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REVIEW

# Smart Textiles with Living Interfaces: Microbiome–Electronics Integration for Advanced Skin Health Management

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## Abstract
Smart textiles have emerged as a transformative class of materials that extend the role of conventional fabrics into personalized health management. This evolution is driven by the seamless integration of textiles with flexible electronics, enabling new paradigms in skin-interfaced systems. In the exploration of novel smart textiles for skin health, microorganisms living in the skin microenvironment necessitate consideration. Skin microbiomes are essential to skin homeostasis and balance the barrier to infection. Moreover, microbes have been extensively explored as functional components in skin health monitoring and therapeutic devices. In this review, the distribution of skin microbes, interactions between host and resident microbiota, and mechanisms of microbial functions in the skin microenvironment are introduced systematically. In addition, recent progress in skin-based flexible devices for health management, and design and fabrication methods for smart textiles are discussed. However, some challenges still exist in association with the integration of microbes into smart textiles, such as the biosafety of microbes, long-term storage, and activation. This review provides a summary of innovative technologies including microencapsulation, synthetic biology, optogenetics, and artificial intelligence for microbe-integrated smart textiles. Next-generation smart textiles will hold significant promise for precision skin disease diagnostics, personalized therapeutics, skin status monitoring, and intelligence regulation.

**Keywords** Smart textiles · Skin interface · Microbiomes · Flexible electronics · Health management

## 1 Introduction

Textiles are essential to human life and skin health and are exploited for a range of applications including clothing, protective equipment, and medical health care [1]. Conventional textiles are primarily composed of natural materials such as cotton, wool, and silk, which provide comfort and breathability but lack advanced functionalities. Modern textiles have evolved with functions that advance comfort, health, and safety such as ultraviolet (UV) protection, moisture-wicking, and antimicrobial resistance [2–4]. The emergence of flexible electronics has revolutionized textile applications, paving the way for smart textiles that seamlessly integrate electronic functionalities into fabrics. These smart textiles include electronic skin (e-skin), smart wound dressings, and intelligent clothing. Compared with basic textiles, they can offer advanced functions such as monitoring and therapeutic modules. For instance, e-skin can monitor physiological parameters such as body temperature, heart rate, humidity, and biomarkers related to skin health [5–7]. Smart wound dressings can track wound healing by detecting potential of hydrogen (pH), moisture, and temperature [8–10]. Some advanced dressings can even identify inflammatory responses or tissue regeneration status and release drugs accordingly to reduce inflammation and accelerate healing [11, 12]. These real-time health monitoring and therapeutic

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capabilities are particularly valuable for personalized medicine, sports performance tracking, and chronic disease management. According to a market research report by Straits Research [13], the global value of the smart textile market was USD 3.45 billion in 2024 and it is expected to increase from USD 4.23 billion in 2025 to USD 21.46 billion by 2033.

For the effective design of advanced textiles for skin health management, commencing with an in-depth study of the skin microenvironment is imperative. Micro-organisms that live on human skin comprise a diverse ecosystem known as the skin microbiome, which is essential for maintaining skin health. This microbiota forms a dynamic and symbiotic relationship with the host [14], contributing to the skin barrier, immune regulation, metabolic function, and disease prevention [15–18]. However, when the balance of this microbial community is disrupted, it can lead to various skin disorders [19, 20]. A notable example is atopic dermatitis (AD), which is a condition characterized by skin inflammation and barrier dysfunction. Patients with AD often exhibit decreased skin microbiota diversity, accompanied by an over-colonization of *Staphylococcus aureus*, which exacerbates symptoms by eliciting aberrant immune responses [21, 22]. Current treatment strategies include the use of topical corticosteroids and calcineurin inhibitors to reduce inflammation, moisturizers to restore the skin barrier, and antimicrobial peptides (AMPs) to control pathogens over-colonization [23, 24]. In addition, emerging therapies such as probiotics, microbiome transplantation, and targeted modulation of the skin microbiota are garnering increasing attention, offering new strategies for the management of AD [25, 26]. Therefore, understanding the skin microenvironment and intervention measures for microbial balance is crucial for advancing the development of microbial-integrated smart textiles.

As important components of living interfaces, these microorganisms can play key roles in innovative smart textile substrates, sensing, energy harvesting, and therapy. Moreover, they expand the range of substrate materials available for flexible electronics. For example, bacterial cellulose exhibits exceptional flexibility, biocompatibility, and tunable biodegradability, making it desirable for use as a wearable substrate [27, 28]. Microorganisms also serve as the basis for biosensing in flexible devices. Body fluids such as sweat contain lactic acid, glucose, urea, and diverse microbial species, and their metabolic byproducts, such as short-chain fatty acids (SCFAs), are closely linked to human health [29]. Monitoring these biomarkers enables noninvasive health assessment. Sweat-based flexible sensors have been extensively studied, and flexible sensors for other biofluids have been further explored [30]. Meanwhile, the impact of microorganisms and their metabolites on device performance must be considered, as acidic metabolites in sweat can corrode electronic components, affecting device longevity [31]. Furthermore, certain microorganisms in living interfaces can utilize components of bodily fluids as fuel from the skin surface [32, 33], demonstrating their potential as bioenergy harvesters or self-powered sources for continuous energy supply to next-generation smart textiles.

