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Hydrogel Functionalized Textiles for Smart and Sustainable Applications

HOSSAIN Khan Rajib[1,2*], JALIL M. Abdul[1*], KHAN Ayub Nabi[1], FUAD Khan Md. Salman Adib[1], MONIRUZZAMAN Md.[1], SAYEK Shabir[1], SAGOR S. M. Shahadat Hossain[1]

1. Department of Sciences, BGMEA University of Fashion and Technology, Dhaka 1230, Bangladesh
2. Center of Materials Science and Opto-Electronics Technology, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Hydrogels have garnered significant interest due to their remarkable hydrophilicity, biocompatibility, and customizable biomimetic properties. However, their use is limited by inherently poor mechanical properties, arising from their low-density chains and irregular microstructures. It remains challenging to improve the strength and toughness. To address these drawbacks, hydrogels are incorporated into textiles to create functional hydrogel-based composites. This paper reviews advances in hydrogel textile composites, focusing on design strategies and property enhancement. It also discusses the progress of these composites in areas such as medical dressings, wearable electronic devices, and flame-retardant protection while looking ahead to future research directions.

Keywords: hydrogel; smart textile; stimulus-responsive material; sustainable textile; polymer integration

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0 Introduction

Hydrogels are highly hydrophilic three-dimensional (3D) network structure gels that rapidly swell in water, retaining a large volume of water in their swollen state without dissolving. They have wide applications for their close interaction with biological organisms due to their biocompatibility, including biological research, drug delivery, and tissue engineering[1]. Recently, owing to their excellent softness, wettability, responsiveness, biocompatibility, and bioactivity, researchers have explored the use of hydrogels in various device applications, including sensors, actuators, coatings, optics, electronics, and water collectors[2]. Hydrogel polymers respond to minute changes in external stimuli, such as pH or temperature. They can be spun into fibers with different responsive properties by selecting appropriate processing and modification methods, and then processed into smart textiles[3].

Thermo-sensitive fibers can be obtained by introducing temperature-responsive hydrogels into the fibers through copolymerization, crosslinking, blending, coating, or composite spinning[4]. These thermo-sensitive hydrogels have been exploited in a range of smart textile applications, including smart breathable fabrics, controlled drug-release textiles, innovative wound dressings, smart diving suits, anti-exposure suits, and temperature-regulating sports textiles, highlighting their potential for advanced healthcare, protection, and wearable comfort applications. Beyond thermal regulation, hydrogels offer additional functionalities such as conductivity[5], responsiveness, and self-adjustment[6], making them promising candidates for flexible electronics, environmental sensors, and wound healing[7]. A thorough understanding of hydrogel synthesis methods, including crosslinking methods, chemical modifications and composite formulations that add various functionalities, is essential. These engineered hydrogels have demonstrated practical applications in multiple fields, such as wearable electronics, biomedicine, environmental remediation, and smart textiles, underscoring their growing importance in the development of advanced materials[8].

Electron beam irradiation-induced grafting has been used to modify polyester fabrics. A poly(acrylic acid) (PAA) hydrogel layer was successfully formed on the surface of polyester fibers, exhibiting swelling properties[9]. Electron beam-induced grafting of acrylic acid (AA) or acrylamide (AAm) onto cotton fibers was performed to form a hydrogel layer on the fiber surface. The modified polyester/cotton fabric (CF) acquired the ability to respond to dry-to-wet environmental changes, making it water-responsive. The hydrogel can be used in cooling clothing by utilizing its swelling effect when absorbing water and its evaporation during deswelling to remove heat. This hydrogel cooling agent is soft and elastic at room temperature, possessing dual functions of thermal insulation and cooling storage[10]. The developed cooling vests (CVs) and cold atmospheric plasma

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* Correspondence should be addressed to HOSSAIN Khan Rajib, email: apexlabbd2@mails.ucas.ac.cn; JALIL M. Abdul, email: abduljalil@buft.edu.bd

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(CAP) devices are both made of hydrogels. Before use, the clothing is soaked in ice water for a period of time. The cooling material can combine with a large amount of water and form a gel in a crosslinked state. By removing heat during vaporization, the human body temperature can be lowered, allowing the wearer to feel cool and comfortable within a short time[11-12].

In this review, we discuss the state of the art in hydrogel-based functional textiles, highlighting the design strategies, fabrication approaches, and recent applications. Moreover, the review introduces some of the challenges (scalability, durability, and environmental impact) that must be addressed to maximize the benefits of these hybrid systems. This review aims to provide valuable resources for both researchers and practitioners in functional textiles and materials science by synthesizing existing knowledge and highlighting future directions.

1 Hydrogel Types and Properties

1.1 Hydrogel classification

Hydrogels have good water absorption, smooth surfaces, and biocompatibility[13]. They are polymer materials comprising up to 70% water[14] and exhibit stretchability of more than 500% and transparency of more than 90%[15]. Several frameworks are available for classifying hydrogels.

1.1.1 Classification based on bonding of hydrogel networks

Based on bonding of hydrogel networks, hydrogels can be divided into physical and chemical ones. Physical hydrogels are formed through physical forces, including electrostatic interactions, hydrogen bonding, and chain entanglement[16]. Owing to the non-permanent nature of these interactions, physical hydrogels can dissolve upon heating, and are therefore also referred to as pseudo-gels or thermoreversible gels[17]. At room temperature, many natural polymers, such as κ-carrageenan and agar, remain in a stable gel state. Polyvinyl alcohol (PVA), a typical synthetic polymer, can also form physical hydrogels via freeze-thaw cycling, and the resulting gels remain stable at temperature below 60 ℃[18]. In contrast, chemical hydrogels, also known as true gels[19], are formed through covalent crosslinks, resulting in permanent 3D network polymers that do not dissolve upon heating.

1.1.2 Classification based on response to external stimuli

Hydrogels can be classified into two types based on their response to external stimuli: traditional hydrogels and environmentally sensitive hydrogels. Traditional hydrogels exhibit no significant response to environmental changes such as temperature or pH[20]. In contrast, environmentally sensitive hydrogels can sense subtle external stimuli (temperature, pH, light, electricity, pressure, etc.) and produce corresponding changes in physical structures and chemical properties[21]. The most remarkable feature of this type of hydrogels is that the swelling behavior changes significantly in response to environmental changes. This stimulus-response can be used as a sensor or a controlled-release switch[22].

1.1.3 Classification based on material source of hydrogels

Hydrogels are classified into natural polymeric hydrogels and synthetic polymeric hydrogels based on the sources of their materials[23]. Natural polymers have received increasing attention from researchers due to their superior biocompatibility, environmental responsiveness, abundant sources, and low cost[24]. Natural polymeric hydrogels can be prepared from natural polymers including hyaluronic acid, chitosan, collagen, gelatin, alginate, cellulose, agarose, dextran, guar gum, and fibrin, among others. These hydrogels are especially prized for their fast and efficient biodegradation, which is compatible with short-term biomedical applications and sustainable techniques[25]. Synthetic polymeric hydrogels consist of materials such as poly(ethylene glycol) (PEG), PAA and its derivatives, PVA, poly(ethylene oxide), polyacrylamide (PAAm), poly(2-hydroxyethyl methacrylate), poly(methacrylic acid), and others. They are designed to offer tunable mechanical properties, chemical stability, and controlled degradation profiles, and are suitable for long-term wearable electronics, smart fabrics, and controlled drug-releasing textiles[26].

1.1.4 Classification based on structural arrangement of interpenetrating polymer network (IPN) hydrogels

IPN hydrogels are categorized based on their structural arrangement, the nature of polymer interactions, and synthesis methods. IPN hydrogels have numerous unique applications due to their combination of different materials, including *N*-isopropylacrylamide, AA, calcium alginate, collagen, chitosan, and silk fibroin. Innovations in these materials cover a wide range, from quantum dot doping and nanocomposites to grafting with PAA or PEG. IPN structures have a wide range of applications, from biomedical to textile and environmental materials, as they can serve various functional and biomimetic purposes in advanced technology[27-29].

1.2 Hydrogel properties

Many hydrophilic groups, such as hydroxyl, carboxyl, and amino groups, can form hydrogen bonds or other intermolecular interactions with water molecules in hydrogels[30]. The water absorption rate and moisturizing properties of hydrogels are excellent. The water content typically ranges from 1% to 99%[31]. Hydrogels with a high crosslinking density have been shown to be very strong and elastic, making them suitable for load-bearing applications, such as protecting an outer surface from forces[32]. Hydrogels are among the most biocompatible materials, stable and harmless in live tissue. Therefore, they are utilized in various medical fields, including medical treatment, tissue engineering,

and biosensing[33]. Biodegradable hydrogels have biomedical applications because they can degrade through hydrolytic or enzymatic cleavage in the body or the environment[34]. An advanced four-dimensional (4D) printing technology was developed with a heat-assisted self-assembly procedure to prepare MXene hydrogel electrochemical energy-storage devices. Using poly(3,4-ethylenedioxythiophene) : poly (styrene sulfonate) (PEDOT : PSS) as the crosslinker, the as-prepared device has a high specific capacitance of 232.9 F/g at 10 mV/s, a low-temperature resistance of −20 ℃, a high capacity retention of 90.6%, and a high energy density of 92.88 μWh/cm^2 (Fig. 1(a))[35]. The 3D printed devices are fabricated using a curable, tailored hydrocarbon-doped paste and a stretchable hydrocarbon-based silver paste for individual parts of the device. The conductive hydrogel ink exhibits high conductivity, approximately 1.4×10^3 S/cm (Figs. 1(b) – 1(d)). A hydrogel radio-frequency identification (RFID) device that integrates protocol control information (PCI) and electronic product code (EPC) can maintain stable operation under tensile deformation and be identified by an RFID reader. After printing, the entire matrix and embedded circuits are cured at 60 ℃ to form soft (an elastic modulus of less than 5 kPa) and stretchable (an elongation at break of around 18%) monolithic hydrogel electronics[36].

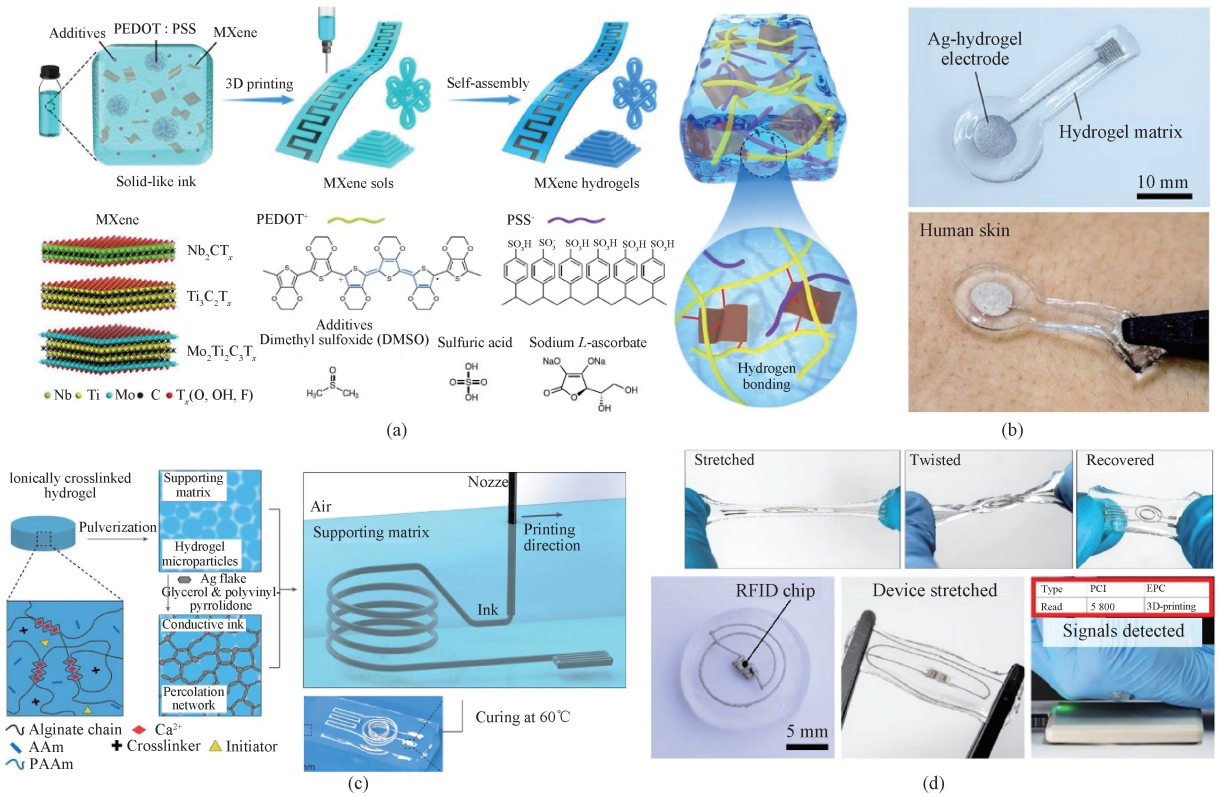


Fig. 1 Schematics of printing techniques and stretchable hydrogel devices: (a) schematic of 4D printing for MXene hydrogels[35]; (b) Ag-hydrogel electrode embedded in hydrogel matrix and attached to human skin[36]; (c) covalently crosslinked network of PAAm by embedded 3D printing[36]; (d) hybrid-printed hydrogel RFID device traceable to commercial reader after stretching[36]

Hydrogel-derived metals exhibit a highly twinned microstructure with surprisingly high hardness, paving the way for the development of advanced metallic micromaterials. A vat photopolymerization (VP)-based hydrogel impregnation additive manufacturing (HIAM) technique has been developed for the preparation of microstructured metals and alloys. This method utilizes digital light processing (DLP) printing of poly(ethylene glycol) diacrylate (PEGDA)/dimethylformamide (DMF) organic gels, followed by solvent exchange to form hydrogels, impregnation with metal salt precursors, and finally, calcination and reduction to obtain the target metal microstructures[37]. A simple and efficient stretch-spinning process has been developed to continuously produce high-strength and tough PAAm hydrogel microfibers under ambient conditions. The hydrogel microfibers have a sheath-core structure and hydrogen-bonded nanoclusters produced by self-assembly induced by water evaporation, similar to spider silk. They can carry objects weighing more than 50 000 times their own weight. Through traditional textile drafting and twisting technology, the hydrogen-bonded nanoclusters within the microfibers have been further optimized, making them comparable to natural spider silk and most synthetic fibers in terms of the tensile strength, toughness, and damping capacity[38]. Self-healing elastic conductive hydrogel

fibers have been fabricated by using different concentrations of *N*-acryloyl glycinamide (NAGA) and AAm via the continuous dry-wet spinning method, highlighting the physically crosslinked thermally reversible sol-gel transition of NAGA-co-AAm. The tensile properties of these hydrogel fibers, which exhibit a high stretchability (900%) and high tensile strength (2.27 MPa), recover reversibly within 36 min and also conduct electricity (0.69 S/m), are impressive. The poly(NAGA-co-AAm) (PNA)/poly(methyl acrylate) (PMA) core-sheath fibers also featured a PMA elastomeric sheath, which exhibited superior water evaporation and absorption resistance[39]. Liquid-metal sheath-core microfibers fabricated via coaxial wet spinning exhibit a high conductivity of 4.35×10^4 S/m and unparalleled stretchability, with an elongation at break ranging from 200% to 1 170%[40].

