Advanced Composites and Hybrid Materials https://doi.org/10.1007/s42114-026-01746-2

Article in Press

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Received: 21 January 2026

Accepted: 10 March 2026

Published online: 01 April 2026

Cite this article as: Arab K., Sheikhzade M.H., Fakhri V. *et al.* Advanced conductive textiles: from nanomaterial integration to wearable applications. *Adv Compos Hybrid Mater* (2026). https://doi.org/10.1007/s42114-026-01746-2

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Advanced Conductive Textiles: From Nanomaterial Integration to Wearable Applications

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Table of Contents

Abstract

Integrating electronic parts with the human body is a complex challenge that requires materials that are not just effective but also comfortable, breathable, and flexible. Porous Conductive Textiles (PCTs) are emerging as an exciting breakthrough, inspiring researchers with their potential to revolutionize smart wearable devices. This review examines the latest developments in PCTs, from basic materials to groundbreaking real-world applications. It covers innovative developments, including active therapeutic systems designed for on-demand thermotherapy, capable of achieving temperatures exceeding 120 °C at low operating voltages (<9 V), low-voltage (<2 V) textile actuators with notable electromechanical efficiencies exceeding 6% and exceptional durability under significant strain (over 500%), and integrated energy solutions such as flexible solar cells with power conversion efficiencies nearing 19% and supercapacitors offering volumetric capacitances as high as 1500 $F.cm^{-3}$. Additionally, we explore the rapid advancements in PCT-based sensors that demonstrate ultra-high sensitivity, capable of pressure detection at ~1 Pa, strain gauge factors surpassing 10^7, and gas detection at <50 ppb levels, and highly efficient, secure wireless communication for Body Area Networks (BANs). Finally, we address the key challenges related to durability, washability, and multifunctional integration, offering a future-focused view on developing autonomous, smart garments that can self-power and interact seamlessly with the human body.

Keywords:

Porous Conductive Textiles (PCTs); Smart Textiles; E-textiles; Wearable Electronics; Flexible Hybrid Electronics; Conducting Polymers

1. Introduction

The development of next-generation wearable electronics is a major focus in materials science and engineering. Its aim is to address the limitations of traditional wearables, which are often bulky, inflexible, and uncomfortable for long-term use [1–3]. Conventional wearables mainly use rigid electronic parts attached to flexible bases. This setup causes a mismatch with the softness of human skin, making it difficult for the devices to integrate smoothly [4]. To tackle this challenge, recent innovations have concentrated on two main strategies: transforming normally rigid components into flexible or stretchable versions and using inherently soft materials [1]. The first strategy includes new designs like serpentine circuits and improved semiconductor structures that maintain electrical functionality under deformation [2]. The second, more transformative strategy focuses on materials like conductive polymers, fabric-based substrates, and hydrogels. These materials naturally possess the mechanical flexibility and biocompatibility necessary for wearable applications [5,6]. The combination of these methods has led to major advancements in creating sensors, actuators, and energy storage devices that easily conform to the human body. This opens up new possibilities in healthcare, fitness tracking, and human-machine interaction [2,5].

Among soft materials, conductive hydrogels show significant potential because they closely mimic human tissue, with features like low modulus, flexibility, and high water content [7]. These 3D polymer networks achieve conductivity through two primary modalities: ionic conduction, reliant on the mobility of free ions (e.g., Na^+, Li^+) dispersed within the hydrogel matrix, and electronic conduction, facilitated by the integration of conductive fillers such as polymers (polyaniline, poly(3,4-ethylenedioxythiophene) polystyrene

sulfonate (PEDOT:PSS)), carbon-based nanomaterials (graphene, CNTs), or metallic nanoparticles [8]. While ionic hydrogels are highly transparent and suitable for skin-like applications, electronic hydrogels generally offer better conductivity and faster response times, making them ideal for high-performance electronics. Recent advances in hydrogel synthesis have led to enhanced functionalities, such as self-healing, strong adhesion, anti-freezing features, and environmental resistance, greatly increasing the durability and lifespan of wearable devices [5,7,9,10]. Moreover, the incorporation of natural biopolymers like starch and cellulose has gained renewed attention for developing eco-friendly, biocompatible, and biodegradable devices [11,12].

Textile-based electronics, also known as e-textiles, constitute another foundational aspect of wearable technology, leveraging the inherent comfort, flexibility, and breathability of fabrics as a medium for electronic integration [13]. Textiles are ideal substrates because they are soft and highly porous, allowing microelectronic components to be integrated smoothly without affecting comfort or movement [14]. The flexibility of textiles is enhanced by the ability to tailor their mechanical properties through choosing natural or synthetic fibers and employing different manufacturing techniques like knitting, weaving, and embroidery [3,6,15]. A notable breakthrough in this field has been developing techniques to make fabrics conductive, turning them into Porous Conductive Textiles (PCTs), as shown in **Figure 1** [4]. This transformation can take place at different points, including spinning intrinsically conductive fibers, weaving or knitting conductive yarns (made from metal or carbon), or applying conductive materials to finished fabrics through methods like coating, printing, or chemical polymerization [14–17].

These technological advancements enable the development of various e-textile components, from simple interconnects to advanced sensors for monitoring body functions [6,17]. For example, embroidered electrodes

ensure excellent skin contact for accurate measurement of biopotentials like electrocardiogram (ECG) and electroencephalogram (EEG), while knitted sensors are highly stretchable, making them suitable for monitoring body movements and respiration [15]. The integration of sensors, power sources, and wireless communication modules, such as Bluetooth, into a single garment results in a "smart clothing" system that enables real-time, remote health monitoring [3]. These systems are invaluable in healthcare, sports, and military applications, where continuous, non-invasive feedback is essential [17,18]. Despite the notable advancements, several challenges regarding durability, washability, power management, data security, and the absence of standardized testing protocols present critical obstacles to the widespread commercialization of smart textiles [3,6,13,14]. The accelerating integration of textile engineering, materials science, and electronics drives innovation, positioning e-textiles as a cutting-edge platform for the future of connected, intelligent wearable systems.

This review offers a detailed look at the latest developments in designing, producing, and applying PCTs for smart wearables. It begins by examining different materials, from traditional conductive polymers and carbon-based substances to innovative 2D materials like MXenes and liquid metals. Then, it discusses techniques used to achieve conductivity without compromising textile qualities such as flexibility, breathability, and comfort.

The main part of this review examines the practical applications of PCTs across five major areas: therapeutic systems, actuators, energy harvesting and storage, and sensors, and wireless communication systems. We provide a critical assessment of the current state of research in each domain, spotlighting key studies that have pushed the limits of thermotherapy, developed textile-based artificial muscles, enabled self-sustaining wearable devices, and achieved remarkable sensitivity in monitoring physiological signals, as well as establishing secure, battery-free near-field communication.

By connecting foundational materials science with application-focused engineering, this review not only catalogs recent accomplishments but also sheds light on the scientific principles and design guidelines that influence the performance of PCTs. Our goal is to give readers a well-rounded understanding of the current landscape as well as a vision for the future of seamlessly integrated and intelligent wearable technology.

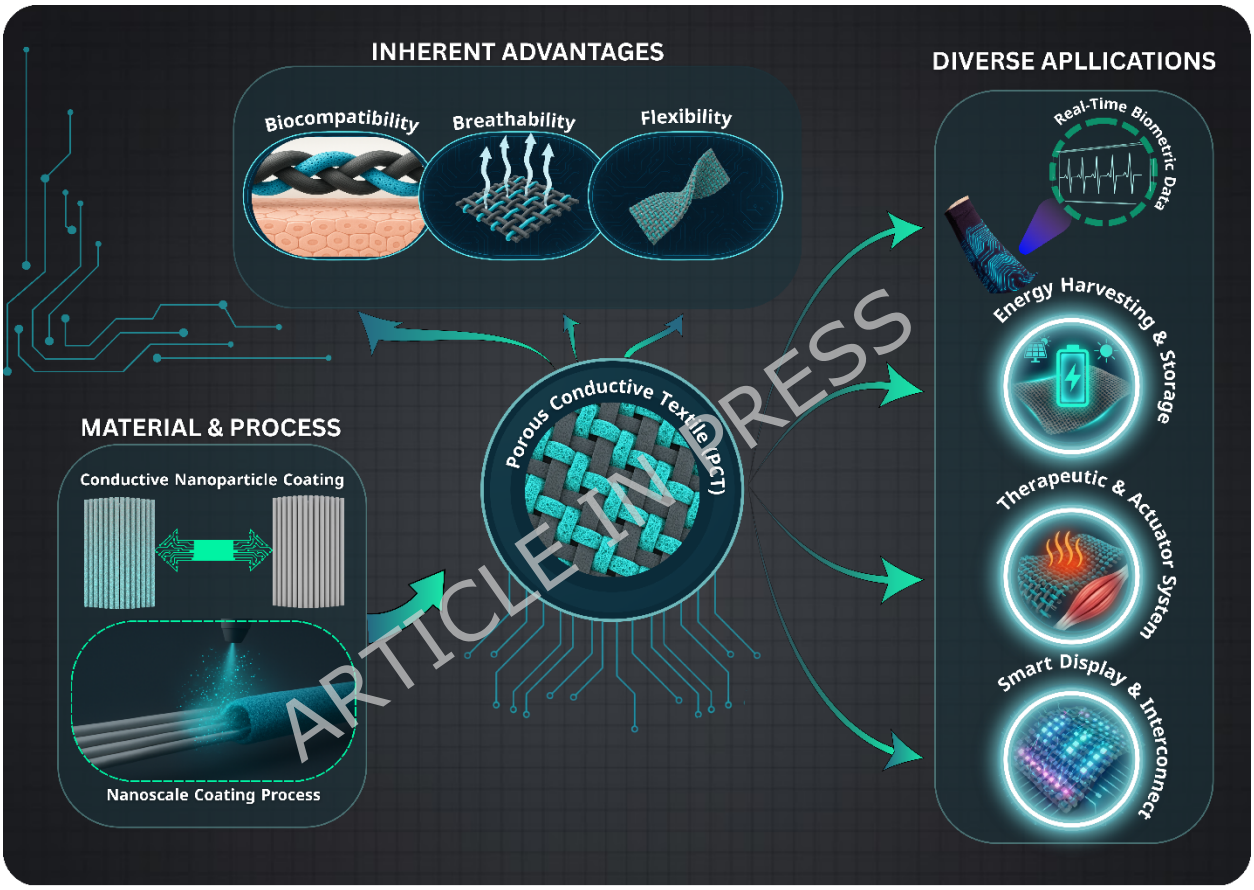


Figure 1: Comprehensive conceptual overview of the PCT platform designed for smart wearable devices: The schematic details the fabrication steps, beginning with the application of conductive nanoparticles to conventional fibers and culminating in the formation of a porous, multifunctional textile hub. The resulting material maintains essential attributes such as biocompatibility, breathability, and flexibility, which support comfortable wear. Due to these properties, the PCT platform is suitable for a variety of applications, including continuous biometric monitoring (e.g., ECG), energy harvesting and storage, therapeutic delivery and actuation, and the development of smart displays and interconnects.

2. Materials and Fabrication Strategies

Creating PCTs is a collaborative process that brings together traditional textile engineering and modern materials science. To unlock the full capabilities of these smart wearables, it's important to grasp both the physical structure and the special materials involved. This section first introduces the key textile designs, like woven, knitted, and nonwoven fabrics, that shape the device's flexibility and breathability. Next, it describes the wide range of functional materials added to these fabrics, such as conducting polymers, carbon-based nanomaterials, and metals. Finally, it explores how these advanced conductive materials can be woven into textiles so they work reliably, all while keeping the fabric comfortable to wear.

2.1. Textile Integration Architectures

The development of PCTs relies on the distinctive structural characteristics and inherent flexibility of textile materials. This makes them well-suited for advanced wearable electronic devices that demand flexibility, breathability, and other essential features [19–21]. Fibers, the fundamental building blocks of textiles, are spun into yarns that are then processed into fabrics, where each structural architecture possesses unique mechanical properties (**Figure 2**) [21]. The wide range of textile substrates, including woven, knitted, and nonwoven types, combined with their diverse compositions, makes PCTs a highly versatile and promising group of materials. This diversity enables a variety of innovations in wearable electronics, such as advanced health monitoring devices, textile-based energy storage solutions, and smart garments with integrated actuation and thermal regulation [22–24].

The hierarchical structure of textiles, composed of fibers, yarns, and fabrics, provides a versatile and highly porous framework that enables the integration of conductive pathways while maintaining tactile comfort [25,26].

2.1.1. Weaving

Woven fabrics tend to be very stable dimensionally and exhibit minimal stretch, thanks to their orthogonal interlaced yarn pattern. This makes them ideal for applications such as stable fabric-based supercapacitors and triboelectric sensors that require consistent shape and form [27,28].

2.1.2. Knitting

Knitted fabrics are distinguished by their interlocked yarn structure, which grants them notable stretchability and flexibility [29,30]. This feature makes them ideally suited for comfortable, body-conforming wearable sensors that can accurately track dynamic human motions and physiological signals under high strain [31].

2.1.3. Nonwovens

Nonwoven fabrics consist of fibers bonded through thermal, chemical, or mechanical methods. This manufacturing process gives them unique characteristics such as high, adjustable porosity and low density, making them ideal as substrates for flexible electronic applications that require breathability. For example, their porous nature has been used to create lightweight electrodes from compressed nonwoven towels coated with polyaniline (PANI)/graphene composites. as well as to develop highly conductive composite nonwovens with polyacrylonitrile (PAN) and AgNWs for functional textiles [32–34].

2.1.4. Embroidery

Machine embroidery has emerged as a scalable, additive manufacturing technique for electronic textiles, capable of patterning conductive textiles through numerically controlled sewing processes [35,36]. Utilizing commercially available embroidery machines allows for the rapid and consistent fabrication of customized components [37]. This method facilitates

the precise placement of functional patterns directly onto the finished textile surface without being restricted to pre-defined directions [38]. The process is computer-aided design (CAD) based, enabling high-resolution fabrication as fine as 100 µm, and allows for the seamless integration of circuit networks and sensors into clothing using computer numerical control (CNC) processes [39,40].

Embroidery is particularly effective for creating low-resistance interconnections; for instance, circuits patterned with specific twisted metal composite yarns have demonstrated electrical resistance as low as approximately 0.05 $\Omega.cm^{-1}$ [39]. Furthermore, in biopotential monitoring applications such as surface electromyography (sEMG), embroidery-based electrodes offer enhanced aesthetic customizability and improved skin-electrode contact. Research indicates that increasing the embroidered area of conductive yarn effectively decreases skin-electrode impedance, thereby improving signal acquisition [38]. Additionally, the technique offers superior mechanical integrity; compared to screen-printing or conductive fabric adhesion, embroidered conductive threads demonstrate the highest resistance to degradation from washing cycles, while maintaining the robustness and flexibility required for daily wear [36,40].

2.1.5. Braiding

Circular braiding is a textile manufacturing method in which three or more yarns are intertwined diagonally along a helical path, producing seamless tubular or flat structures with enhanced structural integrity . This technique distributes mechanical stress evenly among all yarns, resulting in high torsional stability and resistance to rupture due to the combined effects of the strands and any elastic core present [41]. For PCTs, such braiding is particularly useful in fabricating one-dimensional coaxial fiber devices such as fiber-shaped supercapacitors (FSCs), artificial muscles, and smart load-bearing ropes. In these applications, the braided structure serves both as a charge-transport channel and as a mechanical support element [42,43]. The

braiding process also allows for the continuous formation of a strong outer sheath that closely surrounds the active core. This sheath provides electrical insulation to prevent short circuits, accommodates changes in volume, and maintains stability during complex deformations like bending and twisting. Fine-tuning the braid angle and reducing structural flaws help coaxial assemblies store energy efficiently at any size, while also making them more durable over time. As a result, these assemblies can hold more energy without losing the flexibility that's essential for wearable electronics [44,45].

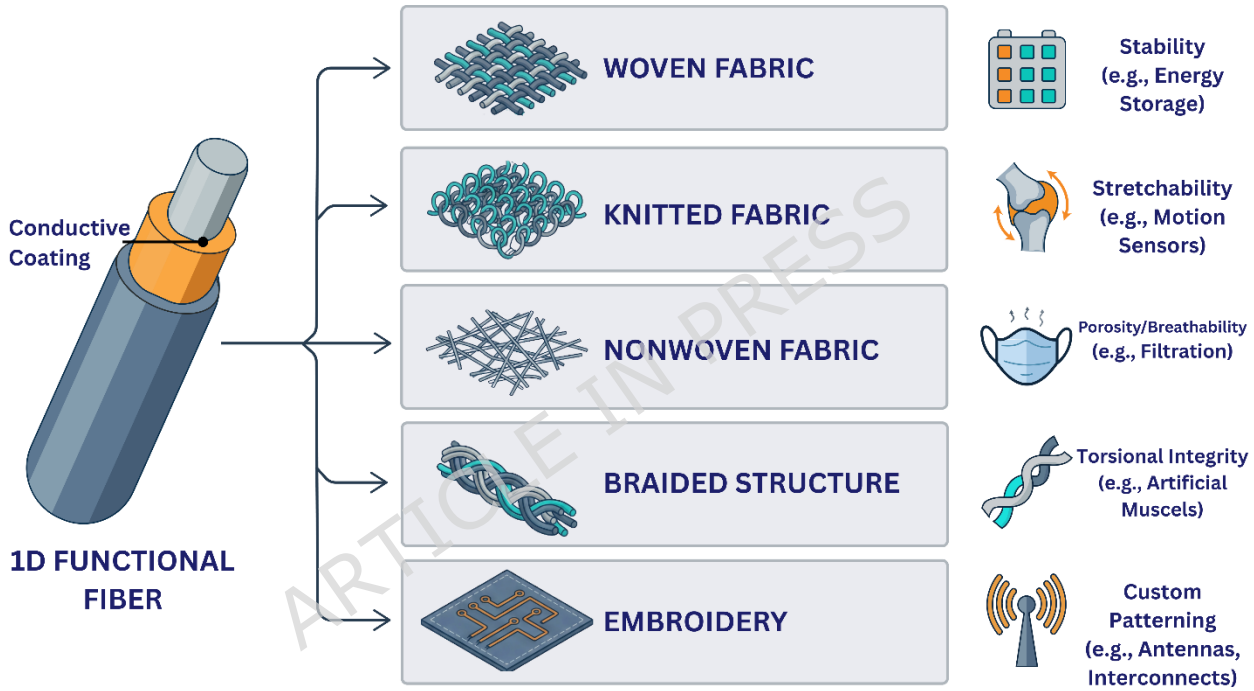


Figure 2: Multi-scale structural integration in conductive textiles involves progressing from one-dimensional (1D) functional fibers to complex, large-scale architectures. Foundational 1D fibers, such as core-sheath or conductively coated yarns, are combined using textile manufacturing techniques like weaving, knitting, nonwovens, braiding, and embroidery. Each structural arrangement offers specific mechanical and electrical properties, which determine their effectiveness for various wearable technologies, including stable energy storage devices, adaptable motion sensors, and customizable circuit layouts.

2.2. Conductive Materials

To turn the textile substrates mentioned earlier into active electronic parts, they need to be coated with conductive materials. These conductive components mainly include conducting polymers, carbon-based nanomaterials, and metallic compounds.

2.2.1. Conducting Polymers

These materials are crucial for creating interconnects and electrodes. Notably, conducting polymers such as PANI, polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT) are extensively utilized due to their conjugated π-electron systems that enable electrical conductivity [46,47]. These organic polymers provide substantial benefits for wearable applications, including low weight, high mechanical flexibility, and inherent electrochemical activity, facilitating their integration with the dynamic movement of the human body [48,49]. While the intrinsic electrical conductivity of Conductive Polymers typically lags behind that of metals, it can be markedly improved through chemical doping, which introduces charge carriers into the polymer backbone, thereby enhancing electron mobility [50].

2.2.2. Carbon-Based Nanomaterials

Carbon-based materials such as carbon fiber, graphene, and CNTs are fundamental to the development of PCTs due to their remarkable combination of chemical stability, low density, mechanical durability, and adjustable electrical conductivity [51–53]. For example, carbon fiber (CF) is typically synthesized via the thermal transformation of polymer precursors like PAN, involving processes such as controlled stabilization followed by high-temperature carbonization [54,55]. The produced carbon cloths function not only as conductive substrates but also as three-dimensional, porous, and flexible current collectors. This structure is particularly suitable for high-performance energy storage applications, enabling the direct growth of

active materials such as manganese dioxide (MnO_2) nanoflowers or doped carbon networks onto the fiber framework to fabricate binder-free, wearable supercapacitors and flexible batteries [56–58].

Carbon nanotubes are highly valued for their remarkable tensile strength and natural electrical conductivity. Generally created through chemical vapor deposition (CVD), these nanotubes are then woven into durable yarns or processed into nonwoven films [59,60]. maintaining conductivity even when stretched extensively. These characteristics make such yarns ideal for use in washable wearable strain sensors and textile-based artificial muscles [61,62].

Graphene, a two-dimensional allotrope of carbon, exhibits exceptional mechanical strength, a high surface area, and superior electrical properties [63]. The most common route to creating graphene fibers involves the wet spinning of graphene oxide (GO) liquid crystals, which are subsequently reduced chemically or thermally to regenerate the sp^2-hybridized carbon network, thereby enhancing the electrical conductivity [64–66]. To mitigate the intrinsic brittleness of pure graphene and enhance its processability, graphene is often compositeized with other materials. For example, graphene/CNT hybrids have been successfully used to develop highly durable and extremely sensitive e-textiles capable of cardiorespiratory monitoring [67].

The inherent characteristics of these nanocarbon materials, notably their elevated surface area and electrical conductivity, render them highly effective for energy storage applications. This enables the development of flexible supercapacitors capable of fulfilling the high power density and rapid charge-discharge demands characteristic of contemporary wearable electronics [51,52].

2.2.3. Metallic Materials

Metals and alloys remain crucial in wearable electronic devices because of their excellent ability to conduct electricity and their strong resistance to chemical damage [68,69]. Instead of using bulk metals, integration into PCTs is achieved through nanoscale structures like nanowires or by applying thin-film coatings to polymer fibers, which helps preserve the textile's inherent flexibility and comfort [68,69]. Metal nanowires, notably AgNWs, are widely utilized in the fabrication of transparent conductive films and flexible conductive networks. Their high aspect ratio facilitates the formation of electrically conductive pathways at minimal volume fractions, which is essential for applications that require both electrical conductivity and optical transparency [70,71]. Although copper nanowires (CuNWs) are a more cost-effective option, their tendency to oxidize requires the use of protective passivation layers to ensure longevity [72].

Silver has been widely used to create multifunctional electronic textiles that demonstrate excellent conductivity, durability, washability, and natural antibacterial properties. These qualities make them particularly well-suited for long-term health monitoring [73,74].

2.2.4. Emerging Liquid Metals and MXenes

Recent progress in stretchable electronics has focused on replacing rigid solid conductors with deformable, fluidic materials such as eutectic gallium-indium (EGaIn), thereby enabling devices with mechanical properties comparable to biological tissues [75–77]. EGaIn's inherent fluidity allows for robust architectures; for example, superelastic fibers with a polyurethane core sustain 500% strain with high conductivity ($>10^3$ $S.cm^{-1}$) [78]. Alongside these advancements, two-dimensional MXenes are becoming increasingly popular because of their excellent metallic conductivity and water-friendly surfaces, making them ideal for creating high-quality conductive inks that can be used in scalable inkjet printing [79–81].

To summarize the different material strategies covered in this section, **Table 1** offers a straightforward comparison of the main conductive material types, their fabrication methods, and their respective trade-offs.

2.3. Fiber and Yarn Fabrication Strategies

The functionalization of textiles into PCTs is usually achieved using two main strategies: either by shaping inherently conductive materials into textile forms or by applying conductive coatings to nonconductive textiles. [21,82]. The first method involves making composite yarns by mixing conductive fillers like carbon nanotubes (CNTs) or graphene with polymer matrices such as thermoplastic polyurethane (TPU) before spinning [83,84]. The approach typically uses different deposition techniques, including layer-by-layer assembly of conductive polymers like PEDOT:PSS, dip-coating fibers in AgNW solutions, or twist-assisted deposition of liquid metal (LM) composites stabilized with agents such as tannic acid to improve adhesion [85–88].

