrangement, fabrication technique, system-level integration, and novel applications are rapidly shaping the field. Smart fabrics demonstrate remarkable capabilities, including seeing, hearing, speaking, feeling, actuating, energy harvesting, and storing energy, regulating temperature, and even acting as exoskeleton and data processors, enabling unique solutions to the challenges in advanced healthcare, wearables, human-machine interface, Internet of Thing, intelligent industry, and many more.

In this section, the common issues, current research focus, and future perspectives in the aforementioned aspects are discussed. More importantly, we present our vision on the future development, both fundamentally and technologically towards computing fabrics that are expected to be at the next frontier of data management, machine learning, Artificial Intelligence, and closed-loop smart network.

7.1. Fibre Materials

Innovation in materials is one of the foundations for the development of smart fibres. The challenges in materials selection are tightly related to the requirements of particular function and application, as well as user preferences. The core challenge is to expand the accessible materials that can be processed into the fibre form factor itself or integrated with others while possessing excellent performance.

To address the core challenge, there are some critical requirements for candidate materials

to be incorporated into the fabrication of smart fabrics for the future needs. 1) To ensure the effectiveness of smart fabric in wearable systems, it's crucial to develop materials that not only fulfill the desired functional requirements but also exhibit exceptional mechanical stability. These materials must be capable of seamlessly adapting to the curvature of the human body and enduring the physical strain of daily movements. By prioritizing both mechanical stability and desired functionality, we can guarantee the stability and reliability of device performance. Further research can be focused on developing soft, low-modulus elastic fibre materials that can cover the irregularly-shaped human body conformally while offering complex multifunctionality, [365-367] and developing novel materials that are capable to eliminate external crosstalk and filter noise in real-time.[368, 369] 2) The real-time monitoring of the multifaceted and intricate parameters of human body using the fabric system has not yet been achieved. Gel materials have emerged as a promising solution with the capabilities to monitor signals such as strain, temperature, and humidity simultaneously.[370, 371]Nonetheless, further fundamental research on the composition, structure, mechanical performance, high-yield production and device assembling is needed. 3) Fibre bioelectronic device can be implanted to record brain activity, stimulate neural networks, sense chemicals and light, and deliver drugs with precision, while largely lower its interference on physiological activities.[372, 373] However, the long-term biocompatibility of fibre materials remains a paramount concern. Development of fibre materials that avoid cellular toxicity and immune responses in biological systems is the focus. Using natural feedstocks derived from plants and animals, such as chitosan, collagen, silk, gelatin, lignin, cellulose, and lipoic acid, present an unprecedented opportunity in this area.[374-380] 4) The burden imposed on the environment by electronic waste from abandoned conventional products is significant. Therefore, green development is a crucial consideration from the initial stage of fibre device development. Self-healing polymers designed by supramolecular chemistry offer an idea solution for assembling fibre devices.[381, 382] These materials can extend that extends the lifespan by healing defects, thereby controlling to the reduction of electronic waste generation.[383]

