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Review

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Research progress of responsive electrospun dressings for precise monitoring and treatment of diabetic wounds

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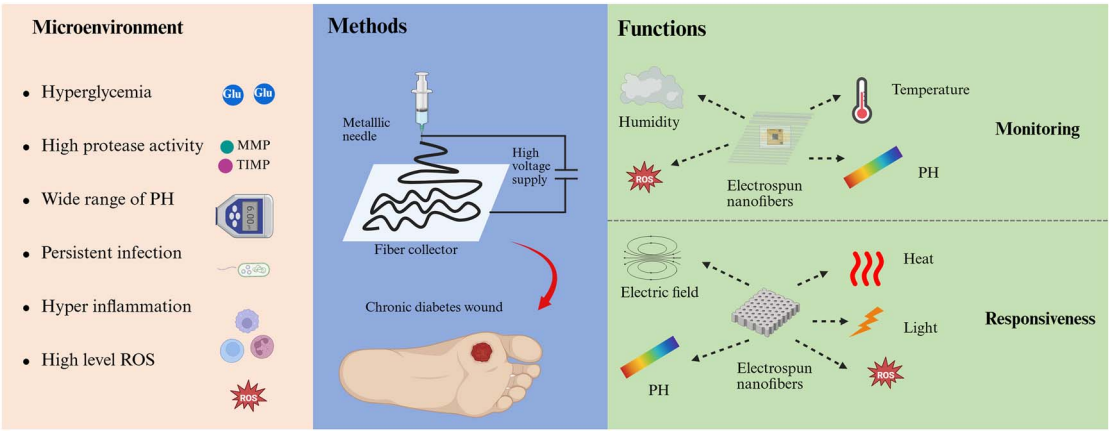
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Abstract

Chronic diabetic wounds pose a serious health and economic burden globally. In recent years, there has been widespread attention on the research of functional and even personalized wound dressings, among which responsive smart nanofiber dressings made using electrospinning technology have shown great potential. Nanofibers have advantages such as extremely fine pore size, high porosity, and large specific surface area. By combining electrospinning technology with responsive materials and integrating electronic engineering and other manufacturing techniques, it is possible to weave smart nanofibers that can respond to specific diabetic wound environments (such as low pH, high reactive oxygen species, high glucose concentration, and overexpressed enzymes) or external conditions (such as temperature, light, and magnetic fields). This allows for the monitoring of the wound microenvironment and/or the automatic release of drugs based on changes in the wound microenvironment. Compared with ordinary dressings, this dressing can not only predict the wound state, but also respond to the specific wound (such as diabetic wound) microenvironment to promote wound healing rapidly and accurately. This article outlines the characteristics of the chronic diabetic wound microenvironment, electrospinning technology, and its application in responding to the chronic diabetic wound microenvironment.

Graphical Abstract



Keywords Chronic diabetic wounds, Microenvironment, Electrospinning technology, Responsive dressing, Monitoring

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Highlights

- **The healing environment of chronic diabetic wounds is characterized by hyperglycemia, high level reactive oxygen species, hyper inflammation, persistent infection, high protease activity and wide range of PH.**
- **This article offers a comprehensive overview of electrospinning technology principles, the selection of materials (including natural, synthetic, and composite types), and recent progress in structural design, such as core-shell and Janus configurations.**
- **Strategies for developing smart responsive nanofiber dressings can be categorized into two approaches: those that respond to internal stimuli (like pH, glucose, reactive oxygen species and enzymes) and those that react to external stimuli (such as light, heat, and electricity).**
- **Multifunctional dressings that combine real-time monitoring of wound conditions (through visual or electronic signals) with controlled drug delivery (targeting antibacterial, anti-inflammatory, and angiogenic effects) have promising potential for widespread use.**

Background

The normal healing process of chronic diabetic wounds typically progresses through four stages: hemostasis, inflammation, proliferation (re-epithelialization), and remodeling (scar maturation). However, hyperglycemia associated with diabetes can lead to various systemic complications, resulting in a series of local lesions within the wound microenvironment [1]. These lesions may include hyperglycemia, ischemia, hypoxia, excessive inflammation, persistent infection, elevated protease activity [2], insufficient energy supply, local necrotic tissue [3], and a wide range of pH changes during the chronic phase (ranging from 5.4 to 8.9) [4]. These alterations in the microenvironment ultimately contribute to the chronicity of diabetic wounds through the pathophysiological mechanisms of neuropathy, peripheral arterial disease, and infection [5].

Wound dressings are the primary method for treating diabetic wounds. Nanofibers (NFs) possess extremely fine pore sizes, high porosity, and large surface areas [6], which effectively protect wounds from pathogen infections while facilitating the transport of gases and liquids, thereby maintaining a stable wound environment. In addition, electrospinning technology continuously expands the range of materials that can be utilized in its development, allowing for the customization of unique structures. This advancement enhances the mechanical properties of fiber membranes, improves biocompatibility, and facilitates functions such as drug loading, antibacterial action, and anti-inflammatory effects. At present, electrospun NFs and electrospun microspheres are the main forms of this technology that can be applied to wound healing, but based on the above characteristics of NF, we believe that electrospun NFs are more representative, so we mainly review the content of NFs.

Furthermore, emerging research fields are integrating electrospinning technology with responsive materials, combining electronic engineering and other manufacturing techniques to create smart NFs that can react to specific diabetic wound environments—such as low pH [7], high levels of reactive oxygen species (ROS) [8], temperature [9], and humidity [10]—or to external conditions like temperature [11], light [12], and electric fields [13]. This responsiveness includes: (i) the ability to monitor the wound microenvironment to predict wound status and (ii) the capability to automatically release drugs based on the wound microenvironment, promoting rapid and precise wound healing. Although most efforts are still in the laboratory stage and achieving real-time monitoring of wounds in clinical settings faces numerous challenges, electrospinning technology has already demonstrated tremendous potential in the treatment of chronic wounds.

This article will summarize the wound-healing process and the microenvironment of chronic wounds in diabetes. It will introduce the principles and operational procedures of electrospinning technology, with a particular focus on the advancements in intelligent electrospinning technology in recent years. We will discuss the role and potential value of smart dressings created using this technology, which can monitor the wound microenvironment and/or automatically release drugs in response to changes within that environment. This discussion aims to provide constructive ideas and insights for the development of more effective intelligent electrospun dressings for chronic diabetic wounds.

Review

Diabetic wounds

Patients with diabetes are susceptible to wounds characterized by impaired healing, chronic inflammation, and reduced epithelialization. Between 19% and 34% of the individuals with type 2 diabetes mellitus (T2DM) develop ulcers localized in the lower limbs, known as diabetic foot ulcers (DFUs). These ulcers represent the most severe manifestation of diabetes and can lead to lower limb amputation or even death [14]. DFUs pose significant health and economic burdens worldwide. It is estimated that up to one-third of diabetes care costs are associated with lower-limb complications, amounting to ∼$5.9 billion annually in the USA. Furthermore, the recurrence rate within 1 year of successful healing is ∼40%, making the management of chronic diabetic wounds particularly challenging [15].

The environment surrounding diabetic wounds is not only related to haemostasis, inflammation, proliferation, and tissue remodeling [16, 17] but also more complex, leading to overlapping wound-healing processes and prolonged inflammation periods [2]. Consequently, diabetic wounds are prone to relapse and do not heal completely.

Normal wound-healing process

At present, the most common understanding of skin wound healing involves continuous or overlapping stages [18]. The basic

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stages of wound healing and their most important functions are briefly described.

Hemostasis Hemostasis is the first step in wound healing. After an injury, blood vessels immediately constrict to reduce bleeding; subsequently, platelets gather and are activated at the wound site, forming a platelet plug, a process known as primary hemostasis [19]. Activated platelets can secrete various cytokines, such as platelet-derived growth factor (PDGF), transforming growth factor beta (TGF-β), and epidermal growth factor (EGF), to recruit inflammatory cells and promote the proliferation and migration of fibroblasts and keratinocytes. Next, the classical intrinsic and extrinsic coagulation pathways are activated to achieve coagulation and reinforcement of the platelet plug, stimulating fibrin formation, and creating fibrin strands in the wound. Under the action of factor XIII, the fibrin strands cross-link with each other, establishing a dense fibrin network and ultimately forming a thrombus at the wound site. The thrombus serves as a temporary matrix for wound healing, providing a scaffold for cell migration and protecting the wound from pathogen invasion [20, 21].

Inflammation This event promotes the expansion and recruitment of cells that are used to digest inactive tissues, foreign substances, and bacteria (neutrophils and macrophages) and initiates the next stage. The rapidly increasing Ca^{2+} concentration at the wound site, damage-associated molecular patterns (DAMPs), hydrogen peroxide (H_2O_2), lipid mediators, and chemokines released by injured cells serve as signals to recruit inflammatory cells [22, 23].

In the acute phase of a wound, neutrophils are the primary responding cells. They combat microorganisms through phagocytosis and subsequently release ROS and express matrix metalloproteinases (MMPs) and secrete cytokines that enhance inflammatory signals. Additionally, neutrophils release vascular endothelial growth factor (VEGF) to prepare for the proliferative phase [24, 25].

In the later stage of wound healing, monocytes, macrophages, and lymphocytes are the predominant cell types [24]. Monocyte infiltration into local tissues, followed by their differentiation, promotes an increase in the number of macrophages at the wound site. Pro-inflammatory macrophages (M1 type) produce ROS and pro-inflammatory cytokines [such as interleukin-6 (IL-6), tumour necrosis factor-alpha (TNF-α), and IL-1] to exert bactericidal effects; subsequently, M1 macrophages clear neutrophils by shedding and phagocytosing pathogens. Finally, driven by "cytokinesis" or other signals, M1 macrophages polarize to M2 type, and the wound gradually transitions to the proliferative phase [19, 21]. Macrophage polarization is crucial for subsequent wound healing.

Proliferation Fibroblast migration is a hallmark event that marks the onset of the proliferative phase. During the proliferative stage, granulation tissue formation, angiogenesis, and the establishment of re-epithelialization can be observed simultaneously [20, 26].

Formation of granulation tissue is closely related to fibroblast activity. Fibroblasts at the wound site originate from the proliferation and migration of fibroblasts at the wound edges, transdifferentiation of M2 macrophages, and differentiation of circulating fibroblasts [27]. Under the stimulation of cytokines released by platelets, macrophages, and alkaline fibroblasts, fibroblasts migrate to the injured area, synthesizing procollagen, proteoglycans, fibronectin, and hyaluronic acid to promote the formation of extracellular matrix (ECM) and scar tissue [19, 20]. At this stage, the new cells (such as macrophages) and other tissues (such as newly formed blood vessels) included in the granulation tissue will replace the thrombus from the first stage, becoming the new scaffold for the wound [20, 26].

Angiogenesis is another important process that occurs at this stage. Under moderate hypoxia, cytokines (such as VEGF, angiopoietin, and TGF), proteolytic enzymes, and endothelial cells are activated to induce angiogenesis [20, 26, 28].

Reepithelialization is primarily related to the migration and proliferation of keratinocytes at the wound edges. This process begins at the wound margins and continues until the opposite edges meet, adjacent to the development of the underlying granulation tissue. Once migration is complete, a basement membrane is formed [28]. This process is stimulated by various cytokines that are secreted by different cells. In turn, keratinocytes can produce signals that act on other cells to promote macrophage activation, granulation tissue formation, and angiogenesis, among other processes [20, 29].

Organizational restructuring The remodeling phase is the final stage of wound healing, with the primary goal of restoring normal tissue structure and enhancing the tensile strength of the tissue [30]. During this phase, type III collagen in granulation tissue is gradually replaced by type I collagen under the influence of factors such as transforming growth factor (TGF), fibroblast growth factor (FGF), platelet-derived growth factor (PDGF), and interleukin (IL). Additionally, under the action of proteases and their inhibitors, the ECM in the granulation tissue undergoes continuous growth and degradation, leading to rearrangement and repositioning, which alters its random distribution and subsequently increases the tensile strength of the tissue [31]. Driven by signals such as alpha-smooth muscle actin (α-SMA) and growth factors, some fibroblasts differentiate into myofibroblasts to promote matrix contraction [32]. Finally, most of the macrophages, myofibroblasts, and endothelial cells involved in wound repair gradually disappear through apoptosis, differentiation, or other unknown mechanisms [19, 30]. The duration of remodeling depends on the extent of the injury and may last from several weeks to several years.

Wound healing involves dynamic interactions between cells and other cells, signaling factors, tissues, blood vessels, and elements of the immune system. Each healing stage provides corresponding signals for subsequent stages, and there are varying degrees of overlap between the stages [3, 19]. Organisms protect themselves through complex processes. Research on these specific mechanisms relies on the efforts of many scientists. However, some mechanisms remain unclear and will be studied in depth in the future.

Factors affecting wound healing in chronic diabetes

Compared to typical and other types of chronic wounds, diabetic wounds have a complex microenvironment that disrupts the cascade healing process, leading to stagnation at certain stages [32]. For example, DFUs are one of the most severe complications of diabetes and are characterized by a complex pathogenesis and difficulty in treatment [30]. This is primarily due to the relatively complex microenvironment of DFUs, which includes

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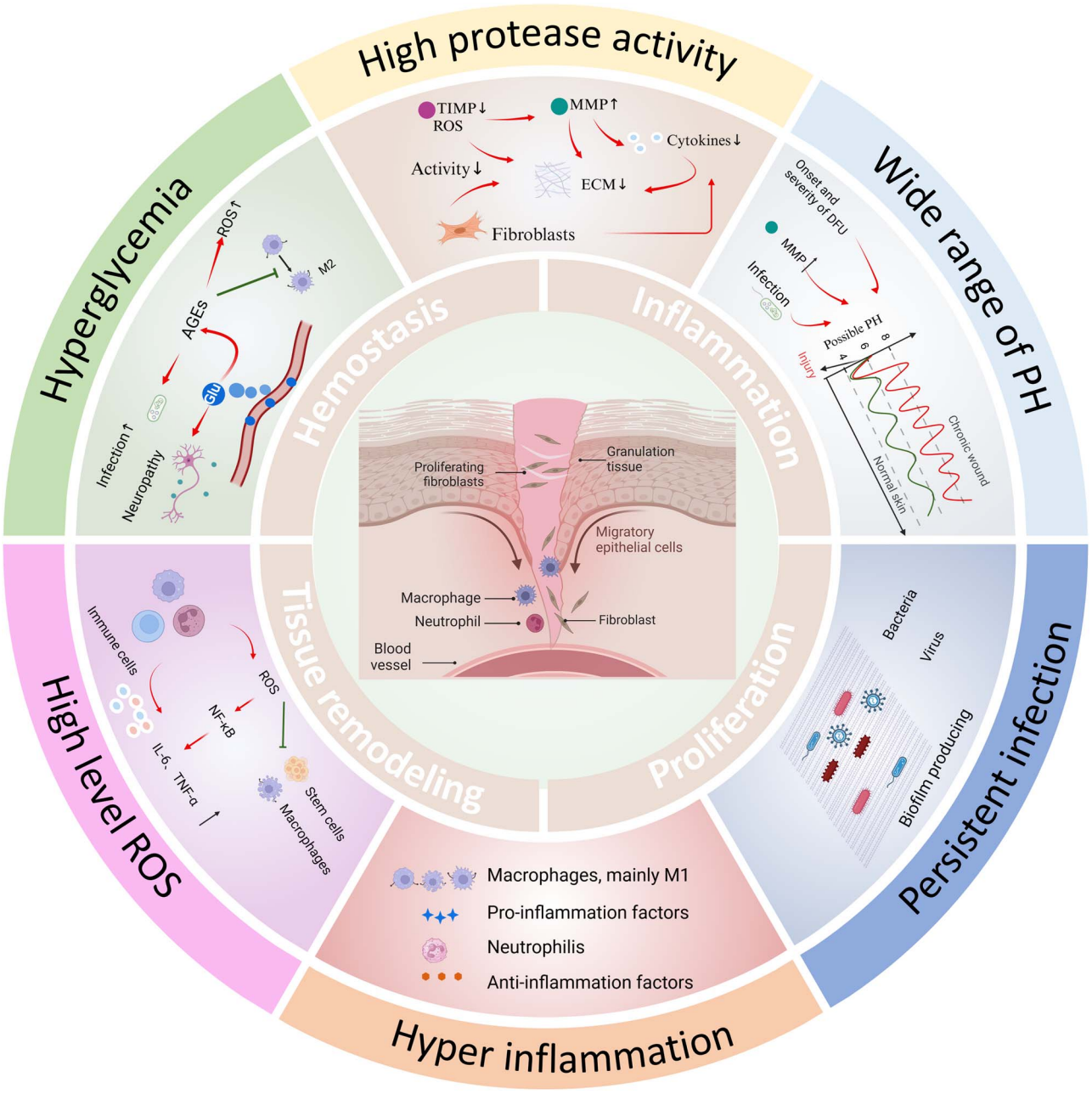


Figure 1 The complex microenvironment of chronic diabetic wounds, including hyperglycemia, high protease activity, high-level ROS, hyperinflammation, and persistent infection; these factors adversely affect the four stages of normal wound healing: hemostasis, inflammation, proliferation, and tissue remodeling. Copyright © 2025 by the authors. *MMP* matrix metalloproteinase, *TIMP* tissue inhibitors of metalloproteinases, *ROS* reactive oxygen species *ECM* extracellular matrix, *IL-6* interleukin-6, *TNF-α* tumor necrosis factor-alpha, *DFU* diabetic foot ulcer, *AGEs* advanced glycosylation end products

features such as hyperglycemia, ischemia, hypoxia, excessive inflammation, persistent infection [33], high protease activity [2], insufficient energy supply, local necrotic tissue [3], a wide range of pH changes [4] in the chronic phase (7.0–8.9), accumulation of ROS, and impaired angiogenesis and tissue regeneration [34]. Understanding the mechanisms and changes in these complex microenvironments is important for the research and development of current clinical smart dressings. Therefore, in this section, we discuss the microenvironmental characteristics of chronic diabetic wounds involved in the application of smart dressings, such as excessive inflammation, high metalloproteinase levels, high levels of ROS, and hypoxia (Figure 1), as well as how these microenvironments hinder the wound-healing process.

High blood sugar levels Clinical research indicates that high blood sugar levels at the site of injury lead to cellular and vascular damage, limiting proliferation and remodeling processes, and significantly increase the risk of bacterial infections. For example, abnormal glucose metabolism caused by high blood sugar can induce the production of advanced glycosylation end products (AGEs), which can directly activate immune cells, leading to high levels of ROS, ultimately

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resulting in increased oxidative stress, disruption of the redox balance of cells, and exacerbation of metabolic disorders in the wound area [35–38]. Additionally, AGEs inhibit the transition of macrophages from a typical pro-inflammatory activation (M1) state to an alternatively activated (M2) state with anti-inflammatory and tissue repair functions [39]. Excessive infiltration of M1 macrophages leads to the sustained accumulation and activation of pro-inflammatory cells at the lesion site, thereby prolonging the duration of inflammation [40]. Elevated blood sugar levels can cause cell membranes to harden and constrict blood vessels, reducing blood flow and depriving the wound area of nutrients and oxygen, thereby prolonging the healing process [41]. Higher blood sugar levels provide more nutritional resources for bacterial growth and proliferation, leading to recurrent bacterial infections [42].

pH value has a wide range and varies unpredictably The pH of the wound changes dynamically. During the wound-healing process, factors such as bacterial infection, enzyme activity, oxygen supply, and cell proliferation can cause fluctuations in pH levels [43]. To resist microbial invasion, the pH of intact skin is typically maintained within a mildly acidic range of 4–6 [43]. Starting from the surface, the pH of the skin gradually increases with depth, reaching ∼7.4 [44]. When the skin is damaged, the underlying subcutaneous tissue is exposed to a pH of 7.4, presenting a weakly alkaline condition; during the healing process, the pH usually shifts from alkaline to acidic. Owing to persistent inflammation, the pH of chronic and infected wounds often remains alkaline for extended periods, and prolonged healing times can also lead to a decrease in the pH of the wound bed [45]. Dissemond *et al.* [46] assessed the pH of 39 patients with chronic wounds due to various reasons and found that the pH values ranged from 5.45 to 8.65. Compared with normal skin, the initial pH of the chronic wound microenvironment is higher, which favors bacterial growth and reproduction, thereby increasing the risk of long-term bacterial infections [47]. It is worth emphasizing that the pH value of chronic wounds varies widely and is influenced by the time course and stage of the wound. For example, chronic wounds may also exhibit acidic pH values during the healing process. Therefore, the status of a wound can be predicted by monitoring its pH. Designing dressings that can accurately regulate the pH of diabetic wounds may significantly promote wound healing.

High-level reactive oxygen species Normal levels of ROS serve as second messengers for many immune and nonlymphoid cells, effectively promoting angiogenesis and resisting bacterial infections. However, prolonged elevated levels of ROS can lead to chronic inflammation and irreversible cell damage in the microenvironment, making wounds more vulnerable and inhibiting the functions of endogenous stem cells and macrophages, thereby hindering wound healing [48]. In diabetic wounds, inflammation induced by oxidative stress can result in the degradation of collagen and ECM, as well as impaired angiogenesis [49]. Additionally, the high levels of ROS produced by immune cells in the wound can activate the nuclear factor NF-κB, significantly increasing the expression of inflammatory mediators such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), leading to chronic inflammation and delayed wound healing. Therefore, maintaining appropriate levels of ROS at the wound site may help promote wound healing.

Overexpression of proteases MMPs play a dual role in wound healing in diabetes. MMPs are gelatinases produced in the dermis after injury and play a crucial role in degradation of the ECM and tissue remodeling during the healing process [50]. Studies have shown that the expression of tissue inhibitors of metalloproteinases is downregulated in DFUs, whereas signaling factors such as ROS, pro-inflammatory cytokines, and components of ECM lead to the upregulation of MMP expression [51–53]. However, excessive expression of MMPs can inhibit early connective tissue granulation and inactivate growth factors that are critical for the wound-healing process. The overexpression of ECM proteases in wounds reduces the accumulation of ECM in DFUs, hinders wound closure, and increases the risk of bacterial infection and chronic inflammation [20, 54]. Although scientists have demonstrated that the overexpression of MMPs (such as MMP-2 and MMP-9) impedes the wound-healing process [55], other studies have indicated that certain MMPs (such as MMP-8) are beneficial for diabetic wound healing [56]. Therefore, selective inhibition of MMP function is key to diabetic wound healing. Notably, the levels of active MMPs in the wounds of diabetic patients may differ significantly from those in the diabetic mice used in the experiments. These experimental results also suggest that attention should be paid to the differences between humans and experimental animals when designing responsive hydrogel wound dressings.

Excessive inflammation High blood sugar levels promote excessive inflammation in wounds. As mentioned earlier, AGEs induced by high blood sugar can upregulate the expression of pro-inflammatory factors (such as TNF-α, IL-1, IL-6) and promote the polarization of M1 macrophages. The presence of M1 macrophages further increases the levels of pro-inflammatory factors, leading to a vicious cycle between the infiltration of M1 macrophages and oxidative stress, which is a major factor in the persistence of inflammation [39, 40]. Additionally, during the inflammatory phase, high blood sugar levels inhibit the expression of chemokines, thereby delaying the migration of monocytes and macrophages to the wound site and hindering the timely clearance of neutrophils. This results in increased oxidative stress in the wound and exacerbated inflammation.

Additionally, as mentioned earlier, diabetic wounds experience persistent oxidative stress, which promotes the aging of fibroblasts, endothelial cells, keratinocytes, and mesenchymal stem cells, thereby hindering the normal healing process, including the formation of granulation tissue, blood vessels, and epithelial cells [57, 58]. Furthermore, chronic inflammation coexists with collagen damage and MMP overexpression, which together impede tissue remodeling [35].

Persistent infection The hypoxic environment and immune-inflammatory abnormalities caused by vascular lesions increase the incidence of persistent infections in chronic diabetic wounds [59]. In diabetic wounds, capillary damage and impaired angiogenesis lead to an insufficient oxygen supply, creating an environment conducive to bacterial infections. Simultaneously, hypoxia reduces the immune response and results in an inadequate energy supply for wound repair, further exacerbating bacterial infections [29]. In clinical practice, hyperbaric oxygen therapy is used when necessary to treat patients with diabetic foot to promote wound healing and reduce the risk of amputation. However, hyperbaric oxygen therapy remains an expensive

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treatment option [60, 61]. Therefore, it is important to design convenient and relatively inexpensive wound dressings that can improve the oxygen environment in wounds.