Various fabrication methods are used to create conducting polymer fibers, each offering distinct benefits and challenges. Once the conductive material is selected, it must be processed into 1D fibers or yarns to serve as the building blocks of the textile.

2.3.1. Wet Spinning

Wet spinning involves pushing a polymer solution through a small opening into a coagulation bath, which helps produce long, continuous fibers ideal for textile use. This technique has successfully been applied to make composite fibers such as PEDOT:PSS combined with poly(vinyl alcohol) (PVA), commonly used in wearable sensors [89,90]. However, the process depends on certain solvents and involves complex steps that can increase manufacturing costs and impact the environment [91]. The process relies on specific solvents and involves intricate steps, which can raise manufacturing expenses and impact the environment [48].

2.3.2. Melt Spinning

Melt spinning is an industrial process where thermoplastic polymers are heated until they melt and are then extruded into fibers. This technique is commonly used to produce fibers with antistatic or conductive properties by incorporating conductive fillers such as carbon black into the polymer material [92,93]. This method is primarily limited to thermoplastic polymers.

2.3.3. Electrospinning

Electrospinning remains a highly versatile technique, employing a strong electrostatic field to stretch a polymer solution into fibers that can be nanometers to micrometers in diameter [46,94]. This process allows for detailed regulation of fiber size, porosity, and the structure of the nonwoven membrane, making it well-suited for producing lightweight, high-surface-area materials. These are ideal for uses like biomedical scaffolds and advanced sensors [95–97]. Electrospinning, while versatile, often faces issues with low production speeds and the use of volatile or toxic solvents. These factors raise concerns about scalability, environmental impact, and safety.

2.3.4. Coating and Sheathing (Yarn Level)

A key method for translating the nanoscale properties of materials into practical applications is the fabrication of core-sheath composite yarns [98,99]. By encasing sheets of CNTs around a flexible core like spandex, it is possible to create yarns that are both highly elastic and durable [98]. Similarly, metallized yarns can be created by coating polymer fibers using scalable, solution-based techniques such as electroless plating or magnetron sputtering [100–103]. This results in a core-shell structure that merges the flexibility of the polymer core with the high electrical conductivity of the metal shell [69,104].

The various fabrication techniques emphasize the critical balance between manufacturing capacity, the desired material properties, and sustainability. Managing these aspects is key to improving the performance and market

readiness of conductive polymers in PCT applications, especially for advancing healthcare and consumer electronics [48,105].

Table 1: A comparative overview of conductive materials used in PCTs, highlighting their common fabrication strategies, key advantages, and primary limitations.

Material Category	Specific Examples	Common Fabrication Method(s)	Key Advantages	Key Limitations & Challenges	Reference(s)
Conducting Polymers	PANI, PPy, PEDOT:PSS	Dip-coating, in-situ polymerization, screen printing, vapor phase deposition (VPD/oCVD), wet spinning, inkjet printing	Low cost and lightweight. Good biocompatibility. Solution-processable and easy to synthesize. Inherent flexibility. Tunable electrochemical properties.	Lower intrinsic conductivity compared to metals, poor mechanical strength or brittleness, instability (environmental, mechanical, wash), and potential toxicity (PANI) or corrosiveness (PEDOT:PSS).	[69,106–113]
Carbon-Based Materials	Carbon Nanotubes (CNTs, SWCNTs, MWCNTs), Graphene (G, GNP), GO, Reduced Graphene Oxide (rGO), Carbon Black (CB), Activated Carbon (AC)	Dip-coating, screen printing, spray coating, inkjet printing, chemical vapor deposition (CVD), liquid phase	Excellent mechanical strength and stiffness, high chemical and thermal stability, high electrical conductivity	Dispersion and agglomeration issues in inks. GO is an insulator and requires a reduction step. Brittleness	[69,106–110,112–115]

		exfoliation (LPE), pyrolysis.	(pristine graphene/CNTs), low cost and lightweight, and large surface area (good for sensors/storage).	(graphene) or high stiffness (CNTs). Scalability of high-quality, defect-free material. Low wash durability (CB).	
Metallic Materials	Silver (Ag, AgNPs, AgNWs, AgFDs), Copper (Cu, CuNPs, CuNWs), Gold (Au, AuNPs, AuNWs), Nickel (Ni)	Electroless plating (ELD), electrodeposition, dip-coating, screen printing, sputtering (PVD), inkjet printing, transfer printing	Highest electrical conductivity, robust and stable (especially Au, Ag), with antibacterial properties (Ag).	High costs of Ag and Au oxidation and instability of Cu. Rigidity and stiffness can cause cracking. Poor adhesion to certain textile substrates. Often requires high-temperature sintering.	[69,106,108,109,111–113,115–117]
2D Materials (non-graphene)	MXenes (e.g., $Ti_3C_2T_x$)	Dip-coating, spray-coating, vacuum-assisted filtration.	Exceptional metallic electrical conductivity, hydrophilic surface (good for inks), excellent volumetric capacitance, and good EMI shielding.	Prone to oxidation (poor stability in air and water), scalability of synthesis, and use of hazardous chemicals during production.	[97,108,113,118–121]

Liquid Metals (LMs)	Eutectic Gallium-Indium (EGaIn)	Direct printing, inkjet printing, used as a composite filler.	Intrinsically stretchable and maintains high conductivity under large deformation.	Requires encapsulation to prevent leakage; simplifies processing and patterning complexity.	[69,115,120]
Composites & Hybrids	Graphene/Carbon Black/PEDOT:PSS (G-C-P), CNT/MXene/PANI/LM (CTPLM), AgNWs/PEDOT:PSS, CNT/PPy	Screen printing, dip-coating, in-situ polymerization	Synergistic properties (e.g., high sensitivity and wide strain range), improved conductivity over single Conductive Polymers, enhanced stability (e.g., PANI protecting MXene), and improved adhesion (e.g., PEDOT:PSS aiding AgNWs).	Complex ink formulation and rheology: Optimizing component ratios is critical. Wash and wear durability remains a challenge.	[106–109,112,113,117,120,122]

aiming to overcome the mechanical limitations of solid-state materials. The broad range of metallic systems, including flexible nanowire networks, conformal fiber coatings, and deformable liquid metal composites, plays a crucial role in enhancing the capabilities of wearable technology. This progress paves the way for applications in personalized health monitoring, smart textiles, and soft robotics [69,123].

3. Applications in Wearable Electronics

3.1. Therapeutic Applications

The development of textile-based electronic systems has advanced from passive physiological monitoring to include active therapeutic functions, allowing on-demand, body-conformable treatments [124,125]. While emerging applications include transcutaneous electrical nerve stimulation (TENS) for pain relief and iontophoresis for targeted drug delivery, the most established and widely proven therapeutic application is thermotherapy [126–128]. Traditionally limited to bulky clinical devices, thermotherapy is now more often delivered through non-invasive, flexible, and comfortable wearable solutions that work on the principle of Joule heating [129,130].

The fundamental mechanism of PCT-based thermotherapy is based on establishing a percolating conductive network within a hierarchical textile matrix [130–132]. When a low-voltage electrical current is applied, the interconnected nanomaterials enable efficient electron transport, resulting in heat generation [133]. Simultaneously, the intrinsic air gaps present within the porous fabric serve as thermal insulators, reducing heat dissipation through phonon scattering to the environment and directing the thermal energy toward the skin [134].

PCTs are especially well-suited for this purpose; unlike stiff metallic wires, they offer the essential flexibility, stretchability, and breathability needed for

continuous, comfortable skin contact [130,135]. Researchers have developed durable heating fabrics by coating them with carbon-based nanomaterials or conductive polymers, allowing them to reach temperatures above 120°C safely at low voltages around 9 V [136,137]. Additionally, conductive polymers such as PEDOT:PSS and PPy have been successfully functionalized onto stretchable knitted fabrics. This facilitates the development of flexible heaters with rapid thermal response times (<60 seconds), suitable for on-demand therapeutic applications [138,139]. Recent advancements in 2D materials, such as MXene ($Ti_3C_2T_x$) nanosheets and AgNWs, have enabled their integration into cotton and other textiles to fabricate highly efficient, flexible, and washable heating elements. These materials exhibit low sheet resistance and facilitate uniform temperature distribution across the fabric surface [74,140]. The inherent softness and conformability of the textile substrate facilitate intimate contact with the skin, which is critical for efficient heat transfer and user comfort. This characteristic underpins various therapeutic applications, such as enhancing local blood circulation, alleviating muscle soreness, and enabling personalized thermal regulation for both comfort and medical purposes [130,139].

Silver nanofiber networks, for example, have been sputtered onto electrospun PVA nanofibers to produce hyperthermia patches, which are encapsulated in polydimethylsiloxane (PDMS) to ensure biocompatibility and comfortable skin contact [141]. These materials establish a stable conductive network that ensures uniform heating performance while maintaining mechanical flexibility, allowing adaptation to different body contours. Additionally, liquid metals such as EGaIn have garnered interest due to their fluidic properties, which facilitate the creation of stretchable, conductive textile-based heating devices [142]. EGaIn's liquid state allows it to flow under stress, maintaining conductivity even when stretched. This is especially beneficial for wearable applications that need to adapt to constant movement. Such advances in textile-based electronics are transforming how

therapeutic interventions are delivered, making them more accessible, comfortable, and suitable for continuous wear. This development in PCTs highlights a growing synergy between materials science and biomedical engineering, opening the door for multifunctional wearable devices that can offer both monitoring and therapeutic functions in a single, unobtrusive garment. Conductive nanomaterials, such as metal nanowires, CNTs, graphene, and MXenes, are integral to the advancement of flexible electric heating devices, particularly in wearable technology applications. To develop effective heating textiles, conductive materials can be incorporated either by creating standalone conductive networks or by coating the fabric directly [143,144]. These methods each have their own benefits in terms of performance and longevity. For example, free-standing networks made of carbon nanotubes or graphene are commonly produced through vacuum filtration. This process assembles the nanomaterials into a porous, interconnected, and flexible film that can function independently as a heating element [145–147].

A significant advantage of this method is that the resulting network maintains its intrinsic high conductivity and flexibility without being constrained by an underlying substrate. For example, freestanding CNT films are effective as iron-on biosensors and heating elements, demonstrating the versatility of this approach [145]. Applying coatings directly onto textile substrates is a more practical and scalable approach. Techniques like dip-coating and spray-coating are commonly used for their ease and ability to produce consistent conductive layers [136,148,149]. For example, dip-coating has been utilized to deposit CNT/waterborne polyurethane (WPU) composites, resulting in highly durable and washable conductive yarns [149]. Similarly, spray-coating has been successfully used to deposit graphene inks, AuNP/DWCNT Various conductive solutions like hybrids and PEDOT:PSS are applied to fabrics to create flexible Joule heaters [136,150–152]. Key to their success is ensuring a strong bond between the conductive layer and the

textile fibers, which must endure mechanical stress and washing. This is often achieved by adding adhesive agents such as polyurethane (PU) or polydopamine (PDA) into the ink or as a pretreatment [149,153].

Conductive polymers like PPy and PEDOT:PSS are ideal for textile coatings due to their flexibility and fiber compatibility. Applied via in-situ polymerization or solution coating, they form a thin, conformal conductive layer that retains fabric comfort and breathability. These techniques enable durable wearable sensors and heaters on materials like cotton and polyester/spandex blends [138,154,155].

A novel approach involves carbonizing natural textiles such as silk or cotton. Through controlled heat treatment, these textiles are transformed into flexible, stretchable carbon-based fabrics that function effectively as Joule heating elements [156,157]. These carbon textiles can reach temperatures exceeding 100 °C with relatively low applied voltages and demonstrate resilience under tensile strain, making them ideal for wearable thermotherapy where flexibility and consistent heat generation are essential [157]. The inherent characteristics of PCT-based Joule heating devices provide significant potential for use in personal thermal management and wearable therapeutics, allowing localized and precisely controlled heat for muscle relaxation, pain relief, and even faster wound healing [158–160]. A key challenge in science and engineering is ensuring the safety and reliability of these devices during extended, close skin contact. Uncontrolled heating can cause user discomfort, skin irritation, or even low-temperature burns, making real-time temperature sensing and feedback control systems essential in their design for any practical use [161,162].

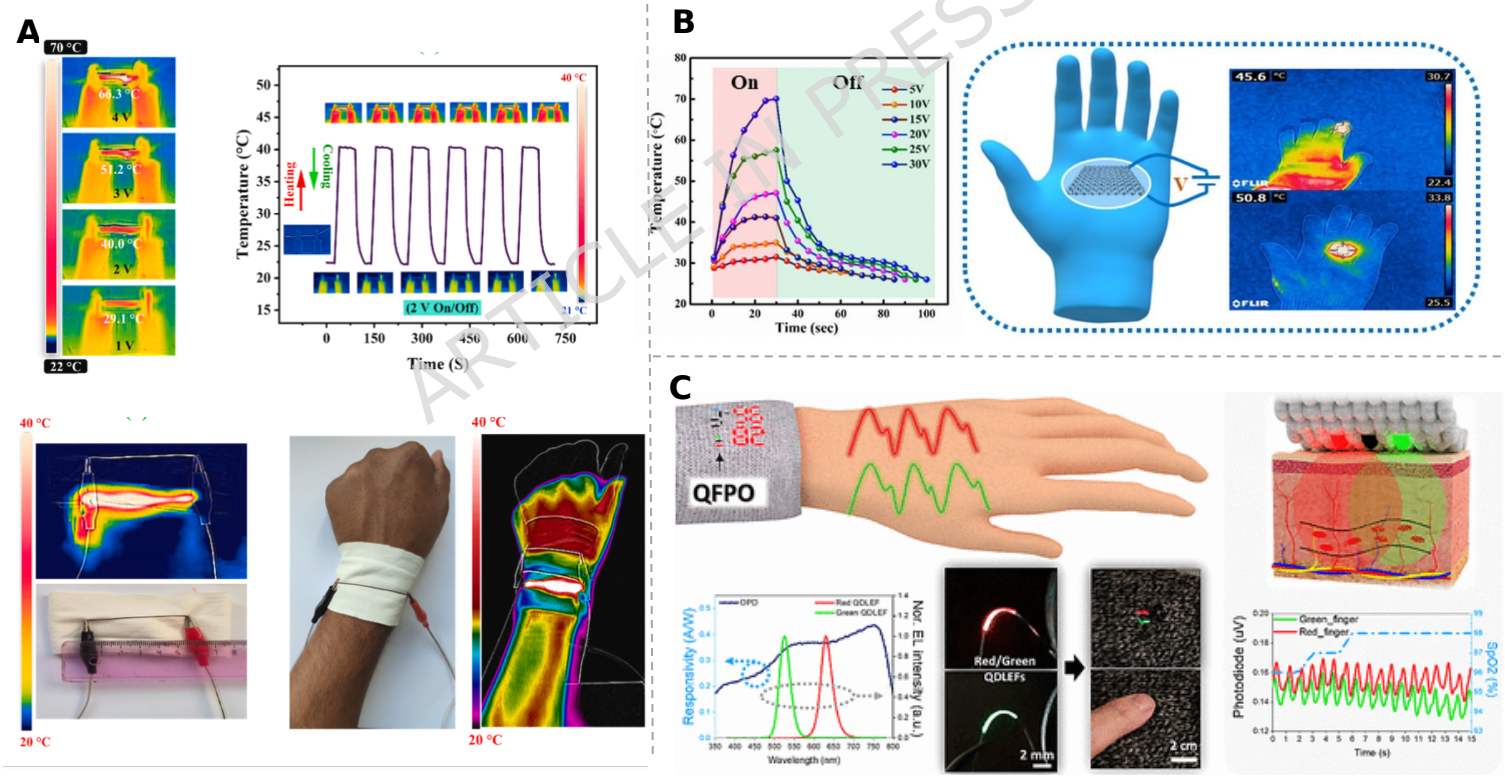
In particular, Shak Sadi and colleagues have developed a novel method to produce highly conductive yarns by depositing copper particles onto polyamide 6 (PA6) yarns through electroless plating, thereby extending their application potential for wearable sensors and Joule heating devices. The

resulting Cu/PA6 yarn demonstrated superior electrical conductivity (2.3 $\Omega.cm^{-1}$) while maintaining favorable mechanical properties [163]. The Cu/PA6 yarn demonstrated significant strain-sensing capabilities, making it suitable for monitoring various human motions such as finger bending, wrist bending, and writing. As shown in **Figure 3A**, in addition, Joule heating performance results demonstrate that the yarn generated rapid and uniform heat, reaching a surface temperature of 66.3 °C at 4.0 V within 45 seconds. The durability of the yarn was preserved even after multiple washing cycles, maintaining a substantial level of conductivity (9.0 $\Omega.cm^{-1}$) after 10 washes, demonstrating its potential for practical applications. The Cu/PA6 yarn exhibited excellent electrical conductivity along with favorable mechanical and electromechanical properties, which rendered it suitable for sensing and heating functionalities.

In a related study, Ahmed et al. explored a novel wearable Joule heater constructed from cotton textiles integrated with reduced graphene oxide (rGO) and PEDOT:PSS via a scalable dip-coating process [164]. The results demonstrate that the composite fabric (CGP) exhibits significant improvements in electromechanical properties due to the synergistic effects of rGO and PEDOT:PSS. Specifically, the incorporation of these materials leads to enhanced electrical conductivity, evident from a reduced sheet resistance of 153 $\Omega.sq^{-1}$ for the CGP4 sample, which underwent optimal dipping cycles of rGO and PEDOT:PSS. The thermal characterization indicates that the CGP heater can reach surface temperatures up to 70°C at an applied voltage of 30V, with a rapid response time of 15-25 seconds (**Figure 3B**). Furthermore, the heater demonstrates stable performance under mechanical deformation, exhibiting only approximately a 9.0% temperature variation at a tensile strain of 60%, which underscores its mechanical robustness.

In addition, Lee et al. investigated wearable optoelectronic devices for medical diagnosis, emphasizing that pulse oximetry sensors fabricated on fiber platforms are promising candidates for integration into clothing due to their minimal form factor and potential for unobtrusive health monitoring [165]. In their study, red and green quantum-dot light-emitting fibers (QDLEFs), built on a 250 μm-diameter one-dimensional fiber, were successfully created, achieving high current efficiencies of approximately 22.46 $mW.sr^{-1}.A^{-1}$ and 23.6 $mW.sr^{-1}.A^{-1}$, along with a narrow full-width at half-maximum (FWHM) of about 33 nm. The device's omnidirectional flexibility was confirmed through vertical and lateral bending tests, with a strain of 0.92%. Using a transparent and flexible elastomer, the researchers demonstrated a wearable pulse oximeter for monitoring oxygen saturation levels on the finger and wrist (**Figure 3C**). The device was also washable. It could operate for up to 18 hours. Thanks to its elastomer material and bottom emission, it showed excellent wear resistance during a 50-cycle reciprocating test conducted with 220-grit abrasive paper at roughly 2180.43 kPa.

Figure 3: **A)** Performance of a wearable Joule heater made from copper-coated Polyamide 6 (Cu/PA6) yarn: Infrared thermography images reveal that increasing the applied voltage from 1V to 4V results in a corresponding rise in surface temperature, reaching a maximum of 66.3°C. The associated graph demonstrates that the heater maintains consistent and repeatable heating and cooling cycles at an operating voltage of 2V. Additionally, the images show the heater integrated into a wristband, with thermal imaging confirming that heat is distributed evenly across the targeted area. Adapted with permission from [163], Elsevier B.V., 2024. **B)** Electrothermal performance of a composite graphene-PEDOT:PSS (CGP) wearable heating element: The left graph displays the temporal temperature profiles of the CGP heater, demonstrating rapid heating capability and reaching temperatures up to 70°C at applied voltages between 5V and 30V. The schematic on the right depicts the conceptual integration of the heater onto the dorsal side of a glove. Infrared thermal imaging confirms effective heat dispersion across a human hand. Adapted with permission from [164], Royal



Society of Chemistry, 2022. **C)** A wearable pulse oximeter utilizing quantum-dot light-emitting fibers (QDLEFs). The top-left panel schematically depicts the device as a clothing-embedded sensor for vital sign monitoring. The bottom-left graph illustrates the spectral overlap between the red and green QDLEF emissions and the responsivity spectrum of the organic photodetector (OPD), accompanied by photographs of the flexible fiber device. The

top-right schematic explains the photoplethysmography (PPG) mechanism, depicting the differential optical penetration and absorption within cutaneous tissue. The bottom-right graph displays real-time, modulated photodiode signals and the derived oxygen saturation (SpO_2) levels, confirming the device's operational capability. Adapted with permission from [165], American Chemical Society (ACS), 2024.

Separately, Yu and colleagues developed a highly crosslinked hydrogel with multifunctional properties suitable for flexible electronics [166]. Their method involved chemically crosslinking a polyacrylamide matrix with lithium magnesium silicate, creating numerous covalent bonds that significantly improve the hydrogel's mechanical strength. Incorporating carbon quantum dots (CQDs) into this matrix gave the material distinctive luminescent features, expanding its potential uses (**Figure 4A**). As a strain sensor, the hydrogel showed excellent performance, with a high gauge factor of 2.6, an extensive strain response range (0–2000%), and strong durability over 1250 cycles, making it ideal for monitoring human motion. At the same time, the hydrogel acts as a flexible, self-supporting triboelectric electrode. It can sense pressure from 1 to 25 N and produce a short-circuit current (Isc) of 2.6 μA, an open-circuit voltage (V_{oc}) of 115 V, and a transferred charge (Qsc) of 29 nC. These dual capabilities make the hydrogel a promising material for advancing human-computer interaction and creating advanced electronic "skin" for.

Transcutaneous electrical nerve stimulation (TENS) is an established, non-invasive therapeutic modality that alleviates chronic and acute pain by delivering mild electrical pulses through the skin to stimulate underlying sensory nerves [125,127]. The underlying scientific mechanism of this electrotherapy involves modulating nociceptive signals in both the peripheral and central nervous systems, providing a non-pharmacological approach to managing conditions such as osteoarthritis and musculoskeletal discomfort. For the optimal therapeutic results, it is crucial to create a stable, low-resistance connection between the electrode and the skin surface.

Traditionally, this is done using moist, gel-based electrodes such as Ag/AgCl, where a conductive hydrogel ensures consistent electrical contact [167]. However, these electrodes face significant practical challenges for long-term use: the hydrogel tends to dry out, reducing signal quality, and the adhesives can cause skin irritation or allergic reactions, making them unsuitable for continuous, truly wearable applications [50,168].

The limitations of existing technologies have increased the need for alternatives that are more comfortable, durable, and user-friendly. In this context, dry electrodes, especially those manufactured from PCTs, are gaining prominence as advanced options for next-generation wearable TENS devices [22,167]. The scientific basis for utilizing textile materials lies in their intrinsic properties: they offer flexibility, high breathability, and the ability to conform to the body's dynamic and curved surfaces, thereby maintaining stable electrical contact while permitting movement and moisture management [163,169]. Advanced fabrication methodologies have facilitated the creation of durable textile electrodes characterized by low skin-contact impedance. For instance, stretchable textile substrates can be functionalized through the application of conductive polymers such as PPy or by embedding silver-plated yarns directly into the knit structure [170]. These approaches yield electrodes that demonstrate high electrical conductivity alongside mechanical resilience capable of withstanding repeated mechanical deformation and laundering cycles. These textile-based electrodes can be integrated into therapeutic apparel such as smart sleeves and leggings, offering comfortable, discreet, and functionally effective solutions for continuous and daily pain management [171,172].

Building on this approach, Wong et al. advanced the concept by developing a TENS-enabled garment using intarsia knitting with silver conductive yarns [173]. This innovative design integrates electrodes and conductors directly into the fabric, enabling electrical stimulation while ensuring wearer comfort

during extended use. The key challenges include ensuring the durability of the devices, maintaining consistent electrical conductivity, and providing long-lasting comfort. A significant issue with PCT-based dry electrodes is achieving stable skin contact, which can lead to higher impedance and lessen therapeutic effectiveness. To tackle this, recent research focuses on developing ultrathin, highly conformable materials such as conductive films and microneedles that better adhere to the skin, reducing impedance and enhancing signal transmission. Wearable TENS systems also face difficulties regarding power sources; traditional batteries tend to be bulky, affecting comfort, limiting wearability, and constraining design options for TENS garments. Consequently, innovative solutions like triboelectric nanogenerators (TENGs) are being explored. These devices can generate electrical energy from biomechanical movements, potentially replacing bulky batteries and boosting both comfort and device performance.