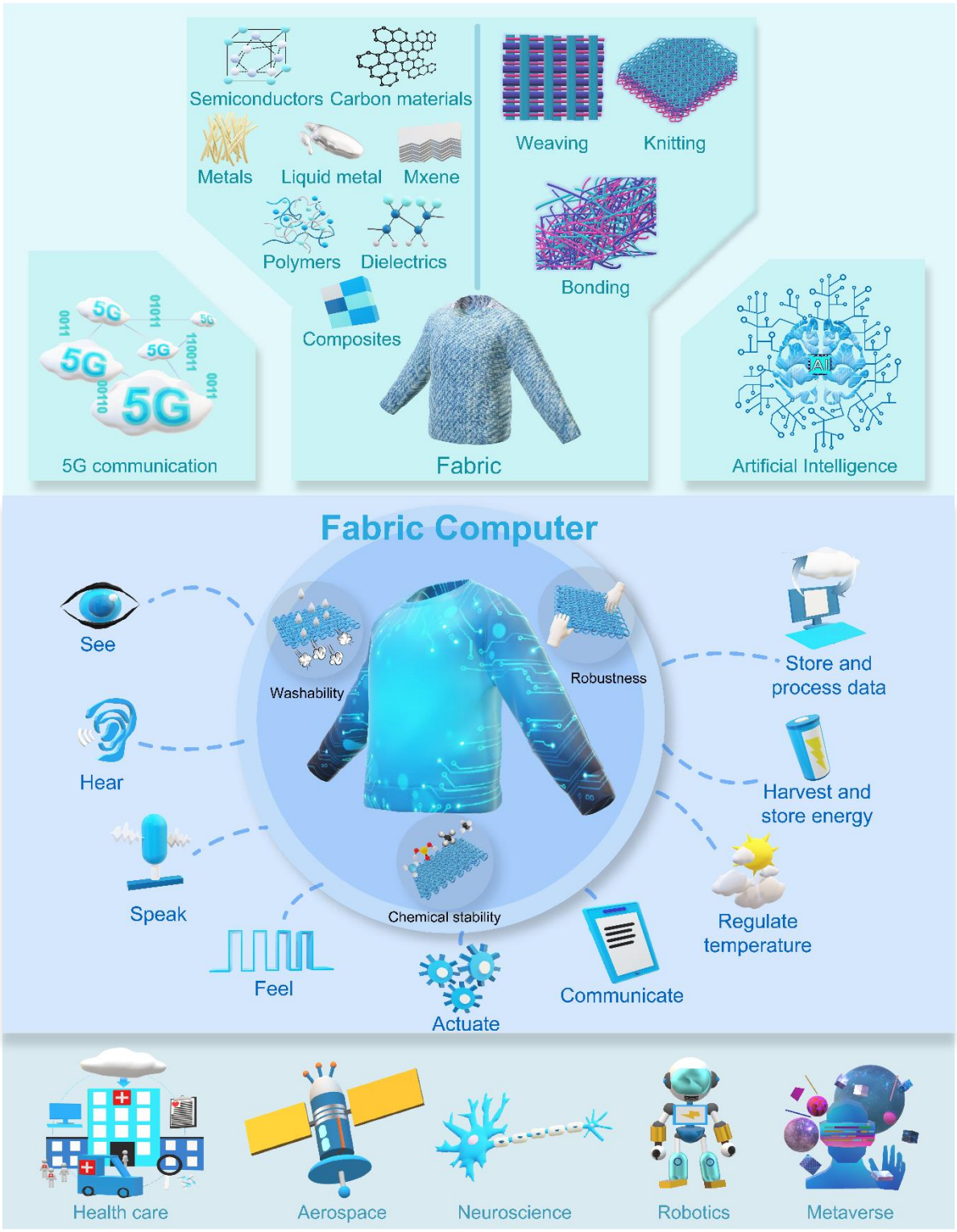

Fig 19. Perspective regarding the fabric computer, fibre materials, fibre and fabric design, fabrication methodologies, 5G communication and Artificial Intelligence technologies can be integrated into traditional fabrics to create fabric computer that can simultaneously see, hear, speak, feel, actuate, communicate, regulate temperature, harvest and storage energy, as well as store and process data. Promising application scenarios of health care, aerospace, neuroscience, robotics, and metaverse can be revolutionized by forthcoming fabric computer.

7.2. Design Principles and Fabrication Techniques

Future research on smart fibre-based fabrics is expected to evolve by the "Moore's Law" from the semiconductor industry, which foresees a continuous integration of multi-materials and devices into singular or multiple fibres, thereby enabling functionality in a predictable manner.[33] Therefore, the miniaturization of materials and devices is imperative for the advancement of smart fibre enabled fabrics. Adhering to the "Moore's Law" design principle, which drives the constant evolution of technology, necessitates the continuous refinement of smart fabric. The core challenge lies in innovating mass-production strategies for smart fibres with micro- or nano- feature sizes, while simultaneously ensuring the seamless packaging of electronic components within them.

Although multiple spinning-based techniques, including wet spinning, dry spinning, jet spinning, and electrostatic spinning have been proposed for the mass-production of functional fibres with micro- or nano- feature sizes, their use of organic solvents poses limitations on integrating electronic components into fibre. In the contrast, the perform-to-fibre thermal drawing method enables the conversion of large-scale performs containing electronic components and delicate structures into thin fibres.[37, 302] This approach circumvents solvent constraints and facilitates the in-suit combination of electronic components in fibre form-factor, thus realizing multiple functionalities such as sensing, temperature control, energy harvesting, and interactive communication. Moreover, its scalability is noteworthy: a fibre of thousands of meters in length can be produced in a single draw of a centimeter-scale perform. Thermal drawing method represents a promising strategy for achieving the integration of multiple materials, components, structures, and functions into fibres. However, the preform preparation must be separated from the fibre drawing process, limiting the continuous production of smart fibre enabled fabrics. It is necessary to develop a continuous and cost-effective preform preparation process in the future. One promising approach is using 3D or 4D printing technologies, which enables direct bottom-up manufacturing of preforms with intricate structures. Such methods are simple, efficient, and autonomous.[384-386] The fibres drawn from printed preforms can then be used as feedstocks for a second-step printing for recursive manufacturing, further enhancing the fibre's complexity and functionality.