1.3 Stimulus-responsive hydrogels

Stimulus-responsive hydrogels have gained attention as potential biomaterials for tissue engineering and regenerative medicine. Dynamic changes may be controlled by the hydrogel's nature (isotropic or anisotropic) or guided by localized stimuli[41].

Temperature-responsive hydrogels prepared from temperature-responsive polymers, such as methylcellulose derivatives, poly(*N*-isopropyl acrylamide) (PNIPAAm), and poly(2-oxazoline), exhibit rapid phase or volume changes at the upper critical solution temperature (UCST) and lower critical solution temperature (LCST)[42]. PNIPAAm-based thermosensitive hydrogel patches can release the vascular endothelial growth factor (VEGF) upon body-temperature stimulation, promoting collagen deposition and angiogenesis, and significantly accelerating the healing of diabetic wounds[43] (Table 1).

A hydrogel patch composed of poly(gallic acid) (PGA) and gelatin methacryloyl (GelMA) demonstrates temperature-triggered adhesion and separation, unlike conventional hydrogel patches. Upon contact with the skin surface, the hydrogen bonds between GelMA chains can weaken at body temperature (37 ℃), exposing active groups, such as amino and carboxyl groups, thereby increasing adhesion. After cooling, intermolecular hydrogen bonds are re-formed, resulting in a decrease in the adhesion of the hydrogel to the skin, enabling on-demand removal. It can improve immune function by modulating skin microorganisms, thereby accelerating diabetic wound healing[44]. A series of responsive hydrogels with high transmittance, a fast thermal response, and a wide response temperature range of 20–50 ℃ has been developed. The main design principle is shown in Fig. 2(a). AAm is covalently crosslinked by *N*, *N*'-methylenebisacrylamide (MBA) to form a permanent polymer network. The alkyl chains of the C18 units are polymerized to form dynamic hydrophobic associations. The anionic surfactant sodium dodecyl sulfate (SDS) is selected as the heat/pH-responsive unit, which is key to the formation of micelles. The micelles can scatter incident sunlight, thereby changing the transmittance of the hydrogel to light[45]. The PPG conductive hydrogel, prepared from PVA, phytic acid (PA), and gelatin, possesses a rich hydrogen-bonded structure and exhibits temperature-responsive adhesion. It can stably adhere to the skin, collect electrophysiological signals during heat applications, and easily peel off during cold applications. Furthermore, its transparency, breathability, and antibacterial properties enhance long-term wearing comfort, making it suitable for human health monitoring[46].

Table 1 Comparison of several stimulus-responsive hydrogels

Hydrogel	Type of stimulus	Drug/bioactive agent	Profile of release	Results of wound healing
PNIPAAm-based hydrogel[43]	Temperature-responsive	VEGF	Continuous release at 37 ℃	Increased angiogenesis and improved recovery in diabetic rats
pH-sensitive hydrogel[47]	pH-responsive (alkaline)	hyaluronic acid oligosaccharide (HAO)	A cumulative release of 98.7% over 8 h at pH of 8	Rapid recovery under alkaline wound conditions
Alginate/silver nanocomposite hydrogel[48]	Passive	Silver ions	70% burst release in 24 h	Antimicrobial; moderately cured
GelMA hydrogel + bioactive glass[45]	Bio-interactive	Si/Ca ions, extracellular matrix mimetic cues	Slow release of ions	Promoted cell division and extracellular matrix renewal

Thermosensitive hydrogel-based actuators are of great importance for fundamental research and industry. A new all-temperature-driven bilayer hydrogel actuator was synthesized and composed of a poly(*N*-acryloyl glycinamide) (PNAGA) layer with a UCST-type volume phase transition and a PNIPAAm-laponite nanocomposite

layer with an LCST-type volume phase transition. Due to its superior performance, the actuator is a highly efficient and responsive device that can carry out actions such as gripping, moving, and releasing objects or even act as a circuit switch for switching on and off light-emitting diodes (LEDs). In brief, this hydrogel actuator opens up new possibilities for designing and creating materials for artificial intelligence[49]. Hydroxypropyl cellulose (HPC) is a derivative of cellulose with lyotropic liquid crystal properties and thermochromic properties. HPC and thermoresponsive PNIPAAm have been mechanically sheared to create anisotropic single-domain hydrogels. The prepared long-range ordered HPC-PNIPAAm hydrogels exhibit bright and uniform interference colors when viewed between orthogonal polarizers, and are stimulus-responsive to both the temperature and ionic strength[45].

Changes in pH of the microenvironment at the site of diabetic chronic wounds can cause pH-responsive hydrogels to swell, degrade, dissociate, or rupture, which provides the possibility of pH-responsive on-demand release of active substances[50]. A pH-responsive hydrogel has been prepared and functionalized with alginate-calcium, loaded with protamine nanoparticles, and conjugated with HAO. At a pH of 3.0, most carboxyl groups in the hydrogel exist in the form of —COOH, and chemical crosslinks are formed between the polymers, causing the hydrogel to shrink; at a pH of 8.0, the carboxyl groups in the hydrogel exist in the form of $—COO^-$, and the electrostatic repulsion between them causes the hydrogel to swell, and the hydrogen bonds formed between $—COO^-$ and water further aggravate the swelling of the hydrogel. In an alkaline medium, the hydrogel can release 98.7% of HAO within 8 h, which is 2.2 times that in an acidic medium. Therefore, the hydrogel can specifically and effectively deliver drugs to diabetic chronic wounds and promote their healing[47]. By loading silica nanoparticles (SiO_2) with *N*-formyl-methionine-leucine-phenylalanine (fMLP) and recombinant protein (Fas ligand, FasL) into a pH-responsive hydrogel, a hybrid biomaterial (Gel@fMLP/SiO_2-FasL) has been constructed[51]. A pH-responsive and dynamically crosslinked hydrogel has been synthesized using Schiff base crosslinking between chitosan and benzaldehyde-modified polyethylene glycol-poly(sebacic acid glycerol)[52]. The hydrogel can release active substances on demand, providing new ideas for the design of pH-responsive hydrogel dressings for repairing diabetic chronic wounds.

Conductive ionic hydrogel fibers and textiles with enhanced mechanical properties and chemical stability are essential for applications in wearable and flexible electronic devices, strain sensors, and artificial skins[53]. Recent studies have demonstrated the versatility of these materials through various innovations. For instance, hydrogel polyimide (PI) ionic fibers (HPIFs) were prepared from organic-soluble salts of PI by a continuous and straightforward wet-spinning process (Figs. 2(c)–2(d)). Due to the ion-rich nature and strong skeletal framework, HPIFs exhibit excellent electrical conductivity, with a value of approximately 21 mS/cm, and excellent mechanical properties, including a tensile strength of 2.5 MPa and an elongation at break of 215%[54]. Expanding the functionality beyond electronics, a hemicellulose-based magnetic hydrogel[55] exhibits superparamagnetic behavior with a saturation magnetization of 21.83 $A \cdot m^2/kg$, a compressive strength of 0.119 MPa, and a strong adsorption capacity toward methylene blue dye, achieving a removal efficiency of 97%. It not only demonstrates excellent swelling capability and superparamagnetism but also efficiently removes the methylene blue dye, indicating its potential for application in dye removal. Furthermore, regarding mechanical resilience, a dual-responsive and multifunctional ion-conductive hydrogel[56] exhibits excellent stretchability, flexibility, and stability with an impressive tensile strength of 2.2 MPa, a high toughness of 5.26 MJ/m^3, a favorable stretchability of 522%, and a high transparency of 90%. Crucially, it can maintain good elasticity over a temperature range of −50 ℃ to 85 ℃.

A surface-modified woven fabric has been developed for use as an ultraviolet radiation sensor. Radiochromic hydrogels are screen-printed onto cotton and polyamide fabrics (Fig. 2(e)). The hydrogel ink contains water, poly(ethylene oxide)-block-poly(propylene oxide)-block-poly(ethylene oxide) (Pluronic F-127) as the gel matrix, and nitro blue tetrazolium chloride (NBT) as the radiation-sensitive moiety. NBT-Pluronic F-127 hydrogel-printed fabrics can serve as sensors for ultraviolet (UV) radiation[57].

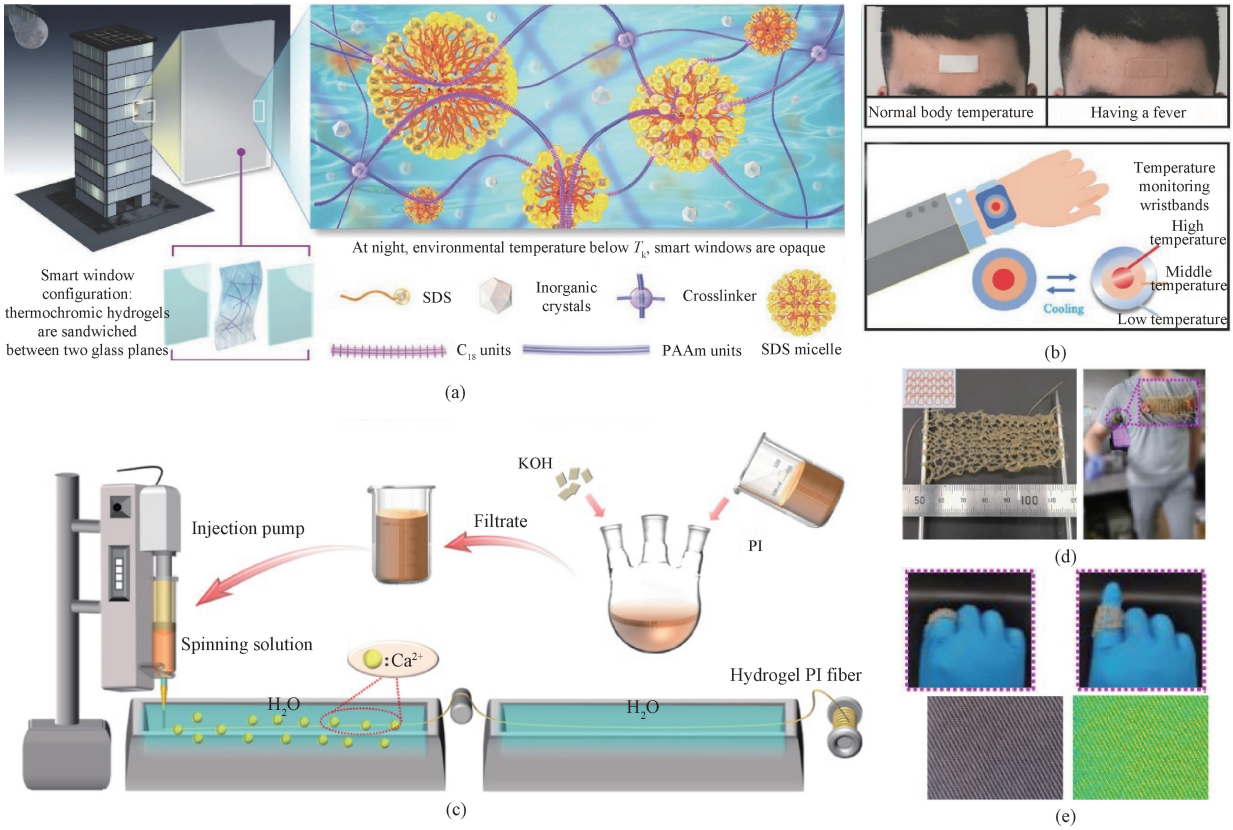


Fig. 2 Representative hydrogel-based functional materials and devices: (a) dual-responsive transparent-opaque phase transition of hydrogel[45]; (b) smart hydrogel forehead patch and wristband for thermal sensing[45]; (c) wet-spinning process of HPIF[54]; (d) HPIF strain sensors for body part activities[54]; (e) NBT-Pluronic F-127 hydrogel-printed fabrics irradiated with 2 J/cm^2 UV[57]

2 Techniques for Hydrogel Functionalized Textiles

2.1 Sol-gel in situ

Sol-gel in-situ gelation is a method for fabric surface modification. It forms a stable 3D network structure (sol system) by hydrolysis or alcoholysis in the precursor solvent (inorganic salt or organic compound), forms an inorganic or organic/inorganic polydimethylsiloxane (PDMS) hybrid coating on the fiber or fabric surface through a gelation reaction, and is then processed by blade coating with an alcohol solution containing tetrahydrofuran (THF), tetraethyl orthosilicate (TEOS), and cetyltrimethoxysilane (CTMS). The sol-gel in-situ gelation process of textiles can be divided into five stages: hydrolysis, coagulation (or gelation), gel aging, applications, and curing, as shown in Figs. 3(a) and 3(b)[58].