An environment of high blood sugar levels makes wounds more susceptible to infection [62]. Moreover, high blood sugar also affects the morphology and function of immune cells, specifically manifesting as a decrease in chemotaxis, phagocytic activity, and the microbial killing ability of immune cells [63].

Thus, microorganisms in the external environment (such as bacteria and viruses) and the microbiota of the organism itself (mainly bacteria) can colonize chronic wounds under the influence of various factors [64]. However, the accumulation and adhesion of multiple microorganisms can stimulate biofilm formation, and treating biofilms is significantly more challenging than treating infections caused by single microorganisms [65, 66].

Infections can hinder wound healing in multiple ways. Persistent infection stimulates the secretion of inflammatory factors (such as TNF-α) and proteases, which prolongs the presence of immune cells in the wound bed and disrupts the remodeling of the ECM. Additionally, microbial infection increases lactic acid accumulation in the wound and alters the pH level, both of which promote an unfavorable microenvironment for wound healing [67, 68]. More importantly, long-term infection poses a significant threat to skin healing, manifesting as adverse cell migration, impaired mitochondrial function, and the ultimate induction of apoptosis [69]. Therefore, wound dressings with antimicrobial properties are particularly important.

Electrospinning dressings

The ultimate goals of treating diabetic wounds are to promote wound healing, prevent wound infections and amputations, and improve the quality of life for patients. Long-term dynamic management is required to achieve good treatment outcomes in chronic diabetic wounds. Wound dressings are key components in diabetic wound treatment [70]. Therefore, based on the characteristics of diabetic wounds, an ideal wound dressing should possess the following features: (i) it should promote the tissue reconstruction process by providing insulation, facilitating gas exchange, increasing drainage, and removing debris; (ii) it should have good biocompatibility and should not cause allergic or immune reactions; (iii) it should effectively prevent secondary wound infections; (iv) it should be easy to remove without damaging the wound; and (v) it should be able to adapt to different stages of the microenvironment during the healing process of chronic diabetic wounds [71].

Traditional wound dressings such as gauze, bandages, and other inert dressings are most commonly used because of their simple production and low cost. These dressings not only effectively absorb exudate and provide a certain level of protection to the wound, but can also be safely used in conjunction with antibiotics to prevent and treat infections. However, traditional dressings do not directly promote wound healing. Additionally, dry dressings often adhere to the wound, causing secondary damage during dressing changes, which can prolong healing time and cause pain and other discomfort for the patient [72–74].

Considering the characteristics of ideal dressings, electrospun NFs, known for their high porosity, small pore size, and controllable properties, are believed to have significant potential in the field of advanced wound dressings. Nanomaterials are fibrous materials that possess two nanoscale dimensions within a 3D space. They can be synthesized using various methods including hydrothermal synthesis, template methods, and self-assembly. Among these techniques, electrospinning, which was first developed by Formhals in 1934 [75] for the preparation of ultrafine polymer fibers, has emerged as an important method for producing NFs. This is because of its simplicity, controllability, and cost-effectiveness, which have garnered widespread attention.

Theory

As a standard solution-spinning process, electrospinning technology utilizes electrostatic forces to elongate polymer solutions, resulting in the formation of fibers. Initially, a polymer solution or molten polymer must be positioned within an electrostatic field and injected into a jet device. Under the influence of a high-voltage electric field, the liquid experiences a charge imbalance, generating electrostatic forces that overcome the surface tension and cause the droplets to elongate into a Taylor cone at the nozzle. As the voltage increases, the electrostatic force intensifies, and when it reaches a critical threshold, the surface tension of the liquid is counterbalanced by the electric field force, resulting in the ejection of a filamentous substance from the Taylor cone. Initially, the jet is straight; however, owing to the electrostatic repulsion between the similar charges on the surface of the liquid, it subsequently undergoes an irregular, extremely high-frequency spiral motion. Throughout this process, the jet undergoes evaporation and charge dissipation, ultimately solidifying into a nonwoven fabric-like felt of fibers on the collection surface [76]. The process is influenced by various parameters, including the distance from the nozzle to the collector [77], type and concentration of solvent in the solution [78], ambient temperature and humidity [79], and type of spinning apparatus used.

Materials

With advancements in technology and evolving application demands, electrospinning technology has undergone continuous improvements and iterations. Materials currently in use include organic polymers, inorganic substances, and active materials. Nanomaterials with diverse structures and functions can be produced by precisely controlling the spinning process, making them suitable for various clinical applications.

Organic NFs, composed of natural and synthetic polymers, are the primary products of electrospinning. Synthetic organic polymers, such as polyethylene oxide (PEO), polyvinyl alcohol (PVA) [80], and polycaprolactone (PCL) [81], are particularly favored because of their straightforward processing, excellent mechanical properties, and good solubility in precursor solutions. However, they generally lack bioactivity, which limits their use. Thus, they are often employed as spinning assistants in blended spinning processes [82] or as encapsulating shells for drugs and other functional substances. Natural polymers generally exhibit superior biocompatibility compared to synthetic polymers. Natural polymers are less likely to induce immune reactions in wound dressings because of their resemblance to the original tissue components of the body [83]. Furthermore, many of these polymers have been extensively used to replicate the ECM, which enhances wound healing and provides antibacterial effects [84]. Natural polymers, including proteins (as collagen [85] and gelatin [86]), polysaccharides (such as hyaluronic acid

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[87] and chitosan [88]), and nucleic acids can all be involved in electrospinning. However, the physical characteristics of natural polymers, such as high surface tension, high viscosity, and inherent charge, often limit their applications in electrospinning. Consequently, they are often electrospun in conjunction with synthetic polymers [82] or modified physically and chemically. In addition, to a textile substrate, organic matter is frequently used as a carrier to achieve therapeutic, antibacterial, and monitoring functions. With advancements in coaxial electrostatic spinning and related technologies, limitations regarding the thermal stability, solubility, and other properties have been significantly reduced, thereby broadening the applications of organic matter in electrostatic spinning.

To meet the demands of emerging research fields focusing on smart materials that can respond to external stimuli, various inorganic materials have been integrated into electrospinning processes because of their conductivity, catalytic properties, and unique optical characteristics. The primary categories include metallic substances (such as metal salts and metal oxides), nonmetallic ceramic materials, and carbon NFs (CNFs). Preparing a viscous solution from inorganic precursors is challenging; therefore, the fabrication of inorganic nanomaterials typically involves combining them with organic polymers and postprocessing to achieve pure inorganic NFs. For instance, owing to the high hardness and melting point of metals, it is challenging to directly obtain viscous solutions suitable for electrospinning. However, pure metal NFs can be produced by lowering the melting point and sintering to eliminate organic solvents. In contrast, CNFs are primarily derived from the carbonization of precursor organic polymer fibers at elevated temperatures. These NFs can serve as carbon-based electrode materials for fabricating flexible capacitors, making them ideal energy supply devices for smart wearable technologies. Research has demonstrated that it is possible to modify the microstructure to enhance the performance or achieve specific functions by controlling the carbonization temperature [89], activating the carbon fiber membrane [90], and incorporating template solutions into the spinning solution [91]. Similar to the doping process used for the aforementioned organic materials, inorganic materials are frequently dispersed in polymer solutions to create composite NFs with unique light, electrical, and thermal properties.

Electrospinning is extensively used in the biomedical field, owing to its ability to create nanofiber scaffolds that replicate the ECM and facilitate tissue regeneration. To address the challenges posed by uneven cell distribution and inadequate penetration, Jayasinghe *et al.* first integrated living cells into NFs in 2006 [92]. They successfully maintained cell metabolism and proliferation for 6 days while incorporating active materials into the electrospinning process. Given the unique properties of the active materials, several factors must be considered to ensure their high viability. Certain solvents can damage cells, and the excessive shear force generated by solvents with high viscosity during the textile process can have detrimental effects [93]. Conversely, solvents with very low viscosities cannot be spun into silk; therefore, it is essential to select the appropriate polymer and solvent, as well as the optimal ratio of each component. During the textile process, electrospinning requires a sufficiently strong electric field; however, an excessively strong electric field can reduce cell activity [94]. Additionally, temperature and humidity not only influence fiber formation by affecting jet morphology but also impact cell activity [95]. The materials and parameters utilized in cell electrospinning differ, owing to the varying physiological environments and requirements of different tissues. Although numerous attempts have been made, limitations, such as poor mechanical properties and challenges in achieving effective 3D structures, persist and necessitate further research (Figure 2).

Characterization

Electrospinning products range in size from nanometers to microns and require scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for the characterization of their physical morphology, including shape, size, and structure, which are affected by many factors. By controlling the types and concentrations of solvents and polymers, environmental conditions such as temperature and humidity, and equipment parameters, including voltage and distance from the nozzle to the collector, the size and shape of the fibers can be precisely regulated. This tunability significantly enhances the versatility and adaptability of electrospinning [96]. Alterations in the fiber surface morphology, such as the presence of nanopores [97] and shish-kebab structures [98], can influence the crystalline properties, porosity, mechanical characteristics, and cell and matrix adhesion. These factors are of great significance in the field of biomedicine [99].

In addition, various electrospinning processes can create distinct internal structures in fibers, including putaminal, Janus, and hollow structures. Coaxial electrospinning produces fibers with a putaminal structure in which one polymer envelops another. Furthermore, three-axis electrospinning yields fibers with a three-layer structure consisting of a core, a sandwich layer, and a shell [100]. The significance of this structure lies not only in its ability to incorporate a variety of materials into a single fiber but also in its capacity to spin materials such as bioactive substances that cannot be directly spun into silk as the internal flow liquid. This innovation significantly expanded the range of selective materials [101]. Additionally, the shell structure effectively controls the diffusion of the contents [102] and plays a protective role [103] by enabling the efficient loading and slow release of drugs. Thus, it is an attractive drug delivery system. The Janus structure is characterized by two surfaces of a fiber membrane exhibiting contrasting physical or chemical properties, often with asymmetric hydrophilicity and hydrophobicity. This structural configuration is advantageous for fluid-transport applications [104]. Such a fiber structure can be achieved through techniques such as side-by-side electrospinning [105] and double-layer synthesis, which involve the sequential weaving of two layers of fiber cloth composed of hydrophobic and hydrophilic materials, followed by the surface treatment of the electrospun fibers.

Nanoscale fibers produced by electrospinning can be organized into a complex 3D network structure that effectively mimics the ECM. When combined with biological materials and optimized technical parameters, this structure facilitates cell attachment, proliferation, and migration, thereby promoting tissue repair and regeneration [106]. The high porosity of this network, characterized by interfiber gaps resulting from residual charges on the fibers, enhances the specific surface area. This increased surface area provides sites for cell adhesion and loading of functional particles such as pharmaceuticals, and ensures wound permeability and exudate absorption while regulating water

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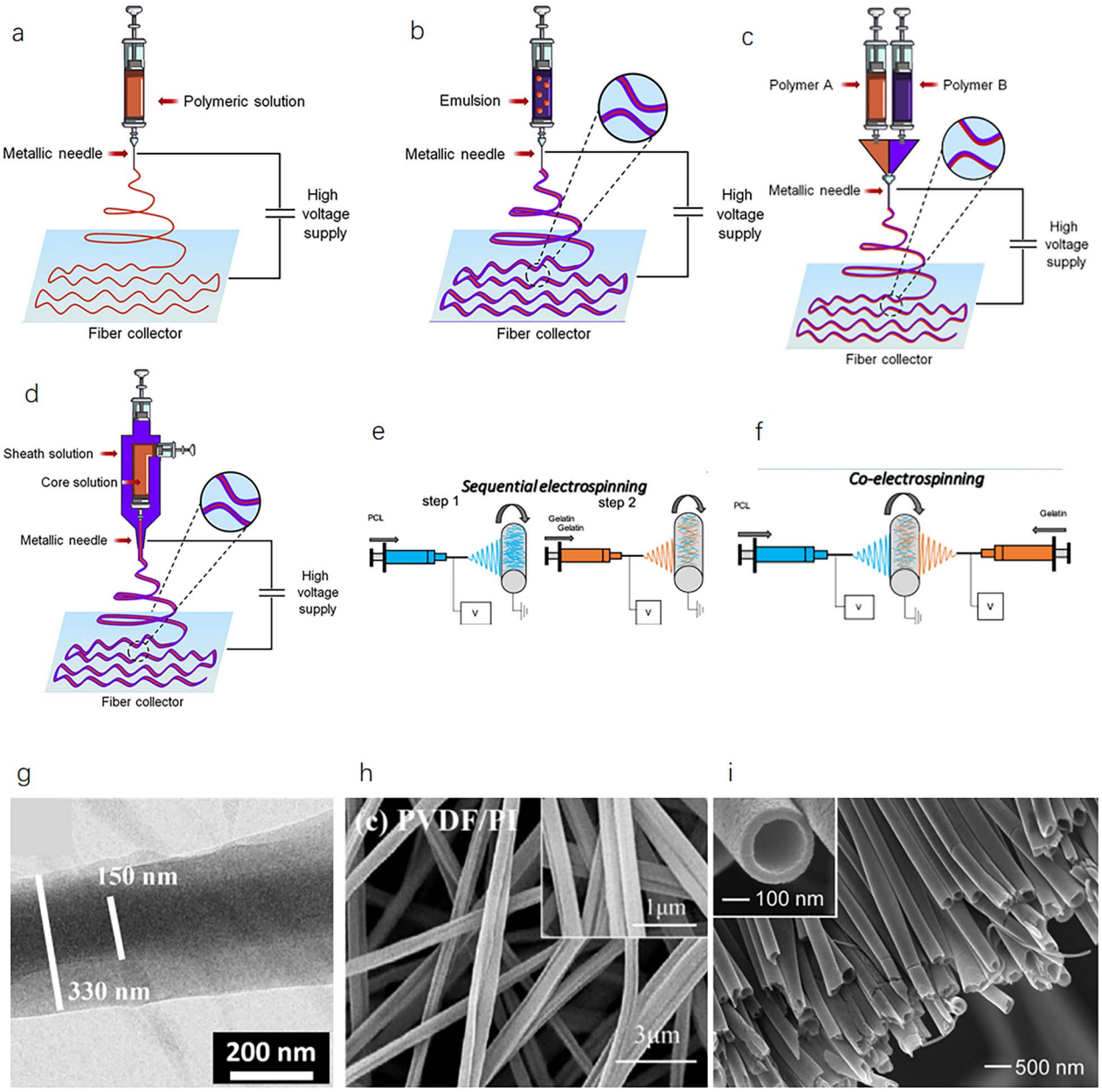


Figure 2 Fabrication and characterization of electrospun nanofiber. (**a**) Single nozzle electrospinning. (**b**) Single nozzle electrospinning with emulsion. (**c**) Side-by-side nozzle electrospinning. (**d**) Coaxial nozzle electrospinning. Reproduced with permission from ref [112]. Copyright 2019, Journal of Controlled Release. (**e**) Sequential electrospinning. (**f**) Simultaneous electrospinning. Reproduced with permission from ref [113]. Copyright 2024, RCS Advances. (**g**) TEM of unstained samples of co-electrospun PEO (shell) and PDT (core). Reproduced with permission from ref [114]. Copyright 2003, Advanced Materials. (**h**) SEM images of PVDF/PI. Reproduced with permission from ref [115]. Copyright 2019, Nanomaterials. (**i**) SEM image of a uniaxially aligned array of anatase hollow fibers that were collected across the gap between a pair of electrodes. Reproduced with permission from ref [116]. Copyright 2004, Nano Letters

evaporation to maintain a moist wound environment [107]. Moisture retention is crucial for preventing dehydration and for fostering angiogenesis and collagen synthesis [108]. Furthermore, the elevated porosity, in conjunction with the nanoscale diameter of the fibers, imparts the electrospun fiber film with properties such as low density and deformability. These characteristics facilitate the development of thin, soft, and breathable dressings that conform to the natural movements of the human body, thereby alleviating the discomfort associated with prolonged application of dressings for chronic wounds [109]. The porosity of the fiber membranes was quantified by assessing the volume of alcohol absorbed after immersion in the membrane for 1 h [110].

In addition to demonstrating high porosity, the nanoscale pore sizes of these membranes facilitate their function as effective drug-loading sites, while concurrently establishing a natural barrier that impedes bacterial contamination, thus preventing wound infections. Research has shown that when the interfiber pore size is $<$800 nm, $>$95% of the bacteria can be effectively isolated. The reason is that the revision enhances

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clarity and maintains academic tone by using precise language and improving sentence structure [111].

Fabrication of responsive nanofibers

Recently, responsive dressings based on the changes in the microenvironment of diabetic wounds have been developed. These dressings dynamically sense changes in environmental stimuli and respond accordingly by adjusting their physicochemical properties, similar to the self-regulation and adaptability of biological systems in nature [73]. If the molecular structure is carefully designed and applied to DFU dressings, these dressings can respond to various stimuli, such as environmental temperature, pH, light, ions, molecules, electric fields, and acoustic fields, thereby promoting the healing of chronic wounds in diabetes.

Various electrospinning technologies have been developed to produce functional NFs to accommodate a growing diversity of applications. Among these, the fabrication of smart electrospinning fibers—capable of responding to external environmental changes—has emerged as a significant area of advancement. The production of smart electrospinning NFs typically entails the incorporation of responsive materials into traditional electrospinning processes. This integration can occur either through the direct application of materials during the electrospinning process or by doping the fibers through subsequent postprocessing techniques [117].

Responsive element

Responsive materials are defined as substances that alter their structural, physical, or chemical properties in response to changes in the external environment. These materials facilitate the direct or indirect conversion of target monitoring parameters, such as temperature and pH, into observable indicators or forms that can be further transformed into other types of signals (Figure 3). The observed changes may arise from alterations in the molecular structure of the material, such as isomerization, which subsequently affect other properties. These changes may also result from interactions between the materials, as exemplified by the carboxyl esterification reaction between polyacrylic acid (PAA) and PVA in response to variations in pH [118]. Furthermore, physical properties such as the ability of magnetic particles to sense magnetic fields may also contribute to these changes [119].

Responsive functional group Functional groups are defined as assemblies of atoms that influence the chemical properties of an organism. These groups may also react to chemical or physical stimuli in the environment owing to their distinct structural configurations or atomic compositions.

Ionizable groups, including carboxyl and amino groups, have been extensively utilized as pH-responsive materials. As the pH was varied, the equilibrium of the polymer ionization reaction shifted. Deprotonation of these functional groups alters their electric charge, which subsequently affects the conformation and structure of the polymer chain. This phenomenon manifests as pH responsiveness at the macroscopic level [120]. Using this principle, Tan *et al.* [121] developed a PVA/PAA electrospun dressing loaded with epigallocatechin gallate (EGCG). In chronic wounds, bacterial infections typically result in an alkaline pH within the wound environment. The ionization of PAA, which contains a significant number of carboxyl groups, was leveraged in this scenario. This ionization influences the hydrogen bonding interactions between the catechol and carboxyl groups of PAA, facilitating the expansion of the dressing and the subsequent release of the drug encapsulated within the fibers. As the pH decreased with the resolution of the infection, the ionization of PAA diminished, leading to a reduction in drug release. This mechanism allows for the controlled release of EGCG, thereby accommodating varying stages of wound healing.

Isomerization is defined as the rearrangement of atoms or groups within a molecule, leading to alterations in its structure and properties. This process can be classified as either reversible or irreversible. Notably, reversible isomerization has significant potential for application in the development of intelligent wound dressings that require continuous monitoring. Numerous photochromic groups exhibit isomeric transformations in response to light, including the trans-structure of azobenzene and ring opening of spirulina, which facilitate photochromism [123].

The unique structural characteristics of certain functional groups facilitate electron transfer, which can be observed through phenomena such as fluorescence quenching and conductivity. Wu *et al.* [124] encapsulated europium (III) coordination polymers (Eu CPs), synthesized via a hydrothermal method using Eu(NO3)3·6H2O and 2,2-thioacetic acid (TDA) as precursors, within a polyacrylonitrile (PAN) nanofiber mat. They employed the S=O group to facilitate electron transfer to Eu3+, leading to alterations in the coordination environment of the Eu3+ ions, resulting in fluorescence changes. The variation in H_2O_2 concentration was monitored linearly through changes in fluorescence intensity.

Intermolecular interaction Molecules lacking specific functional groups may demonstrate diverse interactions with one another under varying external conditions, whether physical or chemical, thus achieving responsiveness at the macroscopic level.

In comparison to chemical bonds, interactions between molecules are relatively weak and more susceptible to influences from the external environment, making them advantageous for environmental monitoring applications. A notable example of this phenomenon is water-soluble thermoresponsive polymers, which form hydrogen bonds with water molecules at low temperatures, thereby exhibiting hydrophilicity. As the temperature increased, these hydrogen bonds were disrupted, leading to dehydration and a transition to hydrophobicity, accompanied by changes in volume. The temperature at which this phase transition occurs is referred to as the lower critical solution temperature (LCST). Given that the normal surface temperature of the human body is relatively constant, it is essential for thermal response materials applied to the human body to be calibrated to this critical temperature in order to effectively monitor temperature fluctuations at any given time. The LCST is significantly influenced by the affinity between the polymer and water, which can be modulated by the incorporation of hydrophobic and hydrophilic materials [125]. Poly(*N*-isopropyl acrylamide) (PNIPAAm) is widely recognized as the most extensively utilized thermoresponsive material, exhibiting solubility below its LCST of ∼32°C and becoming insoluble above this threshold. However, owing to its solubility in water, the direct formation of a polymer suitable for electrospinning is challenging. Consequently, it is often necessary to incorporate additional substances to facilitate crosslinking, thereby

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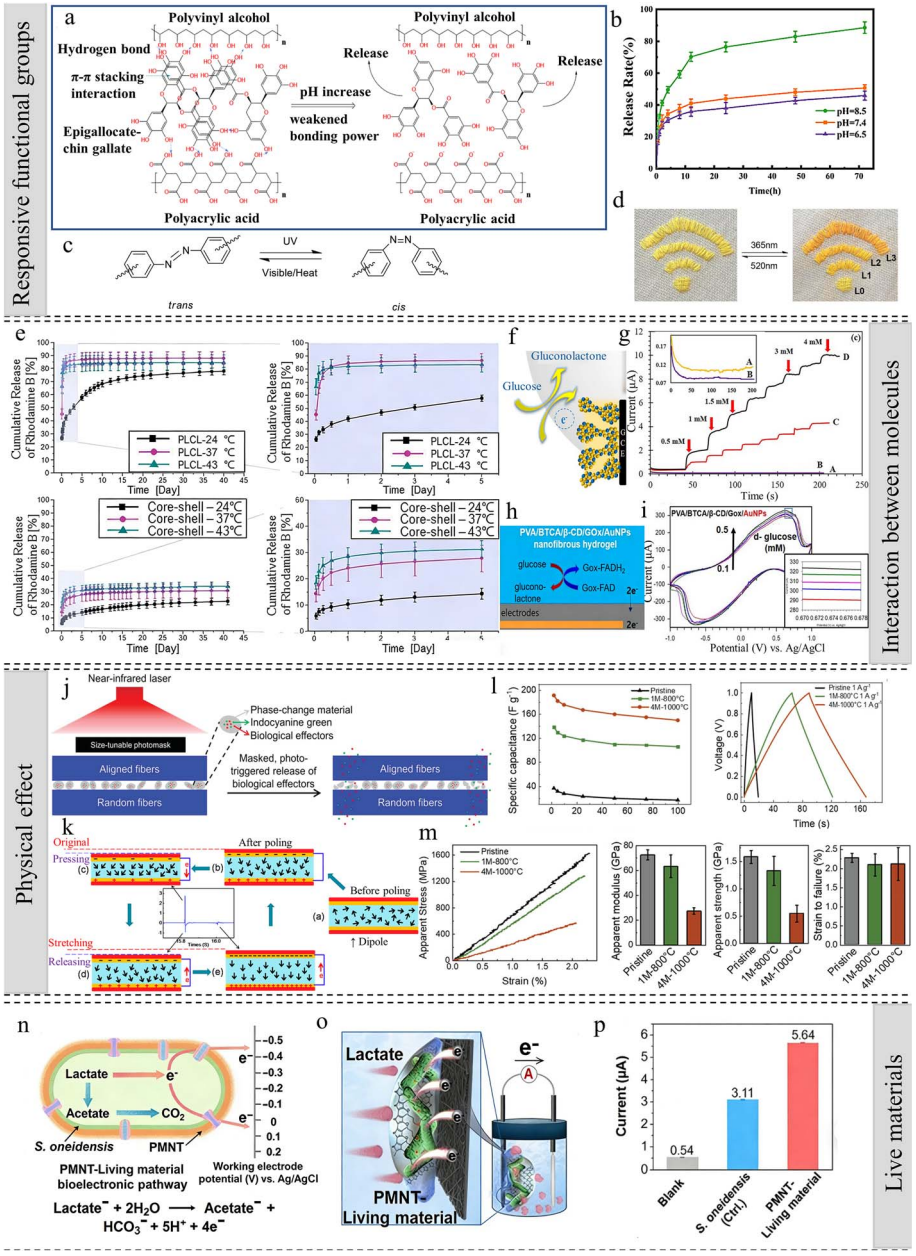