This review explores the significance of smart textiles and microorganisms in skin health management and highlights their potential market value. From traditional textiles to functional and smart textiles, the key points for textile development are briefly summarized in Fig. 1a. Moreover, the number of publications on textile-based flexible electronics has increased exponentially since 1980 (Fig. 1b). To better understand the role and mechanisms of microorganisms in skin health, this article first introduces the distribution of skin microbiota across different anatomical sites, their functions in maintaining skin health, and their interactions with the host. In addition, because next-generation smart textiles are inseparable from flexible electronics and microbes, this review reports the latest advancements in flexible devices related to health management, emphasizing the potential of flexible sensors and devices for real-time health monitoring and personalized medical interventions, as well as the critical role of microorganisms in flexible electronic systems. With respect to the design and fabrication of smart textiles, this review provides an overview of various current materials, structures, and fabrication techniques. Furthermore, the current smart textiles applied to skin health management are reviewed. Considering the intricate interplay among microorganisms, flexible electronics, textiles, and their collective influence on skin health, their synergistic integration is poised to drive the advancement of adaptive, sustainable, and multifunctional smart textiles (Fig. 1c). Despite significant advances in smart textiles, limited attention has been given to their dynamic interactions with the skin microbiome and their potential for real-time physiological monitoring and targeted therapeutic or regulatory interventions. In this review, some technologies are also highlighted that have the capacity to propel the development of next-generation smart textiles, while current technological limitations are critically examined, and future research directions are outlined.

## 2 Human Skin Microbiomes and Their Working Mechanisms

### 2.1 Overview of Human Skin Microbiomes

As the largest organ of the human body, the skin possesses a highly complex physiological structure and a unique microbiome. The skin surface area of an adult covers approximately 1.8–2 $m^2$ [50, 51], and an estimated $10^3$–$10^6$ CFU/$cm^2$ of microorganisms are distributed on the skin [52, 53].