The sol-gel impregnation method involves directly immersing fibers or fabrics in a hydrogel precursor solution to form a gel in situ on the fabric. A cellulose-based hydrogel/nonwoven composite material with excellent mechanical properties was prepared via this method[59]. On this basis, the wool nonwoven fabric was immersed in an aqueous solution of sodium alginate (SA)[60]. Then, the fabric was gelled in a calcium chloride solution to prepare a new biodegradable SA hydrogel wool nonwoven fabric composite. In another investigation regarding fiber reinforcement, the CF was immersed in a mixed solution of PVA and SA, resulting in a CF-reinforced PVA-SA hydrogel obtained through freeze-thaw cycles and high-temperature annealing. The mechanical properties of the material were significantly higher than those of the pure CF or PVA gel (Fig. 3(c)[61]). In addition, the sol-gel impregnation method has been used with selected chitosan and gelatin to prepare hydrogel composites with a poly(lactic acid) nonwoven fabric as the supporting skeleton. The hydrogel and nonwoven fabric are entangled with each other through citric acid ionic crosslinking, which evenly disperses the stress in the system and improves the mechanical properties of the natural polymer hydrogel[62].

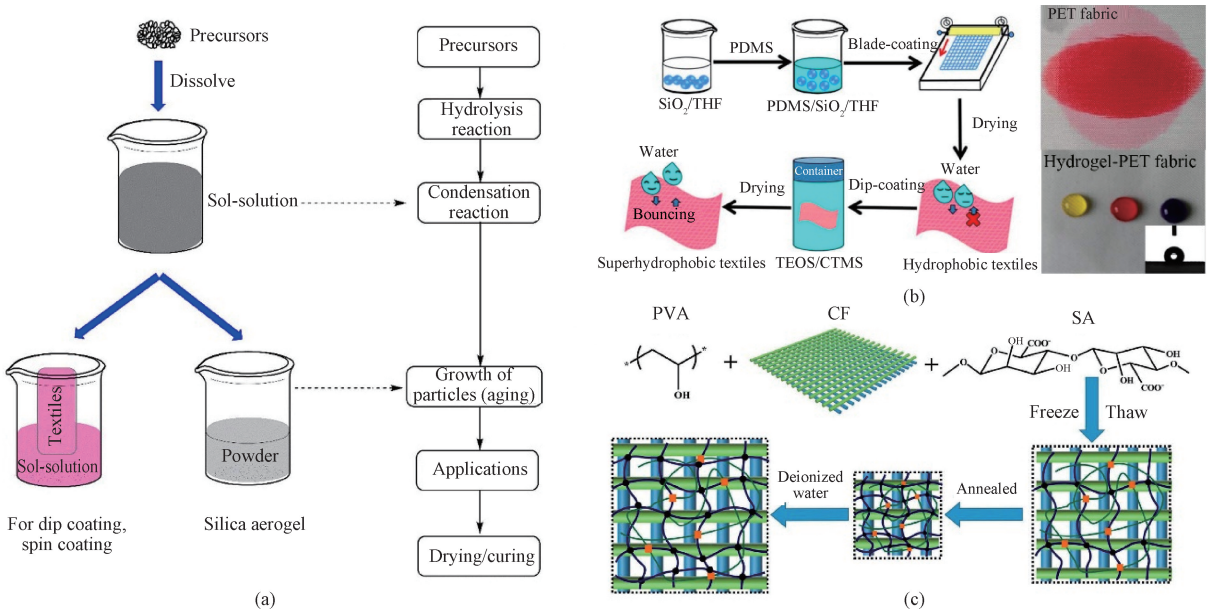


Fig. 3 Fabrication schemes for functional coatings and reinforced hydrogels: (a) schematic illustration of sol-gel process[58]; (b) preparation of water-resistant superhydrophobic fabrics[58]; (c) CF-reinforced PVA-SA hydrogel with physical crosslinking[61]

The sol-gel coating technology is a method that uniformly coats a fabric surface with a pre-prepared hydrogel precursor solution, forming a colloidal layer with specific functions on the fabric through crosslinking methods such as radiation or addition of a crosslinking agent[63]. Polydopamine (PDA) was deposited on the surface of poly(ethylene terephthalate) (PET), and a dihydrolipoic acid-modified sulfobetaine-derived starch (SB-ST-D) hydrogel coating was covalently fixed on the PDA/PET surface via a Michael addition reaction[64]. This process simultaneously introduced disulfide bonds into the network, thereby yielding a durable hydrogel-textile composite. A poly(methacrylate sulfobetaine-hydroxyethyl acrylate)/PVA/borax hydrogel precursor solution was evenly applied to the CF to create a zwitterionic gel-coated CF, which was crosslinked via dynamic borate bonds through a step-by-step coating-gelation process[65]. Using a similar approach, the Ag/AgCl nanoparticle hybrid cellulose-based hydrogel (AHCH) was synthesized via in-situ polymerization of hydroxyethyl cellulose and PAA, and then uniformly coated onto the CF using a screen-printing device to fabricate a hydrogel-based textile (AHCH @ CF) composite with enhanced mechanical properties[66].

2.2 Grafting modification

Currently, the most commonly used methods for modifying material surfaces include chemical grafting, UV grafting, plasma grafting, and lamination.

2.2.1 Chemical grafting method

The chemical grafting method involves the use of chemical modification to graft functional groups onto fibers or fabrics, thereby creating modified fibers with active sites conducive to binding with hydrogels and imparting special properties to the fibers or fabrics[67]. Free radical polymerization is used to polymerize monomers such as styrene (St), polycaprolactone-hydroxyethyl methacrylate (PCL-HEMA), and modified polyhexamethyleneguanidine hydrochloride (M-PHMG) to synthesize silk fibroin-carboxymethyl cellulose-gelatin (SCG) nano-hydrogels, followed by surface functionalization using isophorone diisocyanate (IPDI) and dibutyltin dilaurate (DBTDL). The hydrogel was modified with isocyanate to introduce reactive isocyanate groups (—NCO), yielding NCO-SCG (SCGN) nano-hydrogels that were subsequently grafted onto the CF surface. The finished fabric had good antibacterial properties and thermal stability (Fig. 4)[68]. The surface of the PET fabric was grafted and polymerized with activated AA and then coated with a soy protein isolate (SPI) hydrogel. The hydrogel and the modified PET fabric surface form covalent bonds, which improves the connection between the hydrogel and fabric[69].

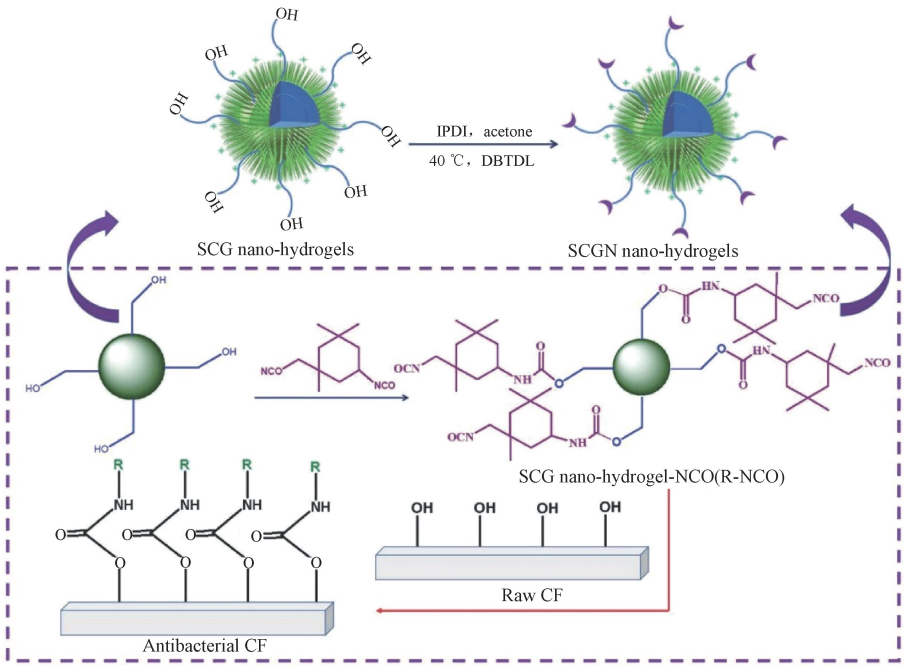


Fig. 4 Preparation of SCGN nano-hydrogel and gel fabric through chemical grafting method[68]

2.2.2 UV grafting method

The UV grafting method primarily generates free radicals on the polymer surface through UV irradiation, triggering free radical graft copolymerization. This method is low-cost and yields pure products[70]. For instance, allylamine (ALAm) was covalently bonded to the PET surface through a grafting reaction of [2-(methacryloyloxy) ethyl] dimethyl-(3-sulfopropyl) ammonium hydroxide (SBMA), followed by UV-induced graft copolymerization to successfully anchor a PNIPAAm hydrogel network onto a carboxylated PET fabric (Fig. 5(a))[71]. Employing a simpler procedure, a padding and baking method was used to modify resorcinol diglycidyl acrylate (RDA) onto the surface of the PET fabric, and free-radical graft copolymerization of different acrylate monomers was initiated by UV light to obtain three hydrogel layers with different structures, namely PAAm, PAA and PNIPAAm[72]. This indicates that UV grafting can be used to obtain a hydrogel layer on the surface of the PET fabric. This technique is not limited to PET substrates; it has also been extended to polypropylene (PP) nonwoven fabrics. The PNIPAAm hydrogel was grafted onto the PP nonwoven fabric through argon plasma treatment (Fig. 5(b))[73].

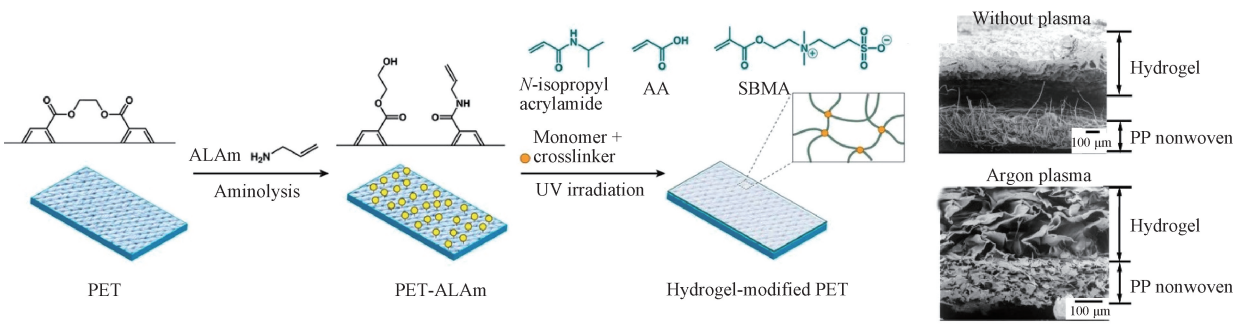


Fig. 5 Surface modification strategies for hydrogel immobilization on textile substrates: (a) UV grafting of PNIPAAm hydrogel on PET fabrics[71]; (b) scanning electron microscopy morphology and grafting chemistry of plasma-grafted PNIPAAm hydrogel on PP nonwoven (ammonium peroxodisulfate (APS) as initiator, *N*,*N*,*N*′,*N*′-tetramethylethylene-diamine (TEMED) as promoter and MBA as crosslinking agent)[73]

2.2.3 Plasma grafting method

Plasma grafting can introduce active groups onto the fiber surface, thereby functionalizing textile materials and improving surface reactivity, coating adhesion, and hydrophilicity.

A combination of ammonia and oxygen plasma gases was selected to plasma-modify the surface of the PET fabric, maintaining pH responsiveness while maximizing deposition on the fabric[74]. Oxygen plasma can increase the surface energy of the polymer and enable coating

deposition on various polymers. After treatment with low-temperature plasma of argon, nitrogen, and oxygen, the surface roughness and the number of active groups on cotton fibers increased, significantly improving adhesion of the PNIPAAm/chitosan hydrogel coating. Furthermore, by using the plasma-grafted poly(lactic acid) meltblown nonwoven fabric, an interpenetrating network hydrogel composite nonwoven material suitable for smart textiles was prepared[75]. Ammonia plasma can achieve amino functionalization and weak etching of the polymer, resulting in a pH response effect[76]. Building on this principle, the interpenetrating hydrogel composite nonwoven structure was further reinforced by combining the plasma-grafted poly(lactic acid) meltblown nonwoven fabric with PEG-dimaleate, fully utilizing the inherent characteristics of the nonwoven substrate[77].

2.2.4 Lamination method

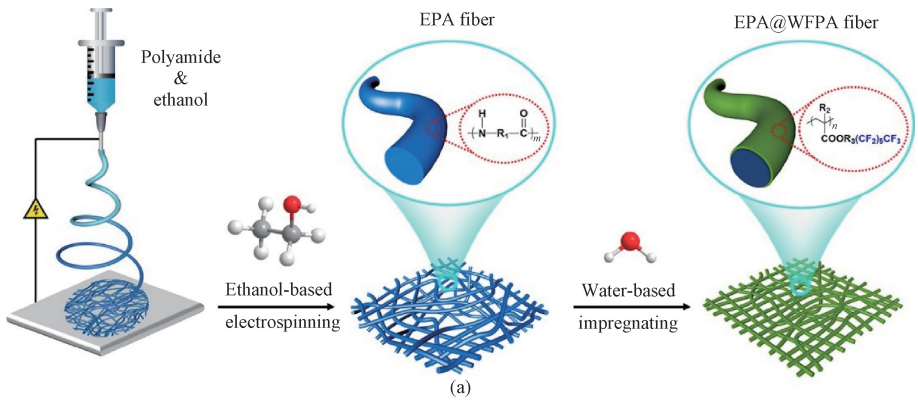
Lamination is a method of endowing materials with specific properties by combining fabrics with functional membranes. A double-crosslinked nanohydrogel was prepared and laminated onto the surface of an aramid fabric. By introducing multiple crosslinked networks and nano-reinforcing components, the toughness, strength, and puncture resistance of the hydrogel matrix can be effectively enhanced. A laminated soft composite exhibiting a synergistic toughening effect was constructed by combining Pluronic/poly(2-methoxyethyl acrylate)(PMEA) hydrogel with hydroxyapatite (HAP) nanoparticles and aramid fabric; the HAP nanoparticles further reinforced the hydrogel matrix, thereby significantly enhancing the composite's puncture resistance and self-healing capability[78]. On this basis, the rational design of the interlayer interface structure can also improve the bonding strength between different materials. By employing a glass fiber fabric as an interfacial interlayer, a stable bond is achieved between a hydrophilic hydrogel and a hydrophobic PDMS elastomer through topological and ionic interactions, without the need for additional chemical surface treatment, while simultaneously significantly enhancing the composite's interfacial adhesion and overall mechanical properties[79]. By using a glass fiber fabric as an interface layer, amphoteric polyelectrolyte hydrogels and PDMS elastomers can be physically bonded without chemical treatment, resulting in a strong bond and significantly improving the composite's mechanical properties. These studies demonstrate that synergistic strategies such as chemical crosslinking, nano-reinforcement, and fiber interface layers can effectively regulate the interfacial bonding, stress transfer, and structural stability of hydrogel/fabric laminate systems, providing important insights for the design of high-strength and high-toughness hydrogel functional fabrics.