Figure 3 Functionalization methods and principles of responsive material. (**a**) Mechanism of EGCG release in PVA/PAA/EGCG nanofiber membranes. (**b**) The EGCG release profiles from nanofibrous membranes under different pH values. Reproduced with permission from ref [121]. Copyright 2023, Materials and Design. (**c**) Reversible trans-*cis* isomerization of azobenzene derivatives. (**d**) Introduction of the photochromic fiber as a flexible UV indicator on soft substrate (L0: no UV, L1:15 mW/cm^2 for 30 s, L2: 45 mW/cm^2 for 30 s, L3, 75 mW/cm^2 for 30 s). Reproduced with permission from ref [122]. Copyright 2022, Surfaces and Interfaces. (**e**) Cumulative release of PLCL fibers and P(NIPAAm-co-NIPMAAm)-PLCL core–shell fibers incubated at 24°C, 37°C, and 43°C for up to 41 days. Reproduced with permission from ref [127]. Copyright 2020, Advanced Materials. (**f**) CuO/ZnO-DSDSHNM non-enzymatic biosensor for the determination of glucose in human blood samples. (**g**) The curves of (A) bare GCE, (B) Nafion/ZnO-MS/GCE, (C) Nafion/CuO-MS/GCE, and (D) Nafion/CuO/ZnO-DSDSHNM/GCE by successive addition of 0.50 mM of glucose to the final concentration of 4 mM. The inset plot of (C) is the magnified view of the (A) bare GCE and (B) Nafion/ZnO-MS/GCE by successive addition of glucose in the range of 0.50–4 mM. Reproduced with permission from ref [128]. Copyright 2021, Scientific Reports. (**h**) Schematic illustration of the patch-type glucose sensor using PVA/BTCA/β-CD/GOx/AuNPs NF hydrogels on electrodes. (**i**) CVs of PVA/BTCA/β-CD/GOx/AuNPs at varied absorbed D-glucose concentrations (0.1–0.5 mM) at pH 7.4 and 25°C; scan rate: 0.1 V s-1 and amperometric responses to successive addition of D-glucose (0.1–0.5 mM) at—0.2 V (*vs* Ag/AgCl) on the PVA/BTCA/GOx. Reproduced with permission from ref [132]. Copyright 2020, Scientific Reports. (**j**) A schematic illustrating how to mask the photo-triggered release of biological effectors from a scaffold by irradiation with an NIR laser. Reproduced with permission from ref [133]. Copyright 2020, Small Methods. (**k**) The work mechanism of the PNG device. Reproduced with permission from ref [138]. Copyright 2016, Applied Materials and Interfaces. (**l**) Galvanostatic charge/discharge curves for pristine, 1 M-800°C, and 4 M-1000°C porous CNFs with a current density of 1 A g-1 and IR drop (voltage drop due to the equivalent series resistance) for pristine, 1 M-800°C, and 4 M-1000°C porous CNFs with different current densities. (**m**) Stress–strain curve for pristine, 1 M-800°C, and 4 M-1000°C porous CNFs, and apparent modulus, apparent strength, and strain to failure for pristine, 1 M-800°C, and 4 M-1000°C porous CNFs. Reproduced with permission from ref [90]. Copyright 2019, Advanced Functional Materials. (**n**) Schematic diagram of electron transport pathway in PMNT-living material. (**o**) Schematic carton diagram for detecting system of PMNT-living material with improved electrogenic property. (**p**) The magnitude of currents generated by the detecting system in the absence of different elements. Reproduced with permission from ref [137]. Copyright 2022, Science Advances

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establishing a stable fibrous structure. Chen *et al.* [126] copolymerized and cross-linked PNMA to produce heat-sensitive fibers characterized by an elevated LCST, which demonstrated reduced solubility in water and exhibited significant volumetric changes. These fibers were subsequently employed in applications related to controlled drug release [127].

The interactions among molecules extend beyond intermolecular forces to include chemical reactions such as redox and electrochemical reactions, which can be utilized to monitor specific environmental substances. Haghparas *et al.* [128] developed a dual-shell hollow porous nanostructure composed of CuO/ZnO and employed electrochemical reactions to create glucose biosensors that exhibited superior performance. Similarly, numerous studies have investigated other transition metal oxides, including CuOx/NiOy [128] and NiO [129], for nonenzymatic monitoring of glucose levels. Tang *et al.* [130] designed ROS-responsive nanoparticles based on poly(1,4-benzophenone divinyl sulfide alcohol) (PPADT). In conditions of elevated inflammatory response, elevated ROS levels disrupt the sulfide bonds, leading to the depolymerization of PPADT and the subsequent release of SDF-1α, which facilitates the targeted delivery of macromolecular drugs.

A diverse range of intermolecular interactions is prevalent within the human body, establishing various pathways that serve to transmit signals. These macromolecular substances demonstrated favorable responsiveness and biosafety, highlighting their potential applications as responsive materials in the field of smart dressings. Kim *et al.* [131] used electrospun hydrogels containing glucose oxidase (GOx) to achieve high sensitivity in glucose detection, while also exhibiting commendable mechanical properties and stability, thereby highlighting their significant potential for noninvasive glucose monitoring.

Physical effects Most temperature-responsive systems are based on the contraction behavior of thermosensitive polymers at the LCST or UCST; however, studies have utilized the simple physical phenomenon of the material melting point to design temperature-responsive drug delivery systems. Xue *et al.* [132] used a phase-change material (a mixture of lauric acid and stearic acid with a melting point of 39°C) to encapsulate functional substances, which were released upon laser heating.

Piezoelectric materials can generate charges when subjected to mechanical pressure or stress and can also deform under electric stimulation, completing a bidirectional change of the force-electrical signal, which has been applied in the biomedical field for the measurement of blood pressure, intracranial pressure, etc. Common piezoelectric materials are piezoelectric ceramic materials with high electrical performance, such as lead zirconate titanate (PZT), sodium niobate (KNN), and lead zirconate titanate barium titanate (BZT). However, owing to the requirement for mechanical flexibility in wearable device sensors to avoid tissue damage, organic polymers such as poly(vinylidene fluoride) (PVDF) and polylactic acid (PLA) are also used in flexible piezoelectric sensors. The piezoelectric effect arises from the generation of electric dipoles by the displacement of the positive and negative charge centers in the material under stress and can be imparted to most crystalline materials with random crystal structures by repolarization, i.e. by applying a high electric field at a high temperature to reorient the electric dipoles and then cooling to maintain the orientation [133]. Shan *et al.* [134] prepared PLLA NFs doped with barium titanate by electrospinning, which demonstrated good piezoelectric properties and integrated a wireless module using a Mo-based degradable coating as the electrode, showing reliable *in vivo* sensing performance.

In addition to being stimulation-responsive materials, with the development of wearable devices, conductive NFs can be used for electrical stimulation therapy, electrical signal conduction, and energy storage, and are considered to have wide application prospects. Common conductive fiber materials include carbon nanoparticles, silver nanoparticles, and metal salt ion solutions, which can be used in electrospun fibers by the doping, grafting, and carbonization of organic fibers.

In 2017, Park *et al.* [135] prepared sterling silver NFs by dispersing silver nanoparticles into ethylene glycol solvents for electrospinning, which can be used to rapidly produce large-area, stretchable transparent conductive electrodes. The team used these materials to prepare transparent heaters and integrated them into batteries and Bluetooth modules. Proving development potential in the field of wearable smart devices. CNFs obtained from electrospun fibers have also been widely used owing to their high specific surface area, good electrical conductivity, and stability. Chen *et al.* [90] obtained electrospinning using polyacrylonitrile (PAN)/PMMA as the shell and PMMA as the core. During the carbonization process, PMMA was vaporized to obtain hollow and porous CNFs with good energy storage and mechanical capabilities.

Living materials Biomaterials are a mixture of biological and abiotic components. The biological components, including bacteria, cells, and algae, provide material with unique functional properties, while the nonbiological part protects biological elements from extreme environments such as low temperatures, high salinity, and lack of water, providing an innovative strategy for the development of bioelectronic devices [136]. Wang *et al.* [137] used *Shewanella oneidensis* MR-1 in conjunction with the cationic conjugated polymer PMNT to develop biomaterials. This approach involves the oxidation of lactic acid to generate electrons via the natural respiratory processes of bacteria. Furthermore, the conductive PMNT were integrated with electronic devices to facilitate the wireless monitoring of lactic acid levels in physiological fluids such as sweat, urine, and plasma.

Modification of electrospun nanofibers

Certain responsive materials can be utilized in electrospinning; however, many are not easily adapted for the process. Therefore, it is essential to implement intelligent functions through substrate-based functionalization. Modification is one of the most frequently employed functionalization methods and encompasses both chemical modifications, such as copolymerization, and physical modifications, including material mixing and composite formation (Figure 4).

Blending modification Blending modification represents a relatively straightforward method for fiber modification and is characterized by the cospinning of responsive materials or other functional substances integrated into polymer solutions [139]. The robust mechanical properties of NFs contribute to the stability of these functional substances, whereas their high surface area facilitates the complete diffusion of stimuli, resulting in a rapid and adequate response [140]. This mixed modification technique can be categorized into two types based on the method

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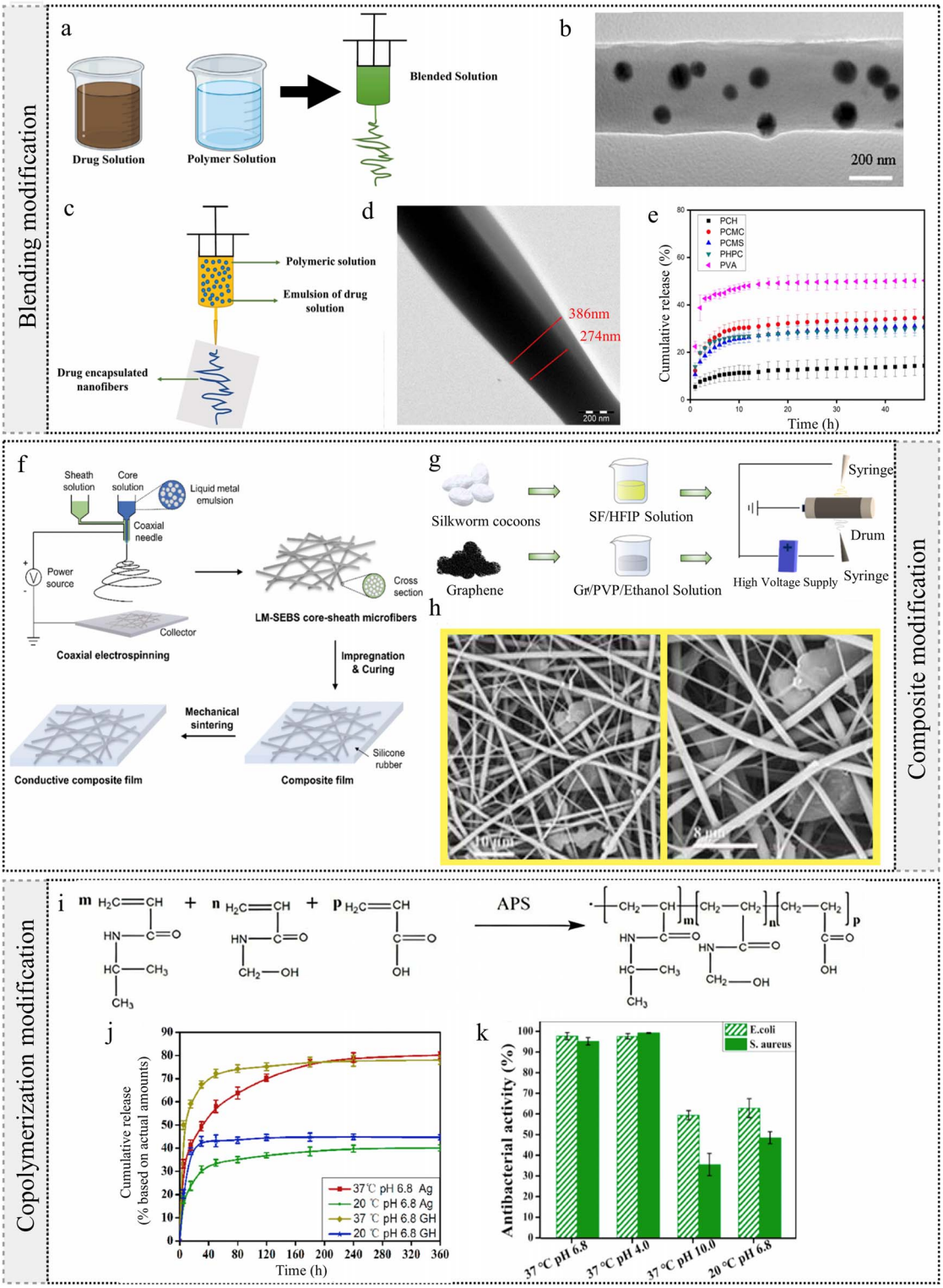


Figure 4 Modification of electrospun nanofibers. (**a**) Blend electrospinning. (**b**) TEM images of the Cu/CNF composite film. Reproduced with permission from ref [142]. Copyright 2023, Journal of Electronic Materials. (**c**) Emulsion electrospinning. Reproduced with permission from ref [141]. Copyright 2023, International Journal of Biological Macromolecules. (**d**) TEM images of PHPC (PVA/HPC). (**e**) *In vitro* drug release from PVA/biopolymer blends: PCH, PCMC, PCMS, PHPC, and PVA. Reproduced with permission from ref [147]. Copyright 2021, Journal of Macromolecular Science. (**f**) Fabrication procedure of LMFCs. The LM-SEBS microfibers are produced by coaxial emulsion electrospinning with an LM-rich core fluid and a SEBS sheath fluid. A composite film is obtained by impregnation of electrospun LM-SEBS fiber mats with silicone rubber. Mechanical sintering is used to activate the electrical conductivity of the composite film. Reproduced with permission from ref [101]. Copyright 2019, Chemical Reviews. (**g**) Schematic diagram of preparing (silk fibroin/graphene) (SF/gr) nanofiber membrane by electrospinning. (**h**) SEM images of SF/gr nanofiber membranes, the concentration of gr is 20 mg/ml, magnified 5000 and 10 000 times, respectively. Reproduced with permission from ref [151]. Copyright 2022, Polymers. (**i**) Synthesis routes of PNIPAm-NMA-AAc copolymers. Reproduced with permission from ref [153]. Copyright 2021, Journal of Colloid and Interface Science. (**j**) GH and Ag release curves of PNIPAm-NMA-Ac GH + Ag fibrous membranes at 37°C and 20°C. (**k**) the antibacterial activity of PNIPAm-NMA-Ac GH + Ag fibrous membrane in a different environment at 37°C and pH 6.8, 37°C and pH 4.0, 37°C and pH 10.0, 20°C and pH 6.8 for 2 h. Reproduced with permission from ref [141]. Copyright 2023, International Journal of Biological Macromolecules

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of incorporating composite materials into the precursor solution: mixed electrospinning and emulsion electrospinning. In mixed electrospinning, additives, such as pharmaceuticals, are directly dissolved or dispersed within the polymer matrix. Conversely, emulsion electrospinning involves the extraction of bioactive substances into the oil phase, thereby addressing the issue of explosive release, which may arise from insufficient solute dissolution [141]. Both the techniques employ single-needle electrospinning. Furthermore, the incorporation of additives into a polymer solution is not restricted to a single substance; multiple additives can be introduced simultaneously to elicit fiber responses to various stimuli. Additionally, other functional substances may be integrated concurrently to enhance fiber performance or facilitate a series of tandem responses.

Numerous studies have demonstrated that the incorporation of metal particles or metal oxides, which are typically integrated into fibers via direct mixing because of their insolubility, can enhance the functionality of CNFs. Zhang *et al.* [142] established that the addition of 30%–40% copper acetate to a polyacrylonitrile (PAN) solution significantly improved the flexibility and conductivity of the resulting fibers. Ramanan *et al.* [143] introduced gold nanorods (AuNRs) into PNPA during electrospinning. These AuNRs exhibit photothermal effects. The heat generated by the gold nanorods in the near-infrared region caused the temperature-responsive polymer fibers to contract, resulting in an increased fiber gap and enhanced fiber film density, indicating their potential for application in photocontrolled drug release. Wang *et al.* [144] prepared NFs by creating suspensions of paramagnetic nanoparticles in PVA and confirmed that these fibers exhibited paramagnetic properties, which enhanced their mechanical characteristics. In addition, certain responsive material precursors can be incorporated into the precursor solution to facilitate the *in situ* synthesis of responsive materials under suitable conditions. Burke *et al.* [145] successfully synthesized *in situ* magnetic nanoparticles during electrospinning by adding metal salts to a mixed solution of polyethylene oxide (PEO) and polyvinylpyrrolidone (PVP), which is considered applicable in glucose sensing and other related fields [146].

The shell-core structure can be synthesized using water-soluble polymers loaded with hydrophobic drugs. This approach effectively addresses the issue of rapid drug release associated with direct mixing and offers advantages in terms of cost-effectiveness and operational simplicity compared with coaxial electrospinning techniques. Hameed *et al.* [147] combined PVA with a biopolymer to produce shell–core NFs, with cephalosporins serving as the core, using a straightforward single-nozzle emulsion electrospinning method. This technique facilitates slow drug release *in vitro*.

Composite modification In addition to the direct incorporation of responsive materials into the polymer solution, various components within the fiber can be segregated to create a specific structure; this process is referred to as composite modification. Composite modification can be accomplished using techniques such as coaxial and side-by-side electrospinning.

Coaxial electrospinning employs concentrically aligned coaxial spinnerets to simultaneously spin two distinct materials, resulting in the formation of coaxial shells or hollow-structured NFs. This technique facilitated controlled release and packaging [101]. Liquid metal (LM), particularly based on gallium (with a melting point of 29.8°C), is a novel functional material that can be alloyed with other metals to create low-melting-point alloys. These alloys exhibit excellent fluidity, high electrical conductivity, and favorable biocompatibility, making them promising candidates for application in flexible electronic devices, particularly in wearable technology [148] [149]. Ma *et al.* [150] integrated emulsion electrospinning with coaxial electrospinning using a styrene–ethylene–butene–styrene block copolymer (SEBS) as the sheath fluid and an LM-SEBS emulsion as the core fluid to fabricate LM NFs. This approach successfully addressed the challenges related to the surface/interfacial tension, viscosity, and fiber strength associated with LM, ultimately resulting in the formation of a conductive pathway following mechanical stress treatment.

The multinozzle electrospinning technique enhances the production efficiency of NFs by increasing the number of needles, holes, and tips, thereby enabling the simultaneous fabrication of fiber films composed of multiple materials. Liu *et al.* [151] employed two syringes to simultaneously introduce solutions A (SF/HFIP) and B (graphene/PVP/ethanol) for electrospinning, resulting in the creation of a filament-in-graphene nanofiber film characterized by a three-dimensional (3D) structure. The film was subsequently encapsulated in polydimethylsiloxane (PDMS) for use as a flexible pressure sensor. The 3D architecture generated by electrospinning contributes to the stability and overall performance of the sensor.

Copolymerization modification The responsiveness of numerous responsive materials is attributed to specific functional groups such as hydroxyl and carboxylic groups found in pH-sensitive materials. To enhance the properties of fiber substrates, certain additives are copolymerized under controlled conditions, thereby imparting these functional groups to the fibers and endowing them with responsive properties. Wei *et al.* [152] conducted a study in which they copolymerized thermally responsive materials, namely, *N*-isopropylacrylamide (NIPAM), *N*-methylacrylamide (NMA), and pH-responsive acrylic acid (AAc) via free radical copolymerization. This process resulted in the formation of a polyn-isopropylamide-*N*-methylacrylamide-acrylic acid (PNIPAm-NMA-AAc) fiber film that exhibited both thermal and pH responsiveness. Similarly, Nezhadghaffar-Borhani *et al.* [153] synthesized nanoparticles containing spiral pyranoid groups by copolymerizing styrene, butyl acrylate (BA), and ethyl acrylate (SPEA). Photostimulation-induced isomerization of spiral pyranoid groups led to alterations in the hydrophilicity of the fibers, resulting in the production of photoresponsive NFs.

Post processing empowerment

Fibrous membranes that lack inherent responsiveness are frequently endowed with monitoring capabilities through a series of post-treatment processes. These processes typically involve the incorporation of responsive components or the modification of their surfaces with responsive materials.

Surface coating The application of functional material coatings on the surfaces of electrospun fibers represents a straightforward and efficient approach to postprocessing these fibers. Immersion and spraying are the predominant techniques employed for surface coating. The substantial surface area of electrospun fibers facilitates the interaction and adsorption of functional nanoparticles with specific functional groups present on the fiber surface.

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Utilizing a straightforward immersion coating technique, Soares *et al.* [155] heated a HAuCl4 solution to 90°C and subsequently introduced a sodium citrate solution while maintaining vigorous stirring and continuous heating. This process facilitates the formation of citrate-functionalized AuNPs. The NFs were immersed in this solution for 12 h to allow the adsorption of nanoparticles onto the fiber surface through hydrogen bonding and electrostatic interactions. The presence of AuNPs, which serve as active sites, enhances the conductivity, thereby generating a substantial electrical response that amplifies the signal and improves the sensitivity of the immunosensor. Similarly, Sun *et al.* [156] immersed CNFs in a solution containing cobalt and nickel and subsequently deposited metals onto the fibers via a hydrothermal method. This approach yielded NiCo2O4/CNF composite materials that demonstrated superior electrochemical performance.

The bonding of the fibers and coating materials primarily relies on physical adsorption and electrostatic interactions, resulting in an unstable connection that adversely affects the sensitivity and longevity of the material. To address this issue, advanced technologies such as surface polymerization coating and ultrasonic anchoring have been developed, building on traditional coating methods to enhance the stability of adsorption. Research has indicated that the polymerization of poly(3,4-ethylenedioxythiophene) (PEDOT) onto the surface of fiber substrates coated with graphene oxide (GO) can significantly broaden the sensing range of the sensor and substantially increase its repeatability [157]. During ultrasonic treatment, the collapse of bubbles within the fiber generates brief high temperatures, micro-jets, and shock waves, which may facilitate a more secure anchoring of nanoparticles onto the surface of electrospun fibers [158, 159]. Luo *et al.* [160] conducted an experiment in which an electrospun polyurethane (PU) fiber pad was immersed in a suspension of multi-walled carbon nanotubes (MWCNTs) and subsequently coated with MWCNTs via high-power ultrasonic treatment. The resulting composite fiber pad demonstrated high sensitivity to external mechanical stimuli, favorable linear response to temperature variations, and high durability and stability. This composite is expected to have promising applications in physiological signal monitoring and wearable electronic devices.

Blending modification Chemical grafting is a process that typically employs specific chemical reagents to covalently bond responsive materials to fibers or uses ultraviolet (UV) irradiation to activate the surface of fiber membranes for the attachment of responsive substances. Compared to surface coating techniques, grafting methods facilitate the stable connection of responsive polymer chains to the membrane through covalent bonds. This approach effectively addresses the limitations of surface coatings, which are susceptible to delamination, and is regarded as a promising method for nanofiber modification. Electrospun NFs, characterized by their high surface areas, multiple active sites, favorable mechanical properties, and porous structures that enhance electron transfer, are utilized in biosensor applications. The chemical grafting method effectively resolved the challenge of antigen binding to fibers.