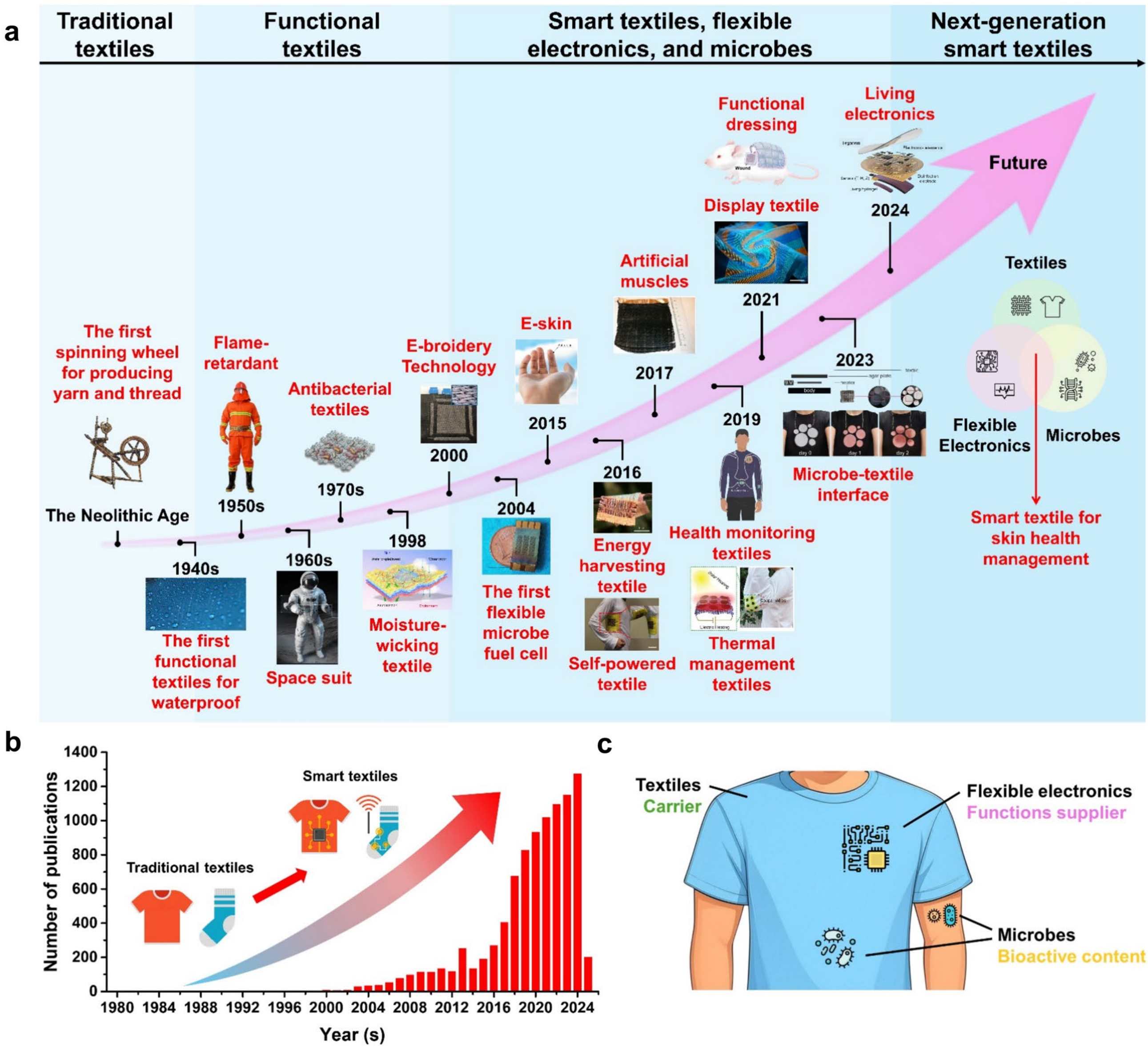


**Fig. 1** Brief history of textiles and the development of smart textiles with flexible electronics and microbes. **a** Key points for the development of textiles. Each junction (red arrow) in the image is a revolutionary development; reproduced with permission from Ref. [34], Copyright © 2022 Elsevier B.V. Reproduced under the CC BY 4.0 license from Ref. [35], Copyright © 2024, The Author(s), Wiley–VCH. Reproduced under the CC BY 4.0 license from Ref. [36], Copyright © 2023, The Author(s), Springer Nature. Reproduced under the CC BY 4.0 license from ref [37], Copyright © 2019, The Author(s), Springer Nature. Reproduced under the CC BY 4.0 license from Ref. [38], Copyright © 2020, by the authors, MDPI. Reproduced with permission from Ref. [39], Copyright © 2004 Elsevier B.V. Reproduced with permission from Ref. [40], Copyright © 2023 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Reproduced with permission from Ref. [41], Copyright © 2016, Springer Nature. Reproduced with permission from Ref. [42], Copyright © 2016 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Reproduced with permission from Ref. [43], Copyright © 2017 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Reproduced with permission from Ref. [44], Copyright © 2019, The Author(s) Springer Nature. Reproduced with permission from Ref. [45], Copyright © 2019 Wiley–VCH. Reproduced with permission from Ref. [46], Copyright © 2020 Elsevier B.V. Reprinted with permission from Ref. [47], Copyright © 2021, The Author(s) Springer Nature. Reproduced under the CC BY 4.0 license from Ref. [48], Copyright © 2023 Owner/Author, Association for Computing Machinery. Reproduced with permission from Ref. [49], Copyright © 2024 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **b** Publication trends of smart textiles. (Data from Web of Science with the keyword "smart textiles" in March 2025). **c** Ternary interactions among textiles, flexible electronics, and microbes (textiles can serve as carriers for both flexible electronics and microbes. Flexible electronics enable various functions into textiles. Moreover, microbes that are encapsulated within the textile or present on the surface of skin can interact with both the fabric and the embedded electronics as bioactive contents)

The composition of these microbial communities varies significantly across different skin regions because of distinct microenvironmental conditions (Fig. 2a), such as dryness, moisture, or lipid richness [54]. For instance, sebaceous areas (e.g., the face) are predominantly colonized by lipophilic bacterial genera such as *Propionibacterium* spp.,