2.3 Hydrogel fiber fabrication method

The development of polymer and textile technologies has enabled various methods for preparing hydrogel textile composites. Hydrogel fibers can be prepared by electrospinning, wet spinning, or dry spinning, and then combined with weaving, knitting, or nonwoven technologies to construct hydrogel textile materials[80].

2.3.1 Nonwoven technology

Since the 1990s, electrospinning has become one of the most direct and effective methods for preparing nano-hydrogel fibers. Currently, the mechanical properties of electrospun membranes made from biopolymers such as gelatin, hyaluronic acid, and silk fibroin are suboptimal[81]. Chemical crosslinking and other methods can be employed to enhance the reaction of related groups within the fiber and improve its mechanical properties. Ethanol-soluble polyamide (EPA) was utilized as the spinning polymer in the electrospinning and impregnating processes to produce amphiphilic polyamide fiber membranes[82]. At the same time, water-based fluorinated polyacrylate (WFPA) was evenly coated on the surface of EPA fibers, giving the fiber membrane an excellent bonding structure (Fig. 6).



(a)

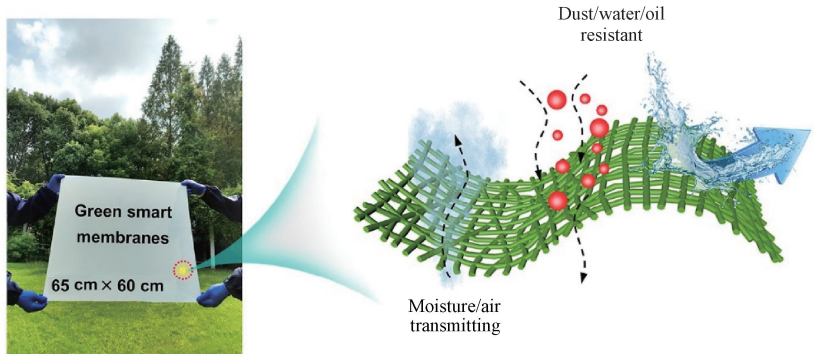


Fig. 6 Preparation and performance of smart EPA@WFPA fiber membranes[82]: (a) preparation procedure; (b) performance

Compared with electrospinning, solution blowing combines the scalability of melt blowing with the versatility of electrospinning. The structure and performance of the prepared hydrogel fibers are significantly improved, and the cost is greatly reduced[83]. High-porosity HPC hydrogel nonwovens were prepared by combining solution-blown spinning with nonwoven processes, and ester bonds were formed by thermal crosslinking with citric acid, thereby improving the material stability (Fig. 7)[84]. A gelatin hydrogel nonwoven fabric (GHNF) was prepared by solution-blowing spinning using a high-speed air nozzle pump, and used as a carrier membrane in a multilayer cell sheet[85].

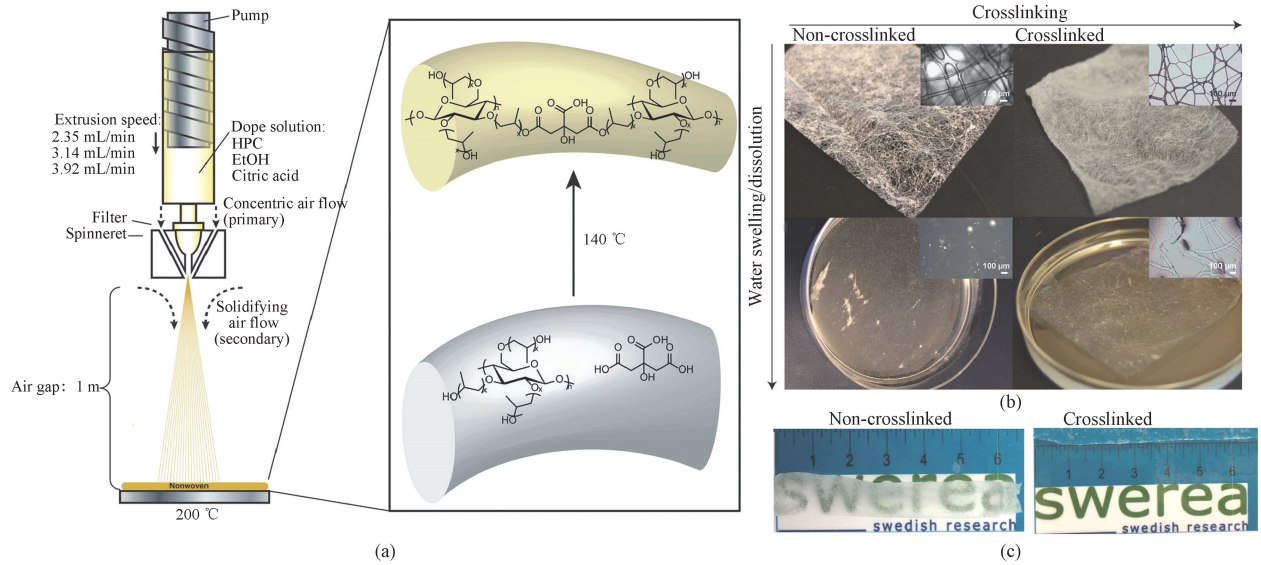


Fig. 7 Fabrication, morphology, and swelling behavior of HPC hydrogel nonwovens[84]: (a) fabrication; (b) photographs and optical microscope images of non-crosslinked and crosslinked HPC hydrogel nonwovens in dry state and their dissolved or swollen state in water; (c) images of dried and swollen HPC hydrogel nonwovens

2.3.2 Weaving technology

Weaving technology refers to the process of weaving two or more yarns into an integral fabric according to a specific pattern. A one-step weaving process was employed to prepare a fabric-reinforced hydrogel structure. Cotton yarns were used as warp yarns, and pure PVA yarns were used as weft yarns[86]. The prepared PVA/cotton fabric was treated with a borax solution to obtain yarn-reinforced hydrogels (Fig. 8(a)). Blended fibers were used to create PVA/viscose (Vi) yarn-reinforced hydrogel composites, resulting in improved mechanical properties (Fig. 8(d))[87]. PVA can be dissolved in the fabric and converted into a crosslinked gel structure, which penetrates the yarn in the form of a matrix, thereby obtaining a cotton yarn-reinforced composite hydrogel material with significantly improved tensile properties[88]. MBA was combined with the hydrogel precursor solution, gelation was achieved during the weaving process, and a 3D fabric-reinforced hydrogel composite composed of AAm and SA was prepared[89].

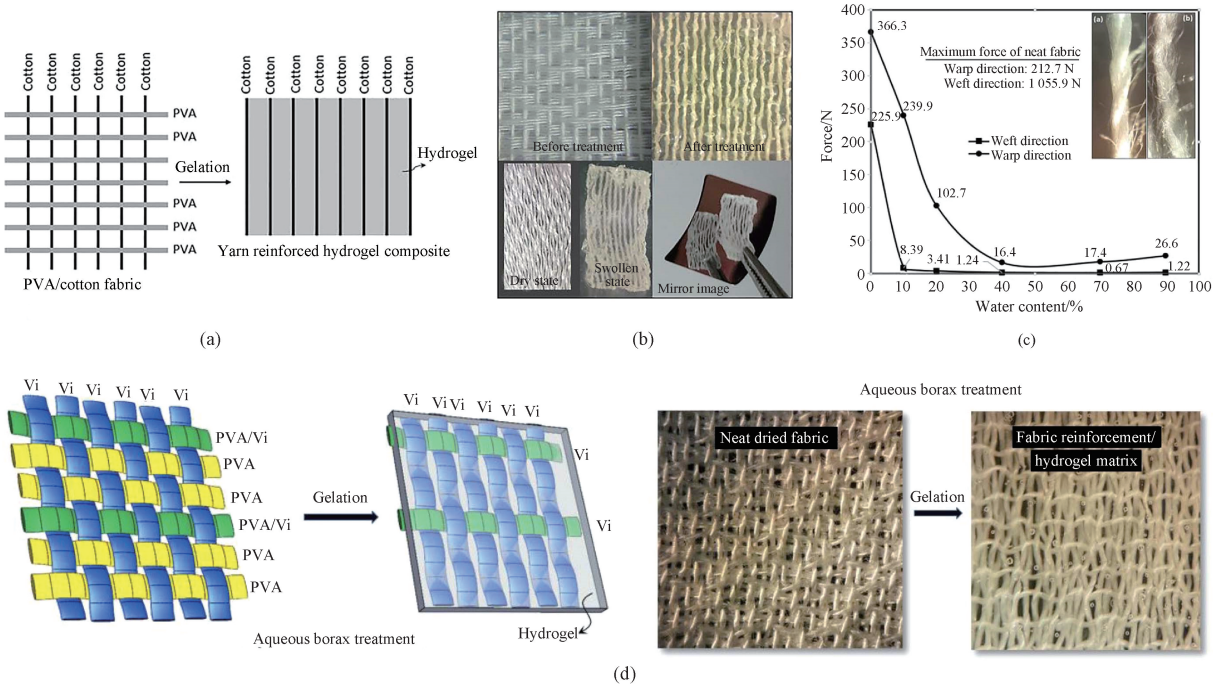
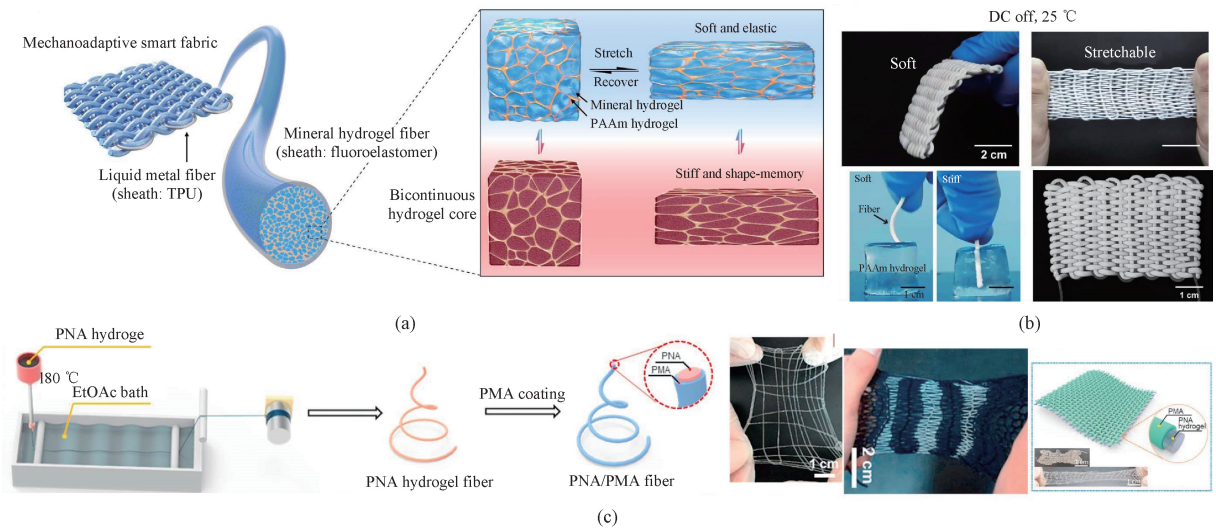


Fig. 8 Yarn-reinforced hydrogels and borax crosslinking: (a) image of yarn-reinforced hydrogel[86]; (b) yarn-reinforced hydrogel (PVA/cotton fabric before borax treatment, yarn-reinforced hydrogel after borax treatment, dry yarn-reinforced hydrogel, and swollen yarn-reinforced hydrogel soaked with water, and mirror image of yarn-reinforced hydrogel composite)[86]; (c) breaking force of hydrogel composite in warp and weft directions[86]; (d) hydrogels treated with aqueous borax[87]

Using PAAm as a model material, an artery-like hierarchical heterogeneous structure was constructed by wet spinning, and a conductive, highly elastic, and fatigue-resistant hydrogel composite fiber was prepared by connecting the two networks with benzophenone[90]. Thermosetting mineral hydrogels were prepared via entropy-driven polymer-cluster interactions, and high-strength and high-resilience core-shell fibers were constructed[91]. When combined with liquid metal fibers, soft and hard states of the fabric could be rapidly switched (Figs. 9(a)–9(b)). Stretchable, conductive, and self-healing hydrogel fibers were prepared by continuous wet-dry spinning. A thermally reversible sol-gel transition was achieved by controlling the concentrations of AAm and NAGA, thereby improving the spinning efficiency (Fig. 9(c))[39]. Coaxial microfluidic printing was utilized to print sensing textiles from hollow conductive hydrogel fibers, allowing for precise control over the hollow channel diameter (Fig. 9(d))[92]. The mesh-like biotextile exhibits a high sensitivity of 4.69 kPa^{-1}, far exceeding that of a solid structure, and, when combined with conductive metal wires, achieves energy harvesting with an open-circuit voltage of approximately 0.74 V. Hygroscopic organogel fibers (HOGFs) were prepared by wet spinning and solvent displacement, and woven into a two-dimensional (2D) water collection device for atmospheric water collection (Fig. 9(e))[93]. However, fatigue and hysteresis problems still exist.