Wang et al. designed an innovative therapeutic patch that harnesses biomechanical energy for autonomous power [174]. This patch combines a TENG with dissolvable microneedles, where the TENG converts patient movements into electrical energy to enable the delivery of drug-loaded nanoparticles (NPs) into the dermis. This electrical energy provides sufficient propulsion to transport therapeutic NPs deeply into tumor tissues, thereby significantly improving drug delivery efficiency. Once the NPs encounter the tumor's acidic microenvironment, they rapidly dissociate in response to the pH change, releasing their therapeutic payloads, which include the chemotherapeutic agent doxorubicin (DOX) and the photodynamic therapy (PDT) agent Ce6. This dual-modal therapy exploits a synergistic mechanism to selectively targets tumor cells. In a mouse model of deep-seated melanoma, a single application of the microneedle (F-MN) patch led to notable inhibition of tumor growth. Additionally, treated mice exhibited a markedly increased survival rate with minimal in vivo biosafety concerns, indicating the potential

clinical applicability of this strategy for treating deep-seated solid tumors (**Figure 4B**).

A prominent therapeutic method integrated into smart textiles is iontophoresis, which is a type of transdermal drug delivery (TDD) that utilizes a gentle, controlled electrical current to help move medication through the skin [125]. This technique is scientifically justified because it can address the major limitations of traditional systemic methods, such as oral drug delivery, which often exhibit poor target specificity, systemic side effects, and reduced bioavailability due to first-pass hepatic metabolism [175]. Conventional transdermal patches offer a non-invasive method for drug delivery. However, their effectiveness is limited by the skin's primary barrier, the stratum corneum, which slows down passive diffusion. This process often results in inconsistent and inefficient drug release, especially for hydrophilic or larger molecules. As a result, such patches may not be suitable for treatments that require quick, precise, or controllable dosing [105,176]. Iontophoresis provides a precise way to deliver ionized drugs through the skin, allowing for adjustable rates that depend on factors like drug concentration and the applied current [177]. The system uses a low-voltage electrical charge applied between two electrodes on the skin to facilitate the movement of ionized drug molecules through the skin barrier. This process involves electromigration and electro-osmosis mechanisms [126,128]. This process is supported by scientific reasoning because it addresses key issues found in traditional systemic drug delivery methods, such as low bioavailability, the need for high doses, and adverse systemic effects. It enables highly adjustable drug delivery rates, which can be precisely controlled by modifying parameters like the applied voltage and the drug concentration [125]. Integrating this technology into PCTs represents a notable step forward for wearable therapeutic devices. Using conformable, breathable materials such as fabrics coated with conductive polymers like PEDOT:PSS for electrodes allows these systems to offer comfort and durability over

extended periods [178]. This textile-based device typically features two electrodes linked to a small power source, enabling precise and programmable delivery of medication. It allows for discreet, on-demand therapy [124,125].

In addition to drug administration, iontophoresis is used for diagnostic purposes, such as stimulating sweat production for biosensing or extracting interstitial fluid (ISF) to monitor metabolites and biomarkers, a process known as reverse iontophoresis [179]. Traditional iontophoresis devices usually use hydrogels, moist patches, or microneedles to conduct electricity. Still, conductive textiles are gaining attention as a good alternative because they're more flexible, breathable, and comfortable, especially for wearable use [180,181]. Fabrication methods like electrospinning make it possible to embed pharmaceutical agents directly into textile fibers. This allows for controlled, on-demand drug release that can be activated through iontophoresis [182]. The integration of iontophoresis with textile-based biosensors and energy harvesting parts presents a promising route to creating closed-loop systems. These systems could enable real-time drug delivery, continuous sweat monitoring, and dynamic tracking of drug metabolites [183].

The development of on-demand drug release systems requires advanced smart materials. In this context, Chatterjee et al. developed a dual-responsive hydrogel that responds to changes in both pH and temperature [184]. This hydrogel was synthesized by integrating the thermo-responsive polymer pluronic F-127 (PF127) with pH-sensitive polymers N,N,N-trimethyl chitosan (TMC) and polyethylene glycolated hyaluronic acid (PEG-HA). It was then loaded with gallic acid, a compound found in the traditional Chinese medicinal extract Cortex Moutan, which has shown effectiveness in treating atopic dermatitis (AD). This hydrogel system (PF127/TMC/PEG-HA) is designed for potential application in textile-based transdermal therapies. Its

thermo-responsive properties were characterized using dynamic viscosity measurements and the tube inversion method, while pH responsiveness was assessed by exposing the hydrogel to media with varying pH levels. The findings demonstrated that the rheological parameters, including complex viscosity and the storage and loss moduli, exhibited temperature dependence, with a sol-gel transition observed near 30°C in both hydrogel formulations. The modified PF127 hydrogel (PF127/TMC/PEG-HA) exhibited superior rheological properties in its hydrogel form compared with PF127 alone, indicating improved mechanical stability. Furthermore, the freeze-dried hydrogel exhibited pH-responsive behavior, achieving complete dissolution under acidic conditions (pH 5.4) and maintaining significant stability at neutral pH (7.4), as illustrated in **Figure 4C**.

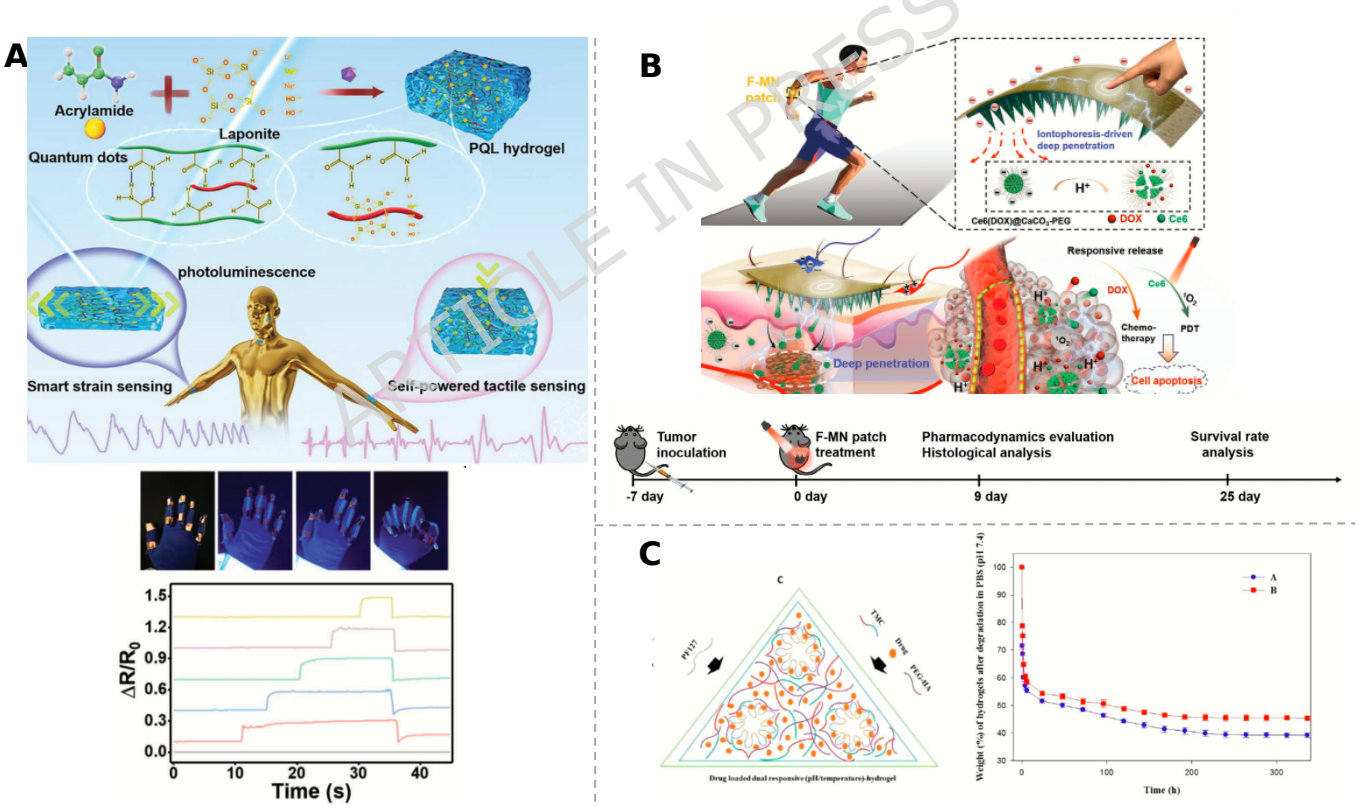


Figure 4: **A)** The schematic depicts the fabrication of a multifunctional photoluminescent hydrogel composed of acrylamide, laponite, and quantum dots, resulting in a poly-quantum-laponite (PQL) network. This hydrogel serves dual functions: as an intelligent strain sensor,

evidenced by its luminescent response to finger motion and a plot illustrating the variation in relative resistance (ΔR/R0) over time during repeated finger bending; and as a self-powered tactile sensor that transduces mechanical contact into electrical signals. Adapted with permission from [166] Wiley-VCH GmbH, 2022. **B)** A wearable, autonomous microneedle (MN) patch designed for the treatment of deep-seated melanoma. The device incorporates a flexible triboelectric nanogenerator (F-TENG) that converts biomechanical energy generated by the patient's movements into electrical energy. This energy facilitates iontophoresis, enabling the efficient transdermal delivery of drug-loaded nanoparticles (Ce6/DOX@CuO_2) from dissolvable MNs into tumor tissue. The acidic tumor microenvironment (characterized by reduced pH) triggers the localized release of doxorubicin (DOX) for chemotherapy and chlorin e6 (Ce6) for photodynamic therapy (PDT), leading to synergistic induction of cancer cell apoptosis. An in vivo experimental protocol utilizing a murine model was employed to assess therapeutic efficacy and survival outcomes. Adapted with permission from [174], Wiley-VCH GmbH, 2024. **C)** Design and stability assessment of a dual-responsive hydrogel aimed at on-demand drug release: The schematic diagram depicts the hydrogel matrix composed of thermosensitive Pluronic F-127 (PF127) combined with pH-sensitive polymers, specifically TMC and PEG-HA, encapsulating a model drug. The accompanying graph illustrates a dissolution profile comparing the residual weight percentage of two hydrogel formulations under physiological conditions (pH 7.4, 37°C) over time. Results indicate that the dual-responsive hydrogel formulation (PF127/TMC/PEG-HA) demonstrates significantly enhanced stability relative to the PF127-only formulation, suggesting its superior potential for controlled drug delivery systems. Adapted with permission from [184], Scientific Reports, 2019.

3.2. Actuators

Actuating devices that transform external stimuli into mechanical motion are essential for the development of flexible electronics. These devices are vital in advancing fields like soft robotics, artificial muscles, haptic feedback systems, and wearable therapeutic devices [28,185]. PCTs have become an ideal material for creating these actuating devices because of their natural flexibility, light weight, permeability, and compatibility with human tissue [175,186,187].

Compliant and highly porous polymer scaffolds are able to support efficient actuation because they can stretch and accommodate substantial changes in

volume, caused by chemical or electrochemical reactions, while remaining structurally sound and enhancing the force they deliver. In electrochemical devices, an open structure is especially important: it makes the matrix softer and provides enough space for ions and solvent to move quickly from the electrolyte into the active materials, such as conductive polypyrrole. The large surface area between these components promotes efficient charge transfer, which in turn drives the fast and reversible chemical changes needed for significant electromechanical movement. When these charged polymer networks are exposed to electric fields, their connected pores help speed up the movement of ions and water by using electroosmotic flow. This greatly increases both the rate and strength of actuation compared to what is possible through diffusion alone. In a similar way, actuators that respond to solvents or osmotic changes benefit from processing the polymers into pre-stretched, twisted, or coiled yarns. This mechanical treatment prepares the material for swelling in certain directions. By lowering strength around the yarns but keeping them strong along their length, these sheath-core and coiled designs prevent them from expanding outward and allow the material to turn tiny molecular swelling into large, useful movements like stretching or twisting [188,189].

Beyond passive sensing, the use of shape memory polymers (SMPs) allows the creation of active textiles, or actuators, that can change shape in response to external stimuli like heat, light, or moisture. This advancement paves the way for the development of 4D-printed smart systems with adaptive and robotic capabilities [190–192]. Typically, these smart textile actuators are categorized based on what drives them, with electrical stimulation playing a crucial role in enabling real-time interactions with human physiology.

Electrical actuation within textile applications is generally categorized into electromechanical and electrochemical mechanisms, each characterized by unique materials, performance attributes, and associated challenges.

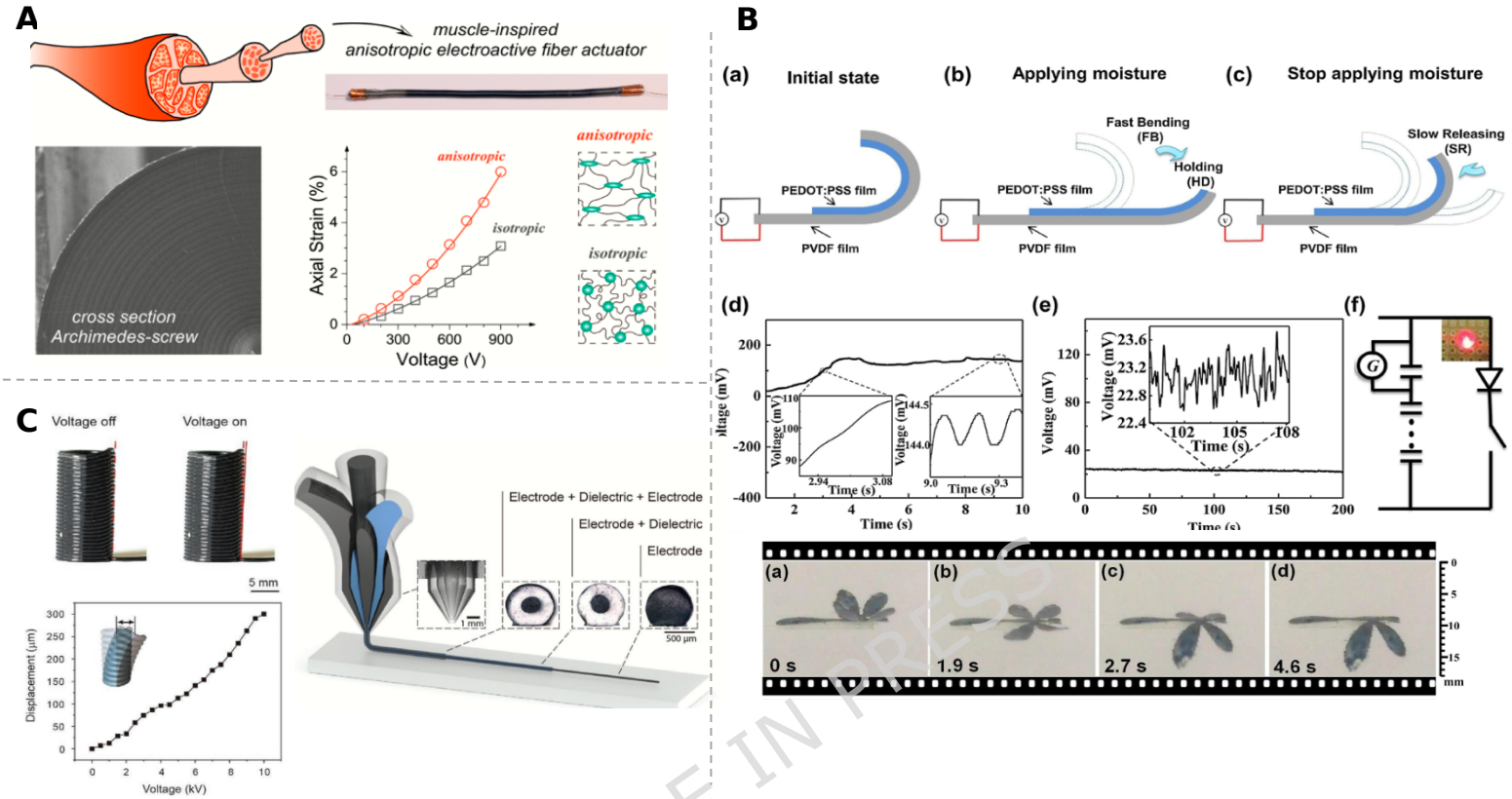
Electromechanical actuators often use materials such as dielectric elastomers or piezoelectric materials, which are often integrated with PCTs to form compliant actuating fibers or fabrics. Specifically, dielectric elastomer actuators function on the principle of Maxwell stress. When a high electric voltage is applied, it causes the elastomeric layer situated between two conductive electrodes [193]. This layered structure allows the material to expand and contract, mimicking muscle-like movement. These actuators can be fabricated using techniques such as thermal stretching, wet spinning, and 3D printing, each offering unique advantages for tailoring actuator properties. Among these, 3D printing offers a streamlined approach by co-extruding dielectric elastomers with conductive electrodes, resulting in enhanced contact and improved actuation efficiency, a significant benefit for wearable applications that require reliable, consistent performance [194,195]. Piezoelectric materials, including barium titanate ($BaTiO_3$), zinc oxide (ZnO), and polyvinylidene fluoride (PVDF), function based on the inverse piezoelectric effect, wherein mechanical deformation generates an electric charge. While mainly explored for sensing and energy harvesting applications, piezoelectric materials are also being researched for actuation, though they require precise control to stay stable during operation. Despite the potential of these electroactive fibers, a key challenge for their use in wearable devices is the high operating voltage needed, often in the kilovolt range, which raises safety concerns for direct contact with skin.

Jin et al. address these challenges by demonstrating, through both theoretical analysis and experimental validation, that the intrinsically anisotropic triblock copolymer known as SBAS exhibits a pronounced directional response upon electroactuation, characterized by a moderate orthogonal modulus ratio of 2.8 [195]. By fabricating ultrathin films of this anisotropic SBAS, they create an all-soft anisotropic dielectric elastomer (DE) fiber. When subjected to a sub-kV voltage (**Figure 5A**), this fiber displays significantly improved linear actuation strain and energy output relative to

its isotropic equivalent. The force output of the DE fiber can be further augmented by either increasing the number of stacked layers within an individual fiber or by bundling multiple fibers together. Furthermore, the prototype bundle allows for independent and programmable control of each fiber, facilitating a wide array of complex movements, including extension, bending, and rotation.

Wang et al. advanced the field by developing a double-layer actuator and generator composed of PEDOT: PSS and PVDF that effectively responds to moisture through a simple and flexible method [196]. The PEDOT: PSS/PVDF strip exhibits remarkable bidirectional bending capabilities and moisture sensitivity, with its curvature varying from −191° to 225° as the relative humidity transitions from 23% to 86% (**Figure 5B**). They also engineered a biomimetic dragonfly and a three-layer flower structure, highlighting potential applications in bionic systems, sensing technologies, and intelligent devices. Moreover, this actuator operates as a moisture-responsive generator, transforming fluctuations in humidity into mechanical motion, which is then converted into electrical energy, achieving a stable direct current (DC) voltage output exceeding 150 mV. To address the challenges of low-frequency

small-signal DC voltage applications, they devised a circuit that provides an innovative approach to energy harvesting and utilization, offering solutions



to future energy challenges

Figure 5: **A)** Muscle-Inspired Anisotropic Dielectric Elastomer (DE) Actuator: This design draws inspiration from the hierarchical structure of muscle tissue. The resulting DE fiber actuator (top right) shows improved performance due to its engineered anisotropy. The graph compares axial strain versus applied voltage for anisotropic and isotropic fibers, highlighting the greater actuation strain of the anisotropic design at sub-kV levels. An SEM micrograph displays the fiber's intricate internal Archimedes-screw-like cross-section. Adapted with permission from [195], American Chemical Society, 2022. **B)** Moisture-Driven Actuator and Energy Generator: This PEDOT:PSS/PVDF bilayer film offers dual functions. As an actuator, it quickly bends when humidified and slowly relaxes (a-c), enabling uses like a biomimetic dragonfly with flapping wings (bottom time-lapse). As a generator, it converts humidity changes into electrical energy, producing a steady DC voltage during humidification (d) and dehumidification (e). The generated energy can power an LED through a simple charging circuit (f). Adapted with permission from [196], Elsevier B.V., 2017. **C)** 3D-Printed Janus Coil Actuator: This features a multicore-shell actuator created using a coextrusion 3D printing method. The schematic illustrates the fabrication of a Janus fiber

with embedded electrode and dielectric parts. When electrically stimulated, the actuator shows noticeable bending, as demonstrated in the 'Voltage on/off' comparison. The graph measures this movement, indicating the actuator's displacement rises effectively with increasing voltage. Adapted with permission from [194], Wiley-VCH GmbH, 2021.

In conjunction with these initiatives, Chortos et al. explored advancements in fabrication methodologies, developing coaxial dielectric elastomer fibers via the coextrusion of dielectric elastomer materials and conductive electrodes [194]. The use of 3D printing techniques significantly improves the contact interface between the dielectric elastomer and fiber electrodes, which results in a marked enhancement in actuation performance (**Figure 5C**). Adjusting the ratio of the internal electrode to the dielectric elastomer optimizes actuation efficiency, with the best results achieved at specific proportions.

Electrochemical actuators represent a particularly promising category for wearable technology, primarily distinguished by their ability to operate at low voltages, which enhances their safety and practicality for skin-interfaced applications [186]. Unlike electromechanical systems that often require hazardous high-voltage fields, these actuators function effectively at voltages typically below 10 V, with advanced demonstrations showing high performance at just ±1.5 V for PPy actuators and 2.5 V for those based on graphdiyne [197,198]. This low-voltage operation is driven by electrochemically induced ion migration between the electrodes and an electrolyte, which is essential for facilitating ion movement.

The actuation itself stems from several distinct mechanisms that depend on the electrode material. In actuators using conducting polymers like PPy, the mechanism is a Faradaic reaction where the electrochemical oxidation and reduction of the polymer backbone causes the incorporation (doping) and expulsion (de-doping) of ions from the electrolyte, leading to significant volumetric changes and mechanical deformation [186,198]. In contrast, actuators based on carbon allotropes rely on non-Faradaic processes. For

example, CNT actuation is attributed to a quantum-mechanical effect, where charge injection alters carbon-carbon bond lengths, while graphene actuation is driven by the simpler electrostatic double-layer effect of ion adsorption. A more advanced mechanism has been identified in graphdiyne, where a reversible "alkene–alkyne complex transition" at the molecular level results in a remarkably high electromechanical transduction efficiency of up to 6.03%, far surpassing other materials [197].

A critical step toward making these devices practical for daily use is the transition from liquid electrolytes, which suffer from leakage and evaporation, to all-solid-state systems [186]. The use of solid-state electrolytes, such as the PVdF/EMIBF4 ionogel demonstrated in graphdiyne actuators, improves device stability, longevity, and enables robust operation in air, thereby increasing the feasibility of integrating these systems into smart clothing [197]. These advanced materials can be fabricated into PCTs through methods like wet-spinning CPs into fibers, coating existing fabrics with conductive layers, or weaving and knitting with functional yarns [108,185,199,200]. The development of these all-solid-state actuators is essential for creating durable and truly wearable systems where flexibility, low power consumption, and high mechanical responsiveness are paramount.

Building on established principles, Wu et al. present a novel approach for developing a flexible and electroactive textile actuator [201]. This innovation involves the direct application of an electrode ink onto a fabric electrolyte, comprised of a composite made from PEDOT:PSS infused with carbonized carbon nanotubes and a zeolite imidazolate framework-8. Prior to this process, the fabric underwent pre-treatment by immersing it in hydrophobic poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) to enhance ionic conductivity (measured at 6.72 $mS.cm^{-1}$) and prevent the penetration of the electrode ink through the substrate.