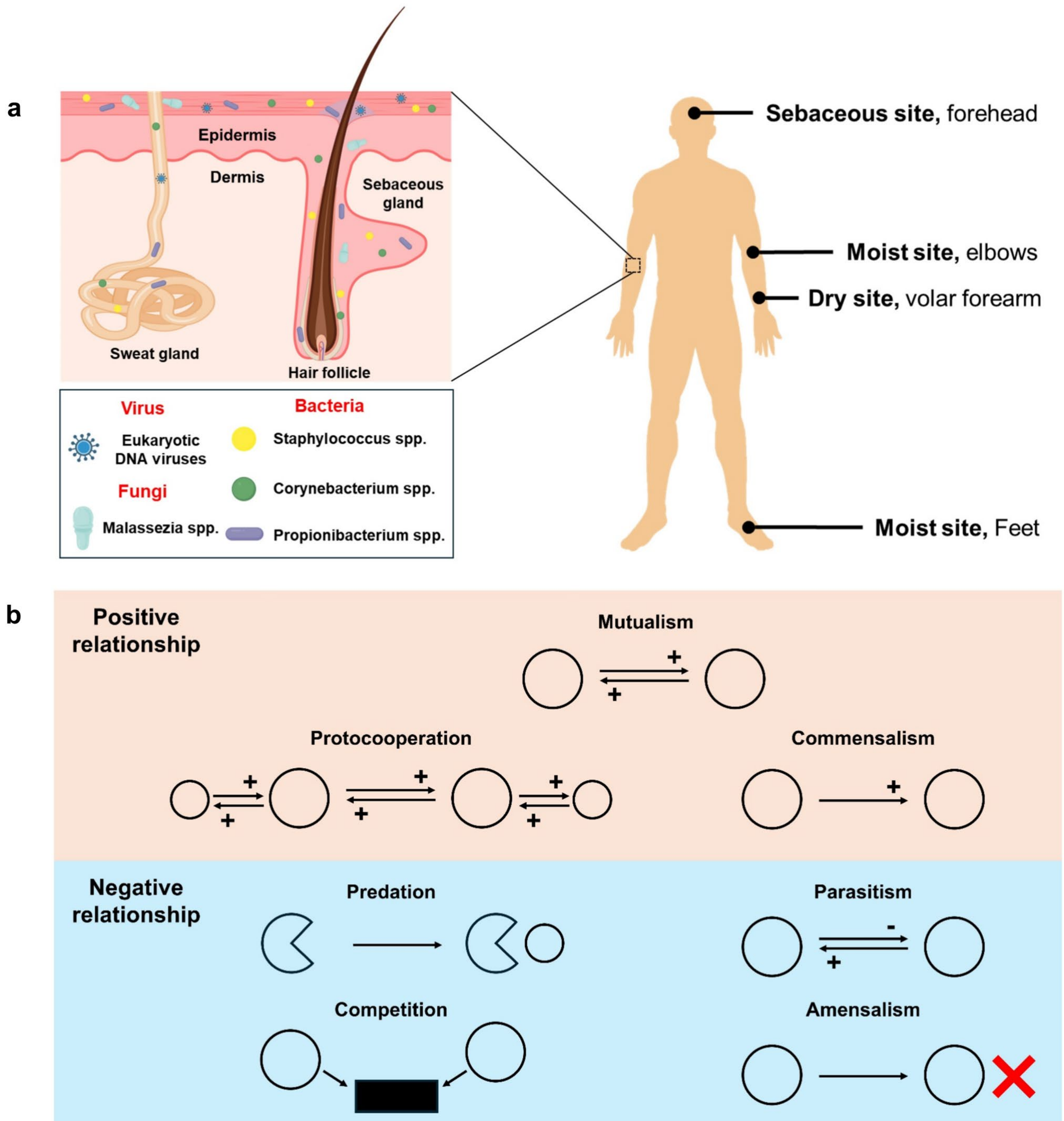


**Fig. 2** Skin microbiome distribution and relationships between commensals. **a** Distribution of microorganisms on sebaceous, moist, and dry skin surfaces with examples and allocation in the epidermis and dermis. **b** Positive and negative relationships of commensals. Mutualism: Two species benefit each other in terms of survival. Protocooperation: Two species benefit each other, but do not essentially depend on each other. Commensalism: one species benefits another species without influence. Predation: One species preys on another species. Parasitism: one species benefits another species with costs. Competition: two species compete for survival. Amensalism: one species is the nemesis of another species

whereas moist regions (e.g., the axillary vault) favor the proliferation of *Staphylococcus* spp. and *Corynebacterium* spp. [55, 56]. The cutaneous microecosystem is primarily composed of bacteria, fungi, and viruses [57]. To better use microbes and design living interfaces, understanding the relationships among different microbes and between hosts and microbes is very important. These microbial communities establish complex symbiotic relationships with the host and other species (Fig. 2b and Table 1). Microbes are essential elements for maintaining the natural barrier function of the skin, modulating host immune homeostasis, participating in metabolic processes, and sustaining microbial equilibrium [58, 59]. When the skin microbiome becomes imbalanced, it may contribute to various dermatological disorders, such as acne, AD, and psoriasis [60, 61]. Furthermore, the composition and stability of the skin microbiome are influenced by a multitude of intrinsic and extrinsic factors, including climatic conditions, environmental pollutants, ultraviolet radiation, lifestyle habits, antibiotic exposure, and the overall health of the immune system [62, 63].

## 2.2 Mechanisms of Skin Microbial Functions

The symbiotic relationship between the skin microbiota and the human body reflects a complex and dynamic equilibrium. In a healthy individual, these micro-organisms are primarily categorized into three types: commensal microbes, mutualistic microbes, and pathogenic microbes. Under normal circumstances, these microbial communities work collectively to maintain skin health. However, when the delicate balance is disrupted, pathogenic microbes and some mutualistic microbes may dominate and lead to various skin disorders. Consequently, understanding the functions and mechanisms of the skin microbiota is essential for preserving microbial homeostasis. Skin microorganisms contribute primarily to barrier function, immune regulation, metabolic processes, and disease prevention. This section focuses on these four key functions and their underlying mechanisms.