Another common issue is the coordination of techniques from the electronic and textile

industries. Electronic technology is costly and intricate, while the textile industry has already succeeded in achieving large-scale production of textiles at low-cost. In the future, the research focus of functional-fibre-based smart fabrics functional-fibre-based smart fabrics will be on creating a seamless, complementary, and large-scale production chain that integrates the manufacturing capabilities and advantages of the two distinct industries.

7.3. Functions and Application Scenarios

The extraordinary functions of smart fibre enabled fabrics provide a sustained driving force for the design and integration of devices and technology reformation in the Moore era. In the future, functional fibres are poised to integrate various capabilities including energy storage, multimodal sensing, data processing, intelligent communication, and even programming. However, several pivotal challenges in functionality remain to be considered prior to the commercialization. 1) Although carbon neutrality has become a prominent societal goal,[387] the academic community of smart fabrics still has paid limited attention in terms of sustainability. This goal can only be realized using recyclable materials and developing eco-friendly manufacturing technologies. 2) The most neglected property is the comfort of wearing, which is one of the most critical factors to determine fabrics' commercialization. In the future, more fundamental research needs to be devoted to the comfort of smart fabrics while maintaining the functionality.[388-391] In addition, improving durability of smart fabrics in extreme environments is also a consideration. 3) Smart fibre enabled fabrics are usually active devices which may encounter the issue of power shortage. In real-world scenarios, functional-fibre-based smart fabrics are used in off-grid situations and may face the dilemma of either replacing the batteries frequently or carrying bulky power sources in the cost of mobility. With this issue, it is impossible to realize a truly wearable system. High-energy-density thin film materials, fibre batteries and energy harvesting devices that can match flexible fibrous substrates are the necessary components for solving the issue.[238, 392-394] This allows wearable future fabrics to be powered in a more comfortable manner.

From the perspective of commercialization, the development of smart fibre enabled fabrics can be focused on the applications in luminescence, sensing, and thermal management. Specifically, the smart luminous fibre enabled fabrics can be applied in the field of large-area

soft and wearable display to provide real-time navigation for polar expeditions and even geological prospecting. Thermal management of fibre-enabled fabrics can serve multiple purposes, including regulating body temperature and maintaining optimal temperatures for batteries in electric vehicles. This capability enables these fabrics to adapt to environmental temperature changes effectively. The proactively sensing fibre-enabled fabrics with the capability of monitoring physiological functions are anticipated to find usage in protective and military equipment. In addition, we also notice that the continuous upgrading and integration of functions will push the smart fibre-enabled fabrics to interactive diversification. A seamless interaction between user and machine can be effortlessly accomplished *via* such fabrics by using advanced technologies such as interactive perception and networked communication.[395-397] While enabling the remote control of sophisticated machines, such as robotic prosthetics, smart fabrics also offer users valuable feedback by the precise monitor of a series of physical signs and indicators. Beside human-machine interface, flexible sensors, microprocessors and wireless communication systems can be incorporated into fibres and fabrics to bridge physical world to digital world.[398-400] We can imagine that a future fabric capable of collecting real-time data of gas, corrosive liquids, and high temperature will help to identify potential hazards in daily activities. Furthermore, enhancing the ability of future fabrics to collect, compute and analyze vast quantities of sensory data will facilitate the advancement of artificial intelligence. This can then be integrated into the Internet of Things, realizing the intelligent prediction and decision-making potential.[401-405]

7.4. Fabric Computation

At present, the field of pervasive computing is mainly dependent on information technology provided by silicon-based devices. However, the scope for further advancement in semiconductor integration technology is beginning to diminish.[406] Expectedly, the computing power is likely to reach a bottleneck soon. It is urgent to explore the innovative ways to expand information technology. In the section of "Functions and Applications of Smart Fibres Enabled Fabrics", the smart fabrics based on multi-material smart fibres demonstrate a myriad of advanced functions, including sensing, communication, data storage and processing, feedback, and power supply. In addition, the thermally-drawing technology proves that digital chips can

be integrated into the fibre matrix on a large scale, forming ultra-dense sensory interaction channels.[345] These breakthroughs are expected to realize revolutionary sensing and interactive functions based on fabric computation. We believe that the forthcoming fabric computation rests upon three core parts. The first is to advance smart fabric sensing module with sophisticated resolution and ultrahigh sensitivity for capturing a profusion of diverse sensing data; The second is to create fabric data management module that enables real-time data visualization and algorithmic control, facilitating prompt processing, analysis, and feedback of sensor information; The third is the establishment of fabric closed-loop smart network, weaving together the energy supply, sensing, calculation, feedback and interaction into a comprehensive closed-loop scheme.