The operation of the textile actuator is facilitated by both Faraday capacitor and electric double-layer mechanisms. Upon application of voltage, cations migrate towards the cathode while anions move to the anode, prompting redox reactions and the establishment of an electric double layer, which in turn results in the swelling and shrinkage of the electrode layer. As depicted in **Figure 6A** small electrode textile actuator functioning at a frequency of 0.1 Hz is capable of actuating larger fabric pieces. Furthermore, an array of four actuators connected in parallel can produce substantial movement when supplied with 3V DC. Interestingly, these actuators can also adjust the porosity of textiles, which in turn affects their ability to insulate against heat, responding dynamically to ambient temperature changes. This capability highlights their promising use in smart clothing technologies.

Thermally responsive actuators, which exhibit programmed deformation in response to thermal stimuli, are essential components for advancing dynamic wearable systems [175,186]. These actuators incorporate a range of materials, including thermally expanding polymers, Liquid Crystal Elastomers (LCEs), Shape Memory Polymers (SMPs), and Shape Memory Alloys (SMAs), each offering distinct advantages in response time, recovery ability, and mechanical strength. PCTs act as an ideal substrate for these active materials, providing both flexibility and breathability, and enabling actuation through mechanisms such as electrothermal (Joule) methods [34,108].

Among these materials, shape memory alloys such as nickel-titanium (NiTi) wires are commonly used because they can withstand high actuation stresses, up to 700 MPa, and can recover strains up to 10%), and outstanding reliability [186]. SMAs can be seamlessly incorporated into textile frameworks through techniques such as weaving or knitting, or by forming chain-like configurations, which can be directly activated by applying an electric current to induce Joule heating, prompting the martensite-to-austenite phase

transition [202]. This straightforward approach allows for the development of robust textile actuators capable of generating substantial force and executing complex motions, as evidenced in soft robotic grippers and different wearable devices[203].

An additional compelling method involves creating actuators from twisted or coiled yarns made from thermally expansive materials, which may include standard polymers like nylon and advanced materials such as CNT yarns [185]. The actuation mechanism in these structures relies on the anisotropic expansion of fibers. When heated, the fibers expand more in their radial direction than along their length, causing the helical yarn to either untwist or contract. This behavior results in torsional or tensile movement [186]. The exceptional electrical and thermal conductivity of CNTs renders them particularly suitable for rapid and uniform electrothermal actuation [204]. In addition, LCEs provide an alternative means of thermal actuation, facilitated by a reversible phase transition between an ordered liquid crystalline phase and a disordered isotropic phase upon heating, allowing for large, programmable shape alterations within a textile framework [186]. By harnessing these advanced materials and textile manufacturing techniques to develop sophisticated smart wearables. These innovations hold promise for applications such as mobility support, individualized thermal regulation, and soft robotics [175,185].

In a related development, Chen and colleagues devised a simple, innovative method to create multistimulus-responsive hydrogels from carboxymethyl cellulose and polyacrylic-acrylamide [160]. These hydrogels demonstrated impressive mechanical properties, achieving a maximum stress of 339 kPa and a maximum strain of 963%, along with good elasticity and stable conductivity. These qualities stem from their dual network structure and the presence of freely moving metal ions.

The conductive hydrogel exhibited strong mechano-responsiveness to movements of the human body as well as to changes in environmental temperature. Additionally, the conductive hydrogel was combined with a thermoresponsive PNIPAM hydrogel to create a bilayer structure that showed bidirectional bending when subjected to different thermal stimuli. This bending behavior resulted from the differing swelling and shrinking properties of each layer.

In terms of functionality, the hydrogel was utilized for sensing strain, compression, and temperature through changes in electrical signals. It also served as a thermal actuator. The bilayer hydrogel, formed by integrating CMC0.25-P(AA-AM)-Al^{3+} with PNIPAM, bent in opposite directions when immersed in water at 25°C (swelling) and at 45°C (shrinking), effectively demonstrating its thermoresponsive bending and unbending properties, as shown in **Figure 6B.**

Solvent-driven actuators, which convert changes in ambient humidity or direct liquid contact into mechanical motion, are a highly promising technology for creating self-powered, adaptive smart textiles [185]. The primary mechanism for this actuation is the hygroscopic expansion of hydrophilic materials, which swell upon absorbing water molecules and contract as they dry [186,205]. The effectiveness of these actuators depends critically on both the intrinsic properties of the material and the engineered structure of the fiber.

A variety of materials are employed for this purpose. Natural fibers, such as cotton, wool, and silk, along with bio-based materials like carboxymethyl cellulose (CMC), are inherently moisture-responsive and biocompatible [205]. Among advanced materials, GO is particularly effective due to its abundant oxygen-containing functional groups, which allow for rapid and significant water adsorption [109,206]. While carbon-based fibers like CNTs are naturally hydrophobic, their surfaces can be modified, for example, through

oxygen plasma treatment, to become hydrophilic, enabling powerful actuation in response to water.

To translate the microscopic swelling of these materials into large-scale, usable motion, two primary design strategies are employed. The first is the creation of bilayer structures, where a moisture-responsive layer (e.g., GO) is patterned onto a passive, non-responsive layer (e.g., polypyrrole or reduced GO). The differential expansion between the two layers forces the structure to bend or curl, enabling programmable shape changes [28]. A more powerful and widely used strategy involves engineering hierarchically twisted and coiled yarns. In this design, the anisotropic swelling of the fibers, expanding more in their radial dimension than their axial one, causes a twisted yarn to untwist, generating a rapid and powerful torsional motion. This torsional actuation can achieve speeds exceeding 5000 rpm in GO fibers. By further twisting this yarn into a spring-like coil, the torsional motion can be converted into linear tensile actuation, capable of producing contractions as high as 70% in silk fibers [186].

These actuators are ideal for creating comfort-adapting clothing that can autonomously regulate breathability by opening and closing pores in response to the wearer’s sweat. However, significant challenges remain. While these devices demonstrate impressive speed and stroke, their output force is often low, and their response time, especially during the drying or recovery phase, is limited by the slow rate of water desorption. Enhancing the mechanical strength, durability, and force generation of these actuators is essential for expanding their use beyond passive thermal regulation into more demanding applications like artificial muscles and soft robotics [186,205].

Addressing these limitations, Fang et al. developed solvent-driven actuators by programming twisted fibers, specifically twisted graphene oxide fibers (TGFs) with mirrored handedness, mechanical robustness, and superb

flexibility [206]. The large twists (exceeding 4800 turns per meter), hair-like diameter (down to 63 μm), significant tensile strain (29%), and lightweight nature (1.49 $g.cm^{-3}$) of TGFs enable them to generate a large start-up torque of $2.7 \times 10^{-7}\ N \cdot m$ and deliver a record rotor kinetic power of 89.3 $W.kg^{-1}$ when stimulated by polar solvents such as acetone and water (**Figure 6C**). By assembling TGF units with opposite handedness, they achieve precise control of rotor kinetic energy (Franging from 0.78 $W.kg^{-1}$ to 12.5 $W.kg^{-1}$), controllable harvesting of electrical energy (from 2.37 $W.kg^{-1}$to 11.5 $W.kg^{-1}$), and the ability to handle heavy objects freely. The activeness, inertness, and operation of all the actuating systems are effectively controlled by the handedness of the TGF units.

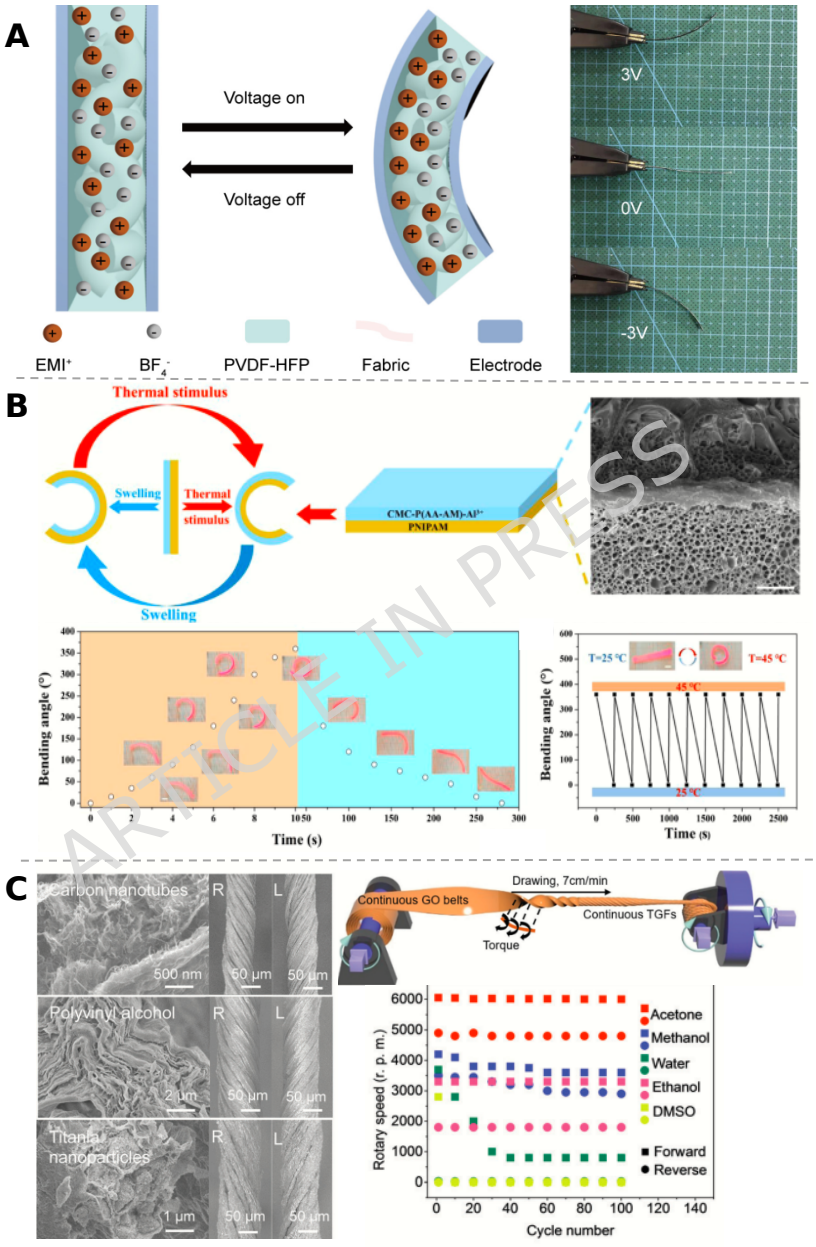


Figure 6: **A)** Operation of an all-solid-state electroactive textile actuator: *Left*: Schematic showing the actuation mechanism. When a voltage is applied, mobile ions (EMI^+ and BF_4^-) move toward the oppositely charged electrodes within a PVDF-HFP solid electrolyte supported by a fabric substrate. This ion redistribution causes volumetric changes in the electrodes, leading the structure to bend. *Right*: Photographic demonstration of a physical

actuator exhibiting reversible and significant bending under a low operating voltage of ±3 V. Adapted with permission from [201], Frontiers in Bioengineering and Biotechnology, 2020. **B)** A thermoresponsive bilayer hydrogel exhibiting bidirectional actuation: The upper layer comprises a conductive hydrogel substrate attached to a thermoresponsive PNIPAM layer. A cross-sectional SEM image illustrates the distinct porous architectures of each layer. The plots showcase the hydrogel's dynamic behavior, where the actuator demonstrates reversible, bidirectional bending driven by differential swelling and deswelling of the layers. The graphs depict consistent changes in bending angle upon cyclic temperature variation between 25°C and 45°C. Adapted with permission from [160], American Chemical Society, 2020. **C)** High-performance solvent-driven torsional actuators constructed from twisted graphene fibers (TGFs): The SEM images depict the hierarchical, tightly twisted microstructure characteristic of the hybrid fibers. The schematic illustrates the continuous fabrication process, wherein graphene oxide belts are drawn and twisted to form TGFs. The performance plot illustrates the actuator's high and stable rotational speeds across over 140 cycles when powered by various polar solvents, such as acetone and water, highlighting the device's operational power and durability. Adapted with permission from [206], The Royal Society of Chemistry, 2019.

3.3. Energy Harvesting and Storage

Developing flexible energy solutions is essential for autonomous wearable electronics, and PCTs provide an effective alternative to traditional batteries. PCTs can be utilized for energy harvesting in lightweight devices, such as flexible solar cells and mechanical nanogenerators (TENGs and PENGs), which harness ambient energy and movement to generate electricity [185,207]. For energy storage, the high surface area of textiles allows for the creation of supercapacitors by coating fibers with active materials [109,208–210]. Additionally, conductive textiles, such as CNT fabrics, can serve as flexible battery electrodes, eliminating the need for rigid components. These innovations contribute to the development of self-powered smart clothing [47,202].

3.3.1. Solar cells

Photovoltaic (PV) cells, also known as solar cells, are devices that convert sunlight directly into electrical energy using the photovoltaic effect. This phenomenon, first observed in scientific studies, involves the generation of electrical voltage when light strikes certain materials [211,212]. Contemporary solar technologies are categorized into three generations: first-generation cells that are wafer-based (e.g., crystalline silicon), second-generation thin-film cells (e.g., CIGS, CdTe), and third-generation emerging technologies, which encompass dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), and perovskite solar cells (PSCs) [212,213]. Third-generation technologies are particularly promising for wearable electronics because they offer high power-to-weight ratios, are inherently flexible, lightweight, and compatible with low-cost, solution-based fabrication methods [212,214]. However, traditional polymeric substrates like PET and PDMS are common in flexible electronics but lack the porosity needed for breathability and moisture control, which are essential for comfort in wearable devices. As a result, textiles have become a preferred platform for integration due to their natural breathability, softness, and flexibility, including characteristics like drape and shear, that align well with the requirements of comfortable, body-conforming wearables [215]. The process of integrating solar functions into textiles mainly involves two methods: first, applying flat photovoltaic films or coatings directly onto fabric surfaces; second, developing one-dimensional photovoltaic elements, like fibers or yarns, which can then be woven, knitted, or embroidered into the textile material [83,213,216]. Fiber-shaped solar cells (FSSCs) are commonly designed in various configurations, including coaxial (core-sheath), twisted, or woven/interlaced, each providing unique mechanical and electrical benefits [213,214,217]. The core of these fibers typically consists of conductive materials such as metal wires (e.g., titanium, stainless steel), carbon-based fibers (e.g., carbon nanotubes), or conductive polymers, which

serve to provide mechanical support and establish an electrode pathway [214,216]. For instance, titanium and stainless steel wires are frequently employed in DSSCs and PSCs due to their remarkable mechanical strength and ability to tolerate high processing temperatures. While twisted and woven structures often deliver enhanced flexibility and can be processed using conventional textile machinery, coaxial FSSCs have exhibited superior power conversion efficiencies (PCE). This improved performance results from the coaxial configuration's optimized three-dimensional shape, which allows for omnidirectional light absorption at all angles and enables better charge collection thanks to the strategic placement of functional layers around the core. For example, a fiber-based DSSC has achieved a record PCE of 10%, while a coaxial fiber PSC reached 7.1%, surpassing many twisted or woven designs [213,214,216,218,219]. In this way, for example, the double-twisted fiber PSC achieved a PCE of 3.03%, maintaining its performance even after 1,000 bending cycles. This emphasizes the durability of the twisted design [219,220].

Xu and their team have successfully developed a new polymer donor called PX1, focusing on enhancing the performance of materials for flexible applications [221]. They achieved this by thoughtfully selecting precursor materials and designing a synthetic approach to incorporate fluorine atoms and alkylsilyl chains into the thiophene-substituted benzodithiophene (BDTT) structure. These adjustments allowed PX1 to attain deeper energy levels and increased crystallinity.

In their experiments, OSCs incorporating PX1 and L8-BO achieved a power conversion efficiency (PCE) of 10.13%, accompanied by a notable V_{OC} of 0.928 V. This performance enhancement is attributed to the strong crystallinity of PX1, which led to overaggregation and significant phase separation. By integrating PX1 into the PM6:L8-BO system, they facilitated improved exciton dissociation and charge transfer. The structural similarities

between PM6 and PX1 enabled the formation of an alloy-like phase. PX1's high crystallinity also enhanced PM6's crystallization behavior, contributing to a favorable morphology in the active layer.

These modifications resulted in improved charge transport and reduced energy loss (E_{loss}) (**Figure 7A**). Consequently, this ternary system achieved an impressive PCE of 18.82%, with an enhanced V_{OC} of 0.880 V, a short-circuit current density (J_{sc}) of 26.81 mA/cm², and a fill factor (FF) of 79.6%. These figures surpass those of the PM6:L8-BO binary device, which had a PCE of 17.97%, V_{OC} of 0.865 V, J_{sc} of 26.63 $mA.cm^{-2}$, and FF of 78.0%. This achievement marks the highest efficiency reported for alkylsilyl-containing polymer materials and ranks among the top efficiencies overall.

In a parallel advancement focused on device durability Jeong et al. introduce a washable encapsulation barrier that retains its properties in aqueous environments by using a nano-stratified SiO2-polymer composite [222]. The SiO_2-polymer composite maintained a low Water Vapor Transmission Rate (WVTR) even in wet conditions due to its high chemical stability. Photovoltaic cells (PSCs) with this encapsulation barrier demonstrated excellent reliability, showing only a 2% degradation after 20 washing cycles of 10 minutes each.they also integrated organic light-emitting diodes (OLEDs) with PSCs on a practical textile. Thanks to the textile's excellent mechanical properties, the devices functioned well under severe bending conditions (up to 3 mm). Despite washing and bending, the electrical characteristics of the encapsulated devices remained unchanged, as shown in **Figure 7B**. Even if cracks formed due to tensile stress during bending, no significant deterioration was observed during washing The prototype modules (NPSC = 8, NOLED = 5) were tested every 7 days after 1000 bending iterations and 10 minutes of washing. The optoelectronic module prototype showed high reliability, maintaining 98.3% of the initial PCE for the PSC and 94.2% of the initial intensity for the OLED after 30 days. In summary, this study

successfully developed a washable textile-based optoelectronic module using a functional encapsulation barrier that preserved low WVTR after washing.

However, by using a vapor-assisted deposition technique, a coaxial PSC achieved a PCE of 10.79%, demonstrating the potential for even greater efficiency with optimized fabrication methods [223]. PCTs are particularly advantageous in photoelectrochemical devices, such as dye-sensitized solar cells (DSSCs), due to their high surface area, which enhances the interaction between the dye and electrolyte, ultimately improving efficiency [224]. CNT-based fiber DSSCs have achieved remarkable PCEs, with hierarchical CNT (HCNT) fiber electrodes reaching up to 11.94% [225]. Wang et al. further developed this concept by designing a DSSC counter electrode using a titanium core with a CNT sheath, achieving a PCE of 25.53% under indoor lighting conditions. This demonstrates how specific structural adaptations can enhance performance in low-light environments [226].

Fiber-based solar cells present promising opportunities for integration into textiles, resulting in fabric-based solar cells that exhibit both flexibility and efficiency. For instance, dye-sensitized solar cell (DSSC) fabrics have been fabricated using nylon filaments alongside platinum-coated carbon yarns or through the amalgamation of DSSCs with TENGs, facilitating scalable and wearable energy solutions [227]. Perovskite solar cells (PSCs) are pivotal in these textile-integrated solar cells due to their flexibility and extensive surface area, which enhance mechanical durability and adaptability to movement. Advances in transparent conducting oxide (TCO)-free DSSCs utilizing stainless steel mesh electrodes and carbon cloth-based PSCs have significantly expanded the potential of wearable solar technology. For example, carbon cloth-based PSCs have achieved a PCE of 17.02% while maintaining good stability. TCO-free DSSCs also mitigate transparency constraints, allowing for flexible design alternatives [228]. Moreover, polymer fabrics, including polyester-cotton substrates coated with silver

nanowires, have been explored as both substrates and electrodes for OSCs, highlighting the feasibility of fully solution-processed, flexible solar cells [229]. These developments in fiber-based and textile-integrated solar cells signify the potential for wearable photovoltaic systems that merge high efficiency, flexibility, and durability, thus paving the way for sustainable, large-scale wearable energy solutions applicable across a range of uses.

In a significant step toward metal-free wearable electronics, N. Alwadai and their team have developed a novel all-carbon photovoltaic wire that does not depend on metal-based electrodes [230]. The structure includes TiO_2-coated CNT fibers, sensitized with N719 dye and serving as the working electrode (**Figure 7C**). Meanwhile, polyaniline-coated CNT fibers act as the counter electrode. These fibers are twisted together to form the photovoltaic wire. Electrochemical impedance spectroscopy (EIS) techniques were used to evaluate triiodide reduction and charge-transfer resistance within the device. Performance testing under simulated light conditions showed that the device with the polyaniline-modified counter electrode achieved a photoelectric conversion efficiency of 3.57%. This marks a significant improvement over the 2.26% efficiency observed in the device using unmodified CNT fibers. The enhanced performance of the modified counter electrode was further supported by a lower peak separation (ΔE_p = 0.42 V) and a reduced charge transfer resistance (RCT = 19.28 Ω), as measured by CV.

3.3.2. Generators

Generators, also known as energy scavengers, are increasingly essential for sustainable power generation in environments where conventional batteries are impractical, particularly in wearable electronics and other portable devices. Piezoelectric nanogenerators (PENGs) offer a promising solution for harvesting mechanical energy from sources like human movement. These devices often incorporate PCTs combined with piezoelectric materials such as ZnO, $BaTiO_3$, or PVDF to convert mechanical strain into electrical energy.

PENGs are generally designed as either 1D fiber-type or 2D fabric-type devices, each providing unique structural benefits and manufacturing options. In 1D fiber-type PENGs, conductive fibers serve as the core electrode, subsequently coated with a layer of piezoelectric material and finished with an outer electrode layer. For instance, ZnO nanowires can be grown directly on carbon fibers, with additional electrode layers made from materials like indium tin oxide (ITO) or gold plating to enhance conductivity and durability [231]. PVDF-based PENGs can be produced through methods such as winding or heat-stretching, enabling scalable manufacturing of piezoelectric fibers suitable for a range of applications [232].

2D fabric-type PENGs, on the other hand, incorporate piezoelectric threads woven into textile fabrics or utilize PCTs combined with piezoelectric films in a sandwich-like structure, providing enhanced flexibility and structural integrity for wearable applications. Techniques such as electrospinning and the direct growth of piezoelectric materials onto conductive fabrics are employed to enhance bonding and optimize performance, enabling the fabric to retain its piezoelectric properties even under repeated mechanical stress. For example, breathable piezoelectric fabrics have been developed by growing ZnO nanorods on PVDF nanofibers combined with silver cloth electrodes, achieving stable, enhanced performance and output voltages reaching up to 4 V [233,234]. These innovations in PENGs highlight the potential of textile-integrated energy harvesters to capture mechanical energy from daily activities, powering low-energy wearable devices and reducing the reliance on conventional batteries [235].

TENGs represent a sophisticated class of energy-harvesting devices that effectively transduce mechanical energy into electrical energy through the processes of contact electrification and electrostatic induction [236]. When compared to piezoelectric nanogenerators (PENGs), TENGs exhibit superior electrical output, rendering them particularly suitable for applications that

necessitate effective energy capture from kinetic movement [237]. TENG textiles primarily function in two operational modes: vertical contact-separation and single-electrode configurations [238]. In the vertical contact-separation mode, a configuration comprising two electrodes and friction layers separates and re-establishes contact during mechanical deformation to generate an electrical charge [236]. In contrast, the single-electrode mode, which is structurally simpler and relies on only one electrode, typically exhibits lower output efficiency compared to its two-electrode counterpart [239].

To enhance energy collection efficacy, researchers have innovated methods to weave one-dimensional TENG fibers into two-dimensional and three-dimensional textile architectures, with three-dimensional configurations showing particularly promising advancements [240]. For example, three-dimensional TENG fabrics featuring multiple layers have achieved notable output voltages of up to 90 V, attributed to their increased surface area and enhanced contact points, which intensify the triboelectric effect [241,242]. Additional improvements in TENG performance have been realized with the introduction of the freestanding triboelectric layer mode, which has exhibited exceptional output voltages as high as 1600 V and currents approaching 15 μA, highlighting the capacity of these devices to generate substantial voltage from relatively simple mechanical inputs [243]. Although limitations persist, TENG textiles have demonstrated substantial efficiency as energy-harvesting mechanisms, and ongoing exploration aimed at augmenting their current output represents a promising direction for future advancements.