### 2.2.1 Barrier Protection

Three mechanisms of microbes-assisted barrier protection of skin have been shown in Fig. 3a. The pH of the skin surface is typically 4.5–5.5 [83]. This acidic environment contributes to the establishment of an antimicrobial barrier. Certain mutualistic microorganisms, such as *Staphylococcus epidermidis* and *Cutibacterium acnes*, contribute to lowering the pH of skin. The mechanism of this process involves the activity of lipases within these microbes, which hydrolyze phospholipids into free fatty acids (FFAs) and contribute to acidifying the skin surface [84, 85]. Some studies have shown that FFAs also possess certain antimicrobial properties [86]. In addition, as host and symbiotic microbes coevolve, beneficial microbes will colonize the skin and possess a certain ability to directly resist foreign pathogens [87]. Alternatively commensal microbes and

**Table 1** Microbes distributed in the human skin and influence factors

| Main type | Distribution | Factors | Refs. |
|---|---|---|---|
| Bacteria | | Host: Sex, age, distribution, diseases, immune system, living place, life habits, medicines, etc<br>Environment: Occupation, climate, ultraviolet light, location, contamination | |
| *Propionibacterium* spp. | Dry, moist, and sebaceous sites | | [64, 65] |
| *Corynebacterium* spp. | Dry, moist, and sebaceous sites | | [14, 66] |
| *Staphylococcus* spp. | Dry, moist, and sebaceous sites | | [67, 68] |
| *Streptococcus* spp. | Dry and sebaceous sites | | [69] |
| *Micrococcus* spp. | Dry and moist sites | | [70] |
| *Veillonella* spp. | Dry sites | | [71] |
| Fungi | | | |
| *Trichophyton mentagrophytes* | Moist sites | | [72, 73] |
| *Epidermophyton floccosum* | Dry sites | | [74] |
| *Malassezia* spp. | Dry, moist, and sebaceous sites | | [75, 76] |
| *Aspergillus* spp. | Dry and moist sites | | [77] |
| *Candida* spp. | Dry sites | | [78] |
| Virus | | | |
| *Molluscum contagiosum virus* | Dry, moist, and sebaceous sites | | [79] |
| *Human papillomavirus* | Dry, moist, and sebaceous sites | | [80] |
| *Herpes simplex virus* | Dry, moist, and sebaceous sites | | [81] |
| *Actinomyces phage* | Dry and moist sites | | [82] |