Wen *et al.* [161] successfully electrospun PVA and PAA fibers by activating specific functional groups on the surface of the fibers, such as the carboxyl and amino group, using organic solvents (Figure 5). The carboxyl groups on these fibers were subsequently activated with an EDC/NHS solution to immobilize the 19-nitrotyrosine-ovalbumin (19-NT-OVA) antigen on the surface, facilitating competitive binding with Nb2F7-HRP. This process resulted in the development of an electrochemical immunoassay sensor for the detection of 19-NT. In a separate study, Temocin *et al.* [162] coated a hydrogen peroxide–sensitive modified glassy carbon electrode (MGC) with a mixture of polyethyleneimine (PEI) and electrospun PVA fibers. The amine groups of PEI were activated using glutaraldehyde to bind glucose oxidase (GOx). GOx immobilized on the PEI/PVA mixed NFs catalyzes the conversion of glucose into gluconic acid, concurrently producing hydrogen peroxide. This hydrogen peroxide then migrates through the high-porosity and insulating nanofiber structure to the MGC surface, where it undergoes electrochemical decomposition, generating a measurable electrical signal that correlates with the glucose concentration. The research team established a relationship between the strength of the electrical signal and the glucose concentration, confirmed the reproducibility and resistance of the sensor to interference, and successfully applied it to the analysis of real samples.

The application of electrospinning intelligent dressing in the treatment of diabetic wounds

Smart monitoring dressing

Different stages of wound healing are accompanied by specific biomarkers such as pH, temperature, tissue oxygenation, and glucose concentration, which provide information about the wound status [8]. To clarify the condition of the wound for better management, one or a combination of these biomarkers can be used to monitor the healing stage. Table 1 summarizes different types of responsive electrospun nanodressings developed to monitor wound biomarkers.

Smart dressing for humidity monitoring As early as the last century, humans have found through domestic experiments on pigs that wet environments help promote the formation of wound epithelial tissue, thereby helping wound healing. However, excessive wound humidity, such as excessive wound exudates, can overhydrate the wound, inhibit fibroblast proliferation, prolong the inflammatory period, and hinder the healing process, leading to life-threatening complications and increased patient morbidity. Recently, the use of wound humidity as a monitoring index has attracted considerable attention. Relevant research has shown that an increase in wound pus is an indicator of wound infection. Second, according to the characteristics of wound healing, the surface area of the wound gradually decreases during the healing process. Therefore, the amount of wound seepage naturally decreases with a decrease in the wound area. Therefore, wound effusion has great potential as a monitoring index for wound healing rates and wound infections. Traditional hydrophilic wound dressings such as cotton have a limited absorptive capacity and are quickly saturated. More advanced dressings, such as plant-based self-draining dressings, require infrared photothermal drives, and their exudate emissions are unstable. Dressings with monitoring properties can be used to monitor wound healing in real time to help medical workers

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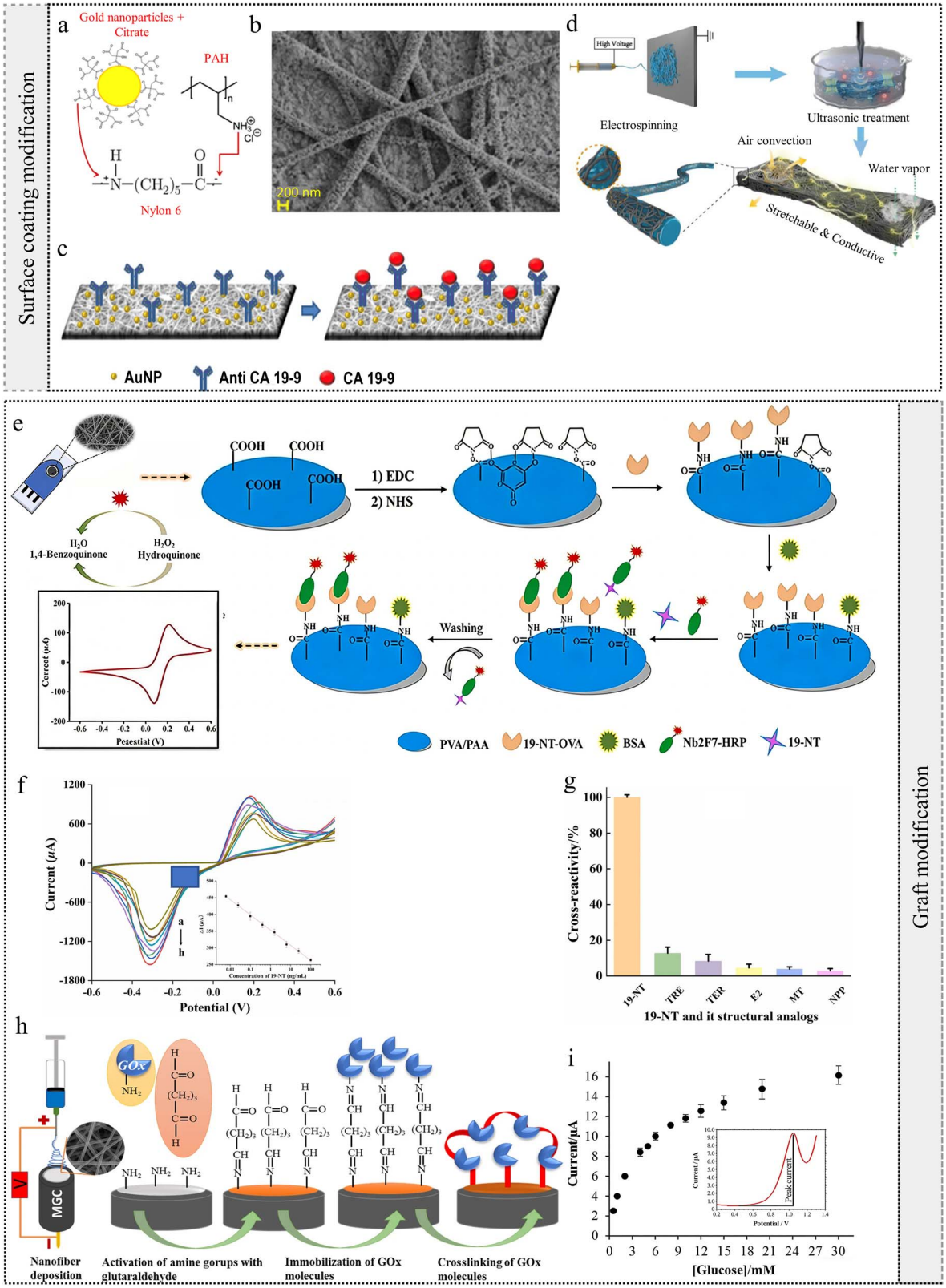


Figure 5 Surface coating in functionalizing nanofibers**.** (**a**) Schematic diagram for the binding between nylon 6 (PA6), PAH, and gold nanoparticle. (**b**) SEM images of nanofiber mats of PA6/PAH/AuNPs. (**c**) Mechanism of immunosensors based on nanostructured mats of electrospun nanofibers of polyamide 6 and poly(allylamine hydrochloride) coated with multiwalled carbon nanotubes (MWCNTs) or gold nanoparticles (AuNPs) [155]. Reproduced with permission from ref [154]. Copyright 2020, Materials Science and Engineering: C. (**d**) schematic illustration of the fabrication for stretchable electrodes of EPUM/CNTs by ultrasoniccavitation process. Reproduced with permission from ref [159]. Copyright 2023, Chemical Engineering Journal. (**e**) Schematic illustration of fabrication process and sensing mechanism of immunosensor for 19-NT detection. (**f**) Electrocatalytic current responses under different concentrations of 19-NT. (**g**) Specificity of the electrochemical immunosensor. ($n = 3$). Reproduced with permission from ref [161]. Copyright 2022, Sensors and Actuators B: Chemical. (**h**) Schematic description of the GOx-based BEC construction. (**i**) Peak current values of BEC for different concentrations of glucose. Reproduced with permission from ref [162]. Copyright 2022, Journal of Applied Electrochemistry

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Table 1 The different types of responsive electrospun nanodressings that have been developed to monitor wound biomarkers include wound biomarker sensors and their monitoring principles

Dressing characteristics	Wound biomarker	Monitor principle	Reference
The SF-PCNT-AL film was prepared by adding Alantan (AL) to fibroin (SF) nanofiber film, and the hardware circuit of polydopamine functionalized carbon nanotubes (PCNTs) was implanted	Humidity	Electrochemistry	[163]
The thermoplastic polyurethane (TPU) nanofiber membrane was loaded with sodium polystyrene sulfonate (PSS) and citric acid (CA) as humidity-sensitive materials	Humidity	Electrochemistry	[164]
A circular Ag/Zn electrode array was constructed on the surface of PLA nanofiber film by magnetron sputtering, and a DHT11 micro sensor was integrated	Temperature	Electrochemistry	[166]
Hybrid nanodiamond (NDs)—fibroin multifunctional nanofiber wound dressing	Temperature	Other principle	[9]
The PAN fiber layer was doped with phenol red (PSP) to monitor the pH value of the wound	pH	Optical	[167]
Cu MOFs loaded with carbon dots (CDS) and glucose oxidase (GOx) were dispersed in polyvinyl butyral (PVB) spinning solution to form GOx by electrospinning device/CDs@MOF NFS	pH	Optical	[168]
Eu-CPs loaded onto PAN nanofibers induced the wound concentration of H_2O_2 through changes in fluorescence	H_2O_2 level	Optical	[124]

take timely and appropriate measures. Advanced dressings produced by electrospinning mainly monitor changes in wound moisture through electrochemical principles. Polydopamine-functionalized carbon nanotubes (PCNTs) can be spun into conductive media. With the hardware circuit designed to change the resistance of the monitoring part with the change in ambient humidity, the conductive advanced dressing can meet the functions of wound treatment and humidity detection at the same time. Humidity sensitivity can be achieved by directly spinning humidity-sensitive materials such as polystyrene sodium sulfonate (PSS) and citric acid (CA) into a dressing or by changing the number of internal conductive paths through absorbing liquid, indirectly changing the resistance of the monitoring part to respond to the moisture of the wound.

Zhang prepared an advanced dressing with Silk Fibroin (SF) electrospun film as a base material [163]. The dressing used PCNT as a conductive medium, and alantan (AL) as an antibacterial drug was added to the fibroin (SF) nanofiber membrane to prepare an SF-PCNT-AL film, which was then assembled into a wound humidity-monitoring dressing system by combining a hardware circuit and software system.

The conductivity of the SF-PCNT-AL film reached 1.28 ms·cm^{-1}. After the film absorbed the wound seepage, the internal conductive paths increased, and the resistance decreased. The moisture content of the wound surface was measured by varying the film voltage. The SF-PCNT-AL film had excellent mechanical properties, with a tensile rate of up to 62% and a tensile strength of up to 1.6 MPaSF-PCNT-AL, which are sufficient to meet the strength requirements of dressings. The response time of the film to simulated body fluids of different volumes increased linearly. The response time of 10 μL simulated body fluids was 14 s, but the recovery time was 559 s, which was slightly insufficient.

Ding S prepared a nanofiber dressing with a dual-function humidity pressure sensor with excellent air permeability and biosafety (Figure 6a–g) by combining electrospinning and screen printing [164], thermoplastic polyurethane (TPU) nanofiber membrane was used as the dressing base, sodium polystyrene sulfonate (PSS) and citric acid (CA) were used as the humidity-sensitive materials to make the dressing sensitive to water molecules, and CNTs were used as the electrode. The TPU ENMs doped with PSS or CA particles have abundant microstructures with uneven surfaces and porous three-dimensional network, which can effectively improve the wet pressure sensitivity and response time of the sensor. CA/TPU Humidity pressure sensors (CTHPS) exhibit high sensitivity (2.15%/RH in the range of 50–90% RH, 10.53 kPa) in the low-pressure range of 0–2.25 kPa), fast humidity response time (3.8 s), and pressure response time (88 ms). Compared with the previous dressing, it also had the property of fast humidity response recovery (7.26 s). In addition, this dual-function sensor based on an all-nanofiber membrane shows excellent breathability and biosafety and has broad application prospects in respiratory monitoring and smart wound dressing.

Ding also developed a three-layer smart wound dressing with asymmetric wettability that had both humidity- and pressure-sensing functions. It also promoted wound healing [165]. Dressing can prevent infection and accelerate wound healing by mimicking natural skin structures and properties (Figure 6h). Janus phase change materials are constructed by electrospinning and screen-printing using MSP as the inner layer, chitosan sponge (CS) as the middle layer, and a hydrophobic PLA@Ag3 Purchase Order 4 nanofiber film as the outer layer. The MSP mimicking the dermis showed high linear sensitivity (−99%), wide response range (11–98% RH), fast response/recovery time (0.6 s/1.4 s), and good cycle stability (10 cycles). In addition, it can identify 1% RH changes without interference from bending or pressure stimulation, indicating its potential for practical applications in wound humidity monitoring. As an intermediate layer, CS, with a loose porous structure prepared by freeze-drying, simulates a transparent layer to control skin moisture and provides excellent liquid absorption

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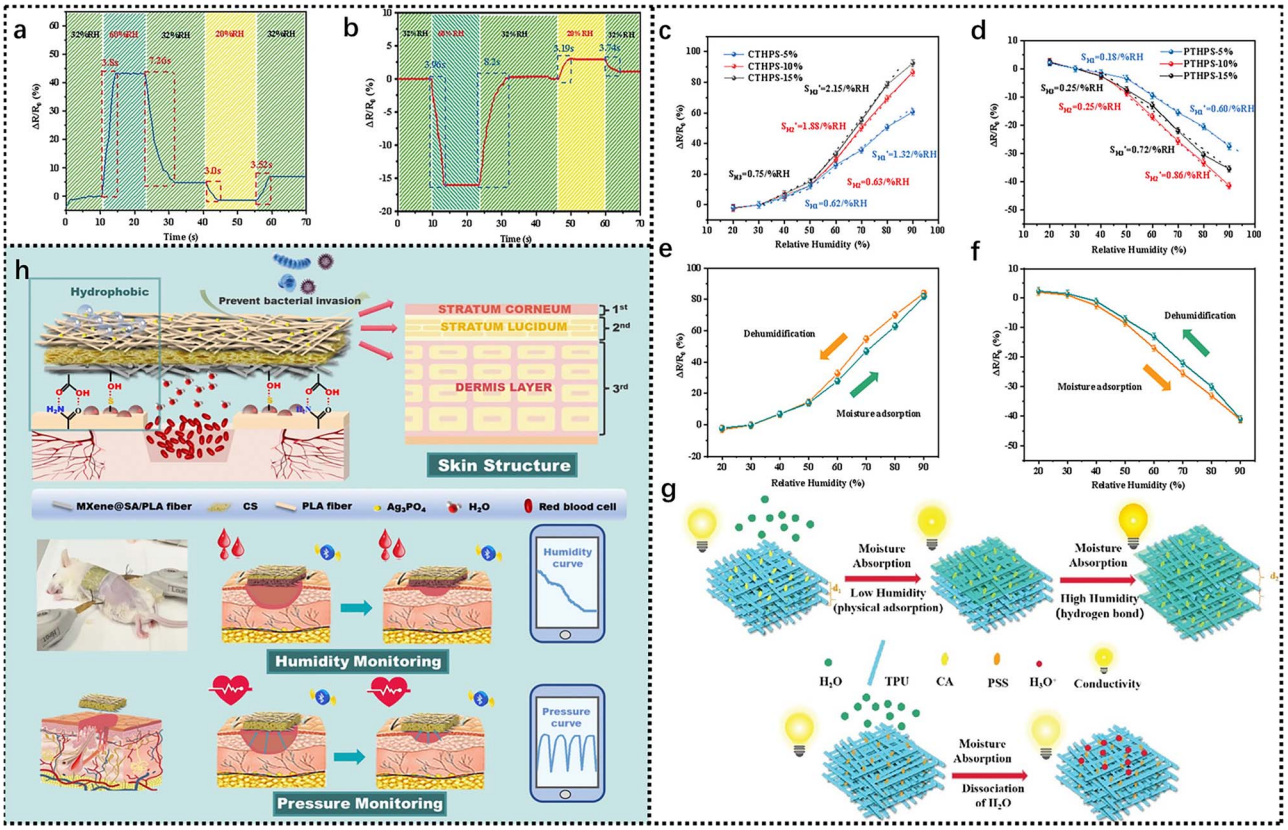


Figure 6 Electrospinning wound dressing responsive to humidity. (**a**) CTHPS and (**b**) PTHPS response–recovery time curve from ambient humidity (32%RH) to high humidity (60%RH) and low humidity (20%RH). (**c**) Humidity response sensitivity curves of CTHPS and (**d**) PTHPS. (**e**) Lag curves of CTHPS and (**f**) PTHPS. (**g**) Humidity sensing mechanism of CTHPS and PTHPS. Reproduced with permission from ref [164]. Copyright 2022, Macro Molecular Materials and Engineering. (**h**) The structure of phase change materials and the function of preventing bacterial invasion and promoting wound healing, as well as the schematic diagram of monitoring through humidity and pressure signal. Reproduced with permission from ref [165]. Copyright 2024, Advanced Fiber Materials. *CTHPS* CA/TPU humidity pressure sensors, *PTHPS* PSS/TPU humidity pressure sensors, *TPU* thermoplastic polyurethane, *CA* citric acid, *PSS* sodium polystyrene sulfonate, *CS* chitosan sponge, *PLA* polylactic acid

(2399.68%) and compressive resilience (99.5%). The hydrophobic outer layer, adsorbed by loaded silver phosphate (Ag3 Purchase Order 4) nanoparticles onto PLA NFs (PLA@Ag3 Purchase Order 4), simulated the cuticle and displayed an all-weather antibacterial function (99.99%) to prevent bacterial invasion. The PCM is a capacitive pressure sensor with high sensitivity (199.22 kPa^{-1}) and excellent cycle stability (1500 cycles). More importantly, by integrating the smart wound dressing with the terminal device, capacitive signals caused by pressure and humidity changes during the wound-healing process can be monitored, and the data can be transmitted to a mobile phone through Bluetooth, so that the patient's wound information can be monitored in real time, helping to achieve a noninvasive diagnosis. This dressing is an efficient, economical, and convenient method for wound treatment.

Smart dressing for temperature monitoring Although it is important to protect the wound during the healing process, the diagnosis of infection or inflammation is equally critical. Traditional methods include checking for redness, heat detected by palpation, and swelling. However, these visual signs appear only when infection or inflammation has progressed to a certain extent, making it difficult for traditional methods to effectively intervene in inflammation or infection. Implementing a new technology that can help clinicians detect infections noninvasively would be both beneficial and cost-effective. Temperature monitoring is a widely used and highly effective method for assessing the wound status. Natural skin temperature fluctuates from 31.1 to 36.5°C. Dilation of blood vessels caused by the inflammatory phase of the healing process, as well as wound infection in the wound environment, are associated with a significant increase in wound temperature, which can approach 39–40°C locally in chronic wounds. In addition, some wounds (such as ischaemia) are associated with reduced temperature in the wound bed, with a specific elevated temperature gradient ranging from +4 to 5°C for chronically infected wounds compared to normal tissue. Temperature-monitoring smart dressings can provide the doctor with the temperature change of the wound in real time without the painful dressing removal process, thus effectively monitoring the wound for infection.

Temperature sensors in temperature-responsive dressings mainly track changes in wound temperature based on optical and electrochemical principles. Optical detection relies on thermochromic materials that exhibit color changes with temperature to instantly monitor skin temperature. When the temperature changes, the protonation or deprotonation of the material produces a corresponding visible color [11]. In summary, colorimetric temperature detection technology can be used to quickly monitor skin temperature using thermochromic materials

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that exhibit color changes in response to changes in temperature. Unlike colorimetric pH sensors, these sensors have higher resolution (about 0.2°C) and shorter response times (1–50 s). However, the use of advanced image-processing techniques can further improve resolution and response time. Electrochemical monitoring depends on electrical conductivity, such as the resistance value of metals and semiconductors, which changes with temperature.

Yang *et al.* sputtered Ag/Zn electrodes onto the surface of PLA nanofiber films to prepare electroactive wound dressings (Ag/Zn@PLA) [166]. The three dressing layers were composed of a drug-loaded thermoresponsive nanofiber film, xene-optimized Joule heating film, and a flexible printed circuit board (FPCB) control chip. The Ag/Zn electrode was set as a ring to facilitate the generation of electrical stimuli from the periphery to the center of the wound. The DHT11 microsensor was then integrated into the Ag/Zn @PLA dressing to achieve real-time temperature monitoring of the wound site, as shown in Figure 6a [166]. By applying a low voltage (0–4 V) to the heating film, precise and stable temperature stimulation can be easily achieved, allowing temperature control from 25°C to 130°C. It can monitor and adjust the temperature of the wound area in real time, showing an accurate and low-pressure Joule heating ability. Thus, the drug-loaded membrane achieved a precise thermoresponsive drug release and significant antibacterial effects *in vitro*.

Khalid reported a hybrid nanodiamond (ND)-fibroin multifunctional nanofiber wound dressing that enabled *in situ* temperature monitoring. The electron spin energy level of NV—the center of the diamond—is affected by the temperature *T*, as shown in Figure 6b [9].

Khalid presented a combination of two unique optical materials, NDs and silk, which were electrospun into membranes, as a multifunctional platform for biosensing and wound-healing applications. Electrospinning of silk generates submicron-thick fibers with high porosity, which is essential for breathable wound dressings. The fluorescent and spin properties of the NV centers in the NDs allow for high-precision microscopic thermometry for wound sensing. Silk enables the attachment and growth of healthy cells inside the scaffold while promoting wound healing.

The NDs with a negatively charged nitrogen vacancy (NV^-) luminous center detect the temperature change by optical probing magnetic resonance (ODMR) technology, with a sensing range of 25 ∼ 50°C. When the wound temperature changes, the NV-exposed scanning microwaves produce a shift in the ODMR spectrum, which indicates temperature changes associated with wound infection. ND-silk nanofiber wipes can obtain wound information through ND temperature reading, provide early warning of wound infection, and provide effective guidance for the treatment of patients with trauma (Figure 7).

Smart dressing for pH monitoring The pH of the wound exudate is an important biomarker that can provide useful information about infection and wound healing status. The intact skin surface is naturally acidic, influenced by organic acids secreted by epithelial cells, with a pH between 4 and 6, and acts as a natural barrier. When the skin is damaged, tissues with neutral pH are exposed to the environment, and chronic wounds are often associated with a more alkaline microenvironment. The pH environment of DFU usually varies widely and changes dynamically depending on several factors, including colonization of different microorganisms, timing of onset, severity, and wound stage.

pH sensors in pH-responsive dressings track changes in the wound pH based on optical and electrochemical principles. Optical pH sensors detect pH changes either through colorimetry, which is based on the change in color of the indicator dye with pH, or through fluorescence, based on changes in the fluorescence properties of pH-sensitive fluorophores. Its main advantage is the ease of miniaturization without integrating electronic components; however, a major drawback is that the dye penetrates the wound and is easily affected by external light, reducing the accuracy of pH measurements. In contrast, electrochemical methods, which rely on ion-to-electron transducers to generate an electric current, are more accurate and stable for determining the wound pH. Electrochemical pH sensors are usually potentiometric and voltammetric. Potential measurements are widely used to monitor wound pH because of their high reliability and wide sensing ranges.

Zhang designed a multifunctional Janus electrospun nanofiber dressing that integrated antibiotics, bioactive POM, and indicators to promote wound healing (Figure 8b) [167]. The dressing consisted of two layers of polymer substrates that differed significantly in terms of wettability. The hydrophobicity of the internal PLA fiber combined with the hydrophilicity of the external polyacrylonitrile (PAN) fiber can drain excess fluid around the wound. In addition, α-K6P2W18O62· 14 h 2O (P2W18) and oxacillin (OXA) were loaded in PLA NFs to achieve synergistic MRSA resistance. In addition, the PAN fiber layer was doped with phenol red (PSP) to monitor the pH of the wound.