Recent advancements have significantly improved the mechanical robustness and energy output of these devices. For instance, Zheng and colleagues created a tough, textile-based TENG that uses dielectric modulation by coating conductive fabrics with PVDF-HFP/$BaTiO_3$. This device can produce up to 261 V and an instant power density of 654.48 $mW.m^{-2}$, making it suitable

for real-time sports monitoring [244]. Further expanding on this area, recent studies have shown very effective PENGs made from organic-inorganic coaxial nanofibers [235], highly stretchable LM-based TENGs designed for capturing complex biomechanical energy [242], and 3D orthogonal woven TENGs that serve as self-powered active motion sensors [243].

Thermoelectric generators (TEGs) provide an alternative way to harness energy by transforming body heat into electricity. Although their efficiency is generally modest (around 5% to 8%) researchers are continually working to improve their materials and designs to make them more suitable for wearable devices. To overcome these efficiency limitations, Burton and colleagues used a pseudo-3D printing technique to create p-type SnSe components, setting a new record with a thermoelectric figure of merit (ZT) of 1.7 at 758 K (**Figure 7E**). To further enhance thermal gradient utilization and overall power generation, ongoing research is increasingly focusing on the advanced knitting and weaving of chemically doped carbon nanotube fibers [245–247]

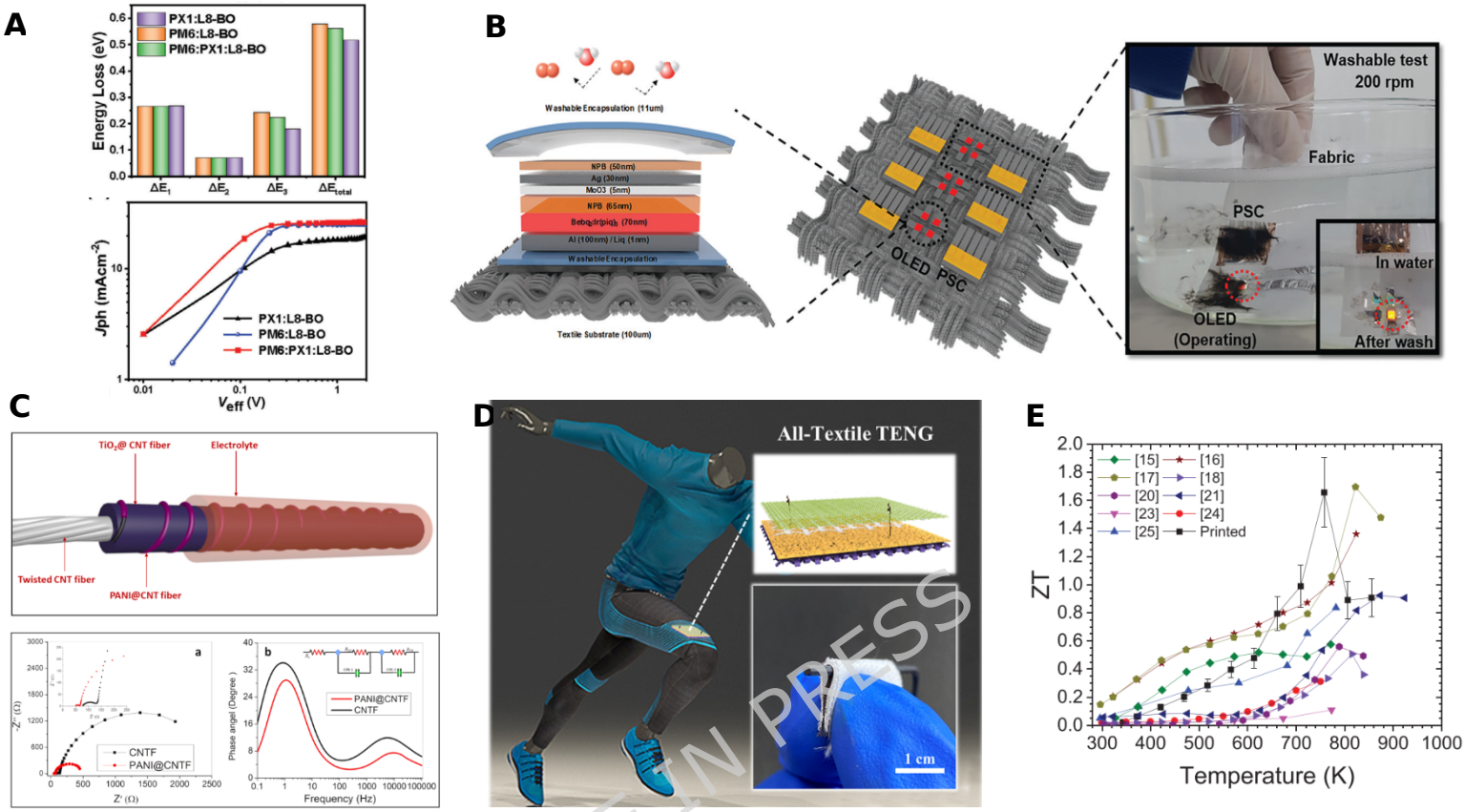


Figure 7: **A)** A Comparative Analysis of Photovoltaic Performance in Organic Solar Cells (OSCs). (*Top*) A histogram showing the distribution of key energy loss components (ΔE1, ΔE2, ΔE3) and the total non-radiative voltage loss (ΔE_{total}) for optimized devices. (*Bottom*) The corresponding photocurrent density (J_{ph}) as a function of effective voltage (V_{eff}), demonstrating the charge generation and extraction efficiency for devices based on PX1:L8-BO, PIM6:L8-BO, and PIM6:PX1:L8-BO blends. Adapted with permission from [221], Wiley-VCH GmbH, 2024. **B)** Design and demonstrate a fully textile-based, washable optoelectronic module. The main schematic shows the integration of an organic light-emitting diode (OLED) and a perovskite solar cell (PSC) onto a textile substrate, protected by a durable encapsulation barrier. The inset displays the detailed layered structure of the OLED component. Photographic evidence illustrates the module's durability, with the OLED functioning flawlessly on fabric during a 200 rpm wash test and after full submersion in water. Adapted with permission from [222], Royal Society of Chemistry, 2019. **C)** An all-carbon, fiber-based dye-sensitized solar cell (DSSC). The main schematic demonstrates the coaxial structure, consisting of a twisted carbon nanotube (CNT) fiber core, a TiO_2@CNT

layer, and an outer PANI@CNT fiber that functions as the counter electrode. The accompanying graphs show electrochemical impedance spectroscopy (EIS) results used to evaluate the device's performance, presenting (a) the Nyquist plot and (b) the Bode phase plot, which compare the charge-transfer resistance and frequency response of a bare CNT fiber versus a polyaniline-coated CNT fiber (PANI@CNTF) counter electrode. Adapted with permission from [230], Elsevier B.V., 2024. **D)** A flexible, all-textile triboelectric nanogenerator (t-TENG) for biomechanical energy harvesting. The main diagram illustrates the multilayer fabric assembly, which uses knotted yarn interconnects to ensure structural integrity and comfort. The photo shows a real-world application, with the t-TENG attached to a running shoe to generate energy from foot motion, emphasizing its potential for use in advanced sports sensing and wearable electronics. Adapted with permission from [244], American Chemical Society, 2024. **E)** Thermoelectric figure of merit (ZT) as a function of temperature. This plot compares the performance of a new pseudo-3D printed p-type SnSe material (prepared with 4% binder, shown in red) with various polycrystalline SnSe samples. The data demonstrates the higher ZT value achieved with the pseudo-3D printing method, reaching about 1.7 at 758 K. Error bars represent a 15% measurement uncertainty. Adapted with permission from [248], Wiley, 2024.

3.3.3. Biofuel Cells

Fuel cells are efficient devices that generate electricity by converting chemical energy into electrical energy through electrochemical reactions at the anodes and cathodes [249,250]. Biofuel cells are a specialized type of fuel cell that use biological catalysts, such as enzymes or microorganisms, to generate electricity. They typically utilize biochemical fuels like glucose or lactate, which are naturally found in bodily fluids [251,252]. This specialized setup allows wearable biofuel cells to harness the body's biochemical resources for energy generation. This makes them especially useful for wearable biosensors and low-power medical devices. PCTs serve as an ideal substrate for integrating biofuel cells because of their high electrical conductivity, flexibility, and large surface area. These features improve the interaction between biocatalysts and biochemical fuels. For instance, glucose biofuel cells that combine carbon fabric with glucose oxidase (GOx) as the anode catalyst and Prussian blue (PB) as the cathode catalyst have been developed. They utilize sweat absorption through a moisture management

layer, which helps in effectively processing glucose and generating energy [253,254]. While carbon fabrics are effective, they often lack the flexibility needed for high-movement activities, which limits their practicality in comprehensive wearable applications. Stretchable PCTs, like pantyhose fabrics treated with conductive CNTs, offer better flexibility and durability, making them more suitable for wearable devices that demand adaptability [255]. An effective approach also involves directly incorporating fibrous anodes and cathodes into fabric structures. When combined with an ionic gel electrolyte, this setup improves both the flexibility and durability of biofuel cells [256]. These textile-based biofuel cells exhibit notable potential as sustainable on-body power sources, capable of continuously generate electricity from body-derived fuels.

Nevertheless, there are important challenges that need to be addressed to make textile-based biofuel cells viable as on-body power sources. Main issues include their limited energy density and stability, especially since human sweat is not always available, which makes consistent power generation difficult [257]. While strategies such as the incorporation of external fuel sources or the stimulation of perspiration may alleviate this concern, they also add to the overall complexity of the system. Moreover, the enzymes typically used in biofuel cells often demonstrate instability under varying temperature or pH levels change. To tackle this, researchers are looking into inorganic catalysts that are more stable and could work well in the conditions of human sweat [258,259]. Recent developments in electrochemistry suggest promising opportunities for creating effective inorganic catalysts. These catalysts could improve both the efficiency and durability of biofuel cells, making them more practical as power sources that can be worn.

Recent advances have greatly enhanced the durability, skin compatibility, and power generation capabilities of wearable biofuel cells (BFCs). For instance, Kwon and colleagues created an enzymatic glucose BFC by screen-

printing PEDOT:PSS and carbon nanotube composites onto a biocompatible elastomer, achieving a maximum power output of 43.6 $\mu W \cdot cm^{-2}$ and maintaining functionality for an impressive 11 hours (**Figure 8A**) [260]. To improve mechanical stability under high strain, Chen et al. developed a highly stretchable BFC using graphene/CNT textile electrodes combined with a polymer hydrogel electrolyte, preserving a high power density of 64.2 $\mu W \cdot cm^{-2}$ even after 400 bending cycles (**Figure 8B**) [261]. Furthermore, Yuan et al. developed a self-adhesive, lactate-powered hybrid biofuel cell using a specially modified PVA hydrogel, enabling smooth attachment to biological tissue and reaching a remarkable peak power density of 224.85 $\mu W \cdot cm^{-2}$ (**Figure 8C**) [262]. Building on these basic designs, the field is quickly advancing by exploring innovative non-enzymatic microfluidic devices and highly conductive gold nanoparticle-assembled carbon fiber electrodes. These developments aim to overcome the long-term instability of enzymes and improve the efficiency of capturing bio-energy from human sweat [253,254,258,259]

3.3.4. Supercapacitors

To enhance the performance of lithium-ion batteries, especially in terms of fast charging and discharging, researchers are turning to flexible supercapacitors that use PCT-based designs. These innovative materials offer a promising solution for improving energy storage capabilities [263]. PCTs serve as either conductive substrates, like carbon cloth, or active materials, such as activated carbon fibers. They naturally offer flexibility and improve electrochemical performance by allowing ions to move quickly and charges to flow more efficiently. Carbon-based materials are primarily used in the electrodes of PCT-based supercapacitors because of their high surface area, excellent conductivity, and cost-effectiveness. Activated carbon (AC), known for its highly tunable pore structure and large surface area, is a common choice for electrode material. However, its capacitance is often limited by the electric double-layer (EDL) mechanism [264,265]. To address this limitation,

various strategies such as heteroatom doping and combining AC with other carbon-based materials have been explored to improve charge storage capacity and overall device performance.

The progress in creating supercapacitor fibers has been rapid, mainly because these fibers are highly flexible and can be easily incorporated into wearable devices. For instance, fibers made with activated carbon, stretching up to 100 meters, have demonstrated strong energy storage capabilities and reliability. This underscores the promising role of fiber-based supercapacitors in expanding scalable, wearable technology applications [266]. Beyond AC, CNTs and graphene are commonly integrated into supercapacitors to enhance their electrochemical properties further [267,268]. While CNTs provide exceptional conductivity and serve as conductive additives, their naturally low capacitance often requires them to be coupled with other materials, such as reduced rGO, which offers a high specific surface area and versatile functionalities [269]. The combination of CNTs and graphene into 3D porous structures has shown significant effectiveness. These hybrid materials exhibit high areal capacitance, strong cycling stability, and flexibility, which makes them promising for energy storage applications in wearable electronics.

Building on this hybrid material approach, Tian et al. developed fiber-based supercapacitors using a polyacrylamide (PAM) matrix combined with a MnO_2/rGO hybrid [270]. This research details the synthesis of MnO_2 nanomaterials with tunable crystalline structures, achieved via a one-step hydrothermal process. The formation of MnO_2 crystals involved a "crimp-phase transition." Among the materials synthesized, the α-MnO_2 nanowires with a 2 × 2 tunnel structure exhibited impressive electrochemical capacitance (43.8 $F.g^{-1}$), excellent rate capability (maintaining 61% capacitance from 0.25 to 6 $A.g^{-1}$), and exceptional cycling stability (99%). These properties were attributed to the nanowires' spatial symmetry and the

high density of shared vertices. Building upon this, the α-MnO_2 nanowires were integrated with GO to create MnO_2/rGO hybrid fibers via a scalable wet spinning process followed by in situ acid reduction (**Figure 8D**). These hybrid fibers displayed a remarkable 50 wt% MnO_2 nanowire content, along with a tensile strength of 11.73 MPa, thanks to the superior surface morphology of the MnO_2 nanowires and the distinctive "cement wall" structure of the fibers.

Metal-based materials, including metal oxides, sulfides, hydroxides, and MXenes, have garnered significant attention for their applications in supercapacitors, primarily due to their ability to utilize pseudocapacitance mechanisms, which result in remarkably higher capacitance compared to conventional electric double-layer capacitors (EDLCs). Ruthenium dioxide (RuO_2) is frequently acknowledged for its exceptional performance in supercapacitors [271]; however, its prohibitive cost restricts its practical application, thereby driving a transition toward more affordable and environmentally benign materials such as manganese, nickel, cobalt, and iron compounds [272–274]. The integration of these materials into PCT-based electrodes requires careful consideration to optimize their performance. Surface modifications of PCTs are often required to establish nucleation sites for metal compound growth, thus enhancing the uniformity and efficiency of electrochemical reactions. Additionally, manipulating the morphology of these compounds, such as forming nanostructured layers or frameworks, is essential for maximizing surface area and charge accessibility. Furthermore, developing 3D conductive networks within the electrode structure significantly improves ion transport and charge distribution, particularly in thicker electrodes designed for high-capacity applications.

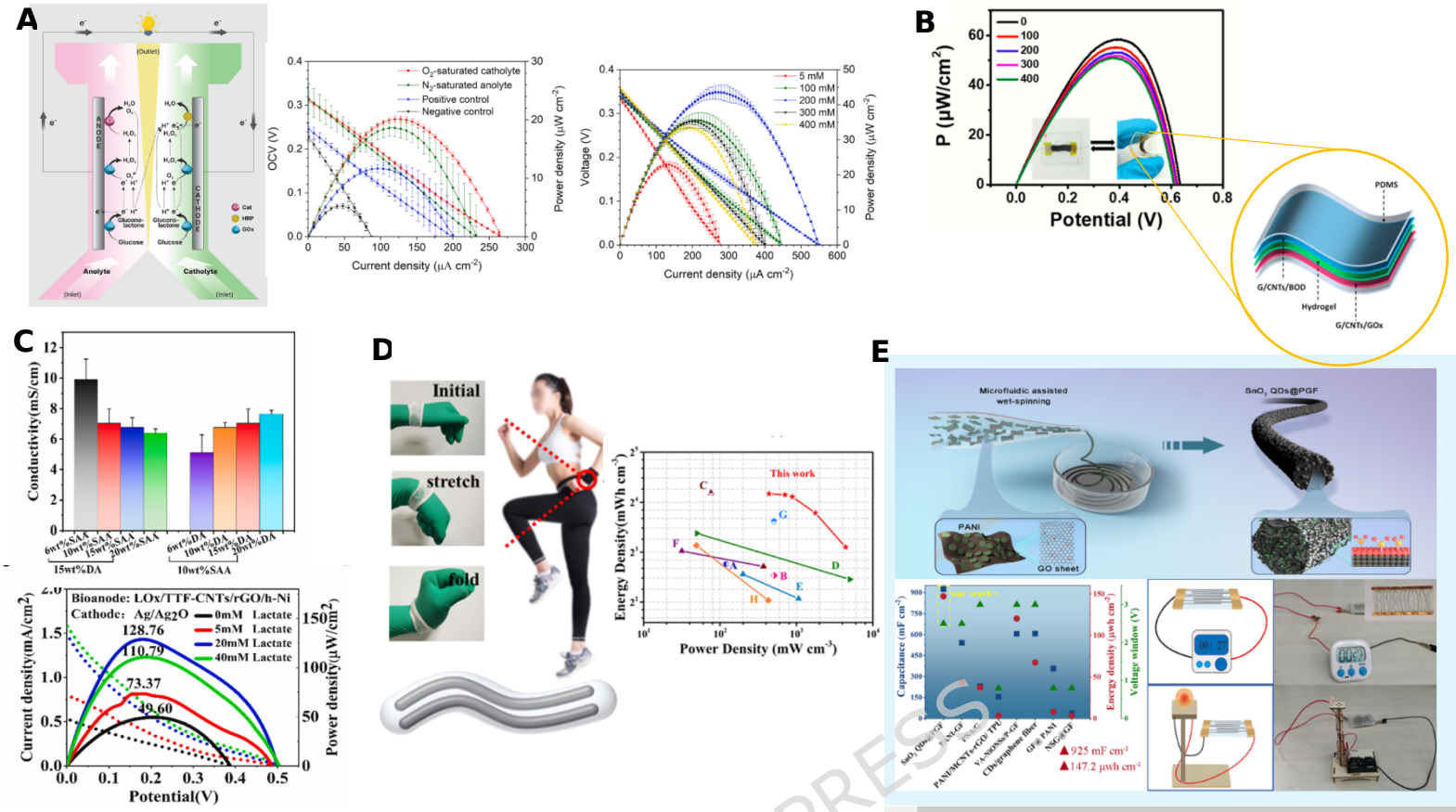
Innovative demonstrations of these strategies include a supercapacitor electrode constructed with alternating layers of MnO and (Iron Oxide) Fe_3O_4, augmented with gold nanoparticles, which exhibited substantial enhancements in both energy and power density [275]. This multilayer

configuration allows for the distinct electrochemical properties of each component to synergistically contribute to overall performance metrics that cater to high-demand use cases. An alternative advanced configuration utilized a 3D carbon scaffold fabricated from CNTs and reduced holey graphene oxide (rHGO), serving as a stable foundation for the deposition of pseudocapacitive materials such as MnO and FeOOH [276]. This arrangement achieved one of the highest energy densities recorded for aqueous wearable supercapacitors, underscoring the efficacy of combining structural support with high-capacitance metal compounds. In another innovative approach, an inverse opaline metallic membrane was employed for the growth of $Ni(OH)_2$, resulting in a binder-free supercapacitor electrode that demonstrated an impressive volumetric capacitance of 1500 $F.cm^{-3}$ over 18,000 charge-discharge cycles [273].

Conducting polymers, such as PANI, PPy, and PEDOT, have received significant focus in supercapacitor studies due to their cost-effectiveness, environmental compatibility, and inherent flexibility, making them especially suitable for incorporation into wearable energy storage systems [277–279]. Nonetheless, their practical application is often impeded by stability issues, primarily stemming from volumetric changes during charge and discharge cycles, which can compromise performance over time. Enhancing the conductivity, capacitance, and particularly the cycling stability of these polymers remains a critical area of research, as such improvements are vital for their use in PCT-based supercapacitors. A viable strategy involves the development of composite materials by integrating conducting polymers with carbon-based or metal-based materials. These hybrid structures can capitalize on the high surface area and stability of carbon frameworks, such as graphene and carbon cloth, alongside the pseudocapacitive characteristics of metal oxides, yielding electrodes with enhanced energy storage capabilities and mechanical robustness.

One illustrative example is a composite electrode composed of lignosulfonate, PANI, functionalized graphene hydrogel, and carbon cloth [280]. This blend results in a highly flexible electrode featuring a durable 3D conductive scaffold that achieves high energy density while maintaining flexibility, exemplifying the potential of multi-component composites for high-performance wearable supercapacitors. Yarn-shaped PCTs, incorporating materials such as PPy, MnO_2, and reduced graphene oxide, have also been successfully developed, attaining competitive capacitance and energy densities suitable for powering multiple LEDs [281]. These yarn-based supercapacitors highlight the potential of integrating conducting polymers with advanced materials to create flexible and effective energy storage devices, bridging the gap between traditional rigid supercapacitors and adaptable, wearable energy solutions.

Building on a composite strategy, Jia et al. developed a continuous methodology for synthesizing polyaniline/graphene fibers (PGF) by integrating nanoscale granular PANI within graphene sheets [282]. They further enhanced the properties of these fibers by functionalizing the PGF surface with tin dioxide quantum dots (SnO_2 QDs), resulting in the formation of SnO_2 QDs@PGF hybrid fibers. These fibers exhibited remarkable mechanical strength, high electrical conductivity, and robust structural stability throughout charge-discharge cycles. The SnO_2 QDs@PGF supercapacitors revealed a high specific areal capacitance of 925 $mF.cm^{-2}$, commendable rate capabilities, and maintained 88% capacitance retention after 8000 cycles. In an alternative electrolyte system, a wide voltage window of 2.5 V was attained, alongside a high capacitance of 678.4 $mF.cm^{-2}$ and an energy density of 147.2 $\mu Wh.cm^{-2}$. The exceptional performance was attributed to the molecular-level integration of PANI and graphene, as well as the robust C-O-Sn covalent bonds, which prevented the restacking of graphene and enhanced ion transport. Under the EMITFSI/PVDF-HFP electrolyte system, the SnO_2 QDs@PGF demonstrated a wide operational



voltage range of 2.5 V, a specific areal capacitance of 678.4 $mF.cm^{-2}$, and an energy density of 147.2 $\mu Wh.cm^{-2}$ at a power density of 500 $\mu W.cm^{-2}$, making it suitable for powering devices such as alarm clocks, electronic timers, and desk lamps that require a 3 V power source (**Figure 8E**).

Figure 8: **A)** Schematic and performance overview of a co-laminar flow bio-enzymatic fuel cell (BEFC). The diagram on the left depicts the device architecture, featuring a bi-enzyme anode and cathode for glucose oxidation and oxygen reduction, respectively. The graphs on the right display the electrochemical performance, including polarization and power density curves under O_2-saturated and N_2-saturated conditions, and how voltage and power density depend on different glucose concentrations ranging from 5 mM to 400 mM. Adapted with permission from [260], Elsevier Ltd., 2023. **B)** Design and mechanical stability of a flexible and stretchable biofuel cell (BFC). The top right schematic illustrates the layered composition of the device, integrating a hydrogel electrolyte and enzymatic electrodes within a stretchable PDMS substrate. The corresponding graph illustrates the BFC's robust power output, demonstrating stable performance over 400 cycles of repeated bending and releasing, which highlights its durability for wearable applications. Adapted with permission from [261],

American Chemical Society, 2021. **C)** Electrochemical properties of a lactate-powered hybrid biofuel cell (HBFC). The bar chart illustrates the ionic conductivity of the PVA/SAA-DA hydrogel used as the electrolyte. The graph below shows the cell's performance, plotting the polarization (current density versus potential) and power density curves at various lactate concentrations (10 mM to 40 mM), highlighting the device's response to different biofuel levels. Adapted with permission from [262], Elsevier B.V., 2023. **D)** Mechanical flexibility and performance of a fiber-based supercapacitor. The schematics on the left illustrate the device's ability to maintain structural integrity during various mechanical deformations, including stretching and folding. The Ragone plot on the right compares the device's energy and power density with other previously reported flexible and asymmetric supercapacitors, highlighting its position within the current state-of-the-art. Adapted with permission from [270], American Chemical Society, 2023. **E)** Synthesis, performance, and application of SnO_2 Quantum Dot-functionalized Polyaniline/Graphene Fibers (SnO_2 QDs@PGF). The schematic shows the microfluidic-assisted wet spinning fabrication process. The chart compares the areal capacitance, energy density, and voltage window of the resulting flexible supercapacitor (FSC) with other reported devices, highlighting its superior performance. The photographs display a practical application where five FSCs connected in series successfully power an electronic timer, confirming its potential for wearable electronics. Adapted with permission from [282], American Chemical Society, 2024.