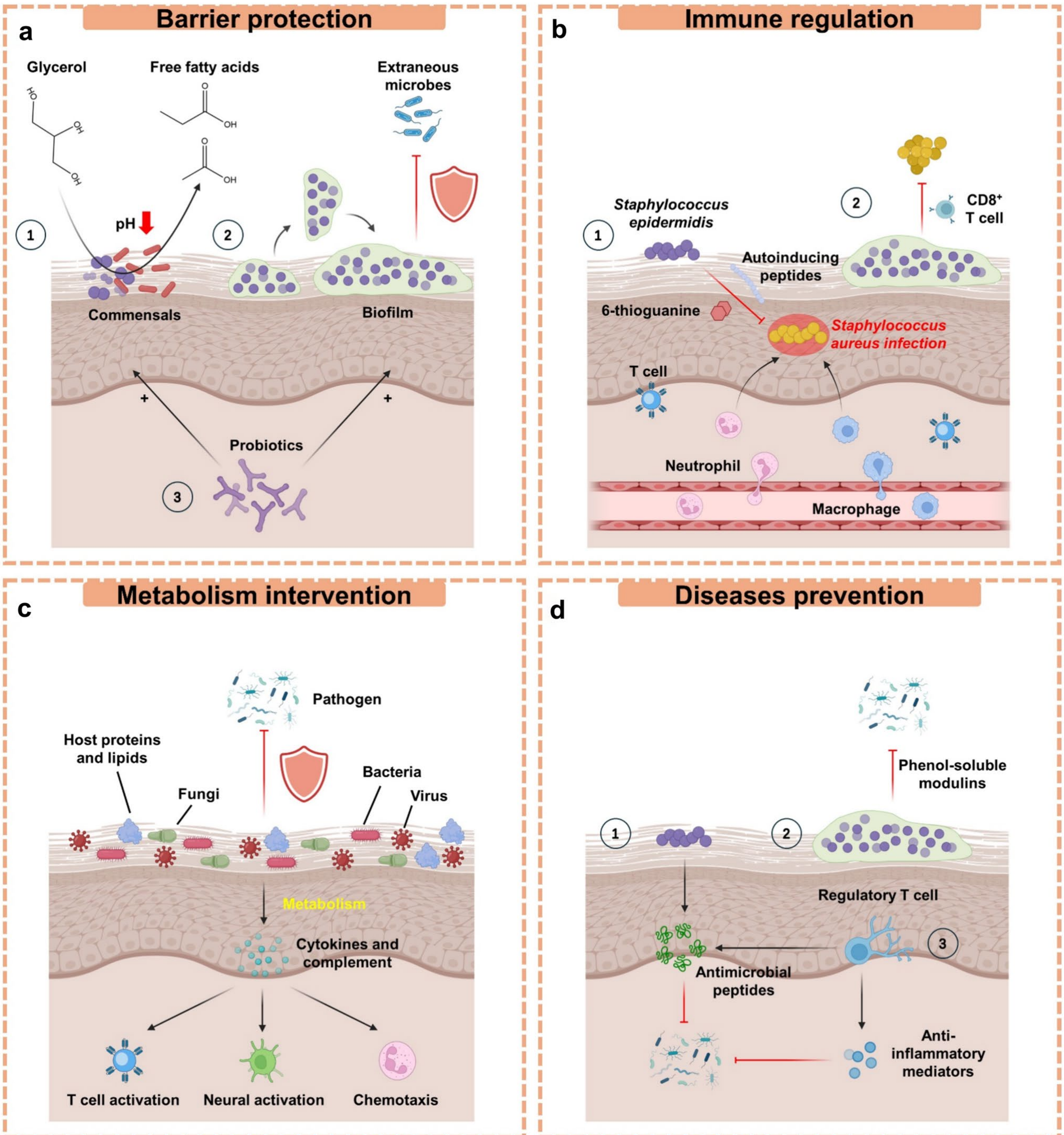


**Fig. 3** Skin microbial functions and related mechanisms. **a** Barrier protection of microbes against extraneous microbes and pathogens. ① Acidification; ② physical barrier; ③ intake of probiotics to balance the microbiome. **b** Immune regulation with the host. ① The host immune response to external pathogens; ② an example of the immune system against pathogens: *Staphylococcus epidermidis* and dendritic cells to control barrier function. **c** Metabolism of commensals with host proteins and lipids to create cytokines and complement for barrier enhancement. **d** Disease prevention by microbes. ① Partial microbes at the skin surface can directly or indirectly secrete antimicrobial peptides to prevent pathogens; ② microbes can release phenol-soluble modulins to disrupt pathogen membranes; ③ regulatory T cells release anti-inflammatory mediators to inhibit pathogen invasion

mutualistic microbes can indirectly reduce the living space of pathogens by competitively growing to occupy nutrients and territory [88]. Furthermore, the intake of probiotics and other beneficial microbes by the host can contribute to maintaining skin stability and enhancing the barrier function [89].

#### 2.2.2 Immune Regulation

In addition to providing a barrier, skin microbes are also involved in regulating the host immune system to maintain a stable symbiotic relationship (Fig. 3b). However, the interaction mechanism between microbes and the immune system is a complex and multifaceted process involving multiple micro-organisms and immune cells. In general, commensal and mutualistic microbes regulate inflammatory responses and skin immune tolerance by interacting with dendritic cells, macrophages, and T cells [90, 91]. For example, the responses of the commensal microbe *Staphylococcus epidermidis* and the pathogenic microbe *Staphylococcus aureus* trigger different T-cell activities. The response of *Staphylococcus epidermidis* inhibits the occurrence of inflammation and promotes tolerance to future commensal colonization. In contrast, the response to *Staphylococcus aureus* promotes neutrophil responses to eliminate pathogens and enhance the resistance of the immune system [67, 92].

#### 2.2.3 Metabolic Intervention

The metabolic effects of commensal and mutualistic microbes are closely linked to the above two functions (Fig. 3c). These micro-organisms metabolize skin-derived compounds, produce bioactive molecules, and influence the chemical environment of the skin, collectively benefiting the host in multiple ways. For example, FFAs are metabolic byproducts of microbes and play a critical role in barrier function. In addition, SCFAs produced by microbes can regulate host cell metabolism, promoting the differentiation of skin cells and immune cells [90, 93]. Moreover, certain microbes in the skin contribute to the synthesis and metabolism of vitamins and support skin health and homeostasis [94, 95]. An essential metabolic function of the skin microbiota is its ability to process xenobiotics and environmental toxins. The micro-organisms residing on the skin can break down and neutralize potentially harmful substances, such as pollutants that accumulate on the surface of the skin. By metabolizing these compounds, micro-organisms help shield skin cells from oxidative stress and inflammation, and support overall skin health [96].

#### 2.2.4 Disease Prevention

A healthy microbiome maintains a stable and mutually beneficial relationship with the host. This microbial system promotes skin homeostasis, inhibits the growth of pathogenic microorganisms, and regulates immune responses to reduce the risk of infections and chronic inflammatory diseases (Fig. 3d). Studies have demonstrated that microbial dysbiosis is closely associated with inflammatory skin conditions such as AD, psoriasis, and eczema. Moreover, some pathogenic microbes that coexist with the host can exacerbate skin inflammation when skin homeostasis is disrupted, and can even potentially lead to further complications [97, 98]. Some commensal microbes can directly synthesize AMPs or stimulate host cells to secrete such molecules to enhance the barrier [99]. For example, *Staphylococcus epidermidis* induces the host to produce AMP β-defensins to directly kill pathogens [100]. Furthermore, *Staphylococcus epidermidis* can physically block pathogenic microbes by forming biofilms and secreting phenol-soluble modulins to disrupt the membrane structure of pathogens [101].