With progress in nanotechnology, metal–organic frameworks (MOFs) have attracted considerable research interest as novel porous nanomaterials. Zhang *et al.* first prepared Cu MOFs loaded with carbon dots (CDs) and glucose oxidase (GOx), dispersed them in a polyvinyl butyral (PVB) spinning solution, and then further deposited them on the wound surface using a handheld electrospinning device to form a Gox/CDs @MOF NFS (Figure 8a) [168]. In the diabetic wound microenvironment, Gox/CDs @MOF GOx provided by NFS continuously catalyzed physiological glucose to produce gluconic acid and H_2O_2. The generated gluconic acid can reduce the pH of the entire system and effectively enhance the peroxidase-like activity of the Cu-MOF. The CD surface contains abundant acidic and basic groups; therefore, it shows a unique colorimetric response to pH changes and pH-sensitive fluorescence [169]. The GOx/CDs@MOF NFS inherited the pH fluorescence sensing behavior of CDs, and the fluorescence signal was captured by smartphones and converted to RGB, providing *in situ* monitoring of the wound status. *In vivo* experiments showed that the multifunctional NF dressing could accurately measure the pH value of the wound and significantly promote wound healing. MOF-based multifunctional NFS provides a new strategy for the clinical diagnosis and treatment of diabetes-infected wounds.

Smart dressing for reactive oxygen monitoring Active oxygen monitoring sensors are based mainly on optical and electrochemical principles. Electrochemical methods are usually based on immobilized REDOX proteins, including superoxide dismutase (SOD) and cytochrome c (Cytc) groups. The SOD electrochemical method is based on the disproportionation of $O_2-\bullet$ into O_2 and H_2O_2 in the presence of SOD and generates voltage, whereas

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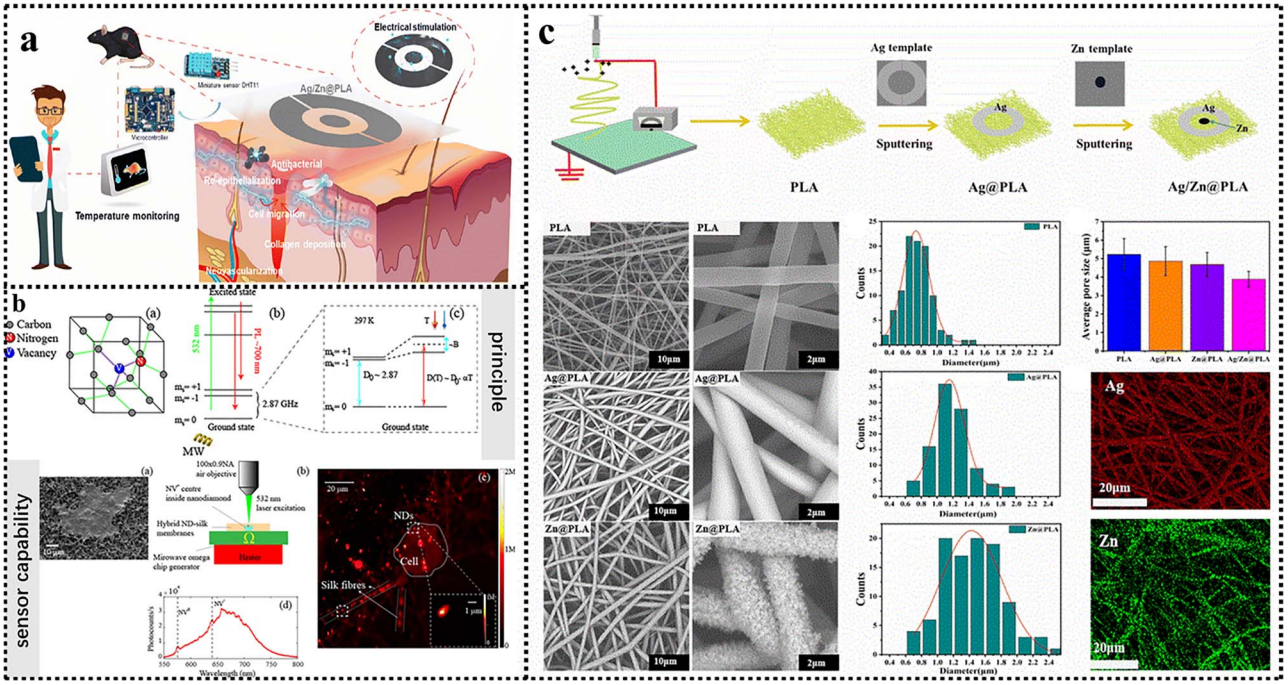


Figure 7 Electrospinning wound dressing responsive to heat. (**a**) Illustration of the possible wound healing–promoting mechanism of Ag/Zn@PLA with a minimum temperature sensor. Reproduced with permission from ref [166]. Copyright 2023, RSC Advances. (**b**) Structure of NV color center in diamond lattice. Reproduced with permission from ref [9]. Copyright 2020, Biological and Medical Applications of Materials and Interfaces. (**c**) Schematic illustration of the fabrication process of the Ag/Zn@PLA dressing and its SEM images, diameter distribution, and average pore size. Reproduced with permission from ref [166]. Copyright 2023, RSC Advances. *PLA* polylactic acid, *NDs* nanodiamonds

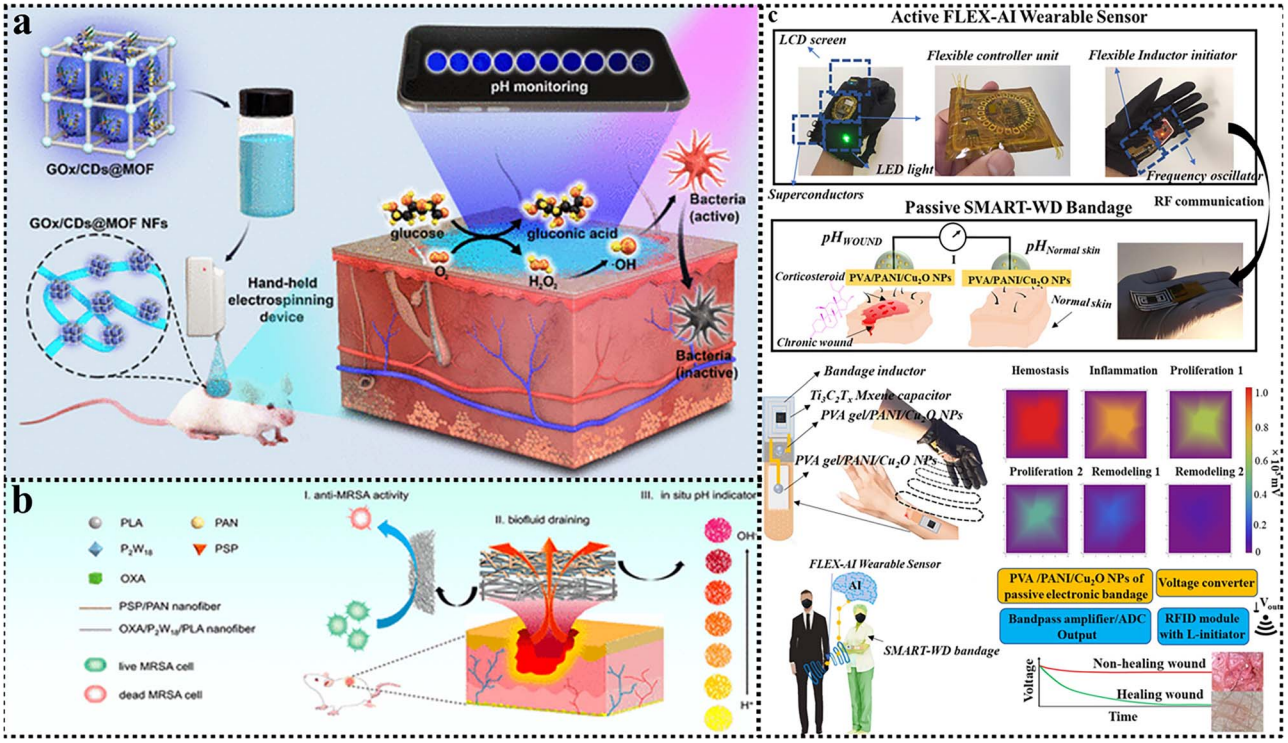


Figure 8 Electrospinning wound dressing responsive to pH. (**a**) Schematic diagram of GOx/CDs@MOF NF dressing for visual monitoring and antibacterial treatment of diabetic-infected wounds. Reproduced with permission from ref [168]. Copyright 2023, Biological and Medical Applications of Materials and Interfaces. (**b**) Scheme for wound healing by a multifunctional Janus electrospun nanofiber dressing. Reproduced with permission from ref [167]. Copyright 2022, Biological and Medical Applications of Materials and Interfaces. *CDs* carbon dots, *GOx* glucose oxidase, *MOFs* metal–organic frameworks, *PVB* polyvinyl butyral, *PLA* polylactic acid, *PAN* polyacrylonitrile, *OXA* oxacillin, *PSP* phenol red, *MRSA* methicillin-resistant *Staphylococcus aureus*

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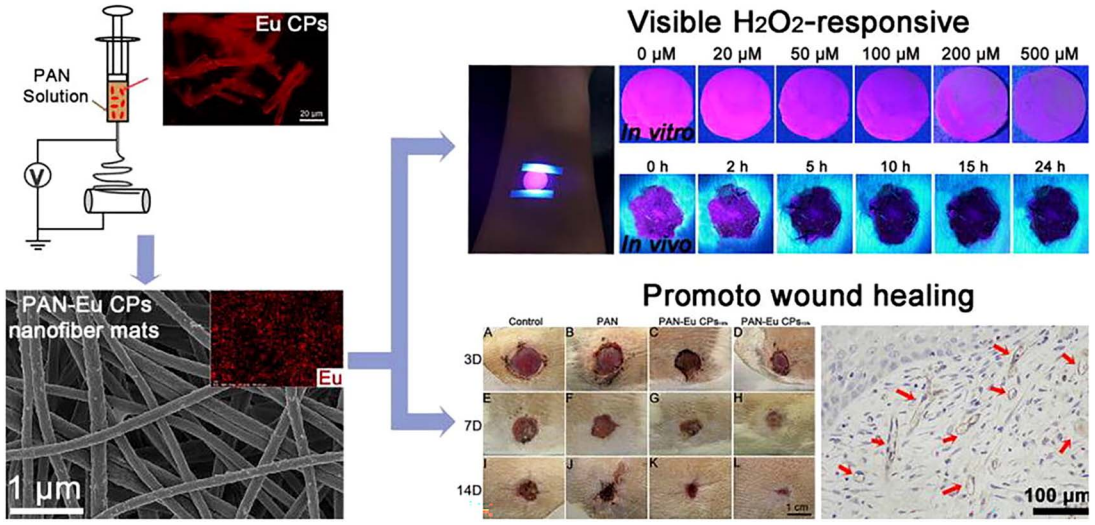


Figure 9 Graphic abstract of H_2O_2-responsive smart dressing for visible H_2O_2 monitoring and accelerating wound healing. Reproduced with permission from ref [124]. Copyright 2020, Chemical Engineering Journal. *PAN* polyacrylonitrile

the Cytc method operates by reducing fixed Cytc to O_2- • free radicals and oxidizing REDOX proteins on the electrode surface. However, the main disadvantage of the electrochemical methods is the incorporation of various electronic components. In contrast, fluorescent optical technology has been used to build wearable platforms for monitoring physiologically relevant concentrations of ROS.

Wu loaded Eu-CPs into PAN NFs to prepare an H_2O_2-responsive smart dressing. Wu *et al.* described a novel smart electrospun mixed PAN nanofiber dressing for wound healing and monitoring the H_2O_2 concentration on the wound surface [124]. As a visible indicator of wound status, smart dressings can sense the wound H_2O_2 concentration through changes in fluorescence. Smart dressings can monitor the wound-healing process and provide real-time information on the condition of the wound without expensive instrumentation. Therefore, wounds can be treated through targeted and effective treatments, which can prevent infection and shorten the wound treatment cycle. The concentration of H_2O_2 in the *in vitro* and *in vivo* wound models was detected based on the fluorescence intensity of the dressing under UV irradiation. The concentration of H_2O_2 has a linear relationship with the fluorescence intensity in the range of 20 ~ 200 μmol/L, and the dressing changes from bright to dark when the wound is inflamed. Although these detection methods are convenient, miniaturized, and free from electromagnetic interference, optical detection is susceptible to external light conditions, making it difficult to detect small changes in the wound environment (Figure 9).

Smart responsive dressing

Wu loaded Eu-CPs into PAN NFs to prepare an H_2O_2-responsive smart dressing. Wu *et al.* described a novel smart electrospun mixed PAN nanofiber dressing for wound healing and monitoring the H_2O_2 concentration on the wound surface [124]. As a visible indicator of wound status, smart dressings can sense the wound H_2O_2 concentration through changes in fluorescence. Smart dressings can monitor the wound-healing process and provide real-time information on the condition of the wound without expensive instrumentation. Therefore, wounds can be treated through targeted and effective treatments, which can prevent infection and shorten the wound treatment cycle. The concentration of H_2O_2 in the *in vitro* and *in vivo* wound models was detected based on the fluorescence intensity of the dressing under UV irradiation. The concentration of H_2O_2 has a linear relationship with the fluorescence intensity in the range of 20 ~ 200 μmol/L, and the dressing changes from bright to dark when the wound is inflamed. Although these detection methods are convenient, miniaturized, and free from electromagnetic interference, optical detection is susceptible to external light conditions, making it difficult to detect small changes in the wound environment.

Humidity-responsive electrospinning nanofibers Ding *et al.* used the interlayer confinement effect of MXene to combine sodium alginate (SA) with MXene to prepare humidity-sensitive composite nanoparticles (MXene@SA) [165]. A flexible resistive humidity sensor was fabricated using electrospinning and screen-printing technology with a polylactic acid (PLA) nanofiber membrane as the substrate. (Figure 10); the sensor has high sensitivity (99%), fast response/recovery time (0.6 s/1.4 s), and a wide detection range (11% RH–98% RH) and is free from deformation interference, with good stability (4 weeks). In the above MXene@SA/Based on the PLA resistive flexible humidity sensor, an intelligent wound dressing with a sandwich structure that has both humidity- and pressure-sensing functions was constructed to monitor the healing of open wounds. The surface layer of this dressing is PLA nanofiber membrane anchored with silver phosphate (Ag3PO4) nanoparticles, which has an all-weather antibacterial function. The middle layer is a chitosan (CS) sponge with a loose porous structure prepared by freeze-drying technology, which provides excellent absorption and conduction of liquid function and compression resilience. The bottom layer is a humidity-responsive MXene@SA/PLA nanofiber membrane that can detect the change of wound humidity in real time and rapidly. At the same time, this sandwich-structure dressing also has a capacitive pressure-sensing function, which is conducive to monitoring the healing of wounds and shows broad application prospects in the field of intelligent medicine (Figure 11).

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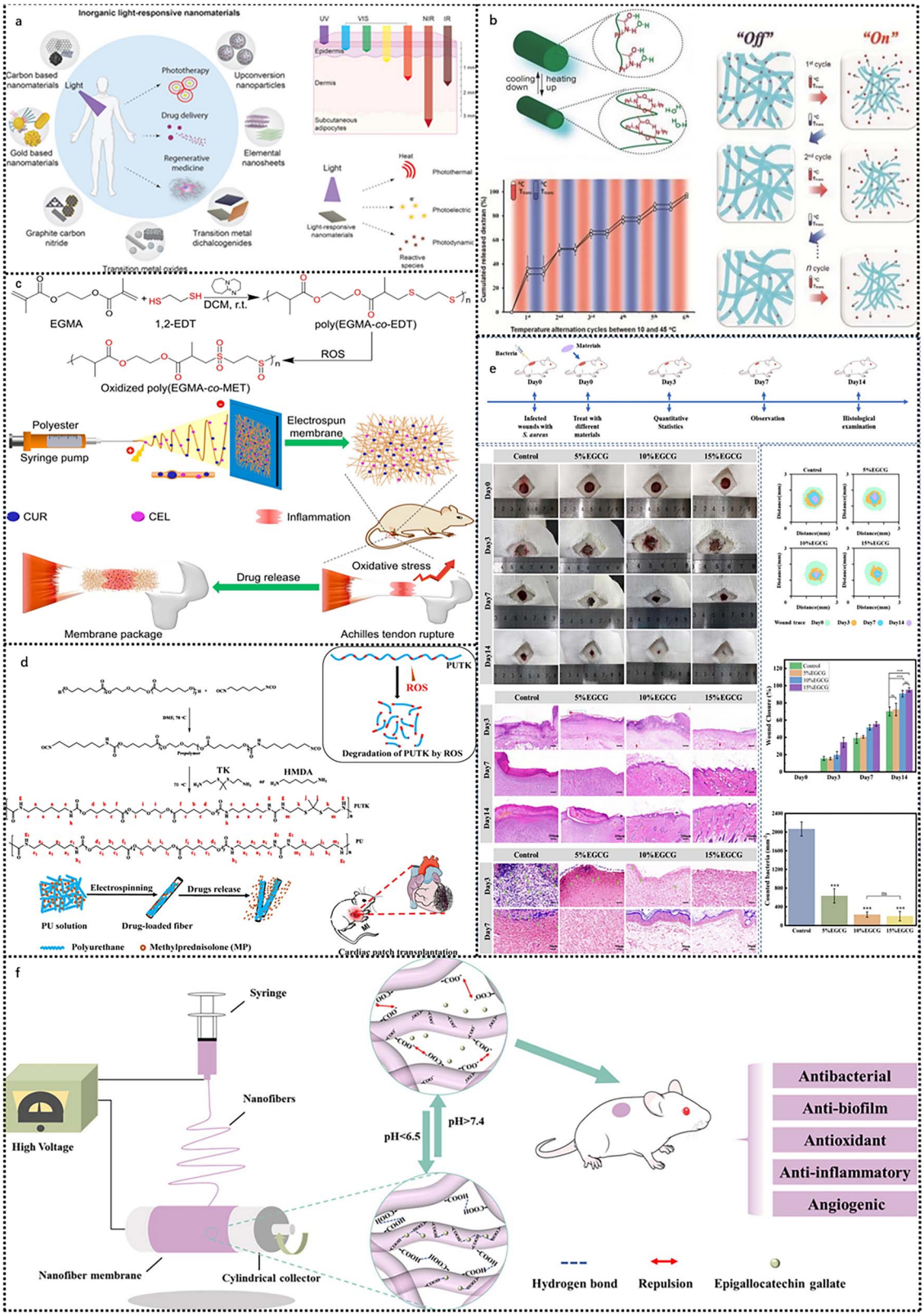


Figure 10 Electrospinning wound dressing responsive to light and ROS. (**a**) Inorganic photoresponsive nanomaterials. Reproduced with permission from ref [183]. Copyright 2020, Advanced Science. (**b**) Hydrogen bond changes between LCST. Reproduced with permission from ref [171]. Copyright 2021, Progress in Biomaterials. (**c**) Electrospinning nanofibers respond to ROS. Reproduced with permission from ref [179]. Copyright 2021, Journal of Controlled Release. (**d**) Synthetic scheme for ROS-responsive polyurethane (PUTK) and nonresponsive polyurethane (PU) from poly(ε-caprolactone) diol, 1,6-hexamethylene diisocyanate, and chain extenders of ROS-cleavable thioketal (TK) and 1,6-hexanediamine (HMDA), respectively. Reproduced with permission from ref [180]. Copyright 2020, Biomaterials. (**e**) The therapeutic effect of PVA/PAA/EGCG nanofiber membrane on infected full-layer wound. Reproduced with permission from ref [121]. Copyright 2023, Materials & Design. (**f**) PVA/PAA/EGCG synthesis diagram. Reproduced with permission from ref [121]. Copyright 2023, Materials & Design. *LCST* low critical solution temperature, *UV* ultraviolet, *EGMA* ethylene glycol dimethacrylate, *poly (EGMA-co-EDT)* poly(ethylene glycol dimethacrylate-co-1,2-ethanedithiol), *CUR* curcumin, *CEL* celecoxib, *ROS* reactive oxygen species, *TK* thioketal, *HMDA* 1,6-hexanediamine, *PUTK* polyurethane containing thioketal

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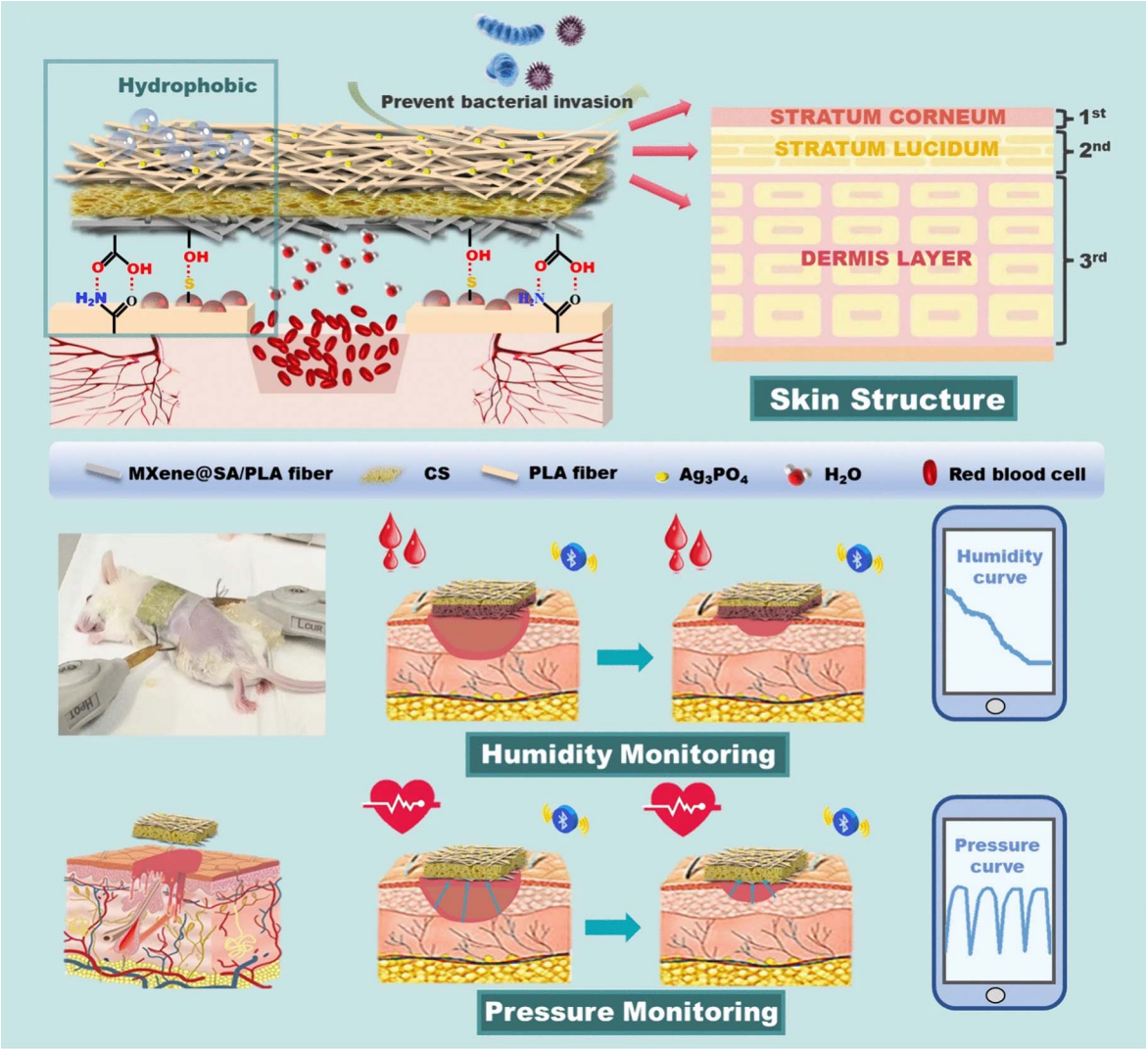


Figure 11 The structure of phase change materials and the functions of preventing bacterial invasion and promoting wound healing, as well as the schematic diagram of monitoring through humidity and pressure signals. Reproduced with permission from ref [165]. Copyright 2025, Advanced Fiber Materials. *CS* chitosan sponge, *PLA* polylactic acid

Temperature-responsive electrospinning nanofibers Temperature changes can trigger and alter drug release depending on the degree of the inflammatory response in DFUs or circadian rhythms (Figure 11). Temperature-responsive electrospinning NFs are usually supplemented with heat-sensitive polymers [64, 170]. Such thermosensitive polymers typically have an LCST, at which they exhibit hydrophilicity and gradually change from hydrophilic to hydrophobic when the temperature increases beyond their LCST [171].