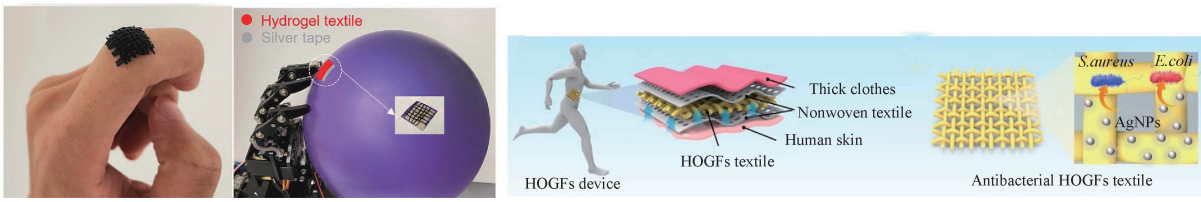


Fig. 9 Hydrogel-based smart textiles: (a) mechanoadaptive mineral hydrogel smart fabric with bicontinuous structure[91]; (b) soft and stretchable smart fabric with sheath-core fibers in PAAm hydrogel[91]; (c) preparation of PNA/PMA core-sheath fibers and knit fabric in stretched state[39]; (d) image of conductive hydrogel textile for motion detection[92]; (e) HOGF device with sandwich structure[93]

2.3.3 Wet-spinning technology

Wet spinning involves injecting a polymer solution into a coagulation bath to induce a phase transition and form fibers. It can be used with a variety of natural and synthetic polymers. Fiber properties are affected by the flow rate, coagulation bath conditions, draw ratios and post-treatment parameters. Post-treatment is often necessary to ensure functionality and stability[94].

Flexible waterborne polyurethane (WPU) macromolecules (30 – 50 nm) and stiff 2, 2, 6, 6-tetramethylpiperidine-1-oxyl radical (TEMPO) cellulose nanofibers (TOCNFs) were used in an adjustable wet-drawing and ionic crosslinking technique to create homogeneous and hierarchical dense structures, as shown in Fig. 10(a)[95]. Thermally/electrically responsive shape memory fibers were prepared by wet spinning of PCL and thermoplastic polyurethane (TPU), and strain-sensing and electric-heating functions were imparted by multi-walled carbon nanotube (MWCNT) impregnation. The fibers can withstand 100% – 400% strain, and exhibit high sensitivity (a gauge factor of 21.11), fast response (187 ms), and excellent stability over 2 000 cycles[96]. Ionic crosslinking wet spinning of natural polysaccharides was employed for the fabrication of an optical hydrogel. Multilayered hydrogel optical fibers were successfully prepared via the highly dynamic ionic crosslinking of polysaccharides[97]. In addition, the intrinsic permeability exhibited by the resulting hydrogels was integrated with plasmonic nanoparticles to facilitate the molecular detection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) on fiber-coupled biomedical swabs, as shown in Fig. 10(b). The spider-silk-like wet adhesion material, namely SA, adopts a polyurethane (PU) core/polyvinylpyrrolidone (PVP) shell core-shell nanofiber structure and achieves wet adhesion through a dissolution-wetting-adhesion mechanism[98]. It can operate stably over the range of −196 to 4 ℃ and exhibits impact resistance and low-temperature resistance to liquid nitrogen (Fig. 10(c)).

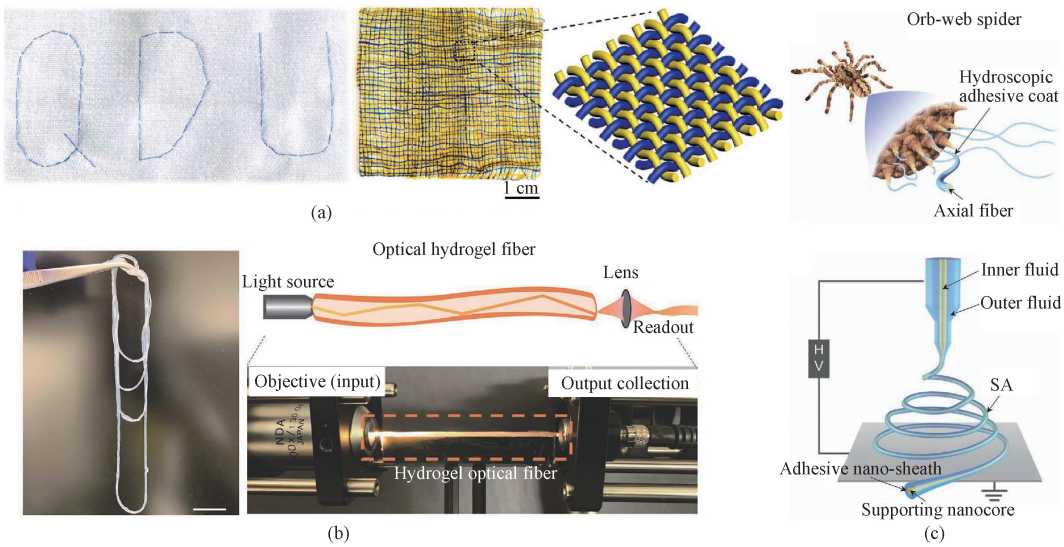


Fig. 10 Flexible, bioinspired, and optical hydrogel fibers for textile and sensing applications: (a) embroidered Q, D and U on fabrics with 700% colored WPU-TOCNFs due to excellent fiber flexibility[95]; (b) core-clad hydrogel optical fiber (a scale bar of 1 cm) and schematic of input-output optical collection setup under semi-dry conditions[97]; (c) bioinspired coaxial electrospinning of spider-silk-like fibers with hygroscopic sticky nano-sheath and central nanocore[98]

Thermotropic rigid hydrogels were prepared via entropy-driven polymer-mineral cluster interactions, resulting in an approximately 13 000-fold increase in the storage modulus and a liquid-liquid-to-solid-liquid phase transition[91]. Long-lasting fibers composed of recombinant resilin and supercharged peptides were prepared by wet spinning[99]. These fibers exhibit a highly ordered structure formed through supramolecular complexation, demonstrating a strength of approximately 550 MPa, a toughness of 250 MJ/m^3, and good biocompatibility (Fig. 11(a)). High-strength and high-stiffness chitosan fibers were prepared in a KOH/urea aqueous solution via wet spinning and a two-step stretching process[100]. Their highly oriented hierarchical structure endows them with excellent mechanical properties, including a tensile strength of approximately 878 MPa and an elastic modulus of 44.7 GPa, comparable to those of spider silk and bacterial cellulose (Fig. 11(b)). TEMPO-oxidized nanocellulose (TOCN), alginate, borax, and PVA were used in conjunction with stretching and water-induced techniques to create tough and robust fibers with an asymmetric structure through wet spinning (Fig. 11(c))[101]. The asymmetric structure endowed the hybrid fibers with humidity responsiveness, and high mechanical properties with a tensile strength of 534.1 MPa and a toughness of 142.8 MJ/m^3.

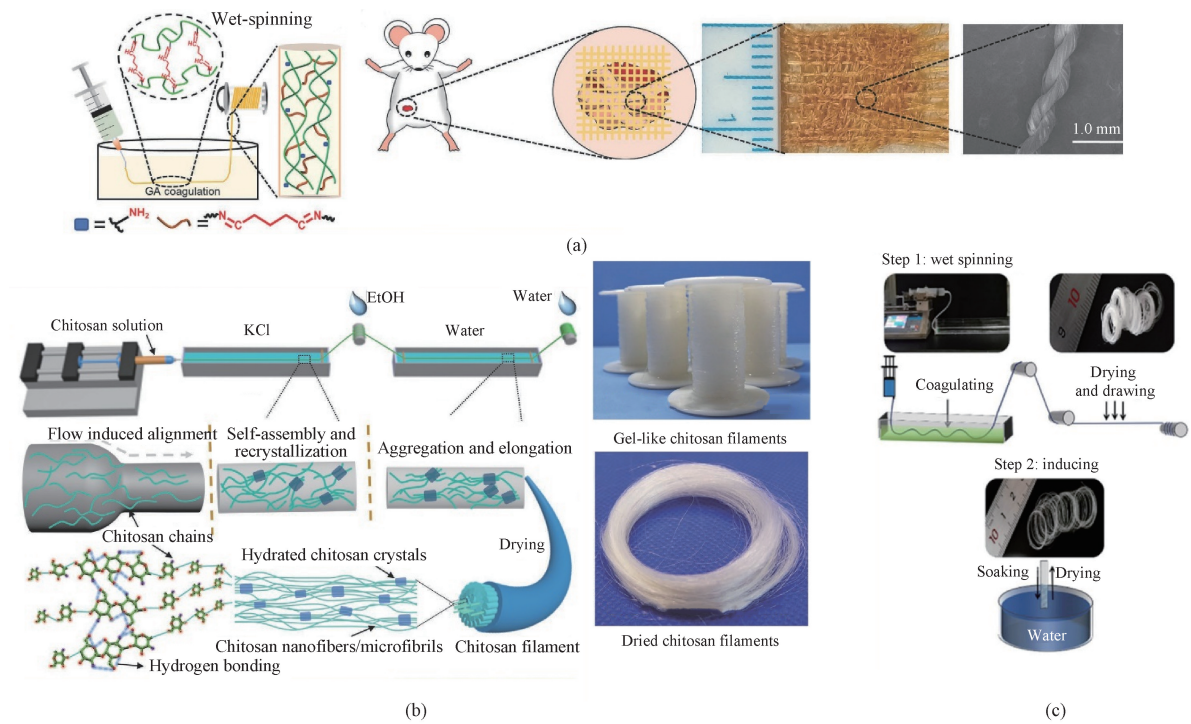


Fig. 11 Wet-spun fibers for biomedical and actuation applications: (a) supercharged elastin moieties-glutaraldehyde (GA) fibers and application in rat abdominal hernia repair[99]; (b) hierarchical structure and two-step wet-spinning process of gel-like chitosan filaments and dried chitosan filaments[100]; (c) fiber preparation and water-induced process schematic[101]

Crosslinked nano-hydrogel fibers were prepared using a spider-silk-like structure, resulting in a tensile strength of 1.27 GPa and a toughness of 383 MJ/m^3. The mechanism by which nano-hydrogel size affected spinnability was also revealed[102]. Different fiber forming and fabric construction methods endow hydrogel functional fabrics with different structural characteristics and performance advantages. Among them, nonwoven, braided, and wet spinning show significant advantages in terms of high specific surface area, mechanical durability, and continuous fiber preparation. However, these methods still have limitations such as insufficient mechanical strengths, complex porosity and structure control, high process sensitivity, and strong equipment dependence (Table 2). Therefore, it is necessary to comprehensively optimize the structure, mechanical properties, and processing efficiency according to the target application.

Table 2 Comparison of hydrogel fiber fabrication method

Method	Characteristic	Application	Advantage	Limitation
Nonwoven[81, 83]	High-porosity, nanoscale fibers, and random fiber deposition (electrospinning, and solution blowing)	Scaffolds, filtration, and wound dressings	High surface area and expandability	Low mechanical strength requires crosslinking
Weaving[86-88]	Yarn interlacing, fabric reinforcement, and 2D/3D structures	Wearable textiles and load-bearing composites	Durable mechanical properties and adaptability	Complex structure, low porosity, and difficulty in precise control
Wet spinning[93-94]	Continuous fiber production in a coagulation bath by phase inversion	Biomedical fibers, wearable sensors, and actuators	Scalable, flexible mechanics and continuous fibers	Process-sensitive and equipment-intensive

3 Applications of Hydrogel Functionalized Textiles

3.1 Biomedical applications

In biomedical applications, hydrogels offer compelling advantages in terms of biocompatibility, mechanical tunability, dynamic responsiveness, etc. These versatile properties have motivated extensive research into hydrogel systems with tailored functionalities for specific biomedical scenarios.

A nanofiber/zwitterionic hydrogel composite has been developed to resist foreign body reactions[103], thereby improving the biocompatibility and longevity of implanted devices. Meanwhile, a dual fluorescent hydrogel derived from crosslinked chitosan-salicylaldehyde-Eu(Ⅲ) enables the visual detection of volatile amines[104]. This sensing mechanism illustrates the broader potential of hydrogels as intelligent platforms for detecting biogenic amines associated with metabolic processes or wound infections. Photoinitiated crosslinking of thiol-ene, using four-armed PEG-norbornene and genetically engineered peptides as thiol donors, enables rapid gelation with lithium phenyl-2, 4, 6-trimethylbenzoylphosphinate (LAP) as the photoinitiator and under 365 nm light irradiation[105]. The mechanical strength could be controllably enhanced by adjusting the irradiation time, while the light dose needed to be optimized to ensure biocompatibility. In soft robotics, poly (2-acrylamido-2-methylpropanesulfonic acid) (PAMPS) and AAm hydrogel fibers were combined with soft robots to enhance responsiveness and flexibility[106]. This was achieved through the free migration of linear polymers during precursor polymerization to form a self-lubricating layer, coupled with the drying and plasticizing effects of triethylene glycol, which collectively reinforced the fibers (Fig. 12).