7.4.1. Fabric Data Management

The management of fabric data can be broadly categorized into three distinct stages: data acquisition, data storage, and data analysis. Data acquisition involves the use of sensor components that are distributed throughout the smart fabric to effectively capture various signals such as heartbeat, breathing, muscle movement, expression, and even fingerprint data. Furthermore, the data acquisition process for smart fabric can be customized by placing integrated fibre functional units in various positions within the fabric, thereby allowing for the collection of multi-modal, multi-layer, and multi-directional signals. This detailed data can subsequently be used for machine learning and Artificial Intelligence. Data security is a crucial consideration during the data acquisition stage, and near field communication (NFC) technology is increasingly being adopted as a more secure alternative to medium and long-distance communication technologies like WIFI and Bluetooth.[407] Flexible micro-network data devices embedded in the fabric enable the data storage and upload, temporarily storing signal data to reduce network burden and transmission delay caused by back-and-forth data transmission to the cloud. Once a certain data threshold is reached, data can be uploaded to the cloud center for backup, and critical real-time task data is retained in the micro-memory while other data is cleaned up. Sensor data is then processed by the micro computing center for data analysis, and a customized application connects the smart fabric with the user interface (including planar-type and fabric devices) for real-time communication. The rapid development

of Artificial Intelligence, such as deep learning and reinforcement learning, will further enhance the intelligent fabric's ability to analyze dig data.

7.4.2. Fabric Artificial Intelligence and Machine Learning

Future fabrics are expected to identify the data pattern via artificial intelligence tools, making the collection and processing of signal data more accurate and reliable. Notably, the combination of AI with fabric computation is useful in smart health care, as it can predict potential disease threats and actively respond to them.[408] Machine learning, as a subset of artificial intelligence, can make the accurate prediction and analysis of data. Furthermore, it can generate knowledge, train algorithms, identify relationships, and recognize patterns. These can be applied to new data sets for predictions and process optimization.[409] Multi-mode future fabrics that combine mechanical, chemical, sensing, and biosensing capabilities provide comprehensive information that can serve as a great platform for machine learning. However, upgrading machine learning algorithms requires considerable effort. The current lack of long-term stability in sensing fibre enabled fabrics leads to poor repeatability of training data, which weakens the predictive accuracy of machine learning models. We are confident that ML enhanced fabric computing will play a significant role in realizing emerging fields such as human-machine interactions, Internet of Things, virtual reality, and the metaverse.

7.4.3. New Generation of Closed-Loop Wearable Systems Enabled by Intelligent Fibres

The concept of intelligent fibres enabled closed-loop wearable systems involves the integration and cooperation of multifunctional fibres, data science, electronics, and mechanical engineering. The Rogers team’s implantable transient closed-loop system, combining a wireless network of skin-integrated devices with a bioresorbable pacemaker, has proved to be a successful example.[410] However, in the face of this booming direction, significant challenges remain to be addressed at the fibre and fabric level. In specific, existing fibre-shaped actuators, sensors, energy harvesting and storage devices have not yet reached maturity in terms of high-power density, fast response, and seamless integration into closed-loop wearable systems.[411] For example, achieving sophisticated electronic devices, like memories and processors, from a

single fibre faces three major problems. Firstly, the range of semiconductors that can be fiberized or integrated into fibres is limited due to their aspect ratio and unique deformation behavior. Secondly, forming complex structures within fibres requires different processes compared to planar-type devices. For example, conventional manufacturing processes for planar devices, such as lithography, are difficult to implement on flexible fibres. Lastly, assembling fabric devices from functional fibres is challenging due to mechanical and topological considerations. Moreover, the development of smart fibre electronics for signal collection, interpretation, correlation, extraction, and transmission is still in its infancy.[412-418] To achieve closed-loop smart fabric system, strategies for innovation in fibre materials, preparation methods, extension of functions, and fine structural design are essential.[419-422]. Additionally, a wearable power supply device compatible with such system is still a bottleneck.

With continuous innovation and development in fibre materials, fibre and fabric design and integration, fabrication methodologies, combining with the increasingly powerful 5G communication and Artificial Intelligence technologies, we are now entering a new era of fabric computation where fabrics can see, hear, speak, feel, actuate, communicate, regulate temperature and energy, analyze data, even infer, alert, and act (Fig. 19).[8, 40, 423-444] Computing fabrics have the potential to revolutionize various fields including health care, aerospace, neuroscience, robotics, metaverse, and many more. We believe, the possibilities of computing fabrics are limitless, and they will offer paramount technologies that can help tackle scientific and technological challenges in the foreseeable future.

Conflicts of Interests

The authors declare no conflict of interest.

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