PNIPAAm is the most widely studied temperature-responsive polymer [172, 173]. It dissolves in water at temperatures below its LCST (32°C) and precipitates at higher temperatures. However, because it is difficult to crosslink PNIPAAm, electrospun PNIPAAm NFs tend to disperse in water. Therefore, they can be copolymerized with cross-linked copolymers to obtain stable NFs in water. In a 2017 study by Li *et al.* [11], the thermosensitive polymer poly (diethylene glycol) methyl ether methacrylate (PDEGMA) was synthesized by blending it with ethyl cellulose (EC) of the supported model drug KET and was electrospun into a fiber. Drug release studies have shown that KET is released longer at 25°C and 37°C and that the fibers have different release curves, reflecting their thermal sensitivity. Therefore, the fibers prepared in this study have the potential to serve as intelligent stimulus-responsive drug delivery systems.

Huang et al. prepared simvastatin-loaded ZIF-8 nanoparticles using electrospinning technology to create polylactide trimethyl carbonate (PLATMC)/polyvinylpyrrolidone (PVP) nanofiber dressings (ZIF-8@SIM NPs) as smart, multi-responsive composites (C-PPZS) for the treatment of chronic wound healing (Figure 12a) [174]. The dressing exhibits liquid-triggered and temperature-controlled contraction properties. The base layer of the PLATMC NFs combines topological morphology with material properties to drive wound closure through a temperature-triggered contractile force. The unique transverse and longitudinal fiber arrangement structures promoted centripetal contraction of the nanofiber membrane.

Cheng *et al.* [175] designed a novel flexible hybrid wound dressing for wound management and monitoring by combining

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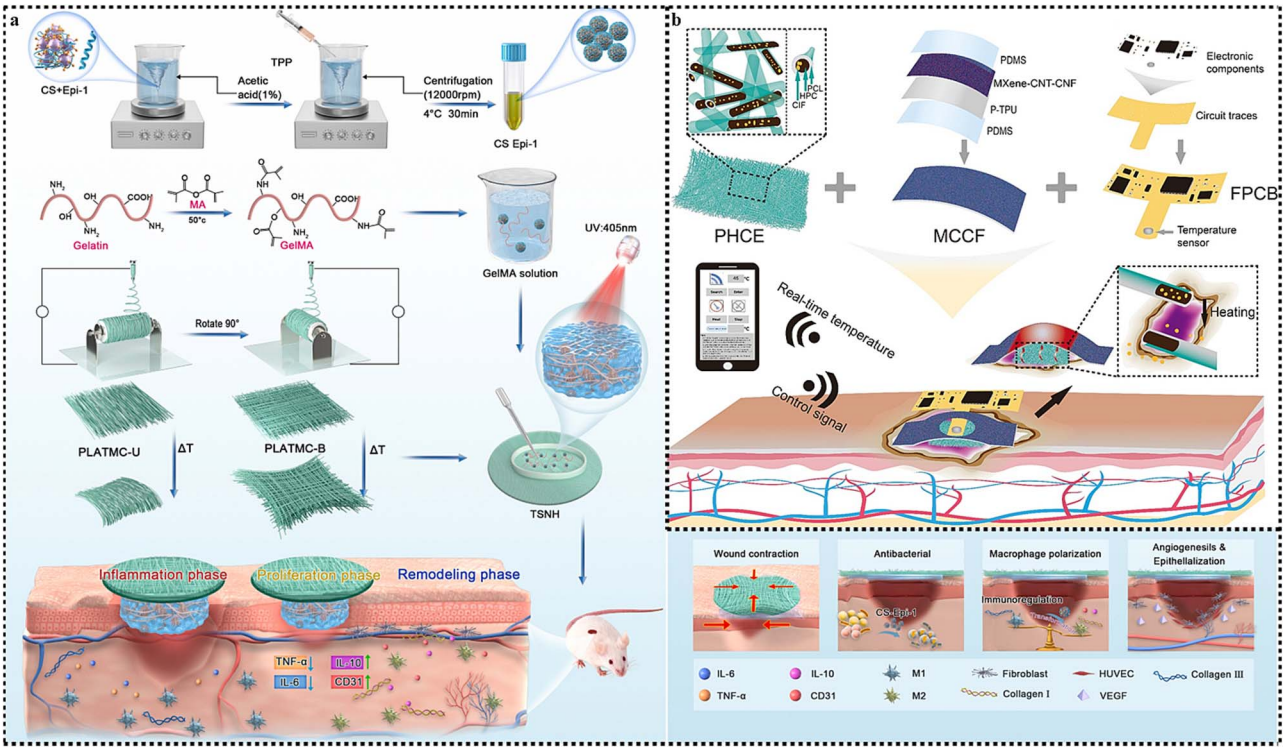


Figure 12 Temperature-responsive electrospinning wound dressing. (**a**) Diagrammatic illustration of the temperature-responsive self-contraction nanofiber/hydrogel composite dressing facilitates the healing of diabetic-infected wounds. Reproduced with permission from ref [174]. Copyright 2025, Materials Today Bio. (**b**) Schematic diagram of the MXene/TPU hybrid fabrics. Reproduced with permission from ref [175]. Copyright 2024, ACS Applied Materials and Interfaces. *PLATMC* polylactide trimethyl carbonate, *TPP* tripoly phosphate, *TSNH* temperature-responsive self-contracting nanofiber/hydrogel, *PDMS* polydimethylsiloxane, *CS* chitosan, *epi* epigallocatechin, *P-TPU* photo-crosslinkable thermoplastic polyurethane, *FPCB* flexible printed circuit board, *TNF-α* tumor necrosis factor-α, *IL-6* interleukin-6, *IL-10* interleukin-10, *HUVEC* human umbilical vein endothelial cells, *VEGF* vascular endothelial growth factor

flexible electronics with electrospun NFs (Figure 12b). The three dressing layers were composed of a drug-loaded thermoresponsive nanofiber film, a xene-optimized Joule heating film, and an FPCB control chip. The thermoresponsive drug-loaded nanofiber membrane (PHCE) has water-soluble hydroxypropyl cellulose (HPC) and ciprofloxacin (CIF) as the core layers and biocompatible polycaprolactone (PCL) as the shell layer. MXene has excellent conductivity, photothermal conversion ability, and biocompatibility and can be used to monitor wound status (such as temperature and humidity) in real time. The integrated sensor in the FPCB patch monitors the wound environment (such as pH and temperature) and sends data to a mobile device via wireless transmission. Therefore, according to the monitoring results, FPCB patches can be conveniently controlled by smartphones to adjust the temperature of the MCCF to provide precise thermal stimulation for regulating the release of CIF loaded in PHCE to achieve on-demand treatment and condition monitoring of wounds simultaneously.

pH-responsive electrospinning nanofibers The pH is one of the earliest and most studied stimuli for triggering and regulating drug release. The most widely used pH-responsive polymers include polyacrylic acid (PAAc), polymethacrylic acid (PMAc), chitosan (CTS), polyacrylamide (PAM), and carboxymethyl cellulose. Ideally, the dressing releases the drug according to the characteristic pH. When the pH of the wound gradually changes to normal, the dressing can reduce the release rate or stop the release completely.

Tan constructed a PVA/PAA nanofiber wi-pH-responsive delivery dressing loaded with galligallocatechin gallate (EGCG) [121]. Chronic wounds with a high bacterial load have a pH between 7 and 9, and acidic pH is a characteristic of the healing process. The fibers in the dressing can undergo reversible swelling and contraction at pH $>$ 7.4 and pH $<$ 6.5, to achieve controlled release of drugs, thereby dynamically adjusting the complex inflammatory environment of the wound. In the wound infection stage at pH = 7–9, the ionization of the polycarboxylic acid groups in the gel network caused the dynamic hydrogen bonds between EGCG, PVA, and PAAc to break, resulting in an increase in the release of EGCG to 87.4%. At pH $<$ 6.5, the stage of wound proliferation, the remodeling of intermolecular hydrogen bonds caused the NFs to shrink, and EGCG release decreased to 45.8%, promoting vascular maturation and collagen deposition and reshaping the wound microenvironment. In the experiments, researchers addressed this dynamic aspect of wound pH using a pH-responsive polyelectrolyte, PAA. However, to overcome the vulnerabilities of pure PAA, PVA with good cytocompatibility, biodegradability, and nontoxicity was added.

Rivero prepared a nanofiber membrane dressing that can selectively trigger antibiotic treatment based on the wound pH when there is a risk of infection [13]. The dressing was prepared via electrospinning by loading furacillin into a copolymer (ES100) solution

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of methacrylic acid and methyl methacrylate. When the wound pH was >7, the ES100 fiber structure loosened owing to the selective dissolution of the pH, resulting in a large drug release. However, the drug release rate of the ES100 fibers prepared by coaxial electrospinning was relatively slow owing to the presence of a diffusion layer.

Abdali incorporated the antimicrobial agent benzyl dimethyl tetragecyl ammonium chloride (BTAC) into biodegradable bacterial polymer NFs (PCL and polyethylene succinate) in two ways. In one way, BTAC was uniformly distributed inside a single nanofiber, and, in the other way, BTAC was wrapped in the core of the core–shell NFs. The lipase secreted by the bacteria and the change in pH can destroy fatty acid esters and acid anhydrides, thus promoting fiber degradation and BTAC release. The inhibitory effects of the single and core-shell NFs loaded with BTAC on *Staphylococcus aureus* and *Escherichia coli* were both >1 log within 2 h. However, the core–shell structure provided a more controlled release of BTAC and longer-lasting antibacterial activity than a single nanofiber.

Reactive oxygen species–responsive electrospun nanofibers

During oxidative stress in foot ulcers, ROS levels dramatically increase, causing severe cell damage. Therefore, ROS-responsive electrospun NFs have been developed to consume ROS or to control drug release at specific sites [13, 176]. ROS-responsive NFs can be obtained by adding ROS-responsive polymers to an electrospinning solution [177]. ROS-responsive polymers typically contain groups, such as thioethers and ketones, in their main or side chains [177, 178]. These groups are cleaved in response to overexpression of ROS in the microenvironment, resulting in polymer dissociation and drug release. For example, Zhang *et al.* synthesized the polymer poly (ethylene glycol dimethacrylate-co-1, 2-ethyl dimercaptan) with a vinyl ether group. The synthetic polymer was electrospun to prepare ROS-responsive NFs loaded with curcumin/celecoxib (CUR/CEL) to prevent peritendinous adhesions. The thioether groups in the NFs can react with ROS to form hydrophilic sulfoxides or sulfoxides, thereby accelerating the rate of drug release and regulating the level of oxidative stress at the site (Figure 10c) [179]. Yao *et al.* synthesized ROS-responsive biodegradable elastic polyurethane containing a thioacetone (PUTK) bond and prepared a glucocorticoid-loaded methylpredone electrospun fiber membrane for the treatment of myocardial infarction. Thioketone (PUTK) bonds in polyurethane membranes can consume excessive ROS, reduce damage to the heart tissue, and have the potential to prevent and treat cardiovascular diseases. In addition, ROS can trigger the degradation of synthetic polyurethanes and accelerate drug release (Figure 10d) [180].

Other responsive electrospun nanofibers

Photoresponsive electrospinning nanofibers

Photoresponsive electrospun NFs can generate heat or release drugs under irradiation at specific wavelengths (UV, visible, or near-infrared regions), and they are characterized by the fact that light can provide additional degrees of freedom to manipulate photoresponsive materials by controlling the light intensity, frequency, polarization, and direction with high spatial and temporal accuracy. Noninvasive automatic sustained-release drugs and photostimulation remotely regulate drug release [181]. Therefore, it mainly kills target cells through heat production or by releasing drugs to specific sites at specific times, which is the main purpose of its application in DFUs. Such stimulus-responsive NFs are usually prepared by incorporating photoresponsive materials into a polymer matrix via electrospinning [182].

In recent years, many direct near-infrared (NIR)-responsive photosensitizers and indirect near-infrared response composites have been developed. Indirect photosensitizers consist of UV- or visible-light-responsive photosensitizers and up-conversion nanomaterials. Direct near-infrared response photosensitizers include near-infrared response organic photosensitizers and inorganic photosensitizers that can directly convert light energy into free radical agents [183]. Currently, the photosensitive materials of great significance for the treatment of DFUs include graphene [12], carbon nanotubes (CNTs) [184], gold nanorods [182], and gold nanocages. The main functions of these materials are to improve the performance of photoresponsive electrospinning nets and the intelligent control of drug release.

Zárate *et al.* incorporated 0.5% or 1% thermally reduced GO (TrGO) into electrospun NFs and evaluated the thermal therapy performance of electrospun NFs without TrGO at different distances and potentials, concluding that the composite electrospun mesh (EM) containing TrGO showed better performance. This promotes the formation of fibers in EM, provides greater stability for the colloidal suspension of NR latex, reduces surface tension, and promotes the ES process, suggesting that EM loaded with TrGO as a near-infrared active heat inducer may be excellent candidates for thermotherapy applications in photothermal therapy [12]. In addition, GO has strong antibacterial properties, and Chong *et al.* demonstrated that light can generate electron–hole pairs by transferring electrons from antioxidants (glutathione and ascorbic acid) to reduced GO, while introducing carbon-centered free radicals to kill bacteria [185]. CNTs are 1D tubular fullerenes that can be divided into single-walled nanotubes (SWNTs) and multiwalled nanotubes (MWNTs) according to the number of graphite layers. MWNTs absorb approximately four times as much light as SWNTs; therefore, MWNTs are more efficient for photothermal conversion. Murakami *et al.* found that CNTs can bind to biomolecules and have a huge drug-carrying capacity for the hollow structure through π-π stacking, serving as a multifunctional carrier for the treatment of chronic wounds [186].

Photoresponsive electrospun NFs can be loaded with drugs to build smart drug delivery systems with controlled drug release. Park *et al.* prepared poly (ε-caprolactone) (PCL) NFs supported by photothermic gold nanocages (AuNCs) by electrospinning. The core can be loaded with drugs, and the shell can be loaded with phase-change fatty acids. When irradiated with near-infrared light, AuNCs generate heat to melt phase-change fatty acids, resulting in the rapid release of drugs from the NFs [170].

Electrospinning nanofibers in response to electric field

Transdermal drug delivery systems (TDSs) support the passage of drugs through the skin. It has several advantages, such as improving patient compliance, avoiding gastric irritation and first-pass effects, and controlling treatment responses [187]. However, because of the low permeability of the drug through the skin, TDSs have been limited to extremely low drug release rates. In general, precise control of the amount and rate of release is required to optimize treatment. As a promising solution, release systems that respond in a repeatable and predictable manner to internal or

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external stimuli, such as electric fields, pH, and temperature, have been extensively studied [188].

For these different stimuli, electric fields are an effective way to increase the amount of release through precise control. Two types of TDS that use electricity are commonly employed. The first is ionic electroosmotic therapy, in which an electric current is applied to deliver dissolved drugs to the skin. However, ionic electroosmotic therapy has several disadvantages. Only water-soluble drugs with molecular weights $<10\,000$ are suitable for ion electroosmosis therapy, and drug sites are prone to problems such as redness, burning, and itching.

Electrosensitive hydrogels have been extensively studied as TDS substrates because of their swelling properties under an electric field. Although considerable research has been conducted on TDS using these electrosensitive polymers, the practical application of TDS is limited because of the low electrical sensitivity of the polymers.

Yun *et al.* developed an effective TDS using multi-walled CNTs (MWCNTs), which can improve the conductivity and mechanical strength of hydrogels, as the conductive component, improving the electrical sensitivity and uniform distribution of conductive components [13]. To improve the distribution of hydrophobic MWCNT in the hydrophilic hydrogel matrix, surface treatment of the MWCNT was performed using oxyfluoridation. Electrospun hydrogel NFs containing MWCNTs have been studied to increase the surface area and thus increase drug release.

Prospects

With the increasing global prevalence of diabetes, the chronic wounds associated with this condition pose significant physical and psychological challenges for individuals as well as an economic burden on society. Consequently, there is an urgent need for the development of advanced wound dressings. The advantage of electrospinning lies in its capacity to encapsulate functional materials. Materials produced through this technology can fulfill two primary functions : (i) utilization of the inherent chemical activity of nanomaterials to inhibit bacterial growth and promote wound healing and (ii) employing nanomaterial-based carriers to deliver materials with monitoring capabilities and/or active ingredients, such as antibiotics, anti-inflammatory drugs, hypoglycemic agents, enzymes, growth factors, stem cells, exosomes, or genes. Considering the wound-healing process and the complex microenvironment of diabetic wounds, researchers have primarily focused on developing responsive electrospun materials in two key areas: (i) creating smart nanodressings with monitoring functions to assess wound status and adjust treatment plans accordingly and (ii) designing smart nanodressings with automated drug release mechanisms that respond to the wound microenvironment, thereby facilitating rapid and precise wound healing. The advantage of responsive electrospun dressing is that it can prompt specific diabetic wound environments (such as low pH, high ROS, and high temperature) to evaluate the wound state and respond and automatically release drugs according to their specific microenvironment to balance the factors unfavorable to wound recovery to accelerate wound healing.

These ideas offer innovative methods for the treatment of chronic diabetic wounds. However, extensive research is required to translate these strategies into clinical applications. Specifically, several issues must be addressed:

1) Practicality: From a clinical application perspective, the physicochemical properties and reproducibility of nanomaterials related to DFUs have not yet yielded ideal results.
2) Biosafety: The biological distribution, degradation processes, and biological effects of nanomedicines within the body—especially their long-term impacts—are not fully understood, and efficient targeting of nanomedicines to specific sites necessitates further research.
3) Theoretical feasibility: Differences between humans and experimental animals highlight the need for more *in vivo* studies in large mammals, rather than relying solely on the small mice or rats predominantly used in current literature.
4) High costs and complex preparation: The currently reported responsive electrospun materials involve intricate processes and numerous environmental factors, rendering them unsuitable for large-scale production, with relatively high costs that limit their practical application in clinical settings.
5) Controllability of material properties: Responsive electrospun materials still need to demonstrate greater stability and more sensitive response linearity. By addressing these issues, we can effectively promote the clinical application of nanomaterials in the treatment of chronic diabetic wounds. The reason is improved vocabulary, enhanced readability and clarity, and corrected grammatical and punctuation errors.

In the future development of responsive electrospun materials for diabetic wounds, several advancements can be envisioned in addition to the aforementioned challenges that require improved solutions : (i) research and develop wound dressings that integrate monitoring and treatment capabilities, promoting wound healing while simultaneously monitoring pH levels, blood glucose levels, and wound infections; (ii) create more effective “multifunctional wound dressings” tailored to the complex microenvironment of diabetic wounds; (iii) investigate gene therapy, cell therapy, and growth factor therapy utilizing nanotechnology, assessing the effectiveness of these approaches on wound healing and establishing relevant theoretical frameworks; (iv) address the high recurrence rates, which are a significant factor in the healing difficulties of diabetic wounds, by designing responsive electrospun nanodressings that are antirecurrence, thereby offering great potential in the treatment of DFU; and (v) further advance theoretical research on electrospinning technology to enhance the stability and production efficiency of the process, reduce costs, and facilitate long-term large-scale industrial production.

In summary, there is currently no product that can perfectly treat all diabetic wounds. Therefore, it is essential to establish systematic monitoring and external control mechanisms to provide personalized wound care to patients with diabetes. Although the preparation, storage, and application of responsive electrospun materials may be complex, personalized treatment often yields significantly better outcomes for complex chronic diabetic wounds. With an aging population and an increasing number of patients with diabetes, it is crucial to consider the likelihood of wound recurrence, the risk of infection, and the costs associated with changing dressings. The development of intelligent electrospun dressings may alleviate the economic burden of chronic diabetes wound care. More importantly, public awareness of wound management is increasing, and the combination of innovation and quality of responsive electrospun materials presents a promising

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market opportunity. Therefore, we are confident that, as these issues are gradually addressed, responsive electrospun materials will increasingly enter clinical practice and become the preferred wound care material for both diabetic patients and healthcare professionals.

Conclusions

Electrospun NFs have the characteristics of high surface volume ratio, high porosity, low cost, easy manufacturing and surface functionalization, and adjustable fiber morphology. With the emergence of various new technologies and devices, the application and packaging of functional materials based on electrospinning technology can realize monitoring and response to the diabetes wound environment (such as low pH, high ROS, and high temperature), thereby accelerating diabetic wound healing. With the increase in the global incidence rate of diabetes, the public's attention to wound management is increasing. We believe that responsive static spinning dressings will gradually become the first choice of wound care materials for diabetes patients and medical staff.

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Author contributions

Chengkai Zhou (Conceptualization, Investigation, Visualization [equal], Writing—original draft [lead]), Yan Geng (Conceptualization, Investigation, Visualization, Writing—original draft [equal]), Chenxi Zhang (Investigation, Visualization, Writing—original draft, Writing—review & editing [equal]), Yuwei Hsu (Validation, Writing—review & editing [equal]), Le Ma (Validation, Writing—review & editing [equal]), Mengen Li (Validation [equal]), Ye Tang (Validation [equal]), Wei Guo (Conceptualization, Funding acquisition, Project administration, Supervision [equal]), Ming Li (Funding acquisition, Project administration, Resources, Software, Supervision [equal]), and Yanhua Wang (Conceptualization, Funding acquisition, Project administration, Supervision [equal])

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Data availability

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

References

1. Baltzis D, Eleftheriadou I, Veves A. Pathogenesis and treatment of impaired wound healing in diabetes mellitus: new insights. *Adv Ther* 2014;31:817–36. https://doi.org/10.1007/s12325-014-0140-x.
2. Uccioli L, Izzo V, Meloni M, Vainieri E, Ruotolo V, Giurato L. Non-healing foot ulcers in diabetic patients: general and local interfering conditions and management options with advanced wound dressings. *J Wound Care* 2015;24:35–42. https://doi.org/10.12968/jowc.2015.24.Sup4b.35.
3. McCarty SM, Cochrane CA, Clegg PD, Percival SL. The role of endogenous and exogenous enzymes in chronic wounds: a focus on the implications of aberrant levels of both host and bacterial proteases in wound healing. *Wound Repair Regen* 2012;20:125–36. https://doi.org/10.1111/j.1524-475X.2012.00763.x.
4. Noor S, Khan RU, Ahmad J. Understanding diabetic foot infection and its management. *Diabetes Metab Syndr* 2017;11:149–56. https://doi.org/10.1016/j.dsx.2016.06.023.
5. Jiang P, Li Q, Luo Y, Luo F, Che Q, Lu Z. *et al.* Current status and progress in research on dressing management for diabetic foot ulcer. *Front Endocrinol (Lausanne)* 2023;14:1221705. https://doi.org/10.3389/fendo.2023.1221705.
6. Behroozi AH, Al-Shaeli M, Vatanpour V. Fabrication and modification of nanofiltration membranes by solution electrospinning technique: a review of influential factors and applications in water treatment. *Desalination* 2023;558:116638. https://doi.org/10.1016/j.desal.2023.116638.
7. Yang T, Ma J, Zhen SJ, Huang CZ. Electrostatic assemblies of well-dispersed AgNPs on the surface of electrospun nanofibers as highly active SERS substrates for wide-range pH sensing. *ACS Appl Mater Interfaces* 2016;8:14802–11. https://doi.org/10.1021/acsami.6b03720.
8. Teepoo S, Dawan P, Barnthip N. Electrospun chitosan-Gelatin biopolymer composite nanofibers for horseradish peroxidase immobilization in a hydrogen peroxide biosensor. *Biosensors* 2017;7:47. https://www.mdpi.com/2079-6374/7/4/47.
9. Nanodiamond–Silk Fibroin Membranes: A Multifunctional Platform for Biosensing and Wound-Healing Applications Khalid A, Bai D, Abraham AN, Jadhav A, Linklater D, Matusica A. *et al.* Electrospun Nanodiamond-silk fibroin membranes: a multifunctional platform for biosensing and wound-healing applications. *ACS Appl Mater Interfaces* 2020;12:48408–19. https://doi.org/10.1021/acsami.0c15612.
10. Ding S, Lou Y, Niu Z. *et al.* A biomimetic asymmetric structured intelligent wound dressing with dual-modality humidity-pressure sensing for non-invasive and real-time wound healing monitoring. *Macromol Mater Eng* 2022;307:2200233. https://doi.org/10.1002/mame.202200233.
11. Li H, Sang Q, Wu J, Williams GR, Wang H, Niu S. *et al.* Dual-responsive drug delivery systems prepared by blend electrospinning. *Int J Pharm* 2018;543:1–7. https://doi.org/10.1016/j.ijpharm.2018.03.009.
12. Zárate IA, Aguilar-Bolados H, Yazdani-Pedram M, Pizarro GDC, Neira-Carrillo A. In vitro hyperthermia evaluation of electrospun polymer composite Fibers loaded with reduced graphene oxide. *Polymers (Basel)* 2020;12:2663. https://doi.org/10.3390/polym12112663.
13. Yun J, Im JS, Lee Y-S, Kim H-I. Electro-responsive transdermal drug delivery behavior of PVA/PAA/MWCNT nanofibers. *Eur Polym J* 2011;47:1893–902. https://doi.org/10.1016/j.eurpolymj.2011.07.024.