## 3 Skin-Based Flexible Electronics for Health Management

### 3.1 Types of Skin-Based Flexible Sensors and Devices

Skin-based flexible sensors are devices that directly or indirectly contact the skin and are capable of detecting environmental changes and converting them into electrical signals. Their fundamental characteristics include being lightweight, thin, stretchable, extremely sensitive, and responsive [102]. These features grant flexible sensors broad application prospects in various fields, such as human health monitoring, human–machine interaction (HMI), and diagnostics. Microbes are an inseparable part of the human body and are very important in biological processes and medical diagnostics. They can interact with various biomolecules, generate bioelectrical signals, and respond to environmental changes, making them ideal components for health monitoring sensors and therapeutic devices [103, 104]. By combining the properties of microorganisms and flexible sensors, researchers can develop flexible, multifunctional devices with high sensitivity, biocompatibility, and eco-friendliness for biomedical applications such as disease detection, metabolite analysis, and personalized medicine. The integration of flexible sensors and microorganisms not only extends the functional boundaries of medical diagnostics but also provides innovative solutions for sustainable development, personalized health management, and intelligent health management. In terms of applications, skin-based flexible sensors and devices can be categorized into three types: monitor, therapy, and energy-supplying devices. The principles, involved microbes, and specific applications of these three types of devices are summarized in Table 2. Detailed descriptions of the three types of flexible sensors and their related devices are provided in this chapter.

**Table 2** Classification of skin-based flexible devices for health management

| Category | Device | Microbe | Substrate | Principle | Application | Refs. |
|---|---|---|---|---|---|---|
| Monitor | Bionic skin | – | PVDF and PVB | Detect the enzymatic oxidation of glucose and lactate | Health management and big data analysis | [105] |
| Monitor | Liquid metal pattern | E. *coli* and *S. aureus* for antibacterial testing | TPU | Monitoring and recording electrocardiograms | Antimicrobial and health monitoring | [106] |
| Monitor | Electronic skin | – | PI | Monitoring of physiological signals, sweat metabolites, and electrolytes | Stress response monitoring | [107] |
| Monitor | Wearable sweat sensor | – | PI | Monitoring key sweat biomarkers | Battery-free wearable system for sweat sensing | [108] |
| Monitor | Wearable pulse sensor | – | PTFE and PDMS | Analyzing individual pulse wave profiles | Cardiovascular monitoring and biometric authentication | [109] |
| Monitor | Smart mask | SARS-CoV-2 for virus detection | PDMS, PEG and $Al_2O_3$ | Monitoring of exhaled breath condensate | Early diagnosis, monitoring, and management of respiratory diseases | [110] |
| Monitor | Soft electromagnetic swimmer | SARS-CoV-2 for virus monitoring | PI | Monitoring of $NH_4^+$, $Cl^-$ levels and virus antigens in water | Pathogen and virus monitoring | [111] |
| Monitor | Flexible in situ optical sensing system | – | PI | Analyzing the TVB-N content, color indices and storage days | Food monitoring | [112] |
| Monitor and therapy | Wireless smart bandage | – | PEDOT:PSS, NIPAAm, and AM | Applying electric bias across a wound, driving the microcontroller unit and other integrated circuits for continuous monitoring | Wound monitoring and therapy | [113] |
| Therapy | Wearable flexible ultrasound microneedle patch | – | NHS ester | Reactive oxygen species-driven dynamic therapeutic strategy | Cancer immunotherapy | [114] |
| Therapy | Microorganism microneedle | *E. aerogenes* for $H_2$ generation | PEGDA | Microbe contains hydrogenase proteins that reversibly catalyze $H_2$ release | Deep tissue drug delivery | [115] |
| Therapy | Implantable electrical stimulation device | – | PI | Wireless charging and precision current driver | Neuroprosthetics and neuromodulation therapies | [116] |
| Therapy | ZIF-8@Cotton fabric | – | ZIF-8 and cotton | Adsorption of hydrogen sulfide | Body odor absorption/removal | [117] |
| Therapy | Wearable filtration system | *E. coli* for antibacterial testing | PVDF and PTFE | Filtration of bacteria based on triboelectric mechanism | Bacteria and virus filtration | [118] |
| Energy-supplying | Flexible microbial fuel cell | *P. aeruginosa* for power generation | PET and PU | Bacteria transfer electrons to the anode | Developing low-power and self-sustainable systems | [119] |
| Energy-supplying | Self-powered flexible electronics | *G. sulfurreducens* for charging | ITO/PET | Biofilm absorbs moisture from the air and forms an internal electric field | Development of high-performance self-powered electronics | [120] |
| Energy-supplying | Enzymatic biofuel cells | – | PDMS | Enzymes as catalysts to convert chemical energy into electrical energy | Generating energy for wearable or implantable devices | [121] |

*AM* acrylamide, *E. aerogenes Enterobacter aerogenes*, *E. coli Escherichia coli*, *G. sulfurreducens Geobacter sulfurreducens*, *ITO* indium tin oxide, *NHS* N-hydroxysuccinimide, *NIPAAm* N-isopropylacrylamide, *P. aeruginosa Pseudomonas aeruginosa*, *PDMS* polydimethylsiloxane, *PEDOT:PSS* poly(3,4-ethylenedioxythiophene):polystyrene sulfonate, *PEG* polyethylene glycol, *PEGDA* polyethylene glycol diacrylate, *PET* polyester, *PI* polyimide, *PTFE* polytetrafluoroethylene, *PU* polyurethane, *PVB* polyvinyl butyral, *PVDF* polyvinylidene fluoride, *S. aureus Staphylococcus aureus*, *SARS-CoV-2* severe acute respiratory syndrome coronavirus 2, *TPU* thermoplastic polyurethane, *TVB-N* total volatile basic nitrogen, *ZIF* zeolitic imidazolate framework