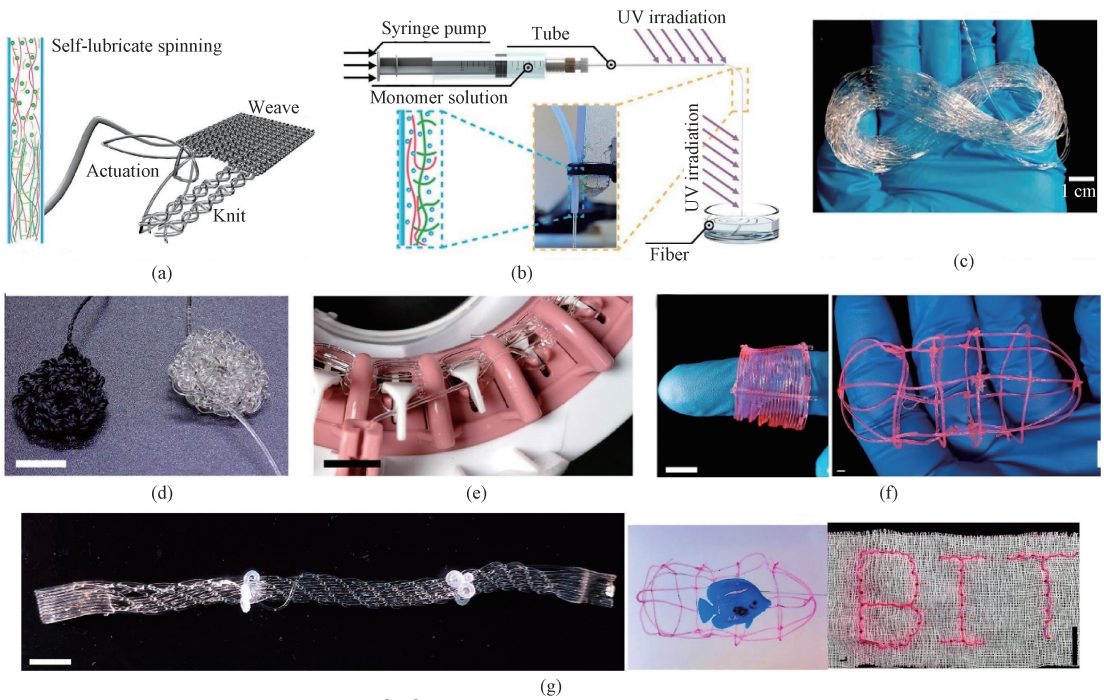


Fig. 12 Self-lubricating hydrogel fibers and applications[106]: (a) selective laser sintering (SLS) of self-lubricating spun hydrogel fiber; (b) schematic of SLS setup (blue line-tube wall; green line—PAAm network; red line—PAMPS chain; blue dot—water molecule); (c) water-swollen hydrogel fiber in hand; (d) crochet flowers made of nylon threads (left) and T-fibers (right); (e) T-fibers inside a weaving machine; (f) T-fiber-assembled tube in dry and swollen states; (g) braided T-fibers, hollow cage for retrieval, and bandage

Collectively, these examples illustrate the expanding role of hydrogels in biomedical engineering, ranging from tissue-mimetic scaffolds to anti-inflammatory implants and responsive diagnostic sensors.

3.2 Hydrogel smart fibers

Artificial muscles can mimic biological movement without a traditional power system, with hydrogels particularly advantageous for their multi-stimulus responsiveness, high sensitivity, and large deformability[107]. Hydrogels with a high water content are similar to biological muscles. Self-helical hydrogel fibers that respond to glucose were used to create artificial muscles (Fig. 13(a))[108]. Inspired by spider webs, a multifunctional hydrogel fiber web was fabricated, exhibiting freeze resistance, conductivity, adhesion, and strain-sensing properties. After UV curing and stretching, a strain range of 0.5%–34.5% could be detected[109]. Highly stable polymerizable deep eutectic solvent (PDES) fibers prepared by photopolymerization could withstand high and low temperatures, organic solvents, and atmospheric environments, overcoming the volatilization and freezing issues of traditional gels, and exhibited low hysteresis, low creep, and excellent cyclic sensing performance (Fig. 13(b)). Using choline chloride (ChCl) and AA as the main components and diphenyl (2, 4, 6-trimethylbenzoyl) phosphine oxide (TPO) as the photoinitiator, smart hydrogel fibers with high transparency and conductivity, excellent mechanical properties, and environmental resistance were prepared by photopolymerization, which could be used for wearable sensing and smart textiles[110].

Stimulus-responsive hydrogels can respond to changes in the wound environment, such as temperature, pH, and glucose levels, enabling on-demand release of active substances and promoting wound healing in diabetic patients. Hydrogel dressings prepared by grafting *N*, *N*-dimethyl-*N*-[3-(trimethoxysilyl) propyl] dodecan-1-amine chloride (CDMA) onto the CF and impregnating them with a sodium acrylate/M-PHMG solution exhibit good absorbency, mechanical properties, andexcellent antibacterial properties, making them suitable as substitutes for medical textile skin barriers[111].

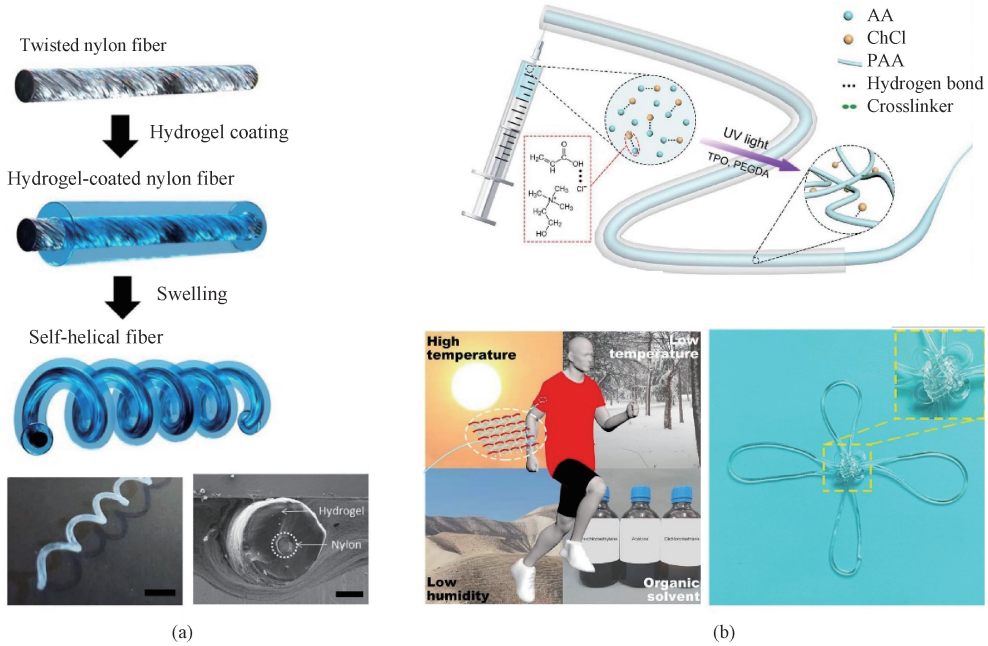


Fig. 13 Artificial muscle fibers and functional cotton dressings: (a) self-helical artificial muscle fiber with nylon core and hydrogel coating[108]; (b) fabrication and features of PDES fibers[110]

The water-resistant PMA was coated onto fibers to form core-shell PMA-sodium polyacrylate hydrogel (MAPAH) fibers. The MAPAH fibers remain stretchable and conductive even at −35 ℃, indicating that they do not freeze. The MAPAH fibers are a notable example of stretchable and conductive fibers. Some waterproof polymers can reduce breathability and moisture transmission, and prolonged contact may cause irritation and microbial growth due to residual monomers or ionic conductors. Smart textiles need to balance ergonomics, skin compatibility, thermoregulation, and mechanical and electrical properties, while incorporating antibacterial and porous structural designs to enhance safety and comfort[112]. Stretchable, conductive, and self-healing PNA hydrogel fibers were prepared using continuous wet-dry spinning, achieving an elongation of 900% and an electrical conductivity of 0.69 S/m[39]. After PMA coating, these fibers exhibit excellent resistance to moisture evaporation, making them suitable for human motion monitoring and enabling their weaving into

triboelectric textile materials.

3.3 Other applications

Spider-silk-like core-shell hydrogel fibers were prepared by self-assembly of PAA and silica nanoparticles. These fibers exhibit a tensile strength of 895 MPa, an elongation at break of 44.3%, a toughness of up to 370 MJ/m^3, and an energy dissipation capacity of 95%. With extremely low resilience and excellent cushioning and shock-absorption performance, they are suitable for applications such as rescue ropes, high-altitude escape nets, helicopter ladders, and parachute ropes[113].

4 Challenges and Future Perspectives in Hydrogel Functionalized Textiles

The approach of hydrogel-textile functionalization presents several challenges that hinder its translation into high-throughput or industrial applications. One key concern is mechanical stability and washing durability[114]. Hydrogels, due to their softness and high water content, typically lack abrasion resistance, tensile strength, and washability, limiting their long-term application in smart clothing and wearable devices. Nanocomposite reinforcement can significantly improve the mechanical stability and durability of hydrogel textiles, while optimized 3D printing technology can help achieve precise deposition, reduce material waste, and enhance adhesion to the fabric substrate, thereby promoting the industrialization of high-performance smart textiles[115-116].

Scaling up production is another significant hurdle. Although laboratory-scale hydrogel functionalization has yielded promising results, scaling up these processes for mass production remains challenging, particularly regarding the uniformity of hydrogel deposition and adhesion strength to different textile substrates, as well as the performance stability across multiple batches[117].

Cost-effectiveness and sustainability are other issues. The production of hydrogels typically requires costly raw materials and energy-demanding processes, posing a significant barrier to commercial applications. Moreover, despite the proliferation of technology, the cost of designs, including both design time and complexity, without consideration of performance or functionality, constitutes a significant bottleneck for applications in developing countries[118].

The environmental impact and biodegradability of hydrogel-modified textiles should be considered. Hydrogels may be designed to be biodegradable, but when paired with synthetic textiles, they can form composites that are difficult to recycle or break down[119]. The challenges and opportunities of hydrogels as flame-retardant materials for textile thermal protection have been discussed. It is believed that improving the bonding strength between hydrogels and fabrics, developing self-healing and flame-retardant hydrogel materials, and creating multifunctional and flame-retardant hydrogel fabrics are future research directions[120]. The development of next-generation smart textiles should focus on large-scale manufacturing, durability, and biocompatibility, while promoting advanced technologies such as automated weaving and 3D knitting to meet the needs of wearable electronics and smart textiles. To address the environmental issues arising from combining hydrogels with non-recyclable fibers such as polyester and nylon, future development should focus on green combinations of biodegradable hydrogels and recyclable bio-based textile substrates, incorporating life-cycle assessment and green chemistry principles to reduce environmental impact[121].

Nanocomposite hydrogels enhance strength and durability by introducing nanoparticles, while biohybrid hydrogels utilize biomolecules to achieve functions such as antibacterial activity and tissue repair. Hydrogel-functionalized textiles hold great promise for smart wearables and medicine, enabling human signal monitoring, drug delivery, and temperature regulation[122]. In the medical field, hydrogel-filled dressings and prostheses are gaining attention due to their improved comfort and functionality. Advanced manufacturing technologies, such as 3D printing, enable precise deposition and the fabrication of customized hydrogel structures, facilitating the fabrication of complex multifunctional textiles and accelerating the commercialization of laboratory findings. Meanwhile, the trend toward sustainable development is driving the application of biodegradable hydrogels and recyclable fabrics to reduce environmental impact, making the functionalization of hydrogel textiles a cutting-edge direction in materials science[123].

5 Conclusions

Hydrogel functionalized textiles are revolutionizing materials science by combining the impressive attributes of hydrogels, such as high water content, biocompatibility, and responsive nature, with the inherent flexibility of textiles. This innovative fusion opens avenues for groundbreaking applications in fields ranging from biomedical devices and wearable technologies to environmental remediation and smart clothing. However, although progress has been made, challenges such as improving mechanical stability, washing durability and scalability still exist. To overcome these obstacles, the adoption of advanced manufacturing techniques, such as 3D printing, and the development of nanocomposite hydrogels are vital, as they can enhance performance and expand usability. Emphasizing sustainability and cost-effectiveness is more critical than before, driven by the demand for environmentally friendly materials. Future research should adopt an interdisciplinary approach, integrating insights from materials science, engineering, and fashion design to refine and harness the full potential of hydrogel-textile composites.

Expanding the application scope of hydrogel-

functionalized textiles, particularly through the integration of bio-hybrid hydrogels for regenerative medicine and smart textiles for real-time monitoring, could significantly redefine their roles across various industries. These advanced materials not only enhance the functionality of traditional fabrics but also pave the way for innovations that meet the demands of an increasingly technology-driven environment. By harnessing the unique properties of hydrogels, we can create textiles that respond dynamically to user needs, offering solutions that promote health and well-being while advancing sustainable practices. Collaborative research and development in this field are crucial for unlocking the full potential of hydrogel textiles, ultimately leading to transformative applications that could improve lives and shape the future of material design. IPN hydrogels and 4D printing are two innovations revolutionizing the field by enabling dynamic, shape-morphing textiles with programmable responses and exceptional toughness, resilience, and adaptability. Whereas IPNs offer synergistic combinations of mechanical strength, responsiveness, and biocompatibility that are essential for wearable electronics and medical applications, 4D printing provides spatial and temporal control over textile function. To advance this field, interdisciplinary collaboration is essential. To develop smart hydrogel textiles with real-time health monitoring, drug delivery, soft robotics, and environmental sensing capabilities, it is necessary to integrate materials science, electronic engineering, and biomedicine. Textile technologists, polymer chemists, biomedical engineers, and electronics designers must collaborate to overcome technical obstacles such as long-term biocompatibility, wash durability, energy harvesting, and sustainable fabrication. Hydrogel-textile systems can advance from conceptual innovation to scalable and practical impact with such collaboration, opening the door to a new generation of smart fabrics that are sustainable, multifunctional and adaptive.

References

[1] Li X Y, Gong J P. Design principles for strong and tough hydrogels [J]. *Nature Reviews Materials*, 2024, 9(6): 380-398.

[2] Hossain M S, Hossain M M, Khatun M K, et al. Hydrogel-based superadsorbents for efficient removal of heavy metals in industrial wastewater treatment and environmental conservation [J]. *Environmental Functional Materials*, 2023, 2(2): 142-158.

[3] Dey R, Mukherjee R, Biswas S, et al. Stimuli-responsive release-active dressing: a promising solution for eradicating biofilm-mediated wound infections [J]. *ACS Applied Materials & Interfaces*, 2024, 16(29): 37795-37805.

[4] Sun C Y, Luo J B, Yan S C, et al. Thermally responsive fibers for versatile thermoactivated protective fabrics [J]. *Advanced Functional Materials*, 2023, 33(9): 2211035.