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14. Senneville É, Albalawi Z, van Asten SA, Abbas ZG, Allison G, Aragón-Sánchez J. *et al.* IWGDF/IDSA Guidelines on the Diagnosis and Treatment of Diabetes-related Foot Infections (IWGDF/IDSA 2023). *Clinical Infectious Diseases*, 2023;ciad527. https://doi.org/10.1093/cid/ciad527.
15. Armstrong DG, Boulton AJM, Bus SA. Diabetic foot ulcers and their recurrence. *N Engl J Med* 2017;376:2367–75. https://doi.org/10.1056/NEJMra1615439.
16. Shah SA, Sohail M, Khan S, Minhas MU, de Matas M, Sikstone V. *et al.* Biopolymer-based biomaterials for accelerated diabetic wound healing: a critical review. *Int J Biol Macromol* 2019;139:975–93. https://doi.org/10.1016/j.ijbiomac.2019.08.007.
17. Raziyeva K, Kim Y, Zharkinbekov Z, Kassymbek K, Jimi S, Saparov A. Immunology of acute and chronic wound healing. *Biomolecules* 2021;11:700. https://doi.org/10.3390/biom11050700.
18. Strodtbeck F. Physiology of wound healing. *Newborn Infant Nurs Rev* 2001;1:43–52. https://doi.org/10.1053/nbin.2001.23176.
19. Ellis S, Lin EJ, Tartar D. Immunology of wound healing. *Curr Dermatol Rep* 2018;7:350–8. https://doi.org/10.1007/s13671-018-0234-9.
20. Rodrigues M, Kosaric N, Bonham CA, Gurtner GC. Wound healing: a cellular perspective. *Physiol Rev* 2019;99:665–706. https://doi.org/10.1152/physrev.00067.2017.
21. Landén NX, Li D, Ståhle M. Transition from inflammation to proliferation: a critical step during wound healing. *Cell Mol Life Sci* 2016;73:3861–85. https://doi.org/10.1007/s00018-016-2268-0.
22. Lansdown AB. Calcium: a potential central regulator in wound healing in the skin. *Wound Repair Regen* 2002;10:271–85. https://doi.org/10.1046/j.1524-475x.2002.10502.x PMID: 12406163.
23. van der Vliet A, Janssen-Heininger YM. Hydrogen peroxide as a damage signal in tissue injury and inflammation: murderer, mediator, or messenger? *J Cell Biochem* 2014;115:427–35. https://doi.org/10.1002/jcb.2468.
24. Su Y, Richmond A. Chemokine regulation of neutrophil infiltration of skin wounds. *Adv Wound Care (New Rochelle)* 2015;4:631–40. https://doi.org/10.1089/wound.2014.0559.
25. Banerjee K, Madhyastha R, Nakajima Y, Maruyama M, Madhyastha H. Nanoceutical adjuvants as wound healing material: precepts and prospects. *Int J Mol Sci* 2021;22:4748. https://doi.org/10.3390/ijms22094748.
26. Sharifi S, Hajipour MJ, Gould L, Mahmoudi M. Nanomedicine in healing chronic wounds: opportunities and challenges. *Mol Pharm* 2021;18:550–75. https://doi.org/10.1021/acs.molpharmaceut.0c00346.
27. Shen T, Dai K, Yu Y, Wang J, Liu C. Sulfated chitosan rescues dysfunctional macrophages and accelerates wound healing in diabetic mice. *Acta Biomater* 2020;117:192–203. https://doi.org/10.1016/j.actbio.2020.09.035.
28. Pastar I, Stojadinovic O, Yin NC, Ramirez H, Nusbaum AG, Sawaya A. *et al.* Epithelialization in wound healing: a comprehensive review. *Adv Wound Care (New Rochelle)* 2014;3:445–64. https://doi.org/10.1089/wound.2013.0473.
29. Kotwal GJ, Chien S. Macrophage differentiation in normal and accelerated wound healing. *Results Probl Cell Differ* 2017;62:353–64. https://doi.org/10.1007/978-3-319-54090-0_14.
30. Nethi SK, Das S, Patra CR, Mukherjee S. Recent advances in inorganic nanomaterials for wound-healing applications. *Biomater Sci* 2019;7:2652–74. https://doi.org/10.1039/C9BM00423H.
31. Xue M, Jackson CJ. Extracellular matrix reorganization during wound healing and its impact on abnormal scarring. *Adv Wound Care (New Rochelle)* 2015;4:119–36. https://doi.org/10.1089/wound.2013.0485.
32. Martin P, Nunan R. Cellular and molecular mechanisms of repair in acute and chronic wound healing. *Br J Dermatol* 2015;173:370–8. https://doi.org/10.1111/bjd.13954.
33. Lu Y, Li H, Wang J, Yao M, Peng Y, Liu T. *et al.* Engineering bacteria-activated multifunctionalized hydrogel for promoting diabetic wound healing. *Adv Funct Mater* 2021;31:2105749. https://doi.org/10.1002/adfm.202105749.
34. Shao Z, Yin T, Jiang J, He Y, Xiang T, Zhou S. Wound microenvironment self-adaptive hydrogel with efficient angiogenesis for promoting diabetic wound healing. *Bioact Mater* 2023;20:561–73. https://doi.org/10.1016/j.bioactmat.2022.06.018.
35. Zhang W, Chen L, Xiong Y, Panayi AC, Abududilibaier A, Hu Y. *et al.* Antioxidant therapy and antioxidant-related bionanomaterials in diabetic wound healing. *Front Bioeng Biotechnol* 2021;9:707479. https://doi.org/10.3389/fbioe.2021.707479.
36. Shaikh-Kader A, Houreld NN, Rajendran NK, Abrahamse H. The link between advanced glycation end products and apoptosis in delayed wound healing. *Cell Biochem Funct* 2019;37:432–42. https://doi.org/10.1002/cbf.3424.
37. Cano Sanchez M, Lancel S, Boulanger E, Neviere R. Targeting oxidative stress and mitochondrial dysfunction in the treatment of impaired wound healing: a systematic review. *Antioxidants (Basel)* 2018;7:98. https://doi.org/10.3390/antiox7080098.
38. Fui LW, Lok MPW, Govindasamy V, Yong TK, Lek TK, Das AK. Understanding the multifaceted mechanisms of diabetic wound healing and therapeutic application of stem cells conditioned medium in the healing process. *J Tissue Eng Regen Med* 2019;13:2218–33. https://doi.org/10.1002/term.2966.
39. Krzyszczyk P, Schloss R, Palmer A, Berthiaume F. The role of macrophages in acute and chronic wound healing and interventions to promote pro-wound healing phenotypes. *Front Physiol* 2018;9:419. https://doi.org/10.3389/fphys.2018.00419.
40. de Oliveira S, Rosowski EE, Huttenlocher A. Neutrophil migration in infection and wound repair: going forward in reverse. *Nat Rev Immunol* 2016;16:378–91. https://doi.org/10.1038/nri.2016.49.
41. Zhu Y, Zhang J, Song J, Yang J, Du Z, Zhao W. *et al.* A multifunctional pro-healing zwitterionic hydrogel for simultaneous optical monitoring of pH and glucose in diabetic wound treatment. *Adv Funct Mater* 2020;30:1905493. https://doi.org/10.1002/adfm.201905493.
42. Li D, Chen T, Zhang Y, Xu Y, Niu H. Synergistical starvation and chemo-dynamic therapy for combating multidrug-resistant bacteria and accelerating diabetic wound healing. *Adv Healthc Mater* 2021;10:e2100716. https://doi.org/10.1002/adhm.202100716.

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43. Schneider LA, Korber A, Grabbe S, Dissemond J. Influence of pH on wound-healing: a new perspective for wound-therapy? *Arch Dermatol Res* 2007;298:413–20. https://doi.org/10.1007/s00403-006-0713-x.
44. Kruse CR, Nuutila K, Lee CC, Kiwanuka E, Singh M, Caterson EJ. *et al.* The external microenvironment of healing skin wounds. *Wound Repair Regen* 2015;23:456–64. https://doi.org/10.1111/wrr.12303.
45. Liang Y, Li M, Yang Y, Qiao L, Xu H, Guo B. pH/glucose dual responsive metformin release hydrogel dressings with adhesion and self-healing via dual-dynamic bonding for athletic diabetic foot wound healing. *ACS Nano* 2022;16:3194–207. https://doi.org/10.1021/acsnano.1c11040.
46. Dissemond J, Witthoff M, Brauns TC, Haberer D, Goos M. pH values in chronic wounds. *Evaluation during modern wound therapy Hautarzt* 2003;54:959–65.
47. Alves PM, Barrias CC, Gomes P, Martins MCL. Smart biomaterial-based systems for intrinsic stimuli-responsive chronic wound management. *Mater Today Chem* 2021;22:100623. https://doi.org/10.1016/j.mtchem.2021.100623.
48. Yao Y, Zhang H, Wang Z, Ding J, Wang S, Huang B. *et al.* Reactive oxygen species (ROS)-responsive biomaterials mediate tissue microenvironments and tissue regeneration. *J Mater Chem B* 2019;7:5019–37. https://doi.org/10.1039/C9TB00847K.
49. Yang L, Liang F, Zhang X, Jiang Y, Duan F, Li L. *et al.* Remodeling microenvironment based on MOFs-hydrogel hybrid system for improving diabetic wound healing. *Chem Eng J* 2022;427:131506. https://doi.org/10.1016/j.cej.2021.131506.
50. Dinh T, Tecilazich F, Kafanas A, Doupis J, Gnardellis C, Leal E. *et al.* Mechanisms involved in the development and healing of diabetic foot ulceration. *Diabetes* 2012;61:2937–47. https://doi.org/10.2337/db12-0227.
51. Chang M, Nguyen TT. Strategy for treatment of infected diabetic foot ulcers. *Acc Chem Res* 2021;54:1080–93. https://doi.org/10.1021/acs.accounts.0c00864.
52. Caley MP, Martins VL, O'Toole EA. Metalloproteinases and wound healing. *Adv Wound Care (New Rochelle)* 2015;4:225–34. https://doi.org/10.1089/wound.2014.0581.
53. Das S, Baker AB. Biomaterials and nanotherapeutics for enhancing skin wound healing. *Front Bioeng Biotechnol* 2016;4:82. https://doi.org/10.3389/fbioe.2016.00082.
54. Castleberry SA, Almquist BD, Li W, Reis T, Chow J, Mayner S. *et al.* Self-assembled wound dressings silence MMP-9 and improve diabetic wound healing in vivo. *Adv Mater* 2016;28:1809–17. https://doi.org/10.1002/adma.201503565.
55. Liu Y, Min D, Bolton T, Nubé V, Twigg SM, Yue DK. *et al.* Increased matrix metalloproteinase-9 predicts poor wound healing in diabetic foot ulcers. *Diabetes Care* 2009;32:117–9. https://doi.org/10.2337/dc08-0763.
56. Gao M, Nguyen TT, Suckow MA, Wolter WR, Gooyit M, Mobashery S. *et al.* Acceleration of diabetic wound healing using a novel protease-anti-protease combination therapy. *Proc Natl Acad Sci USA* 2015;112:15226–31. https://doi.org/10.1073/pnas.1517847112.
57. Louiselle AE, Niemiec SM, Zgheib C, Liechty KW. Macrophage polarization and diabetic wound healing. *Transl Res* 2021;236:109–16. https://doi.org/10.1016/j.trsl.2021.05.006.
58. Zhao H, Huang J, Li Y, Lv X, Zhou H, Wang H. *et al.* ROS-scavenging hydrogel to promote healing of bacteria infected diabetic wounds. *Biomaterials* 2020;258:120286. https://doi.org/10.1016/j.biomaterials.2020.120286.
59. Pitocco D, Spanu T, Di Leo M, Vitiello R, Rizzi A, Tartaglione L. *et al.* Diabetic foot infections: a comprehensive overview. *Eur Rev Med Pharmacol Sci* 2019;23:26–37. https://doi.org/10.26355/eurrev_201904_17471.
60. Zhang Z, Zhang W, Xu Y, Liu D. Efficacy of hyperbaric oxygen therapy for diabetic foot ulcers: an updated systematic review and meta-analysis. *Asian J Surg* 2022;45:68–78. https://doi.org/10.1016/j.asjsur.2021.07.047.
61. Sharma R, Sharma SK, Mudgal SK, Jelly P, Thakur K. Efficacy of hyperbaric oxygen therapy for diabetic foot ulcer, a systematic review and meta-analysis of controlled clinical trials. *Sci Rep* 2021;11:2189. https://doi.org/10.1038/s41598-021-81886-1.
62. Liu H, Li ZH, Zhao Y, Feng YB, Zvyagin AV, Wang JC. *et al.* Novel diabetic foot wound dressing based on multifunctional hydrogels with extensive temperature-tolerant, durable, adhesive, and intrinsic antibacterial properties. *ACS Appl Mater Interfaces* 2021;13:26770–81. https://doi.org/10.1021/acsami.1c05514.
63. Chastain CA, Klopfenstein N, Serezani CH, Aronoff DM. A clinical review of diabetic foot infections. *Clin Podiatr Med Surg* 2019;36:381–95. https://doi.org/10.1016/j.cpm.2019.02.004.
64. Martin JM, Zenilman JM, Lazarus GS. Molecular microbiology: new dimensions for cutaneous biology and wound healing. *J Invest Dermatol* 2010;130:38–48. https://doi.org/10.1038/jid.2009.221.
65. Pouget C, Dunyach-Remy C, Pantel A, Schuldiner S, Sotto A, Lavigne JP. Biofilms in diabetic foot ulcers: significance and clinical relevance. *Microorganisms* 2020;8:1580. https://doi.org/10.3390/microorganisms8101580.
66. Percival SL, McCarty SM, Lipsky B. Biofilms and wounds: An overview of the evidence. *Adv Wound Care* 2015;4:373–81. https://doi.org/10.1089/wound.2014.0557.
67. Johnson TR, Gómez BI, McIntyre MK, Dubick MA, Christy RJ, Nicholson SE. *et al.* The cutaneous microbiome and wounds: new molecular targets to promote wound healing. *Int J Mol Sci* 2018;19:2699. https://doi.org/10.3390/ijms19092699.
68. Ding J, Gao B, Chen Z, Mei X. An NIR-triggered Au nanocage used for photo-thermo therapy of chronic wound in diabetic rats through bacterial membrane destruction and skin cell mitochondrial protection. *Front Pharmacol* 2021;12:779944. https://doi.org/10.3389/fphar.2021.779944.
69. Scalise A, Bianchi A, Tartaglione C, Bolletta E, Pierangeli M, Torresetti M. *et al.* Microenvironment and microbiology of skin wounds: the role of bacterial biofilms and related factors. *Semin Vasc Surg* 2015;28:151–9. https://doi.org/10.1053/j.semvascsurg.2016.01.003.
70. Armstrong DG, Tan TW, Boulton AJM, Bus SA. Diabetic foot ulcers: a review. *JAMA* 2023;330:62–75. https://doi.org/10.1001/jama.2023.10578.
71. Tavakoli S, Klar AS. Advanced hydrogels as wound dressings. *Biomolecules* 2020;10:1169. https://doi.org/10.3390/biom10081169.

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72. Pinho E, Soares G. Functionalization of cotton cellulose for improved wound healing. *J Mater Chem B* 2018;6:1887–98. https://doi.org/10.1039/C8TB00052B.
73. Jones V, Grey JE, Harding KG. Wound dressings. *BMJ* 2006;332:777–80. https://doi.org/10.1136/bmj.332.7544.777.
74. Vermeulen H, Ubbink D, Goossens A, de Vos R, Legemate D, Westerbos SJ. *et al.* Dressings and topical agents for surgical wounds healing by secondary intention. *Cochrane Database Syst Rev* 2004;2004:CD003554. https://doi.org/10.1002/14651858.CD003554.pub2.
75. RICHARD SCHREIBER-GASTELL, ANTON FORMHALS. Process and apparatus for preparing artificial threads: US50028330A[P]. 1934-10-02.
76. Ji D, Lin Y, Guo X. *et al.* Electrospinning of nanofibres. *Nat Rev Methods Primers* 2024;4:1. https://doi.org/10.1038/s43586-023-00278-z.
77. Buchko CJ, Chen LC, Shen Y, Martin DC. Processing and microstructural characterization of porous biocompatible protein polymer thin films. *Polymer* 1999;40:7397–407. https://doi.org/10.1016/S0032-3861(98)00866-0.
78. Choktaweesap N, Arayanarakul K, Aht-ong D. *et al.* Electrospun Gelatin Fibers: effect of solvent system on morphology and Fiber diameters. *Polym J* 2007;39:622–31. https://doi.org/10.1295/polymj.PJ2006190.
79. Yang GZ, Li HP, Yang JH. *et al.* Influence of working temperature on the formation of electrospun polymer nanofibers. *Nanoscale Res Lett* 2017;12:55. https://doi.org/10.1186/s11671-016-1824-8.
80. Irantash S, Gholipour-Kanani A, Najmoddin N. *et al.* A hybrid structure based on silk fibroin/PVA nanofibers and alginate/gum tragacanth hydrogel embedded with cardamom extract. *Sci Rep* 2024;14:14010. https://doi.org/10.1038/s41598-024-63061-4.
81. Meysam T, Le TT LF, Vinikoor T, Das R, Stevens JF, Mundrane C. *et al.* Highly piezoelectric, biodegradable, and flexible amino acid nanofibers for medical applications. *Sci Adv* 2023;9:eadg6075. https://doi.org/10.1126/sciadv.adg6075.
82. Aderibigbe BA. Hybrid-based wound dressings: combination of synthetic and biopolymers. *Polymers* 2022;14:3806. https://doi.org/10.3390/polym14183806.
83. Pasaribu KM, Mahendra IP, Sholeha NA, Masruchin N, Mardawati E, Karina M. Recent developments of the agroindustry byproducts utilization in bacterial cellulose production and its medical devices applications. In Lubis MAR. *et al.* (eds). *Biomass Conversion and Sustainable Biorefinery. Green Energy and Technology*. Springer, 2024, https://doi.org/10.1007/978-981-99-7769-7_10.
84. Nosrati H, Heydari M, Tootiaei Z, Ganjbar S, Khodaei M. Delivery of antibacterial agents for wound healing applications using polysaccharide-based scaffolds. *J Drug Deliv Sci Technol* 2023;84:104516. https://doi.org/10.1016/j.jddst.2023.104516.
85. Ahmadian S, Ghorbani M, Mahmoodzadeh F. Silver sulfadiazine-loaded electrospun ethyl cellulose/polylactic acid/collagen nanofibrous mats with antibacterial properties for wound healing. *Int J Biol Macromol* 2020;162:1555–65. https://doi.org/10.1016/j.ijbiomac.2020.08.059.
86. Razzaq A, Khan ZU, Saeed A, Shah KA, Khan NU, Menaa B. *et al.* Development of Cephradine-loaded Gelatin/polyvinyl alcohol electrospun nanofibers for effective diabetic wound healing: In-vitro and In-vivo assessments. *Pharmaceutics* 2021;13:349. https://doi.org/10.3390/pharmaceutics13030349.
87. Astaneh ME, Fereydouni N. A focused review on hyaluronic acid contained nanofiber formulations for diabetic wound healing. *Int J Biol Macromol*253. https://doi.org/10.1016/j.ijbiomac.2023.127607.
88. Charernsriwilaiwat N, Rojanarata T. Tanasait Ngawhirunpat, Monrudee Sukma, Praneet Opanasopit, electrospun chitosan-based nanofiber mats loaded with Garcinia mangostana extracts. *Int J Pharm* 2013;452:333–43. https://doi.org/10.1016/j.ijpharm.2013.05.012.
89. Xiao J, Zhan B, He M, Qi X, Gong X, Yang J-L. *et al.* Interfacial Polarization Loss Improvement Induced by the Hollow Engineering of Necklace-like PAN/Carbon Nanofibers for Boosted Microwave Absorption. *Adv Funct Mater* 2025;35:2316722. https://doi.org/10.1002/adfm.202316722.
90. Chen Y, Amiri A, Boyd JG, Naraghi M. Promising tradeoffs between energy storage and load bearing in carbon nanofibers as structural energy storage devices. *Adv Funct Mater* 2019;29:1901425. https://doi.org/10.1002/adfm.201901425.
91. Dong W, Wang Z, Zhang Q. *et al.* Polymer/block copolymer blending system as the compatible precursor system for fabrication of mesoporous carbon nanofibers for supercapacitors[J]. *J Power Sources* 2019;419:137–47. https://doi.org/10.1016/j.jpowsour.2019.02.070.
92. Townsend-Nicholson A, Jayasinghe SN. Cell electrospinning: a unique biotechnique for encapsulating living organisms for generating active biological microthreads/scaffolds. *Biomacromolecules* 2006;7:3364–9. https://doi.org/10.1021/bm060649h.
93. Gopinathan J, Noh I. Recent trends in bioinks for 3D printing. *Biomater Res* 2018;22:11. https://doi.org/10.1186/s40824-018-0122-1.
94. Yeo MG, Kim GH. Fabrication of cell-laden electrospun hybrid scaffolds of alginate-based bioink and PCL microstructures for tissue regeneration. *Chem Eng J* 2015;275:27–35. https://doi.org/10.1016/j.cej.2015.04.038.
95. Hong J, Yeo M, Yang GH, Kim G. Cell-electrospinning and its application for tissue engineering. *Int J Mol Sci* 2019;20:6208. https://doi.org/10.3390/ijms20246208.
96. Kong B, Chen Y, Liu R, Liu X, Liu C, Shao Z. *et al.* Fiber reinforced GelMA hydrogel to induce the regeneration of corneal stroma. *Nat Commun* 2020;11:1435. https://doi.org/10.1038/s41467-020-14887-9.
97. Gulfam M, Lee JM, Kim JE, Lim DW, Lee EK, Chung BG. Highly porous core-shell polymeric fiber network. *Langmuir* 2011;27:10993–9. https://doi.org/10.1021/la201253z.
98. Yu T, Gleeson SE, Li CY, Marcolongo M. Electrospun poly(ε-caprolactone) nanofiber shish kebabs mimic mineralized bony surface features. *J Biomed Mater Res B* 2019;107:1141–9. https://doi.org/10.1002/jbm.b.34207.
99. Zaarour B, Zhu L, Jin X. A review on the secondary surface morphology of electrospun nanofibers: formation