3.3.5. Battery

Lithium-ion batteries (LIBs) are highly regarded for their substantial energy density, which can reach up to 300 $Wh.kg^{-1}$, making them one of the most efficient energy storage options available [283–285]. However, their inherent rigidity and dependence on conventional current collectors, such as aluminum and copper, restrict their flexibility and adaptability for wearable applications. These traditional current collectors have low yield strains, which limit the flexibility necessary for integration into wearable systems. To address these challenges, there is growing interest in using pseudocapacitive materials, such as carbon cloth and metallic textiles, as alternatives to traditional current collectors. These materials typically demonstrate high yield strains, often over 5%, coupled with porosity and excellent electrical

conductivity. This combination not only increases the flexibility of the battery structure but also enhances electrode kinetics, allowing for higher loading of active materials [286]. This increased loading is essential for preserving energy and power density in flexible battery configurations.

The addition of active materials into PCTs creates composite electrodes that enable quick charge transfer, enhancing both energy capacity and power in flexible battery systems. For alkali metal anodes like lithium, issues such as dendrite formation and low Coulombic efficiency, which can leading to performance drops and safety issues, are mitigated through the introduction of metal coatings on PCTs [287]. These coatings improve the substrate's affinity for lithium, contribute to the stability of the anode, and reduce the formation of unwanted byproducts [288]. A prominent example is a flexible lithium-sulfur (Li−S) battery utilizing copper-coated and nickel-coated carbon cloth, which achieved an impressive energy density of 288 $Wh.kg^{-1}$ along with reliable cycling stability [289]. Innovations like inverted anode structures and metal coatings capable of alloying with lithium or other alkali metals have demonstrated effectiveness in encouraging even metal deposition and reducing the risk of short circuits.

Recent progress in PCT-based batteries aims to address the significant volume changes that occur in high-capacity conversion anodes like Fe_2O_3 and SnO_2, as well as to stabilize intercalation materials such as LTO and LFP during mechanical deformation. For example, Ha and colleagues incorporated LTO and LFP active materials into a flexible 2D graphene-textile framework, resulting in a capacity of 1.2 $mAh{\cdot}cm^{-2}$ that reliably endured over 1,000 severe bending cycles. (**Figure 9A**) [290]. To better address the natural variations in anode volume, Liu and colleagues developed a standalone Fe3O4/carbon cloth composite using an easy, scalable dyeing and pyrolysis process. This innovative approach resulted in a strong areal capacity of 9 $mAh{\cdot}cm^{-2}$ when used in flexible pouch cells (**Figure 9B**) [291]. Similarly, Du

and colleagues used metal-organic frameworks (MOFs) to create hollow CoS_2@MoS_2 nanotube arrays on carbon cloth. This approach resulted in highly flexible electrodes capable of excellent high-rate lithium storage, as shown in **Figure 9C** [292]. Beyond 2D fabric designs, the field is quickly advancing through continuous solution extrusion, allowing the production of meter-long, weavable LIB fibers that achieve energy densities of up to 86 $Wh.kg^{-1}$ [293]. Additionally, hybrid cotton textiles decorated with nanoparticles are being developed to help stabilize next-generation Li-S full batteries [294,295].

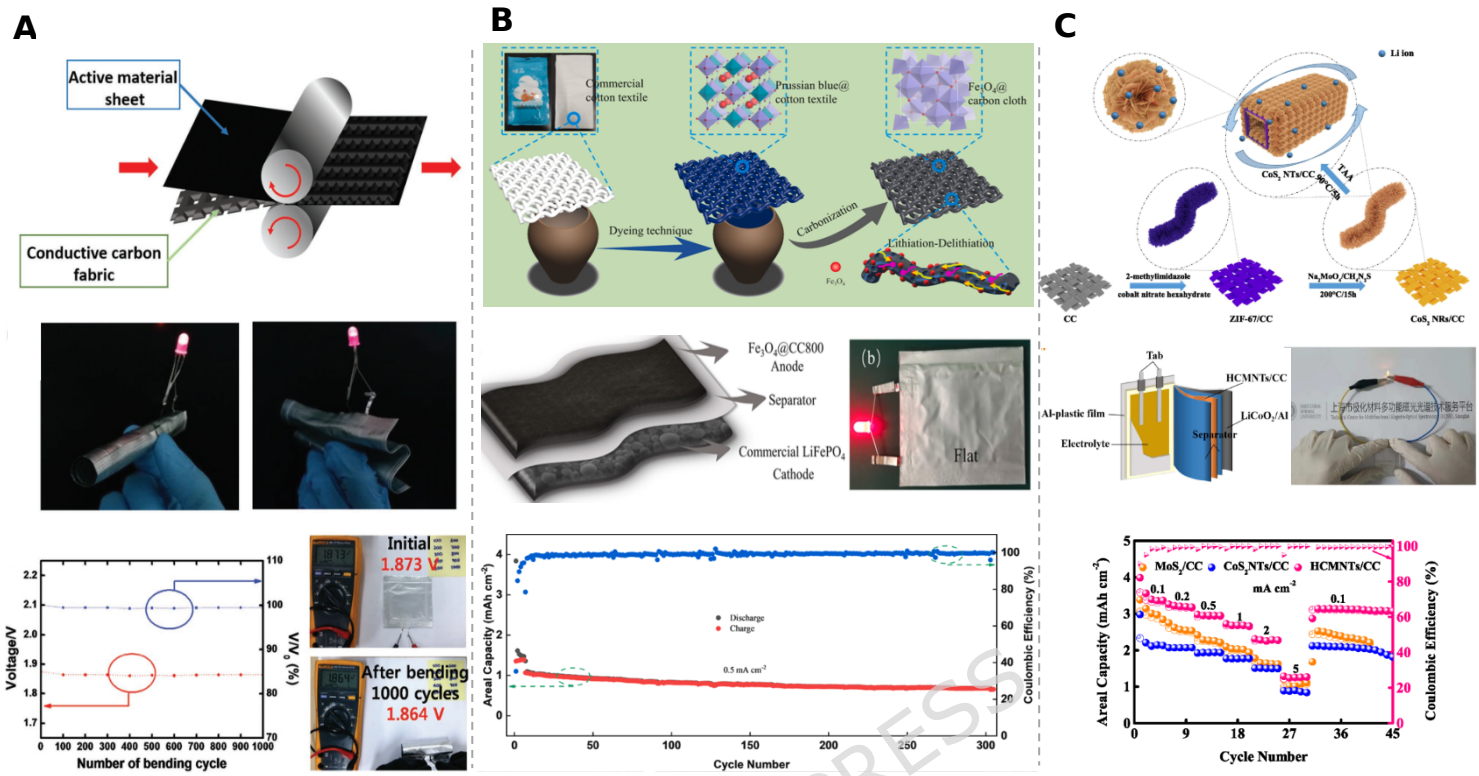


Figure 9: **A)** fabrication and Mechanical Integrity of Flexible LIBs: The schematic illustrates a scalable roll-to-roll process for coating active material onto a conductive carbon fabric to create flexible electrodes. The photographs demonstrate the battery's practical robustness, showing its ability to power an LED even while being actively bent. The graphs quantify this durability, revealing a stable open-circuit voltage (OCV) after 1000 bending cycles and consistent discharge/charge profiles before and after repeated flexing, confirming the design's resilience to mechanical stress. Adapted with permission from [290], Wiley-VCH, 2018. **B)** Synthesis and Performance of a Fe_3O_4/Carbon Cloth Anode: The synthesis process for a flexible Fe_3O_4@carbon cloth (CC) anode is illustrated, involving a simple dyeing technique with Prussian blue followed by carbonization. The schematic of the assembled flexible pouch cell, along with a photo of it lighting an LED, demonstrates its application. The cycling performance graph shows the electrode's excellent stability, with high areal capacity retention and nearly 100% Coulombic efficiency over 300 cycles at a current density of 0.5 $mA.cm^{-2}$. Adapted with permission from [291], Elsevier B.V., 2021. **C)** Hierarchical Hollow Nanostructures for High-Rate Performance. This figure illustrates the design and performance of a hollow core-shell CoS_2@MoS_2 nanotube array on carbon cloth. The top schematic depicts the synthesis process, which uses a MOF as a template, and the proposed mechanism for Li^+ ion storage. The lower panels display the assembled flexible soft-pack battery and a graph showing its rate performance. The graph demonstrates the material's ability to retain stable areal capacities across a wide range of current densities (from 0.1 to

5.0 $mA.cm^{-2}$), highlighting the architectural advantages for fast ion and electron transport. Reproduced with permission from [292], American Chemical Society, 2022.

3.4. Sensors

Wearable physical sensors are essential for real-time monitoring of physiological signals, human-machine interactions, and soft robotics [296–299]. PCTs make excellent sensing substrates because their natural flexibility, breathability, and ability to conform offer comfortable, long-lasting contact with the body [300–304]. Textile-based physical sensors typically operate via piezoresistive, capacitive, piezoelectric, or triboelectric mechanisms [297,299]. Among these mechanisms, piezoresistive sensors are particularly favored for their simple structural design, ease of signal acquisition, and straightforward fabrication [305,306]. Their operation fundamentally depends on changes in electrical resistance induced by mechanical deformation under pressure [304].

The intrinsic porosity and three-dimensional architecture of textiles, such as foams, nonwovens, or spacer fabrics play a vital role in enhancing the functionality of these sensors [301,307]. When external pressure is exerted, these porous structures readily deform, significantly increasing both the number and total area of contact points within the material's conductive network [308]. This structural transformation creates new, more effective conductive pathways, leading to a rapid and substantial reduction in overall resistance [309]. This mechanism improves sensitivity, an essential factor for precise pressure detection in low-force applications, including the monitoring of subtle physiological signals such as arterial pulses, throat vibrations during swallowing, and fine muscular movements associated with facial expressions [305,310,311].

3.4.1. Physical and Mechanical Sensors

Various conductive materials such as CNTs, graphene, MXenes, and metals have been incorporated into PCT structures to develop high-sensitivity textile-based pressure sensors [312]. For example, MXene-coated cotton fabrics and electrospun polyurethane membranes have shown significant sensitivity and stretchability, meeting the flexibility needs for wearable applications [313]. Additionally, sensor designs or those employing three-dimensional porous structures, have improved sensitivity. By mimicking the architecture of natural tissues, these sensors can respond more precisely to pressure changes [314]. However, despite these advancements, several challenges still exist, especially regarding sensor stability in different environmental conditions. For example, temperature changes can affect electrical resistance, and the flexible textile structure may cause variability in both electrical and mechanical performance over time.

Addressing the need for highly stretchable and sensitive materials, Qin et al. introduce a novel class of stretchable, fully biopolymer-supported deep eutectic solvent (DES) gel electrolytes, highlighting their potential in ionic skin devices [315]. The DES gel, containing 22 wt% gelatin, demonstrated remarkable stretchability with a fracture strain of 4300% and an ionic conductivity of 2.5 mS cm^{-1} at room temperature. A strain sensor based on the DES gel showed good linearity with a gauge factor of approximately 0.5, while a pressure sensor prototype could sensitively measure pressures as low as 1 kPa. These features enabled DES gel-based ionic skin devices to accurately monitor human finger bending and multitouch stimuli on a 3x3 sensor array (**Figure 10A**).

Capacitive pressure sensors are highly regarded for their accuracy and wide detection range, which make them suitable for applications requiring precise pressure monitoring, such as in medical diagnostics and human-machine interactions. These sensors function by assessing variations in capacitance between two conductive electrodes separated by a dielectric layer, with the

alterations in capacitance directly reflecting the applied pressure [316]. Porous conductive textiles (PCTs) present an ideal medium for capacitive sensors due to their unique porous structure and flexible conductive properties, which enhance sensitivity. The intrinsic porosity of PCTs creates air gaps within the textile framework, amplifying capacitance changes in response to pressure fluctuations, thereby improving sensor accuracy. Recent innovations include the creation of PCT electrodes utilizing palladium-doped PAN nanofiber membranes coated with silver, which significantly increases the electrode's contact area and boosts pressure sensitivity [317]. Further advancements were achieved by integrating MXene and ionic salts, generating an ion-pumping effect that enhances the capacitance response and further magnifies overall pressure-sensing capabilities [318].

While one-dimensional conductive fibers such as CNTs, graphene, and hydrogel fibers have been deployed in PCT-based sensors, these fibers tend to be more challenging to implement over larger areas, limiting their effectiveness in wearable sensor arrays. To address this challenge, textile manufacturing methods like weaving and knitting have been utilized to produce extensive sensor arrays, enabling a scalable approach to generate large capacitive sensing surfaces. For example, woven elastic yarns coated with silver nanowires have been utilized to create a large-area capacitive pressure sensor array, demonstrating flexibility and durability while reliably detecting pressure across a broad surface area [319].

Electric pressure sensors, including piezoelectric and triboelectric types, are essential in applications that need self-powered, real-time pressure tracking. They work by producing electrical signals directly when forces are applied. Piezoelectric sensors use materials like ZnO, $BaTiO_3$, and PVDF, which create an electric field when they are deformed mechanically [320,321]. Typically, these sensors feature conductive electrodes paired with a piezoelectric sensing layer that directly transforms mechanical pressure into electrical signals. Recent developments include fabric-based piezoelectric sensors that

integrate PCT electrodes with PVDF nanofiber membranes. The natural air gaps within the textile structure improve charge transfer and sensitivity by allowing more space for deformation [322]. This design amplifies the response of piezoelectric materials to pressure, making PCT-based sensors particularly advantageous for wearable technology applications where sensitivity to light pressures is critical.

Conversely, triboelectric sensors operate on the principles of triboelectric electrification and electrostatic induction, enabling a broader range of materials and structural configurations than piezoelectric sensors [323]. In triboelectric sensors, PCTs can act as either the charge-generating parts or the friction layers. They utilize the textile's porous structure and conductivity to boost charge generation [324]. For instance, conductive yarns coated with polymers have been utilized in single-electrode triboelectric sensors, and knitted yarns have enabled the development of pressure-sensing fabrics [325]. Additionally, materials such as liquid metal (LM) integrated into triboelectric sensors can further enhance sensitivity due to their low modulus and high deformability, allowing for a more effective interaction with applied forces [326]. Nonetheless, electric pressure sensors face challenges related to environmental sensitivity, particularly humidity, which can affect their stability and accuracy.

Somkuwar et al. recently introduced a lightweight, comfortable, and durable wearable triboelectric (TE) nanosensor device designed for self-powered applications [327]. The performance of the TE device is enhanced through three main strategies: using textured yarn, altering the textile material, and changing the fabric structure. The researchers examined how these changes affect the triboelectric properties by focusing on surface morphology, roughness, and dielectric characteristics (**Figure 10B**). They compared TE devices made from woven and knitted fabrics composed of nylon, cotton, polypropylene (PP), and polyester. To analyze surface roughness and morphology, a 3D optical profilometer was used. The results showed that

knitted fabrics, especially those made from PP and nylon, tend to have rougher, more irregular surfaces with greater contact areas than woven fabrics, leading to better triboelectric performance. For example, the combination of nylon and PP in knitted form resulted in significant improvements: voltage increased by about 241%, current by nearly 65%, and power density surged by 460%, compared to woven textiles. Additionally, fabrics based on knitting offered better breathability and were more effective in capturing electrical energy from human movements.

Strain sensors are crucial tools for detecting changes in materials induced by external forces, converting mechanical deformation into electrical signals. Their use has grown significantly, especially in wearable devices for health monitoring, where they track respiratory cycles, joint motions, and athletic performance metrics [328]. Textile-based strain sensors utilizing PCTs have been developed in various forms, including resistive, capacitive, and electronic types [329]. Resistive strain sensors are commonly used because they are straightforward in design and easy to produce. They work by detecting resistance changes when subjected to stretching or compression.[330] PCTs with high stretchability act as sensing electrodes in these devices, with distinct equivalent-circuit behaviors influenced by the size of the sensing material, whether it is 1D fibers or 2D fabrics.

For instance, 1D strain sensors can be fabricated from composite fibers comprising multi-walled carbon nanotubes (MWCNTs) and silicone rubber, where resistance variations are attributed to the separation of conductive pathways as the sensor is stretched.[331] Additionally, spiral yarns composed of CNT and polyurethane (PU) nanofibers exhibit notable stretchability and conductivity; in this arrangement, microcrack formation during deformation results in measurable changes in resistance. In contrast, 2D fabric-based strain sensors require a more complex design to create conductive pathways. For example, the incorporation of conductive yarns into textiles via embroidery yields mixed-circuit configurations that respond to strain. In

contrast, CNT-coated fabrics develop microcracks during deformation, increasing resistance and thereby enhancing sensor responsiveness [332]. Despite the potential of textile-based resistive strain sensors for real-world use in healthcare and sports performance tracking, they still face notable hurdles. In particular, their sensitivity to temperature changes can impact how well they work and how dependable they are.

Dakel et al. recently developed a nanocomposite composed of multi-walled carbon nanotubes (MWCNTs) integrated into poly(butylene adipate-co-terephthalate) (PBAT), with concentrations ranging from 0.5 to 10 wt%. This material is designed for use as a strain sensor. To evaluate its potential, the researchers measured the volume resistivity to determine the nanocomposite's conductivity. Findings indicated a low diffusion threshold within MWCNT concentrations of 0.5 to 1 wt%. The observed volume resistivity ranged from $(6.90 \pm 3.16) \times 10^5$ Ω.cm to $(1.24 \pm 0.41) \times 10^1$ Ω.cm, highlighting their viability for strain sensing applications.

The piezoresistive characteristics of the nanocomposites were investigated by measuring electrical resistance changes during tensile testing [333]. The deformation behavior was correlated with the relative resistance change ($\Delta R/R_0$) based on cyclic strain testing, which assessed the stability of the strain sensing performance. The nonlinear, exponential-like increase in $\Delta R/R_0$ values with mechanical strain during tensile tests validated their piezoresistive nature. The $\Delta R/R_0$ values demonstrated a strong correlation with mechanical strain, increasing from 2% to 8% during cyclic strain tests, indicating the nanocomposites' capability for low-strain detection. This assertion is further substantiated by the repeatability of $\Delta R/R_0$values during cyclic strain tests involving 7% strain over 15 cycles (**Figure 10C**).

Capacitive and electric strain sensors, including piezoelectric and triboelectric types, provide different methods for detecting deformation in wearable applications by converting mechanical changes into measurable

electrical signals. Capacitive sensors typically operate based on changes in capacitance, often using a parallel-plate design. However, to meet the flexibility demands of textiles, alternative structures like core-shell or double-helix configurations have been developed. These innovative designs allow textile-based capacitive sensors to better handle strain compared to traditional setups. For instance, Lewis and colleagues created a core-shell fiber that uses an ionically conductive fluid as the electrode and silicone rubber as the dielectric layer, enabling effective strain sensing in flexible textile materials [334]. In another approach, a double-helix structure incorporates conductive fibers that align in response to applied strain, increasing capacitance and providing a sensitive, flexible solution for wearable sensing [335].

Chen and colleagues developed a new fiber-based iontronic sensor that demonstrates exceptional performance in detecting pressure and temperature changes [336]. The sensor is fabricated by integrating two orthogonally arranged, hollow, and porous ionogel fibers filled with liquid metal. As a pressure sensor, it achieves a detection resolution of 1.16 Pa, a sensitivity of 13.30 $k.Pa^{-1}$ within the $0-2$ $k.Pa$ range, and a detection span of approximately 207 kPa, attributable to its novel structural design and the employment of deformable liquid metal electrodes. In temperature sensing applications, it demonstrates a high thermal sensitivity of 25.99% $°C^{-1}$ between 35 and 40 °C, with a resolution of 0.02 °C, accompanied by excellent repeatability and reliability. This sensing technology leverages unique characteristics that allow the device to detect a wide range of pressure stimuli. It can sense everything from small pulses to larger joint movements and even object proximity. Additionally, a large-area fiber array can be woven into fabrics to create pressure maps, which help identify where forces are applied, their strength, and their shape. This approach provides a flexible way to develop fiber-based iontronic sensors that are suitable for use in wearable electronic devices (**Figure 10D**).

Electric strain sensors, including both piezoelectric and triboelectric types, can generate power by directly converting mechanical strain into electrical signals, eliminating the need for an external power source. Piezoelectric strain sensors use materials such as ZnO, which generate an electric field when deformed. However, their practical use is limited by insufficient stretchability, as ZnO-coated carbon fibers can only detect strains within specific ranges due to their inherent properties [337]. In contrast, triboelectric strain sensors operate through the contact and separation of triboelectric layers, enabling more versatile configurations. Helical fiber-based triboelectric sensors have been created using flexible materials such as organogel and silicone rubber, which enhance their flexibility and broaden their strain-detection capabilities, making them well-suited for the evolving requirements of wearable electronics [338–340]. Despite their advantages as self-powered devices, electric strain sensors face issues related to their power generation capabilities, dependence on mechanical movement for signal creation, and susceptibility to environmental influences like humidity and temperature changes.