[5] Li X H, Chen S, Peng Y J, et al. Materials, preparation strategies, and wearable sensor applications of conductive fibers: a review [J]. *Sensors*, 2022, 22(8): 3028.

[6] Zhang L, Zheng M, Zhao D Q, et al. A review of novel self-healing concrete technologies [J]. *Journal of Building Engineering*, 2024, 89: 109331.

[7] Shyeed M A, Hasan M K, Khatun M K, et al. Additive manufacturing of hydrogels in tissue engineering [J]. *Journal of Chemistry Letters*, 2024, 5(1): 17-43.

[8] Li Q Y, Ahmed I, Minh Ngoc P, et al. Contemporary advances in polymer applications for sporting goods: fundamentals, properties, and applications [J]. *RSC Advances*, 2024, 14(50): 37445-37469.

[9] Nasef M M, Gupta B, Shameli K, et al. Engineered bioactive polymeric surfaces by radiation induced graft copolymerization: strategies and applications [J]. *Polymers*, 2021, 13(18): 3102.

[10] Chen J S, Peng Q Y, Peng X W, et al. Probing and manipulating noncovalent interactions in functional polymeric systems [J]. *Chemical Reviews*, 2022, 122(18): 14594-14678.

[11] Hu X Y, Hu P Y, Liu L, et al. Lightweight and hierarchically porous hydrogels for wearable passive cooling under extreme heat stress [J]. *Matter*, 2024, 7(12): 4398-4409.

[12] Sun Y L, Liang F Y, Chen J Y, et al. Ultrathin flexible heat pipes with heat transfer performance and flexibility optimization for flexible electronic devices [J]. *Renewable and Sustainable Energy Reviews*, 2025, 208: 115064.

[13] Hu D L, Liu D S, Hu Y, et al. Dual-physical network PVA hydrogel commensurate with articular cartilage bearing lubrication enabled by harnessing nanoscale crystalline domains [J]. *Nano Research*, 2024, 17(11): 9784-9795.

[14] Nanda D, Behera D, Pattnaik S S, et al. Advances in natural polymer-based hydrogels: synthesis, applications, and future directions in biomedical and environmental fields [J]. *Discover Polymers*, 2025, 2(1): 6.

[15] Liu Y J, De Mulatier S, Matsuhisa N. Unperceivable designs of wearable electronics [J]. *Advanced Materials*, 2025, 37(49): 2502727.

[16] Puza F, Zheng Y J, Han L, et al. Physical entanglement hydrogels: ultrahigh water content but good toughness and stretchability [J]. *Polymer Chemistry*, 2020, 11(13): 2339-2345.

[17] Ding L, Wang Q, Shen M, et al. Thermoresponsive nanocomposite gel for local

drug delivery to suppress the growth of glioma by inducing autophagy [J]. *Autophagy*, 2017, 13(7): 1176-1190.
[18] Gruškienė R, Galinskaitė A, Kavleiskaja T, et al. Application of fucoidan for the encapsulation of yeast K2 toxin [J]. *Carbohydrate Polymer Technologies and Applications*, 2024, 7: 100521.
[19] You L X, Marcolini B, Bour J, et al. Physicochemical, morphological, and rheological properties of cellulose nanofibrils produced via ultra-high-pressure homogenization [J]. *Carbohydrate Polymer Technologies and Applications*, 2025, 9: 100635.
[20] Guo X H, Liu H, Nail A, et al. Design and application of stimuli-responsive nanocomposite hydrogels: a review[J]. *Macromolecular Rapid Communications*, 2025, 46(12): 2401095.
[21] Calderón Moreno J M, Chelu M, Popa M. Eco-friendly conductive hydrogels: towards green wearable electronics[J]. *Gels*, 2025, 11(4): 220.
[22] Yang Z Y, Chen L, McClements D J, et al. Stimulus-responsive hydrogels in food science: a review[J]. *Food Hydrocolloids*, 2022, 124: 107218.
[23] Choi Y, Koh H Y, Han J Y, et al. Synthesis of hydrogel-based microgels and nanogels toward therapeutic and biomedical applications [J]. *Applied Sciences*, 2025, 15(3): 1368.
[24] Dey P, Mandal S, Brahma R K. Cellulose-based hydrogels: biocompatibility, environmental impact, and sustainable management [M]// Deshmukh K, Barua S, Baruah S, et al. Cellulose-based hydrogels. Amsterdam: Elsevier, 2025: 439-458.
[25] Bao Z T, Xian C H, Yuan Q J, et al. Natural polymer-based hydrogels with enhanced mechanical performances: preparation, structure, and property [J]. *Advanced Healthcare Materials*, 2019, 8(17): 1900670.
[26] Van Tran V, Phung V D, Do H H. Advances and innovations in hydrogel particles for sustainable purification of contaminants in aqueous solutions [J]. *Chemical Engineering Journal*, 2024, 486: 150324.
[27] Shahi F, Zarei S, Salah Othman R, et al. Interpenetrating polymer networks in biomedical fields: recent advanced and applications [J]. *Polymers for Advanced Technologies*, 2025, 36(2): e70099.
[28] Pourjavadi A, Heydarpour R, Tehrani Z M. Multi-stimuli-responsive hydrogels and their medical applications [J]. *New Journal of Chemistry*, 2021, 45(35): 15705-15717.
[29] Martwong E, Thusanaphoom P, Naktham A, et al. Asymmetric crosslinked polyacrylamide/natural rubber semi-IPN hydrogel for application of methyl orange dye removal: combined experimental and DFT study [J]. *Journal of Polymers and the Environment*, 2024, 32(5): 1998-2013.
[30] Hu Y B, Barbier L, Li Z, et al. Hydrophilicity-hydrophobicity transformation, thermoresponsive morphomechanics, and crack multifurcation revealed by AIEgens in mechanically strong hydrogels [J]. *Advanced Materials*, 2021, 33(39): 2101500.
[31] Li Y Z, Deng J W, Li H R. Enhancing solar-driven atmospheric water harvesting by a bilayer macroporous hydrogel [J]. *Applied Thermal Engineering*, 2024, 247: 123045.
[32] Türkoğlu G C, Sariişik A M, Karavana S Y. Development of textile-based sodium alginate and chitosan hydrogel dressings [J]. *International Journal of Polymeric Materials and Polymeric Biomaterials*, 2021, 70(13): 916-925.
[33] Jayakumar A, Jose V K, Lee J M. Hydrogels for medical and environmental applications [J]. *Small Methods*, 2020, 4(3): 1900735.
[34] Hossain K R, Lu Y Z, Hu D L, et al. Polymer-based lubricating in 3D printing [J]. *Macromolecular Chemistry and Physics*, 2025, 226(16): e00047.
[35] Li K, Zhao J, Zhussupbekova A, et al. 4D printing of MXene hydrogels for high-efficiency pseudocapacitive energy storage [J]. *Nature Communications*, 2022, 13: 6884.
[36] Hui Y, Yao Y, Qian Q L, et al. Three-dimensional printing of soft hydrogel electronics [J]. *Nature Electronics*, 2022, 5(12): 893-903.
[37] Saccone M A, Gallivan R A, Narita K, et al. Additive manufacturing of micro-architected metals via hydrogel infusion[J]. *Nature*, 2022, 612(7941): 685-690.
[38] Liang J Y, Xu J S, Zheng J X, et al. Bioinspired mechanically robust and recyclable hydrogel microfibers based on hydrogen-bond nanoclusters[J]. *Advanced Science*, 2024, 11(23): 2401278.
[39] Shuai L, Guo Z H, Zhang P P, et al. Stretchable, self-healing, conductive hydrogel fibers for strain sensing and triboelectric energy-harvesting smart textiles [J]. *Nano Energy*, 2020, 78: 105389.
[40] Zheng L J, Zhu M M, Wu B, et al. Conductance-stable liquid metal sheath-core microfibers for stretchy smart fabrics and self-powered sensing[J]. *Science Advances*, 2021, 7(22): eabg4041.
[41] Neumann M, Di Marco G, Iudin D, et al. Stimuli-responsive hydrogels: the dynamic smart biomaterials of tomorrow[J]. *Macromolecules*, 2023, 56(21): 8377-8392.
[42] Sapino S, Chirio D, Peira E, et al. Ocular drug delivery: a special focus on the thermosensitive

approach[J]. *Nanomaterials*, 2019, 9(6): 884.
[43] Chen C W, Wang Y, Zhang H, et al. Responsive and self-healing structural color supramolecular hydrogel patch for diabetic wound treatment[J]. *Bioactive Materials*, 2022, 15: 194-202.
[44] Jiang Y N, Zhang X, Zhang W, et al. Infant skin friendly adhesive hydrogel patch activated at body temperature for bioelectronics securing and diabetic wound healing[J]. *ACS Nano*, 2022, 16(6): 8662-8676.
[45] Xu G, Xia H, Chen P Y, et al. Thermochromic hydrogels with dynamic solar modulation and regulatable critical response temperature for energy-saving smart windows[J]. *Advanced Functional Materials*, 2022, 32(5): 2109597.
[46] Liu W, Xie R J, Zhu J Y, et al. A temperature responsive adhesive hydrogel for fabrication of flexible electronic sensors[J]. *NPJ Flexible Electronics*, 2022, 6: 68.
[47] Wang T, Zheng Y, Shi Y J, et al. pH-responsive calcium alginate hydrogel laden with protamine nanoparticles and hyaluronan oligosaccharide promotes diabetic wound healing by enhancing angiogenesis and antibacterial activity[J]. *Drug Delivery and Translational Research*, 2019, 9(1): 227-239.
[48] Shi H D, Yang Y L, Huang Y P, et al. Anisotropic single-domain hydrogel with stimulus response to temperature and ionic strength[J]. *Macromolecules*, 2023, 56(2): 528-534.
[49] Li J, Ma Q Y, Xu Y, et al. Highly bidirectional bendable actuator engineered by LCST-UCST bilayer hydrogel with enhanced interface[J]. *ACS Applied Materials & Interfaces*, 2020, 12(49): 55290-55298.
[50] Rumon M M H. Advances in cellulose-based hydrogels: tunable swelling dynamics and their versatile real-time applications[J]. *RSC Advances*, 2025, 15(15): 11688-11729.
[51] Liu X M, Dou G, Li Z H, et al. Hybrid biomaterial initiates refractory wound healing via inducing transiently heightened inflammatory responses[J]. *Advanced Science*, 2022, 9(21): 2105650.
[52] Liang Y P, Li M, Yang Y T, et al. pH/glucose dual responsive metformin release hydrogel dressings with adhesion and self-healing via dual-dynamic bonding for athletic diabetic foot wound healing[J]. *ACS Nano*, 2022, 16(2): 3194-3207.
[53] Jia Y L, Zhang X H, Yang W H, et al. A pH-responsive hyaluronic acid hydrogel for regulating the inflammation and remodeling of the ECM in diabetic wounds[J]. *Journal of Materials Chemistry B*, 2022, 10(15): 2875-2888.
[54] Li M M, Chen X, Li X T, et al. Wearable and robust polyimide hydrogel fiber textiles for strain sensors[J]. *ACS Applied Materials & Interfaces*, 2021, 13(36): 43323-43332.
[55] Xu Y, Liu K, Yang Y, et al. Hemicellulose-based hydrogels for advanced applications[J]. *Frontiers in Bioengineering and Biotechnology*, 2023, 10: 1110004.
[56] Lei D M, Xiao Y C, Shao L H, et al. Dual-stimuli-responsive and anti-freezing conductive ionic hydrogels for smart wearable devices and optical display devices[J]. *ACS Applied Materials & Interfaces*, 2023, 15(20): 24175-24185.
[57] Sąsiadek E, Jaszczak M, Skwarek J, et al. NBT-pluronic F-127 hydrogels printed on flat textiles as UV radiation sensors[J]. *Materials*, 2021, 14(12): 3435.
[58] Periyasamy A P, Venkataraman M, Kremenakova D, et al. Progress in sol-gel technology for the coatings of fabrics[J]. *Materials*, 2020, 13(8): 1838.
[59] Ahmad F, Mushtaq B, Butt F A, et al. Synthesis and characterization of nonwoven cotton-reinforced cellulose hydrogel for wound dressings[J]. *Polymers*, 2021, 13(23): 4098.
[60] Ahmad F, Mushtaq B, Butt F A, et al. Preparation and characterization of wool fiber reinforced nonwoven alginate hydrogel for wound dressing[J]. *Cellulose*, 2021, 28(12): 7941-7951.
[61] Zhang R, Wu Y, Lin P, et al. Extremely tough hydrogels with cotton fibers reinforced[J]. *Advanced Engineering Materials*, 2020, 22(11): 2000508.
[62] Wang L L, Li D W, Shen Y, et al. Preparation of *Centella* asiatica loaded gelatin/chitosan/nonwoven fabric composite hydrogel wound dressing with antibacterial property[J]. *International Journal of Biological Macromolecules*, 2021, 192: 350-359.
[63] Zhao C W, Zhou L, Mu C A, et al. Antibacterial hydrogel coating: strategies in surface chemistry[J]. *Advances in Colloid and Interface Science*, 2020, 285: 102280.
[64] Dong X R, Yao F L, Jiang L J, et al. Facile preparation of a thermosensitive and antibiofouling physically crosslinked hydrogel/powder for wound healing[J]. *Journal of Materials Chemistry B*, 2022, 10(13): 2215-2229.
[65] Liu H Y, Yang L, Dou B J, et al. Zwitterionic hydrogel-coated cotton fabrics with underwater superoleophobic, self-healing and anti-fouling performances for oil-water separation[J]. *Separation and Purification Technology*, 2021, 279: 119789.
[66] Liu H Y, Shang J J, Wang Y F, et al. Ag/AgCl nanoparticles reinforced cellulose-based hydrogel coated cotton fabric with self-healing and photo-