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mechanisms, characterizations, and applications. *ChemistrySelect* 2020;5:1335–48. https://doi.org/10.1002/slct.201903981.
100. Yu DG, Li XY, Wang X, Yang JH, Bligh SW, Williams GR. Nanofibers fabricated using triaxial electrospinning as zero order drug delivery systems. *ACS Appl Mater Interfaces* 2015;7:18891–7. https://doi.org/10.1021/acsami.5b06007.
101. Xue J, Wu T, Dai Y, Xia Y. *Chem Rev* 2019;119:5298–415. https://doi.org/10.1021/acs.chemrev.8b00593.
102. Sultanova Z, Kaleli G, Kabay G, Mutlu M. Controlled release of a hydrophilic drug from coaxially electrospun polycaprolactone nanofibers. *Int J Pharm* 2016;505:133–8. https://doi.org/10.1016/j.ijpharm.2016.03.032.
103. Pant B, Park M, Park S-J. Drug delivery applications of Core-sheath nanofibers prepared by coaxial electrospinning: a review. *Pharmaceutics* 2019;11:305. https://doi.org/10.3390/pharmaceutics11070305.
104. Li H-N, Yang J, Xu Z-K. Asymmetric surface engineering for Janus membranes. *Adv Mater Interfaces* 2020;7:1902064. https://doi.org/10.1002/admi.201902064.
105. Tian J, Ma Q, Wensheng Y, Li D, Dong X, Liu G. *et al.* Preparation of Janus microfibers with magnetic and fluorescence functionality via conjugate electro-spinning. *Materials & Design* 2019;170:107701. https://doi.org/10.1016/j.matdes.2019.107701.
106. Xie X, Chen Y, Wang X, Xu X, Shen Y, Khan AR. *et al.* Electrospinning nanofiber scaffolds for soft and hard tissue regeneration. *J Mater Sci Technol* 2020;59:243–61. https://doi.org/10.1016/j.jmst.2020.04.037.
107. Habibi S, Mohammadi T, HMTShirazi R, Atyabi F, Kiani M, Asadi AA. A bilayer mupirocin/bupivacaine-loaded wound dressing based on chitosan/poly(vinyl alcohol) nanofibrous mat: preparation, characterization, and controlled drug release. *Int J Biol Macromol* 2023;240:124399. https://doi.org/10.1016/j.ijbiomac.2023.124399.
108. Figueira DR, Miguel SP, de Sá KD, Correia IJ. Production and characterization of polycaprolactone- hyaluronic acid/chitosan- zein electrospun bilayer nanofibrous membrane for tissue regeneration. *Int J Biol Macromol* 2016;93:1100–10. https://doi.org/10.1016/j.ijbiomac.2016.09.080.
109. Ling Y, An T, Yap LW, Zhu B, Gong S, Cheng W. Disruptive, soft, wearable sensors. *Adv Mater* 2020;32:e1904664. https://doi.org/10.1002/adma.201904664.
110. Correia TR, Antunes BP, Castilho PH, Nunes JC, Maria T, de Amorim P. *et al.* A bi-layer electrospun nanofiber membrane for plasmid DNA recovery from fermentation broths. *Sep Purif Technol* 2013;112:20–5. https://doi.org/10.1016/j.seppur.2013.03.049.
111. Mao Y, Shen W, Wu S, Ge X, Ao F, Ning Y. *et al.* Electrospun polymers: using devices to enhance their potential for biomedical applications. *React Funct Polym* 2023;186:105568. https://doi.org/10.1016/j.reactfunctpolym.2023.105568.
112. Feng X, Li J, Zhang X, Liu T, Ding J, Chen X. Electrospun polymer micro/nanofibers as pharmaceutical repositories for healthcare. *J Control Release* 2019;302:19–41. https://doi.org/10.1016/j.jconrel.2019.03.020.
113. Zheng Q, Xi Y, Weng Y. Functional electrospun nanofibers: fabrication, properties, and applications in wound-healing process. *RSC Adv* 2024;14:3359–78. https://doi.org/10.1039/d3ra07075a.
114. Sun Z, Zussman E, Yarin AL, Wendorff JH, Greiner A. Compound Core–Shell polymer nanofibers by Co-electrospinning†. *Adv Mater* 2003;15:1929–32. https://doi.org/10.1002/adma.&break;200305136.
115. Cai M, He H, Zhang X, Yan X, Li J, Chen F. *et al.* Efficient synthesis of PVDF/PI side-by-side bicomponent nanofiber membrane with enhanced mechanical strength and good thermal stability. *Nanomaterials* 2019;9:39. https://doi.org/10.3390/nano9010039.
116. Li D, Xia Y. Direct fabrication of composite and ceramic hollow nanofibers by electrospinning. *Nano Lett* 2004;4:933–8. https://doi.org/10.1021/nl049590f.
117. Jianxin L, Xuedi C, Xiaolei Z, Xicheng J, Yao Hengzhe F, Junlin R. *et al.* Review on functional electrospun nanofibers: Theory, application and fabrication. *Materials Science and Engineering: B* 2024;307:117488. https://doi.org/10.1016/j.mseb.2024.117488.
118. Jin X. You-lo Hsieh, pH-responsive swelling behavior of poly(vinyl alcohol)/poly(acrylic acid) bi-component fibrous hydrogel membranes. *Polymer* 2005;46:5149–60. https://doi.org/10.1016/j.polymer.2005.04.066.
119. Jedlovszky-Hajdu A, Molnar K, Nagy PM, Sinko K, Zrinyi M. Preparation and properties of a magnetic field responsive three-dimensional electrospun polymer scaffold. *Colloids Surf A Physicochem Eng Asp* 2016;503:79–87. https://doi.org/10.1016/j.colsurfa.2016.05.036.
120. Al-Shaeli M, Benkhaya S, Al-Juboori RA, Koyuncu I, Vatanpour V. pH-responsive membranes: mechanisms, fabrications, and applications. *Sci Total Environ*946:173865. https://doi.org/10.1016/j.scitotenv.2024.173865.
121. Tan S, Han J, Yuan X, Song Z, Gao L, Jing Gao L. *et al.* Epigallocatechin gallate-loaded pH-responsive dressing with effective antioxidant, antibacterial and anti-biofilm properties for wound healing. *Mater Des* 2023;227:111701. https://doi.org/10.1016/j.matdes.2023.111701.
122. Fan S, Lam Y, Yang J, Bian X, Xin JH. Development of photochromic poly(azobenzene)/PVDF fibers by wet spinning for intelligent textile engineering. *Surf Interfaces* 2022;34:102383. https://doi.org/10.1016/j.surfin.2022.102383.
123. Babazadeh-Mamaqani M, Razzaghi D, Roghani-Mamaqani H, Babaie A, Rezaei M, Hoogenboom R. *et al.* Photo-responsive electrospun polymer nanofibers: mechanisms, properties, and applications. *Prog Mater Sci* 2024;146:101312. https://doi.org/10.1016/j.pmatsci.2024.101312.
124. Keke W, Xiaoxian W, Chen M, Haoming W, Jiao Y, Zhou C. *et al.* H2O2- responsive smart dressing for visible H2O2 monitoring and accelerating wound healing. *Chem Eng J* 2020;387:124127. https://doi.org/10.1016/j.cej.2020.124127.
125. Chen K, Li Y, Li Y, Tan Y, Liu Y, Pan W. *et al.* Stimuli-responsive electrospun nanofibers for drug delivery, cancer therapy, wound dressing, and tissue engineering. *J Nanobiotechnol* 2023;21:237. https://doi.org/10.1186/s12951-023-01987-z.
126. Chen L-N, Chiu Y-C, Hung J-J, Kuo C-C, Chen W-C. Multifunctional electrospun nanofibers prepared from poly((N-isopropylacrylamide)-co-(N-hydroxymethylacrylamide)) and their blends with

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1,2-Diaminoanthraquinone for NO gas detection. *Macromol Chem Phys* 2014;215:286–94. https://doi.org/10.1002/macp.201300604.
127. Pawłowska S, Rinoldi C, Nakielski P, Ziai Y, Urbanek O, Li X. *et al.* Ultraviolet light-assisted electrospinning of Core–Shell fully cross-linked P(NIPAAm-co-NIPMAAm) hydrogel-based nanofibers for thermally induced drug delivery self-regulation. *Adv Mater Interfaces* 2020;7:2000247. https://doi.org/10.1002/admi.202000247.
128. Haghparas Z, Kordrostami Z, Sorouri M, Rajabzadeh M, Khalifeh R. Highly sensitive non-enzymatic electrochemical glucose sensor based on dumbbell-shaped double-shelled hollow nanoporous CuO/ZnO microstructures. *Sci Rep* 2021;11:344. https://doi.org/10.1038/s41598-020-79460-2.
129. Long L, Liu X, Chen L, Li D, Jia J. A hollow CuOx/NiOy nanocomposite for amperometric and non-enzymatic sensing of glucose and hydrogen peroxide. *Microchim Acta* 2019;186:74. https://doi.org/10.1007/s00604-018-3183-x.
130. Huang W, Ding S, Chen Y, Hao W, Lai X, Peng J. *et al.* 3D NiO hollow sphere/reduced graphene oxide composite for high-performance glucose biosensor. *Sci Rep* 2017;7:1–11. https://doi.org/10.1038/s41598-017-05528-1.
131. Tang T, Jiang H, Yu Y, He F, Ji S, Liu Y. *et al.* A new method of wound treatment: targeted therapy of skin wounds with reactive oxygen species-responsive nanoparticles containing SDF-1α. *Int J Nanomedicine* 2015;10:6571–85. https://doi.org/10.2147/IJN.S88384.
132. Kim GJ, Kim KO. Novel glucose-responsive of the transparent nanofiber hydrogel patches as a wearable biosensor via electrospinning. *Sci Rep* 2020;10:18858. https://doi.org/10.1038/s41598-020-75906-9.
133. Xue J, Wu T, Qiu J, Xia Y. Spatiotemporally controlling the release of biological effectors enhances their effects on cell migration and neurite outgrowth. *Small Methods* 2020;4:2000125. https://doi.org/10.1002/smtd.202000125.
134. Shan Y, Wang E, Cui X, Xi Y, Ji J, Yuan J. *et al.* A biodegradable piezoelectric sensor for real-time evaluation of the motor function recovery after nerve injury. *Adv Funct Mater* 2024;34:2400295. https://doi.org/10.1002/adfm.202400295.
135. Jang J, Hyun B, Ji S, Cho E, An BW, Cheong WH. *et al.* Rapid production of large-area, transparent and stretchable electrodes using metal nanofibers as wirelessly operated wearable heaters. *NPG Asia Mater* 2017;9:e432. https://doi.org/10.1038/am.2017.172.
136. Park M, Tsai S-L, Chen W. Microbial biosensors: engineered microorganisms as the sensing machinery. *Sensors* 2013;13:5777–95. https://doi.org/10.3390/s130505777.
137. Wang Z, Bai H, Yu W, Gao Z, Chen W, Yang Z. *et al.* Flexible bioelectronic device fabricated by conductive polymer–based living material. *Sci Adv* 2022;8:eabo1458. https://doi.org/10.1126/sciadv.abo1458.
138. Ren X, Fan H, Zhao Y, Liu Z. Flexible lead-free BiFeO3/PDMS-based nanogenerator as piezoelectric energy harvester. *ACS Appl Mater Interfaces* 2016;8:26190–7. https://doi.org/10.1021/acsami.6b04497.
139. Samadian H, Khastar H, Ehterami A, Salehi M. Bioengineered 3D nanocomposite based on gold nanoparticles and gelatin nanofibers for bone regeneration: in vitro and in vivo study. *Sci Rep* 2021;11:13877. https://doi.org/10.1038/s41598-021-93367-6.
140. Mane PP, Ambekar RS, Kandasubramanian B. Electrospun nanofiber-based cancer sensors: a review. *Int J Pharm* 2020;583:119364. https://doi.org/10.1016/j.ijpharm.2020.119364.
141. Kumar M, Hilles AR, Ge Y, Bhatia A, Mahmood S. A review on polysaccharides mediated electrospun nanofibers for diabetic wound healing: their current status with regulatory perspective. *Int J Biol Macromol* 2023;234:123696. https://doi.org/10.1016/j.ijbiomac.2023.123696.
142. Zhang Y, Zhang W, Hui S, Fan C, Sun J, Ying Z. Preparation of a super flexible Cu/carbon composite nanofiber film electrode for high-performance flexible all-solid-state supercapacitors. *J Electron Mater* 2020;49:3165–73. https://doi.org/10.1007/s11664-020-08020-1.
143. Ramanan VV, Hribar KC, Katz JS, Burdick JA. Nanofiber-nanorod composites exhibiting light-induced reversible lower critical solution temperature transitions. *Nanotechnology* 2011;22:494009. https://doi.org/10.1088/0957-4484/22/49/494009.
144. Wang M, Singh H, Hatton TA, Rutledge GC. Field-responsive superparamagnetic composite nanofibers by electrospinning. *Polymer* 2004;45:5505–14. https://doi.org/10.1016/j.polymer.2004.06.013.
145. Burke L, Mortimer CJ, Curtis DJ, Lewis AR, Williams R, Hawkins K. *et al.* In-situ synthesis of magnetic iron-oxide nanoparticle-nanofibre composites using electrospinning. *Mater Sci Eng* 2017;70:512–9. https://doi.org/10.1016/j.msec.2016.09.014.
146. Fang M, Grant PS, McShane MJ, Sukhorukov GB, Golub VO, Lvov YM. Magnetic bio/nanoreactor with multilayer shells of glucose oxidase and inorganic nanoparticles. *Langmuir* 2002;18:6338–44. https://doi.org/10.1021/la025731m.
147. Hameed MMA, Khan SAPM, Thamer BM, Al-Enizi A, Aldalbahi A, El-Hamshary H. *et al.* Core-shell nanofibers from poly(vinyl alcohol) based biopolymers using emulsion electrospinning as drug delivery system for cephalexin drug. *J Macromol Sci A* 2021;58:130–44. https://doi.org/10.1080/10601325.2020.1832517.
148. Wang X, Fan L, Zhang J, Sun X, Chang H, Yuan B. *et al.* Printed conformable liquid metal e-skin-enabled spatiotemporally controlled bioelectromagnetics for wireless multisite tumor therapy. *Adv Funct Mater* 2019;29:1907063. https://doi.org/10.1002/adfm.201907063.
149. Kim M, Cho C, Shin W, Park JJ, Kim J, Won P. *et al.* Nanowire-assisted freestanding liquid metal thin-film patterns for highly stretchable electrodes on 3D surfaces. *Npj Flex Electron* 2022;6:99. https://doi.org/10.1038/s41528-022-00232-1.
150. Ma J, Liu Z, Nguyen Q-K, Zhang P. Lightweight soft conductive composites embedded with liquid metal Fiber networks. *Adv Funct Mater* 2024;34:2308128. https://doi.org/10.1002/adfm.202308128.
151. Liu Z, Wang J, Zhang Q, Li Z, Li Z, Cheng L. *et al.* Electrospinning silk fibroin/graphene nanofiber membrane used for 3D wearable pressure sensor. *Polymers* 2022;14:3875. https://doi.org/10.3390/polym14183875.
152. Wei Z, Yang J, Long S, Zhang G, Wang X. Smart and in-situ formation electrospun fibrous membrane for the control of antimicrobial efficacy. *Smart Mater Med* 2021;2:87–95. https://doi.org/10.1016/j.smaim.2021.02.001.

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153. Nezhadghaffar-Borhani E, Abdollahi A, Roghani-Mamaqani H, Salami-Kalajahi M. Photoswitchable surface wettability of ultrahydrophobic nanofibrous coatings composed of spiropyran-acrylic copolymers. *J Colloid Interface Sci* 2021;593:67–78. https://doi.org/10.1016/j.jcis.2021.03.012.
154. Wei Z, Lin Q, Yang J, Long S, Zhang G, Wang X. *et al.* Fabrication of novel dual thermo- and pH-sensitive poly (N-isopropylacrylamide-N- methylolacrylamide-acrylic acid) electrospun ultrafine fibres for controlled drug release. *Mater Sci Eng C* 2020;115:111050. https://doi.org/10.1016/j.msec.2020.111050.
155. Soares JC, Iwaki LEO, Soares AC, Rodrigues VC, Melendez ME, Fregnani JHTG. *et al.* Immunosensor for pancreatic cancer based on electrospun nanofibers coated with carbon nanotubes or gold nanoparticles. *ACS Omega* 2017;2:6975–83. https://doi.org/10.1021/acsomega.7b01029.
156. Sun J, Wang W, Yu D. NiCo2O4 nanosheet-decorated carbon nanofiber electrodes with high electrochemical performance for flexible supercapacitors. *J Electron Mater* 2019;48:3833–43. https://doi.org/10.1007/s11664-019-07135-4.
157. Qi K, He J, Wang H, Zhou Y, You X, Nan N. *et al.* A highly stretchable nanofiber-based electronic skin with pressure-, strain-, and flexion-sensitive properties for health and motion monitoring. *ACS Appl Mater Interfaces* 2017;9:42951–60. https://doi.org/10.1021/acsami.7b07935.
158. Zhang L, Belova V, Wang H, Dong W, Möhwald H. Controlled cavitation at nano/microparticle surfaces. *Chem Mater* 2014;26:2244–8.
159. Luo G, Xie J, Liu J, Zhang Q, Luo Y, Li M. *et al.* Highly conductive, stretchable, durable, breathable electrodes based on electrospun polyurethane mats superficially decorated with carbon nanotubes for multifunctional wearable electronics. *Chemical Engineering Journal* 2023;451:138549. https://doi.org/10.1016/j.cej.2022.138549.
160. Luo Y, Zhao L, Luo G, Dong L, Xia Y, Li M. *et al.* Highly sensitive piezoresistive and thermally responsive fibrous networks from the in situ growth of PEDOT on MWCNT-decorated electrospun PU fibers for pressure and temperature sensing. *Microsyst Nanoeng* 2023;9:113. https://doi.org/10.1038/s41378-023-00593-1.
161. Wen P, Yang Y-Y, Yin W-J, Jian-Cheng H, Yu-Dong Shen Y, Wang Z-LX. *et al.* Preparation of an ultrasensitive electrochemical immunosensor for the rapid detection of 19-nortestosterone based on polyvinyl alcohol/polyacrylic acid electrospun nanofiber mat. *Sensors Actuators B Chem* 2022;370:132450. https://doi.org/10.1016/j.snb.2022.132450.
162. Temoçin Z. Designing of a stable and selective glucose biosensor by glucose oxidase immobilization on glassy carbon electrode sensitive to H2O2 via nanofiber interface. *J Appl Electrochem* 2021;51:283–93. https://doi.org/10.1007/s10800-020-01502-4.
163. Zhang LQ. *Preparation of a healing dressing that can monitor wound humidity [D]*. Chongqing: Chongqing Medical University, 2021. (in Chinese).
164. Ding S, Lou Y, Niu Z, Wang J, Jin X, Ma J. *et al.* A highly sensitive, breathable, and biocompatible wearable sensor based on nanofiber membrane for pressure and humidity monitoring. *Macromol Mater Eng* 2022;307:2200233. https://doi.org/10.1002/mame.202200233.
165. Ding S, Jin X, Guo J, Kou B, Chai M, Dou S. *et al.* A biomimetic asymmetric structured intelligent wound dressing with dual-modality humidity-pressure sensing for non-invasive and real-time wound healing monitoring. *Adv Fiber Mater* 2025;7:156–71. https://doi.org/10.1007/s42765-024-00473-x.
166. Yang L, Li C, Wang X, Zhang X, Li Y, Liu S. *et al.* Electroactive nanofibrous membrane with temperature monitoring for wound healing. *RSC Adv* 2023;13:14224–35. https://doi.org/10.1039/d3ra01665j.
167. ACS Appl. Mater. *Interfaces* 2022;14:12984–3000.
168. Zhang S, Wang L, Xu T, Zhang X. Luminescent MOF-Based Nanofibers with Visual Monitoring and Antibacterial Properties for Diabetic Wound Healing. *ACS Appl Mater Interfaces* 2023;15:9110–9119. https://doi.org/10.1021/acsami.2c21786.
169. Yang P, Zhu Z, Zhang T, Zhang W, Chen W, Cao Y. *et al.* Orange-emissive carbon quantum dots: toward application in wound pH monitoring based on colorimetric and fluorescent changing. *Small* 2019;15:e1902823. https://doi.org/10.1002/smll.201902823.
170. Oh HH, Ko YG, Uyama H, Park WH, Cho D, Kwon OH. Fabrication and characterization of thermoresponsive polystyrene nanofibrous mats for cultured cell recovery. *Biomed Res Int* 2014;2014:480694.
171. Safari S, Ehsani M, Zandi M. Stimuli-responsive electrospun nanofibers based on PNVCL-PVAc copolymer in biomedical applications. *Prog Biomater* 2021;10:245–58. https://doi.org/10.1007/s40204-021-00168-1.
172. El-Husseiny HM, Mady EA, Hamabe L, Abugomaa A, Shimada K, Yoshida T. *et al.* Smart/stimuli-responsive hydrogels: cutting-edge platforms for tissue engineering and other biomedical applications. *Mater Today Bio* 2022;13:100186. https://doi.org/10.1016/j.mtbio.2021.100186.
173. Kim YJ, Ebara M, Aoyagi T. Temperature-responsive electrospun nanofibers for 'on-off' switchable release of dextran. *Sci Technol Adv Mater* 2012;13:064203. https://doi.org/10.1088/1468-6996/13/6/064203.
174. Huang Y, Song M, Li X, Du Y, Gao Z, Zhao YQ. *et al.* Temperature-responsive self-contraction nanofiber/hydrogel composite dressing facilitates the healing of diabetic-infected wounds. *Materials Today Bio* 2024;28:101214. https://doi.org/10.1016/j.mtbio.2024.101214.
175. Cheng Y, Zhu M, Chi M, Lai Y, Li B, Qian R. *et al.* MXene/TPU hybrid fabrics enable smart wound management and Thermoresponsive drug delivery. *ACS Appl Mater Interfaces* 2024. https://doi.org/10.1021/acsami.3c19604.
176. Federico S, Martorana A, Pitarresi G, Palumbo FS, Fiorica C, Giammona G. Development of stimulus-sensitive electrospun membranes based on novel biodegradable segmented polyurethane as triggered delivery system for doxorubicin. *Biomater Adv* 2022;136:212769. https://doi.org/10.1016/j.bioadv.2022.212769.
177. Lee H, Woo J, Son D, Kim M, Choi WI, Sung D. Electrospinning/electrospray of ferrocene containing copolymers to fabricate ROS-responsive particles and fibers. *Polymers (Basel)* 2020;12:12. https://doi.org/10.3390/polym12112520.
178. Jo YJ, Gulfam M, Jo SH, Gal YS, Oh CW, Park SH. *et al.* Multi-stimuli responsive hydrogels derived from hyaluronic

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acid for cancer therapy application. *Carbohydr Polym* 2022;286:119303. https://doi.org/10.1016/j.carbpol.2022.119303.

179. Zhang J, Xiao C, Zhang X, Lin Y, Yang H, Zhang YS. *et al.* An oxidative stress-responsive electrospun polyester membrane capable of releasing anti-bacterial and anti-inflammatory agents for postoperative anti-adhesion. *J Control Release* 2021;335:359–68. https://doi.org/10.1016/j.jconrel.2021.04.017.
180. Yao Y, Ding J, Wang Z, Zhang H, Xie J, Wang Y. *et al.* ROS-responsive polyurethane fibrous patches loaded with methylprednisolone (MP) for restoring structures and functions of infarcted myocardium in vivo. *Biomaterials* 2020;232:119726. https://doi.org/10.1016/j.biomaterials.2019.119726.
181. Kwak M, Han L, Chen JJ, Fan R. Interfacing inorganic nanowire arrays and living cells for cellular function analysis. *Small* 2015;11:5600–10. https://doi.org/10.1002/smll.201501236.
182. Singh B, Shukla N, Kim J, Kim K, Park MH. Stimuli-responsive nanofibers containing gold nanorods for on-demand drug delivery platforms. *Pharmaceutics* 2021;13:1319. https://doi.org/10.3390/pharmaceutics13081319.
183. Lee HP, Gaharwar AK. Light-responsive inorganic biomaterials for biomedical applications. *Adv Sci (Weinh)* 2020;7:2000863. https://doi.org/10.1002/advs.202000863.
184. Wen T, Xiong S, Zhao H, Wang J, Wang C, Long Z. *et al.* Polylactic acid-based dressing with oxygen generation and enzyme-like activity for accelerating both light-driven biofilm elimination and wound healing. *Burns Trauma* 2024;12:tkae041. https://doi.org/10.1093/burnst/tkae041.
185. Chong Y, Ge C, Fang G, Wu R, Zhang H, Chai Z. *et al.* Light-enhanced antibacterial activity of graphene oxide, mainly via accelerated electron transfer. *Environ Sci Technol* 2017;51:10154–61. https://doi.org/10.1021/acs.est.7b00663.
186. Murakami T, NakaHsuji H, Inada M, Matoba Y, Umeyama T, Hsujimoto M. *et al.* Photodynamic and Photothermal effects of semiconducting and metallic-enriched single-walled carbon nanotubes. *J Am Chem Soc* 2012;134:17862–5. https://doi.org/10.1021/ja3079972.
187. Hu X, Liu S, Zhou G, Huang Y, Xie Z, Jing X. Electrospinning of polymeric nanofibers for drug delivery applications. *J Control Release* 2014;185:12–21. https://doi.org/10.1016/j.jconrel.2014.04.018.
188. Chen M, Li YF, Besenbacher F. Electrospun nanofibers-mediated on-demand drug release. *Adv Healthc Mater* 2014;3:1721–32. https://doi.org/10.1002/adhm.201400166.

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