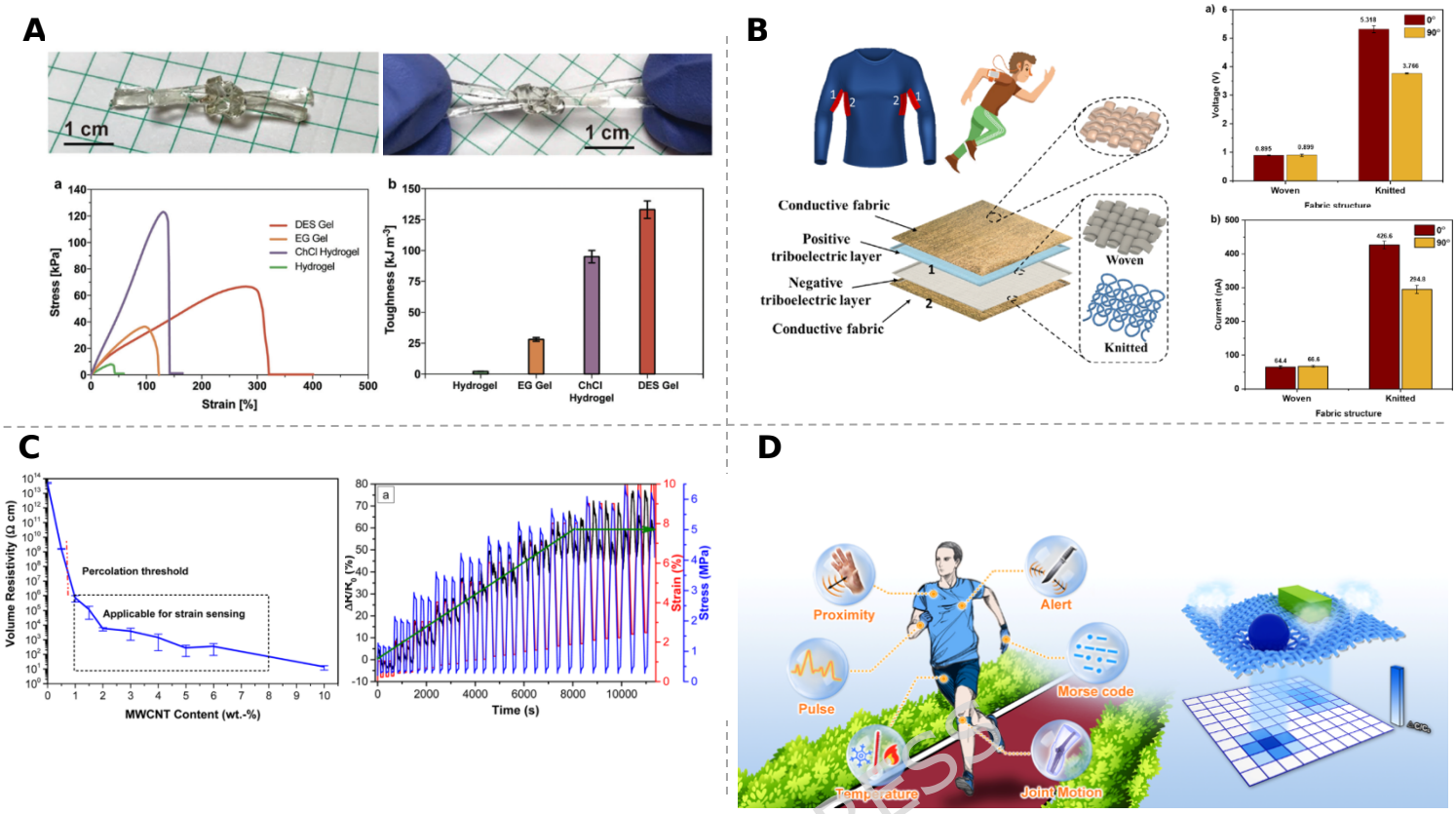


Figure 10: **A)** The remarkable mechanical characteristics of a biopolymer-based deep eutectic solvent (DES) gel are clearly shown through its flexibility, demonstrated by a hand-stretched knotted strip. The mechanical behavior is illustrated with relevant graphs. (a) The tensile stress-strain curves compare the DES gel with an ethylene glycol (EG) gel, a choline chloride (ChCl) hydrogel, and a pure hydrogel, revealing that the DES gel can endure significantly larger strains before breaking. (b) The fracture toughness, calculated from these curves, highlights the DES gel's superior durability, indicating its potential for use in flexible and wearable ionic interfaces. Adapted with permission from [315], Royal Society of Chemistry, 2019. **B)** The Wearable Triboelectric Nanogenerator (W-TENG) is built into clothing to capture energy from human motion, employing an optimized multilayer fabric structure that includes conductive textiles and layers with positive and negative triboelectric properties. The way the fabric is constructed greatly impacts its electrical output. Comparing bar charts, the data show the (a) open-circuit voltage (Voc) and (b) short-circuit current (ISC) generated by woven and knitted nylon/polypropylene fabrics. The knitted fabric, which has a larger surface area and more surface roughness, produces higher voltage and current, making the energy harvesting more effective. Adapted with permission from [327], American Chemical Society, 2023. **C)** Electromechanical characterization of MWCNT/PBAT nanocomposite strain sensors. The left panel depicts the variation of electrical volume resistivity with respect to the multi-walled carbon nanotube (MWCNT) loading. A

pronounced decrease in resistivity between 0.5 and 1 wt-% signifies the establishment of a conductive network at the percolation threshold, which is critical for sensor functionality. The right panel illustrates the piezoresistive behavior during cyclic strain testing. The normalized resistance change (R/R0, represented by the blue line) exhibits a correlation with the applied mechanical strain (black line), indicating the nanocomposite's consistent and dependable response as a low-strain sensing material. Adapted with permission from [333], Royal Society of Chemistry, 2019. **D)** A multifunctional fiber-based iontronic sensor designed for wearable electronics is depicted. The illustration showcases a highly adaptable, fiber-integrated sensor array embedded within textile material to facilitate comprehensive monitoring during physical activities. This sensor can concurrently detect a broad spectrum of stimuli, including proximity, pulse, joint movement, and temperature. The inset illustrates the woven-matrix architecture of the iontronic fibers, which enables the development of extensive sensor arrays for spatial pressure mapping and sophisticated human-machine interfaces. Adapted with permission from [336], American Chemical Society, 2023.

3.4.2. Chemical/Biological Sensors

Wearable gas sensors are gaining prominence as effective instruments for point-of-care diagnostics, capable of detecting a range of gaseous substances, including inorganic compounds and volatile organic compounds (VOCs) emitted by the human body [341]. These sensors operate by capturing gas molecules on their surfaces, which causes changes in their electrical properties. These changes are directly related to the amount of gas present, making them useful for health monitoring and environmental applications [342]. Materials with large surface areas and reactive groups, including CNTs, rGO, MXenes, metal oxides, and MOFs, are frequently employed in gas sensors because of their high sensitivity and specific interaction capabilities [343,344]. PCTs offer a versatile and breathable foundation for wearable gas sensors, making it easy to incorporate them into clothing and allowing direct skin contact for real-time monitoring. For example, sensors designed to detect nitrogen dioxide (NO_2) have been created using GO and ZnO-coated cotton threads. These sensors are highly sensitive and built to be comfortable and durable for everyday use [345]. Furthermore, combining polyacrylonitrile (PAN), PANI, and rGO nanofibers has been developed into

ammonia sensors that can differentiate between healthy individuals and those with chronic illnesses by analyzing ammonia levels. This highlights the promising potential for personalized health monitoring [346]. Flexible gas sensors have also been adapted for environmental monitoring, targeting gases such as hydrogen (H_2) and sulfur dioxide (SO_2) [347]. For example, electrospun carbon nanofibers (CNFs) adorned with platinum-nickel (Pt−Ni) nanoparticles and PVDF nanofibers integrated with MOFs have been developed for the detection of these gases, benefiting from the high surface reactivity and stability of the functionalized nanofibers [348].

Li and colleagues explore the creation of a wearable NO_2 gas sensor that uses hybrid fibers composed of rGO and mesoporous ZnO nanosheets. The study focuses on how these materials can be combined to develop effective sensing technology [345]. These fibers are designed to be flexible, stretchable, and twistable, making them suitable for integration into electronic textiles. They are produced using a scalable, cost-effective dip-coating process. As shown in **Figure 11A**, the fibers demonstrate excellent mechanical durability, surviving 3,000 bending cycles, 1,000 twisting cycles, and strains up to 65% without significant performance loss. The sensor exhibits high sensitivity to NO_2, with a detection limit of approximately 43.5 parts per billion, and shows stable operation over 84 days. Reliability improvements are also achieved through the use of serial and parallel configurations, where parallel setups effectively reduce breakdown rates and improve sensor stability by providing multiple conductive pathways.

Research conducted by Lv and colleagues focuses on developing a flexible, porous film sensor made of PANI and poly(styrene sulfonic acid) (PSS) on a PVDF substrate [349]. This sensor is designed for the sensitive and stable detection of ammonia (NH_3) at room temperature. It is created using an in-situ polymerization process that is both cost-effective and suitable for mass production. The research shows that adding PSS notably improves the sensor's response to NH_3. The optimized PSS-PANI/PVDF film achieves a

response rate of about 70% at 1 ppm NH_3, which is 2.8 times higher than that of the pure PANI/PVDF film. It can detect NH3 levels from 0.1 to 10 ppm, with a detection limit as low as 0.1 ppm, showing a response of 9.4%. The device is also highly stable over time, with less than a 5% decline in response after 30 days, and it remains flexible, experiencing only a 15.1% reduction after 10,000 bending cycles at 1 ppm NH_3 (**Figure 11B**).

Wearable sweat biosensors are gaining recognition as valuable tools for monitoring health noninvasively and in real-time. They can detect various biomolecules present in sweat, interstitial fluid, tears, and saliva. These sensors collect important health data that can be used for a range of purposes, from maintaining general wellness to managing chronic conditions. Often, textile materials are used as the base for these sensors because they are flexible, porous, and capable of absorbing sweat. These properties help enhance sensor performance by improving the stability and attachment of biological receptors [176,350]. Most wearable biosensors function based on electrochemical principles. They use techniques such as potentiometric, amperometric, impedimetric, and transistor-based methods to convert biochemical interactions into measurable electrical signals [351]. Potentiometric sensors measure the voltage between electrodes when the circuit is open. These sensors are often used to detect specific ions in a solution, such as hydrogen (H^+), sodium (Na^+), or potassium (K^+), utilizing ion-selective membranes to target each ion [352]. Amperometric sensors, which detect biomolecules via redox currents, are widely used for glucose and lactate monitoring and often employ enzymatic reactions [350,353,354]. For instance, glucose sensors fabricated on gold-plated elastic fibers with immobilized GOx and Prussian blue provide specific and reliable glucose measurements [355]. Similarly, wearable amperometric sensors have been developed to monitor drug metabolites like Levodopa in sweat, offering a non-invasive method to track medication adherence and effectiveness in real time (**Figure 11D**). Impedimetric sensors measure changes in conductance and

capacitance at the electrode interface, making them suitable for applications such as urea detection, where electrospun PA6/PPy nanofibers are used to create sensitive, responsive urea sensors [356].

Figure 11C showcases how the PAA-SCMC hydrogel responds to changes in temperature and sweat composition, highlighting its potential for wearable health monitoring. The goal of this research is to develop a new conductive hydrogel that is stretchable, self-healing, self-adhesive, antibacterial, and suitable for 3D printing, making it useful for multifunctional wearable sensors. The hydrogel is made from sodium carboxymethyl cellulose (SCMC), acrylic acid (AA), and alkaline calcium bentonite (AC-Bt). The PAA-SCMC hydrogel exhibits a continuous decrease in the $\Delta R/R_0$ value as NaCl concentration increases from 0.25 $mg.mL^{-1}$ to 5 $mg.mL^{-1}$, indicating high sensitivity to changes in sweat composition. Furthermore, the hydrogel demonstrates stable resistance variations when exposed to artificial sweat at different pH levels, revealing excellent perspiration sensitivity; smooth $\Delta R/R_0$ changes are maintained over 29b cycles at a fixed pH of 5.5.

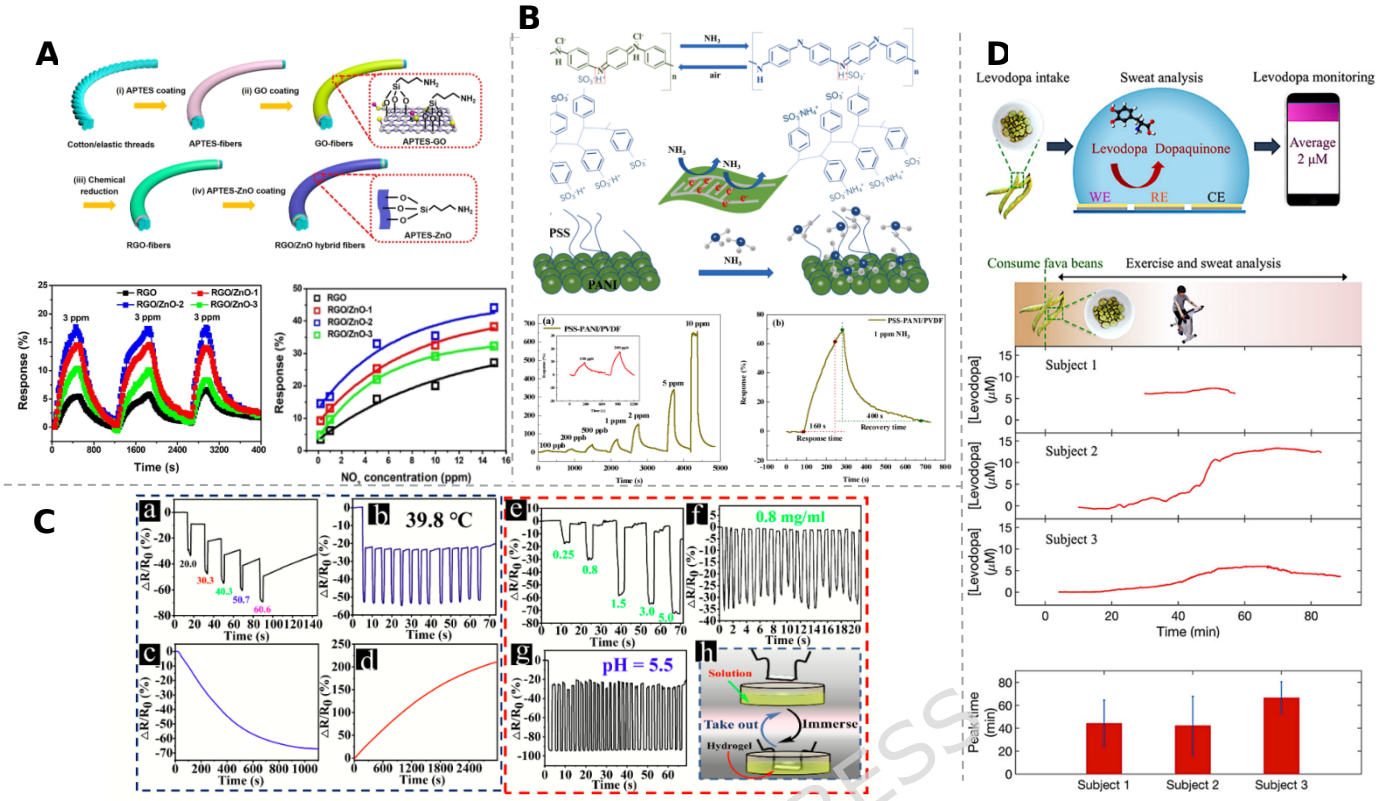


Figure 11: **A)** illustration of Fabrication process, sensing behavior plot and Gas-sensing properties of CT. Adapted with permission from [357], American Chemical Society, 2019. **B)** Schematic of film sensing mechanism, (a) continuous and (b) dynamic response-recovery cycle, Adapted with permission from [349], Elsevier, 2020. **C)** Analysis of the variation in relative resistance ratios (ΔR/R0) for PAA-SCMC hydrogels under various conditions. (a) Influence of different temperatures. (b) Behavior observed during cyclic changes at 39.8 °C. (c, d) Resistance changes sweep. (e) Effects of varying sodium chloride concentrations. (f) Performance during cycles. (g) Response to repeated exposure to artificial sweat with a pH of 5.5. (h) Illustration of the testing methodology. Adapted with permission from [358], Elsevier Ltd, 2024. **D)** Sensing mechanism of the levodopa sensor and Levodopa monitoring via exercise-induced sweat. Adapted with permission from [359], American Chemical Society, 2019.

3.5. Displays

Wearable electronics are progressively integrating flexible displays to enable real-time information sharing, with uses extending across health monitoring, notifications, navigation, and aesthetic improvements in smart textiles [360]. Flexible displays within wearable devices commonly employ electroluminescent and electrochromic technologies, allowing for light emission or color alteration, which enhances the visual appeal of functional smart clothing [361,362]. Electroluminescent devices, particularly organic

light-emitting diodes (OLEDs) and alternating current electroluminescent (ACEL) devices, are well-suited for PCT integration due to their low operational voltage and high flexibility [360,363–366]. Textile-based displays can be built either as flat multilayer panels or as fiber-shaped coaxial structures. The fiber design provides greater flexibility and maintains fabric-like qualities, allowing for their integration into clothing for large, bendable display surfaces [367,368]. Among these technologies, LECs and ACEL devices are especially noteworthy for wearable applications due to their relatively straightforward construction [369]. ACEL devices operate on alternating current and consist of a simple luminescent layer sandwiched between transparent electrodes, thereby enabling flexibility and even washability in wearable displays [370]. Recent advances have led to the development of extensive ACEL textiles that are breathable and washable, tackling key issues of comfort and longevity in wearable display technology. Nonetheless, textile-based displays still lag behind traditional screens in terms of brightness and resolution, which can pose difficulties for applications that demand high visibility.

Looking toward the future, progress in luminescent materials, weaving techniques, and integration strategies will play a vital role in enhancing the capabilities of textile displays. These developments could ultimately enable the creation of high-resolution, bright, and durable displays that are embedded directly into wearable electronics. Such advancements have the potential to revolutionize wearable technology by making flexible, integrated displays a common feature in smart clothing and personal devices.

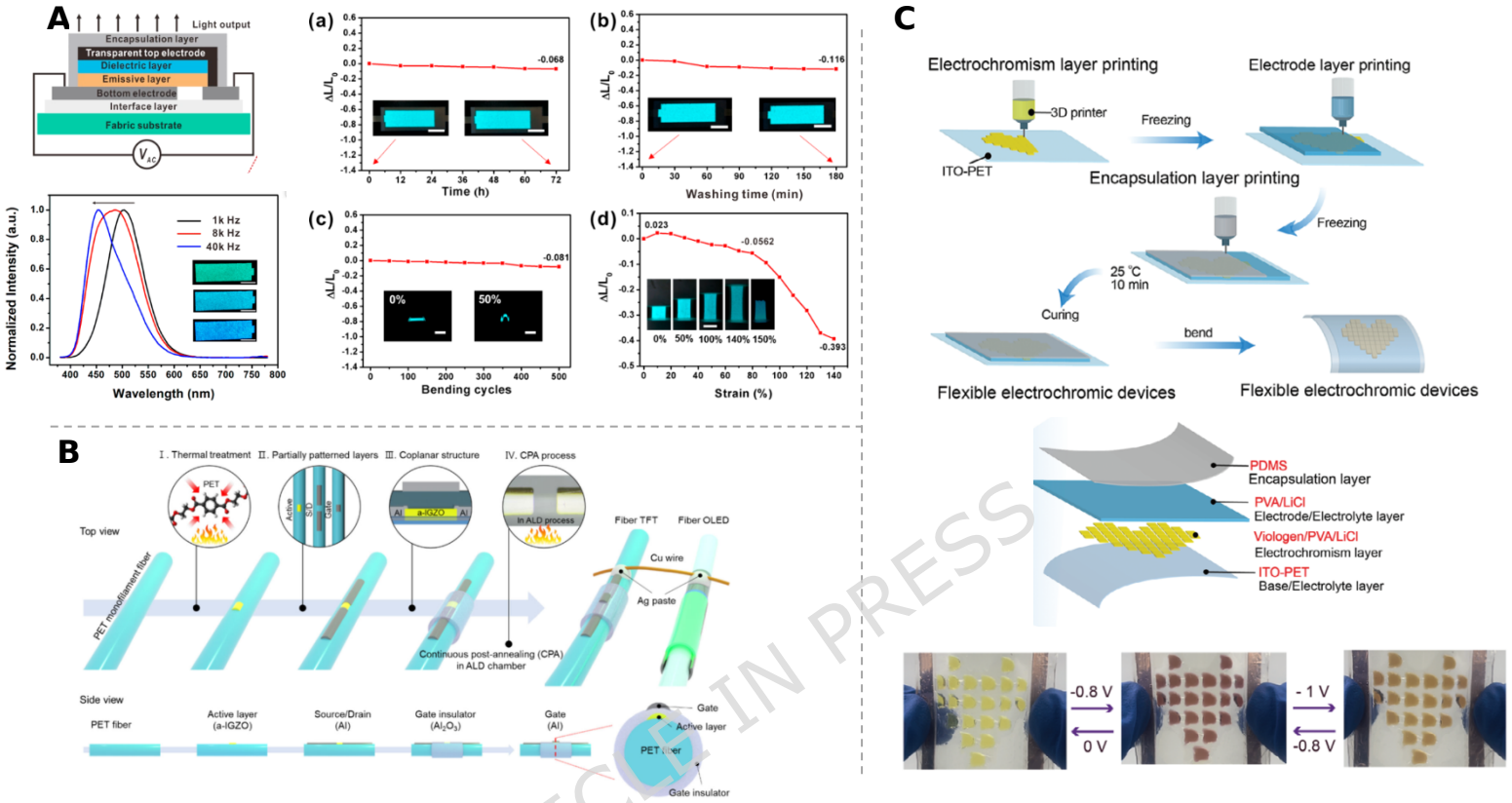
Ma and colleagues recently proposed a novel fabrication method for producing large-sized ACEL devices on fabric, specifically targeting wearable textile displays [371]. They achieved low operating voltages in the light-emitting devices by employing high-permittivity elastomeric materials as the dielectric matrix for the electroluminescent composite and incorporating barium titanate nanoparticles. The fabrication process involves screen

printing and laminating the layers, followed by thermal baking to remove solvents and ensure layer integrity. The ink components consist of Ag flakes, ZnS:Cu microparticles, $BaTiO_3$ nanoparticles, AgNWs, PVDF-HFP, isophorone, and Zonyl FS-300. The substrate consists of black Lycra fabric, which is planarized using a thermoplastic polyurethane (TPU) film. The final composite layer includes a bottom electrode made of elastic, conductive silver ink, an electroluminescent layer containing ZnS:Cu and $BaTiO_3$, a dielectric layer, a top electrode created with AgNWs ink, and an encapsulating TPU film. As shown **in Figure 12A**, these ACEL devices produce bright, uniform light emission at relatively low voltages, making them well-suited for wearable displays. Additionally, the printed devices sustain their performance under mechanical deformation, high temperatures, humid environments, repeated washing, and various external damages.

Kim and colleagues investigate the creation of fiber-based thin-film transistors (TFTs) using amorphous indium gallium zinc oxide (a-InGaZnO). Their goal is to develop wearable textile OLED displays that combine high electrical performance with mechanical flexibility [372]. The TFTs are manufactured using a-InGaZnO, a material known for its high electron mobility. The fabrication process involves four key steps: prethermal treatment, partial patterning of layers, creating a coplanar structure, and final post-annealing (CPA). These steps are carefully designed to accommodate the thermal characteristics and cylindrical shape of the fiber, as illustrated in **Figure 12B**. The created fiber-based IGZO TFTs exhibit a high mobility of 8.6 $cm^2.(V{\cdot}s)^{-1}$ and a low off-current of approximately 10^{-12} A, comparable to that of glass-based TFTs. They maintain their electrical performance under various conditions.

In the domain of electrochromic displays, recently, Luo and colleagues have introduced advanced flexible electrochromic devices (FECDs) utilizing 3D-printed hydrogel-based materials [357]. These FECDs feature a four-layer architecture that includes a PDMS encapsulation layer, a PVA/LiCl hydrogel

layer serving as both electrolyte and electrode, a viologen/PVA/LiCl hydrogel layer for electrolyte purposes, and an ITO-PET substrate/electrode layer (**Figure 12C**). With the exception of the ITO-PET layer, all other functional



layers are fabricated using a direct ink writing (DIW) printer without the need for additional processing steps (Fig. 10C). The FECDs demonstrate a remarkable optical contrast of up to 54% at 360 nm and exhibit outstanding cycling stability, with less than a 5% reduction in electroactivity after 10,000 seconds. Furthermore, these devices maintain mechanical stability, showing less than a 19% decrease in optimal contrast after 5,000 bending cycles.

Figure 12: **A)** Cross-sectional schematic of the textile-integrated alternating current electroluminescent (ACEL) device architecture. Electroluminescent spectral characteristics under 100 V excitation at varying frequencies (1–40 kHz). Environmental stability assessments: (a) Thermal-humidity aging (85°C/85% RH), (b) Laundering durability, (c) Mechanical flexibility under cyclic bending, and (d) Tensile stress resistance. Adapted with permission from [371], American Chemical Society, 2021. **B)** Fabrication protocol for hierarchical lyotropic liquid crystal fiber-based thin-film transistors (HLF-TFTs), highlighting four critical processing phases.

Adapted with permission from [372], American Chemical Society, 2024. **C)** Additive manufacturing workflow for hydrogel-based flexible electrochromic devices (FECDs). Structural configuration of 3D-printed FECDs exhibiting (a) Cardiac-shaped microarrays (3 × 3 mm^2) and (b) Macroscopic SV hydrogel matrices (30 × 30 mm^2) with voltage-dependent optical modulation. Adapted with permission from [357], Wiley-VCH GmbH, 2024.