induced self-cleaning properties for durable oil/water separation [J]. *Polymer*, 2022, 255: 125146.
[67] Majumder S, Ranjan Dahiya U, Yadav S, et al. Zinc oxide nanoparticles functionalized on hydrogel grafted silk fibroin fabrics as efficient composite dressing[J]. *Biomolecules*, 2020, 10(5): 710.
[68] Han H, Zhu J, Wu D Q, et al. Inherent guanidine nanogels with durable antibacterial and bacterially antiadhesive properties[J]. *Advanced Functional Materials*, 2019, 29(12): 1806594.
[69] Norouzi M R, Ghasemi-Mobarakeh L, Itel F, et al. Dual functional antibacterial-antioxidant core/shell alginate/poly (ε-caprolactone) nanofiber membrane: a potential wound dressing [J]. *ACS Omega*, 2024, 9(23): 25124-25134.
[70] Loste J, Lopez-Cuesta J M, Billon L, et al. Transparent polymer nanocomposites: an overview on their synthesis and advanced properties[J]. *Progress in Polymer Science*, 2019, 89: 133-158.
[71] Lorusso E, Ali W, Hildebrandt M, et al. Hydrogel functionalized polyester fabrics by UV-induced photopolymerization [J]. *Polymers*, 2019, 11(8): 1329.
[72] Dai X H, Yu X, Zheng J, et al. A kelp-inspired polyester fabric surface of UV grafted hydrogel for drag reduction [J]. *Journal of Applied Polymer Science*, 2022, 139(7): 51634.
[73] Chen K S, Tsai J C, Chou C W, et al. Effects of additives on the photo-induced grafting polymerization of *N*-isopropylacrylamide gel onto PET film and PP nonwoven fabric surface[J]. *Materials Science and Engineering: C*, 2002, 20(1/2): 203-208.
[74] Primc G, Mozetič M. Surface modification of polymers by plasma treatment for appropriate adhesion of coatings[J]. *Materials*, 2024, 17(7): 1494.
[75] Promdontree P, Ounkaew A, Yao Y, et al. Temperature-responsive injectable composite hydrogels based on poly (*N*-isopropylacrylamide), chitosan, and hemp-derived cellulose nanocrystals [J]. *Polymers*, 2024, 16(21): 2984.
[76] Nair A, Chandrashekhar H R, Day C M, et al. Polymeric functionalization of mesoporous silica nanoparticles: biomedical insights [J]. *International Journal of Pharmaceutics*, 2024, 660: 124314.
[77] Li T T, Wang Z K, Ren H T, et al. Recyclable and degradable nonwoven-based double-network composite hydrogel adsorbent for efficient removal of Pb(Ⅱ) and Ni(Ⅱ) from aqueous solution[J]. *Science of the Total Environment*, 2021, 758: 143640.
[78] Li T T, Xing M F, Gao B, et al. Multiscale synergistic toughened Pluronic/PMEA/hydroxyapatite hydrogel laminated aramid soft composites: puncture resistance and self-healing properties[J]. *Composites Part B: Engineering*, 2021, 216: 108856.
[79] Hubbard A M, Cui W, Huang Y, et al. Hydrogel/elastomer laminates bonded via fabric interphases for stimuli-responsive actuators [J]. *Matter*, 2019, 1(3): 674-689.
[80] Ma Y, Gong J X, Li Q J, et al. Triple-mechanism enhanced flexible SiO_2 nanofiber composite hydrogel with high stiffness and toughness for cartilaginous ligaments[J]. *Small*, 2024, 20(25): 2310046.
[81] Fazel Anvari-Yazdi A, Badea I, Chen X B. Biomaterials in postoperative adhesion barriers and uterine tissue engineering[J]. *Gels*, 2025, 11(6): 441.
[82] Zhou W, Yu X, Li Y, et al. Green-solvent-processed fibrous membranes with water/oil/dust-resistant and breathable performances for protective textiles[J]. *ACS Applied Materials & Interfaces*, 2021, 13(1): 2081-2090.
[83] Sadri B, Gao W. Fibrous wearable and implantable bioelectronics[J]. *Applied Physics Reviews*, 2023, 10(3): 031303.
[84] Nilsson T Y, Trojer M A. A solution blown superporous nonwoven hydrogel based on hydroxypropyl cellulose[J]. *Soft Matter*, 2020, 16(29): 6850-6861.
[85] Nakamura K, Saotome T, Shimada N, et al. A gelatin hydrogel nonwoven fabric facilitates metabolic activity of multilayered cell sheets[J]. *Tissue Engineering Part C: Methods*, 2019, 25(6): 344-352.
[86] Koc U, Eren R, Aykut Y. Yarn-reinforced hydrogel composite produced from woven fabrics by simultaneous dissolution and cross-linking [J]. *Polymers and Polymer Composites*, 2021, 29(2): 117-126.
[87] Koc U, Aykut Y, Eren R. Regenerated cellulose woven fabric reinforced hydrogel composite[J]. *The Journal of the Textile Institute*, 2022, 113(5): 906-914.
[88] Dixit A, Bag D S, Kalra S J S. Synthesis of strong and stretchable double network (DN) hydrogels of PVA-borax and P(AM-co-HEMA) and study of their swelling kinetics and mechanical properties[J]. *Polymer*, 2017, 119: 263-273.
[89] Arjmandi M, Ramezani M, Bolle T, et al. Mechanical and tribological properties of a novel hydrogel composite reinforced by three-dimensional woven textiles as a functional synthetic cartilage [J]. *Composites Part A: Applied Science and Manufacturing*, 2018, 115: 123-133.
[90] Li S M, Xu J W, Mu Y, et al. Fatigue-resistant

and hysteresis-free composite fibers with a heterogeneous hierarchical structure [J]. *Advanced Fiber Materials*, 2023, 5(5): 1643-1656.

[91] Wu J, Wu B H, Xiong J Q, et al. Entropy-mediated polymer-cluster interactions enable dramatic thermal stiffening hydrogels for mechanoadaptive smart fabrics[J]. *Angewandte Chemie International Edition*, 2022, 61(34): e202204960.

[92] Deng P F, He Z J, Shen Y N, et al. Conductive hollow hydrogel fibers toward high-sensitivity bio-textiles[J]. *Cell Reports Physical Science*, 2024, 5(7): 102047.

[93] Zhang C, Xiao P, Zhang D, et al. Wet-spinning knittable hygroscopic organogel fibers toward moisture-capture-enabled multifunctional devices [J]. *Advanced Fiber Materials*, 2023, 5(2): 588-602.

[94] Fahma F, Febiyanti I, Lisdayana N, et al. Production of polyvinyl alcohol-alginate-nanocellulose fibers[J]. *Starch-Stärke*, 2022, 74(5/6): 2100032.

[95] Xi P Y, Quan F Y, Sun Y N, et al. Cellulose nanofibers reinforced nanocomposites with high strength and toughness by tunable wet-drawing and ionic cross-linking method[J]. *Composites Part B: Engineering*, 2022, 242: 110078.

[96] Qu M J, Wang H, Chen Q S, et al. A thermally-electrically double-responsive polycaprolactone-thermoplastic polyurethane/multi-walled carbon nanotube fiber assisted with highly effective shape memory and strain sensing performance[J]. *Chemical Engineering Journal*, 2022, 427: 131648.

[97] Guimarães C F, Ahmed R, Mataji-Kojouri A, et al. Engineering polysaccharide-based hydrogel photonic constructs: from multiscale detection to the biofabrication of living optical fibers[J]. *Advanced Materials*, 2021, 33(52): 2105361.

[98] Liu X, Shi L X, Wan X Z, et al. A spider-silk-inspired wet adhesive with supercold tolerance [J]. *Advanced Materials*, 2021, 33(14): 2007301.

[99] Su J J, Liu B M, He H N, et al. Engineering high strength and super-toughness of unfolded structural proteins and their extraordinary anti-adhesion performance for abdominal hernia repair [J]. *Advanced Materials*, 2022, 34(19): 2200842.

[100] Chen Y J, Zhang Q, Zhong Y, et al. Super-strong and super-stiff chitosan filaments with highly ordered hierarchical structure [J]. *Advanced Functional Materials*, 2021, 31(38): 2104368.

[101] Chen C X, Xi P Y, Zhang L M, et al. A strategy to fabricate tough and strong bioinspired fiber with asymmetric structure and water-driven performance [J]. *Composites Science and Technology*, 2022, 224: 109464.

[102] He W Q, Qian D, Wang Y, et al. A protein-like nanogel for spinning hierarchically structured artificial spider silk[J]. *Advanced Materials*, 2022, 34(27): e2201843.

[103] Dang X Y, Gao Y J, Chen Z Z. Nanofiber/zwitterionic hydrogel composite for anti-foreign body reaction [J]. *Journal of Donghua University (English Edition)*, 2026, 43(3): 32-43.

[104] Wang Y M, Zhang X. Dual fluorescent hydrogel derived from cross-linked chitosan-salicylaldehyde-Eu (Ⅲ) for visual detection of volatile amine and meat freshness[J]. *Journal of Donghua University (English Edition)*, 2026, 43(3): 57-63.

[105] Fairbanks B D, Schwartz M P, Halevi A E, et al. A versatile synthetic extracellular matrix mimic via thiol-norbornene photopolymerization [J]. *Advanced Materials*, 2009, 21(48): 5005-5010.

[106] Duan X Y, Yu J Y, Zhu Y X, et al. Large-scale spinning approach to engineering knittable hydrogel fiber for soft robots[J]. *ACS Nano*, 2020, 14(11): 14929-14938.

[107] Tachibana D, Murakami K, Kozaki T, et al. Ultrafast and highly deformable electromagnetic hydrogel actuators assembled from liquid metal gel fiber[J]. *Advanced Intelligent Systems*, 2022, 4(5): 2100212.

[108] Sim H J, Jang Y, Kim H, et al. Self-helical fiber for glucose-responsive artificial muscle [J]. *ACS Applied Materials & Interfaces*, 2020, 12(18): 20228-20233.

[109] Xu S L, Yan Y G, Zhao Y M, et al. Spinnable adhesive functional-hydrogel fibers for sensing and perception applications [J]. *Journal of Materials Chemistry C*, 2021, 9(16): 5554-5564.

[110] Wang X C, Chen G X, Cai L, et al. Weavable transparent conductive fibers with harsh environment tolerance [J]. *ACS Applied Materials & Interfaces*, 2021, 13(7): 8952-8959.

[111] Petros S, Tesfaye T, Ayele M. A review on gelatin based hydrogels for medical textile applications[J]. *Journal of Engineering*, 2020, 2020(1): 8866582.

[112] Zhao X, Chen F, Li Y H, et al. Bioinspired ultra-stretchable and anti-freezing conductive hydrogel fibers with ordered and reversible polymer chain alignment [J]. *Nature Communications*, 2018, 9: 3579.

[113] Dou Y Y, Wang Z P, He W D, et al. Artificial spider silk from ion-doped and twisted core-sheath hydrogel fibres [J]. *Nature Communications*, 2019, 10: 5293.

[114] Azani M R, Hassanpour A. Electronic textiles (E-Textiles): types, fabrication methods, and recent strategies to overcome durability challenges (washability & flexibility) [J]. *Journal of Materials Science: Materials in Electronics*, 2024, 35(29): 1897.
[115] Guo Y H, Bae J, Fang Z W, et al. Hydrogels and hydrogel-derived materials for energy and water sustainability [J]. *Chemical Reviews*, 2020, 120(15): 7642-7707.
[116] Beckett L E, Lewis J T, Tonge T K, et al. Enhancement of the mechanical properties of hydrogels with continuous fibrous reinforcement [J]. *ACS Biomaterials Science & Engineering*, 2020, 6(10): 5453-5473.
[117] Bauer M, Duerkop A, Baeumner A J. Critical review of polymer and hydrogel deposition methods for optical and electrochemical bioanalytical sensors correlated to the sensor's applicability in real samples[J]. *Analytical and Bioanalytical Chemistry*, 2023, 415(1): 83-95.
[118] Hartmann F, Baumgartner M, Kaltenbrunner M. Becoming sustainable, the new frontier in soft robotics[J]. *Advanced Materials*, 2021, 33 (19): 2004413.
[119] Pattanayak R, Jena T, Pradhan S, et al. Recent advancement of bio-based super absorbent polymer and its biodegradable and recycling behavior: a vision and future [J]. *Polymer-Plastics Technology and Materials*, 2023, 62 (10): 1290-1317.
[120] Vahabi H, Gholami F, Tomas M, et al. Hydrogel and aerogel-based flame-retardant polymeric materials: a review [J]. *Journal of Vinyl and Additive Technology*, 2024, 30(1): 5-25.
[121] Tian Y C, Ding R D, Yoon S S, et al. Recent advances in next-generation textiles [J]. *Advanced Materials*, 2025, 37(8): 2417022.
[122] Pakdel E, Fang J, Fang J, et al. Nanocoatings for smart textiles [M]//Yilmaz N D. Smart Textiles: Wearable Nanotechnology. Hoboken: Wiley, 2018: 247-300.
[123] Diak V. A review of smart structures and adaptation of 3D printing methods for future fashion applications [J]. *Mokslo Taikomieji Tyrimai Lietuvos Kolegijose*, 2024, 2(1): 154-164.

水凝胶功能化纺织品在智能与可持续领域中的应用

HOSSAIN Khan Rajib[1,2*], JALIL M. Abdul[1*], KHAN Ayub Nabi[1], FUAD Khan Md. Salman Adib[1], MONIRUZZAMAN Md.[1], SAYEK Shabir[1], SAGOR S. M. Shahadat Hossain[1]

1. BGMEA 时装与技术大学 自然科学系，孟加拉国 达卡 1230
2. 中国科学院大学 材料科学与光电技术学院，中国 北京 100049

摘　要：水凝胶材料因其优异的亲水性、生物相容性及可定制的仿生特性而备受关注。然而，其固有的低密度链和不规则微观结构使得力学性能不佳、应用受限。因此，强度与韧性的提升仍是亟待解决的难题。将水凝胶材料与纺织品复合以制备功能性水凝胶基复合材料，可以有效解决上述问题。本文综述了水凝胶基纺织复合材料的研究进展，重点阐述了其设计策略及性能调控方法。同时探讨了该类复合材料在医用敷料、可穿戴电子器件及阻燃防护等领域的应用进展，并展望了未来研究方向。

关键词：水凝胶；智能纺织品；刺激响应材料；可持续纺织品；聚合物集成