In a study conducted by Guo and colleagues, the objective was to create electroluminescent displays that exhibit stretchability, breathability, and consistent performance after multiple cycles of stretching and washing [373]. They proposed an ultrathin nanocomposite device, as illustrated in **Figure 13A**, showcasing the overall architecture of the stretchable and breathable ACEL device. To assess permeability, the WVTR of common wearable materials was evaluated at 25°C, a temperature indicative of comfortable ambient conditions. The SEBS microfoam demonstrated significant steam permeability, recording a WVTR of 66.1 ± 5.2 $g \cdot h^{-1} \cdot m^{-2}$, comparable to conventional textiles (73.9 ± 6.8 $g \cdot h^{-1} \cdot m^{-2}$) owing to its rich internal pore structure facilitating gas transmission. The integration of the ACEL device within the microfoam reduced the steam permeability to 23.5 ± 2.3 $g \cdot h^{-1} \cdot m^{-2}$, significantly surpassing the transepidermal water loss (TEWL) of adult skin under normal conditions (TEWL ≈ 5−10 $g \cdot h^{-1} \cdot m^{-2}$). This finding suggests that the material satisfies the body's thermoregulation requirements for comfortable wear. The elastomer matrix of the device comprises abundant free volumes acting as diffusion pathways for gas molecules, thus permitting inherent steam permeability.

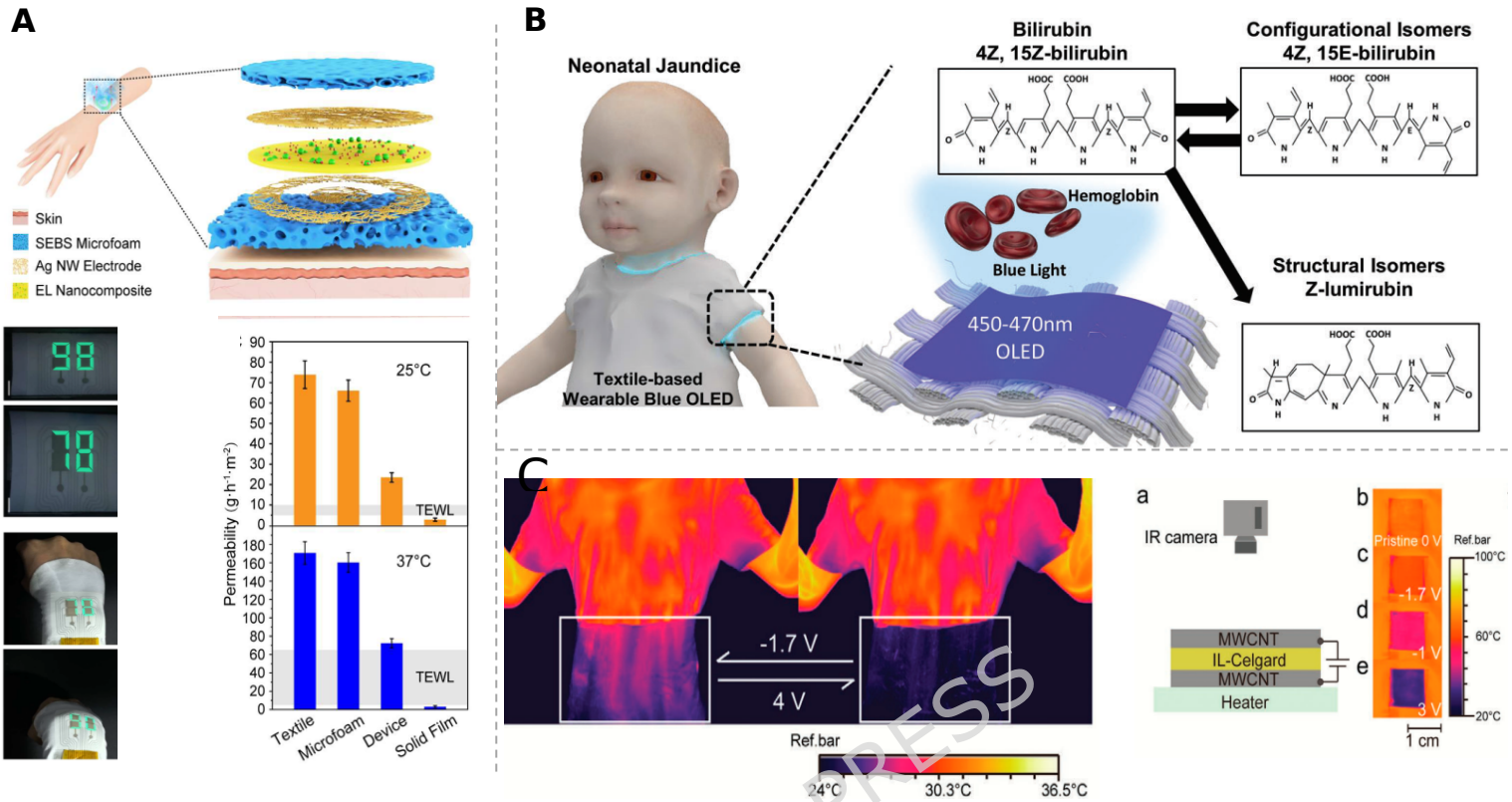
Neonatal jaundice is a common condition seen in newborns. If not properly treated, it can lead to serious complications, including brain damage or even death. Choi and colleagues, in their study, introduced a novel phototherapy method for addressing neonatal jaundice [374]. They developed a textile-based wearable OLED platform that is both flexible and capable of conforming to the body's contours (**Figure 13B**). This blue OLED platform

operates at a peak wavelength of 470 nm, which is effective for jaundice therapy, performing efficiently at low voltages (below 4.0 V) and achieving a radiant emittance intensity of approximately 2000 $\mu W.cm^{-2}$, even at 4.5 V. The device maintains a safe operating temperature around 30°C, thus preventing burns and ensuring over 100 hours of dependable use. Testing revealed that the blue OLED, with a peak wavelength of 460-470 nm, effectively reduced bilirubin levels to 12 $mg.dL^{-1}$ or lower within 3 hours at a standard treatment intensity (10 $\mu W.cm^{-2}.nm^{-1}$). Unlike point source LED arrays, which necessitate a specific distance from the body, this surface light source OLED can be positioned closely on the skin, thereby uniformly diminishing bilirubin concentration in the treatment area. These findings suggest that the textile-based wearable blue OLED platform offers a promising and effective approach for phototherapy in monitoring and treating neonatal jaundice, providing reassurance to parents about their children's health.

Electrochromism refers to a material's ability to change its optical properties, such as color or transparency, when an electric charge is applied. This property is increasingly being utilized in textiles for smart fabrics, displays, and adaptive camouflage systems. Electrochromic textiles work through reversible oxidation and reduction reactions within their electrochromic layer, which causes the optical characteristics to shift when voltage is applied or removed. These systems typically consist of multiple layers: an electrochromic layer, a counter electrode, an electrolyte, a transparent conductive layer, and a support substrate. Each component plays an essential role in maintaining the durability and effectiveness of the color-changing feature. Frequently utilized electrochromic materials encompass transition metal oxides, such as tungsten trioxide (WO_3) and nickel oxide (NiO), recognized for their stability and reliability in coloration cycles, alongside conducting polymers like PANI and PEDOT, which offer a diverse array of color options and flexibility [375,376]. Recent advancements have

highlighted the potential of integrating electrochromic properties directly into textiles. For instance, Sotzing et al. developed a single-layer electrochromic textile by applying PEDOT onto a textile substrate coated with a copolymer of 3,4-bis(2-ethylhexyloxy)thiophene and 3,4-dimethoxythiophene [377]. This electrochromic textile displayed rapid, reversible color shifts between red and blue upon application of a modest voltage, underscoring the potential for practical, color-changing fabrics responsive to environmental or user-driven stimuli. The versatility of electrochromic textiles offers significant opportunities for wearable electronics, especially in creating smart clothing and interactive displays that can change appearance or display information in real-time. These advancements open the door to both functional and aesthetic innovations in smart textiles, with potential uses in fashion, military gear, and environmental monitoring. To realize these applications fully, ongoing research is essential to improve material durability, color retention, and energy efficiency, ensuring these textiles become practical and reliable for everyday use.

Zhou and their team have advanced the limits of functional textiles with their innovative new smart fibers [378]. These innovative fibers are not only knittable and wash-durable but also self-healable, making them perfect for a wide range of applications, especially in wearable electronics (**Figure 13C**). These fibers are distinguished by their unique combination of piezoresistive and luminescent properties, enabling dual-modal sensing capabilities. They are constructed using a sophisticated core-shell nanostructure that enhances their durability during activities like knitting and washing. This design is essential for preserving their structural integrity and functionality over time. Notably, they possess an exceptionally high gauge factor of 12,383,500, indicating a high sensitivity to mechanical changes, which is vital for precise sensing. Moreover, these fibers are water-resistant, allowing them to withstand regular washing without losing effectiveness. They also feature



self-healing properties, with a tensile strength of 30.9 MPa and a healing efficiency of 72.9%. This impressive ability to recover from damage ensures the fibers can remain reliable and durable for more than 100 days, making them well-suited for long-term applications.

Figure 13: **A)** Diagram showing the ultrathin ACEL device embedded in SEBS microfoam. Steam permeability and optical images illustrate the display at two stages: 0% (top) and 50% (bottom). Reproduced with permission from [373], American Chemical Society, 2024. **B)** Demonstration of jaundice treatment through bilirubin isomer formation facilitated by textile-based blue OLED, followed by excretion. Reproduced with permission from [374], Wiley-VCH GmbH, 2022. **C)** Infrared images of the fabricated film under negative (-1.7 V) and positive (4 V) voltages, alongside a schematic of the experimental setup. Reproduced with permission from [378]**,** Wiley-VCH GmbH, 2021.

3.6. Antennas and Wireless Communication

Wearable electronics have progressed beyond basic, localized sensors to become sophisticated systems that interact seamlessly with the Internet of Things (IoT). The success of these systems relies on robust wireless data

transmission, which is essential for building comprehensive Body Area Networks (BANs) [379,380]. As a result, researchers are focusing on developing flexible, textile-based antennas and wireless modules, since conventional rigid printed circuit board (PCB) antennas are not well-suited to the flexible and curved surfaces of the human body [381,382]. In addition, widely used wireless protocols such as Bluetooth and Wi-Fi emit radiative radio waves in all directions. This leads to considerable signal loss due to absorption by human tissues, increased power consumption, and heightened risks of security breaches and unauthorized interception (**Figure 14A**) [380,383].

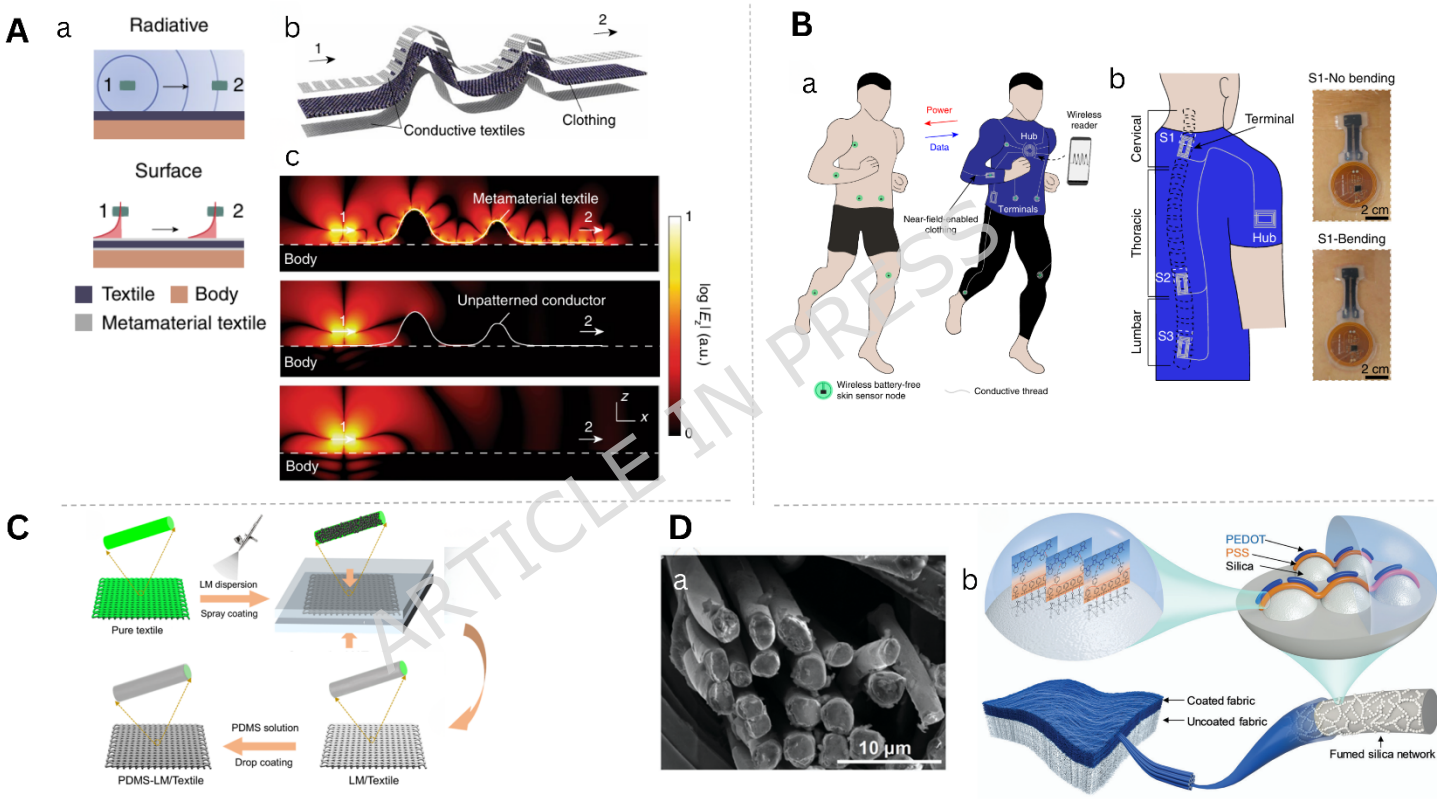
To overcome these electromagnetic obstacles, researchers are developing porous conductive textiles that serve as metamaterial platforms, enabling precise control of electromagnetic waves and reducing signal loss caused by absorption in biological tissues [384]. A significant development in this area is the creation of metamaterial textiles that support surface-plasmon-like modes at standard communication frequencies. By designing conductive textiles with specialized planar comb-shaped patterns, these fabrics guide radio-frequency signals as surface waves that follow the body's contours. This approach confines wireless communication to within approximately 10 cm of the body, increasing transmission efficiency by more than 30 dB compared to conventional radiative networks and substantially improving data privacy by limiting the range for potential eavesdropping [383].

Advances in transmission efficiency and specialized manufacturing methods, such as automated, computer-controlled embroidery, have enabled textiles to support a new generation of battery-free wireless sensor networks [385,386]. By integrating conductive threads into clothing to create large-scale magnetic relays, it is now feasible to wirelessly power sensors distributed across the body and continuously transmit physiological data, such as spinal posture or gait, to a central device like a smartphone. These textile platforms retain reliable connections using contactless proximity and magnetic

coupling, removing the need for hardwired links or bulky batteries and assuring reliable operation even during repeated movement and deformation (**Figure 14B**) [380,385].

Although significant progress has been made in wireless human-machine interfaces, textile-based communication systems continue to encounter substantial environmental and structural obstacles [387]. Textiles are inherently porous, making them prone to absorbing moisture. Since water has a high relative permittivity, its presence can change the dielectric constant of the textile, detuning the antenna's resonant frequency and impairing impedance matching (**Figure 14C**) [380]. To mitigate these effects, innovations such as stretchable liquid metal-based conductive networks with polydimethylsiloxane (PDMS) encapsulation and all-organic PEDOT:PSS coaxial coatings have been developed to maintain electromagnetic stability and surface conductivity under mechanical strain and harsh environmental conditions (**Figure 14D**). Achieving a careful balance between electromagnetic performance, metamaterial engineering, and protective encapsulation is key for advancing the next generation of autonomous, secure, and continuously connected smart garments [383,387,388].

Figure 14: **A)** Metamaterial textiles for efficient surface-wave communication. (a) Schematic comparing conventional radiative transmission, which scatters signals into surrounding space (blue lines), with surface-wave interconnection, which confines signals close to the body (red lines). (b) Illustration of planar conductive textiles integrated into clothing to form a metamaterial platform. Simulated electric field distributions (|Ez|) produced by a dipole antenna above a metamaterial textile (top), an unpatterned conductive textile (middle), and a non-conductive textile (bottom) are shown. In these simulations, performed on an air–body half-space ($\varepsilon_{body} = 40$), the metamaterial textile demonstrates a pronounced ability to confine electromagnetic waves to the body's surface. Reproduced with permission from [383], Nature, 2019. **B)** Battery-free wireless sensor networks using smart textiles. (a) Diagram depicting several battery-free sensor nodes placed on the skin that communicate



continuously with a wireless reader through magnetic relays in specialized clothing. (b) Example application in real-time posture monitoring: battery-free strain sensors on the cervical (S1), thoracic (S2), and lumbar (S3) spine regions transmit physiological data to a central NFC hub using conductive threads in the garment. Inset images show the S1 sensor flexibly adapting to movement of the cervical spine. Reproduced with permission from [385], Nature, 2020. **C)** Fabrication of stretchable liquid metal (LM)-based textiles for electromagnetic stability. The workflow shows a solution-coating process to produce highly stretchable, LM-based conductive textiles designed for electromagnetic interference (EMI) shielding. The process involves spray-coating a pure textile with an LM dispersion to form a conductive network. A drop-cast polydimethylsiloxane (PDMS) layer is then applied to encapsulate the textile, mechanically stabilizing the three-dimensional LM network and maintaining electrical conductivity even during significant stretching or deformation.

Adapted with permission from [387], American Chemical Society, 2020. **D)** Microstructural design of environmentally stable, all-organic conductive fabrics. (a) Cross-sectional SEM image shows the uniform structure of coated fabric fibers. (b) Schematic of the PEDOT:PSS printing process. Integrating a fumed silica nanoparticle network onto the fiber surface improves both the surface conductivity and mechanical durability of the PEDOT:PSS coating. Reproduced with permission from [382], Royal Society Of Chemistry, 2020.

Table 2: State-of-the-Art Performance Benchmarks for Multifunctional PCT Applications.

Application Category	Specific Function	Key Performance Metric	State-of-the-Art Benchmark	Exemplar Material / System	Reference(s)
Therapeutic	Textile Heater (Thermotherapy)	Max. Temperature @ Low Voltage	>120∘C @ ≈9 V	Graphene or CNT-coated textiles	[136,137]
Actuation	Electrochemical Actuator	Operating Voltage / Efficiency	<2 V >6% efficiency	PPy actuator (<2V) Graphdiyne (>6%)	[197,198]
Energy Harvesting	Flexible Solar Cells (PVs)	Power Conversion Efficiency (PCE)	≈18.82%	PM6:PX1:L8-BO ternary system (OSC)	[221]
Energy Harvesting	Nanogenerators (TENGs)	Output Voltage / Power Density	261 V 654.48 $mW \cdot m^{-2}$	Dielectric-modulated t-TENG (PVDF-HFP/$BaTiO_3$)	[244]
Energy Harvesting	Biofuel Cells	Max. Power Density	224.85 $\mu W \cdot cm^{-2}$	Self-adhesive PVA-based HBFC (lactate)	[262]

Energy Storage	Supercapacitors	Volumetric Capacitance	1500 $F \cdot cm^{-3}$	Inverse opaline metallic membrane w/ $Ni(OH)_2$	[273]
Energy Storage	Flexible Batteries (LIBs)	Energy Density	288 $Wh \cdot kg^{-1}$	Flexible Li-S battery on Cu/Ni-coated carbon cloth	[289]
Sensing (Physical)	Pressure Sensor	Sensitivity / Detection Limit	≈1 Pa (1.16 Pa)	Fiber-based iontronic sensor (LM/ionogel)	[336]
Sensing (Physical)	Strain Sensor	Gauge Factor (GF)	$>10^7$ (12,383,500)	Piezoresistive/luminescent core-shell fibers	[378]
Sensing (Chemical)	Gas Sensor (e.g., NO_2)	Limit of Detection (LoD)	<50 ppb (43.5 ppb)	rGO mesoporous ZnO hybrid fibers	[345]
Displays	Electroluminescent (ACEL)	Functionality	Bright, uniform, and washable	Screen-printed ACEL (ZnS:Cu / $BaTiO_3$)	[371]
Displays	Electrochromic (ECD)	Optical Contrast Durability	54% contrast >5,000 bend cycles	3D-printed Viologen/PVA hydrogels	[357]
Wireless Communication	Metamaterial Textile BANs	Transmission Efficiency	>30 dB enhancement (within 10 cm)	Comb-shaped metamaterial conductive textiles	[383]

4. Conclusion Remarks and Future Perspectives

The field of PCTs has seen a notable evolution, moving from making simple conductive fibers to creating advanced, active, and intelligent textile systems. This review outlines a progress that has moved beyond initial proof-of-concept efforts to reach impressive performance levels that were once only seen in traditional electronics. As shown in **Table 2**, Notable advancements include the development of textile-based sensors demonstrating sensitivities in the Pascal range and gas detection capabilities at concentrations as low as parts per billion; actuators designed to replicate muscular action with efficiencies surpassing 6% while operating at safe, low voltages below 2V; and self-sufficient on-body power systems incorporating solar cells with efficiencies nearing 19% and supercapacitors exhibiting volumetric capacitances of 1500 $F \cdot cm^{-3}$. These milestones represent a pivotal moment in the field, reframing the discussion from whether functional electronic textiles can be created to how they can be designed into fully autonomous, durable, and intelligent systems that seamlessly integrate with human physiology.

Despite the undeniable progress, the path to widespread adoption of smart garments faces significant challenges that require a fundamental change in our research approaches. Moving forward, we believe that the next stage of PCT research will center around three strategic initiatives.

The current focus is on moving beyond simply combining individual functional components to creating a cohesive, intelligent system integrated into textiles. The goal is to develop fabrics that can sense, process, communicate, and respond in a closed-loop system. Future research should concentrate on embedding flexible microelectronics and low-power neuromorphic computing directly into textile materials. This will enable real-time on-body data processing, such as filtering noise from ECG signals and applying machine learning techniques to forecast medical events like epileptic seizures or hypoglycemia. Furthermore, the integration of metamaterial textiles will allow these systems to securely transmit processed data via

battery-free wireless networks that follow the body's natural contours. Such systems support user privacy, reduce power consumption, and deliver immediate insights. Additionally, there is a challenge in progressing from detecting single analytes to continuous, multiplexed analysis of multiple biomarkers in sweat. Addressing this requires developing highly selective bioreceptors and sophisticated signal-processing algorithms to address issues such as signal drift and interference.

For any smart textile to gain popularity, it must show resilience against the challenges of everyday use. Additionally, as wearables become consumer products, their environmental impact should be addressed proactively. The development of next-generation conductive materials should focus on inherent self-healing capabilities. Research into dynamic covalent bonding and supramolecular chemistry is promising for creating conductive polymers and composites that can automatically repair micro-damage from mechanical stress and washing, helping maintain consistent performance over many use cycles. The growth of electronic textiles requires a close look at e-waste, making it crucial to develop high-performance conductive and semiconducting materials from fully biodegradable sources like cellulose, lignin, and silk. Designing these systems within a circular economy, where functional elements can be safely broken down or recycled, serves not only as an ethical obligation but also as a significant scientific and commercial opportunity.

Ultimately, the extensive streams of detailed data collected by smart textiles will combine to create a "digital twin", a dynamic, real-time virtual model of a person's physiological state. The full potential of PCTs is realized when data from different sensors, such as mechanical strain for breathing, biochemical markers from sweat, and electrical signals, are integrated. This multi-faceted data approach allows for predictive algorithms that can identify disease markers long before symptoms appear, shifting health management from reactionary to proactive and personalized care. Such systems will establish

the hardware foundation for a new era of decentralized healthcare, enabling continuous patient monitoring in domestic settings. The incorporation of closed-loop therapeutic capabilities, such as textiles that detect arrhythmias and deliver timely electrical stimuli, will metamorphose clothing from passive garments into active contributors to our health and well-being.

In conclusion, the era of simply creating flexible electronics has ended. The future focuses on developing intelligent textiles. The path forward requires an interdisciplinary blend of materials science, biotechnology, data science, and textile engineering to create garments that go beyond passive wearables, becoming truly responsive entities, able to perceive, process, and act in perfect harmony with the wearer.

Funding details

This research did not receive any findings.

Disclosure Statement

The authors report there are no competing interests to declare.

Data Availability Statement

Data sharing is not applicable to this article as no new data was created in this study.

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