### 3.2 Health Monitoring Flexible Sensors and Devices

As one of the core functions, monitoring represents a critical application direction for flexible sensors, further driving technology advancements in portable health care, environmental protection, and intelligent detection. For human health monitoring (Fig. 4a), flexible sensors can detect microorganisms and their metabolites in bodily fluids (such as sweat, saliva, or urine) or exhaled gases [122–124], enabling early disease diagnosis, infection monitoring, and personalized medicine. Depending on the mode of operation, these sensors can be classified into mechanical, electrochemical, and optical sensors.

Electrochemical sensors typically leverage electrochemical reactions to detect microbial metabolites or specific biological markers. Enzyme- or antibody-based electrochemical sensors further expand the ability to detect pathogenic toxins and microbial metabolites, such as enterotoxins secreted by *Staphylococcus aureus* or endotoxins released by Gram-negative bacteria [125]. Beyond traditional biosensing approaches, the latest advancements in enzyme-based electrochemical sensors have significantly enhanced detection sensitivity and stability by increasing the catalytic efficiency of natural enzymes [126]. For instance, enzyme-based electrochemical biosensors have demonstrated exceptional performance in the rapid and highly sensitive detection of hydrogen peroxide and hydrogen sulfide released by cells, paving the way for next-generation diagnostic and monitoring technologies [127].

In recent years, researchers have integrated electrochemical sensor arrays into flexible substrates that mimic the properties of human skin [5, 105, 128]. Flexible e-skin enables the quantitative detection of glucose and lactate by analyzing redox signals in sweat secretions and other signals (Fig. 4b). To provide stable sensing and recording in different environments, such as sweat skin, researchers have demonstrated innovative strategies, such as seamlessly integrating the system and improving hydrophobic encapsulation to enhance performance and durability under sweat-rich conditions. These studies provide valuable insights into device robustness, signal integrity, and energy autonomy [129–131]. In addition, traditional mechanical sensors can be integrated into e-skin for monitoring cardiovascular diseases and long-term heart rate records [132]. Due to the strategic selection of flexible materials and biomimetic design, these sensors can adhere to the skin for extended periods, allowing noninvasive, continuous monitoring.

In terms of human health, environmental and intake monitoring also influence disease prevention and overall well-being. By tracking environmental effects, detecting hazardous chemical intake, food quality, and water quality, and identifying microbial contamination on surfaces, advanced sensing technologies help mitigate health risks associated with pollution and toxic exposure [133]. Furthermore, real-time detection of airborne pathogens can prevent the spread of respiratory diseases, while monitoring food and water safety reduces the risk of contamination-related illnesses. Water quality monitoring and virus detection are shown as examples in Fig. 4c. Integrating monitoring ability into dermal-interfaced flexible systems not only enhances public health but also facilitates early diagnosis and prevents potential health hazards. Owing to the high sensitivity, rapid response, and label-free detection capabilities of optical sensors, they are broadly applied in environmental pollution monitoring and food safety testing. Currently, optical sensors enable detection with various techniques, including fluorescence labeling, surface plasmon resonance, fiber-optic biosensing, and colorimetric analysis [134]. In addition, flexible sensors allow real-time monitoring of volatile organic compounds and airborne pathogenic microorganisms [135].

Beyond monitoring physical health parameters, assessing stress levels is equally important for maintaining mental health and well-being. However, stress arises from the complex interplay of the nervous, endocrine, and immune systems, making its detection particularly challenging. In a recent study, researchers developed a flexible sensor specifically designed for stress monitoring (Fig. 4d). By tracking key physiological signals, metabolites, and electrolytes, and employing machine learning algorithms for data classification and interpretation, the system achieved an impressive accuracy rate of 98% [107].

### 3.3 Invasive, Noninvasive, and Implantable Flexible Devices

Invasive flexible devices refer primarily to innovative medical instruments that integrate microneedle technology with flexible sensors. Microneedle technology is a minimally invasive drug delivery and biosensing technique. It consists of an array of microscale needle-like structures and has garnered significant attention in recent years [136]. Microneedles can effortlessly penetrate the outer layer of the skin without reaching deeper nerves or blood vessels, hence significantly reducing pain and the risk of tissue damage [137]. In the application of invasive flexible devices, microneedles have two primary functions: The first function is serving as a physical interface for sensors, enabling direct access to interstitial fluid to increase detection accuracy. Another function is to serve as a drug carrier, facilitating targeted delivery and controlled release. By integrating the minimally invasive property of microneedles with the high sensitivity of flexible sensors, these devices allow efficient physiological signal monitoring and therapeutic interventions with minimal tissue disruption. Because microneedles can penetrate the skin barrier, enabling direct delivery of drugs or bioactive factors to damaged tissues, microneedle technology has been widely

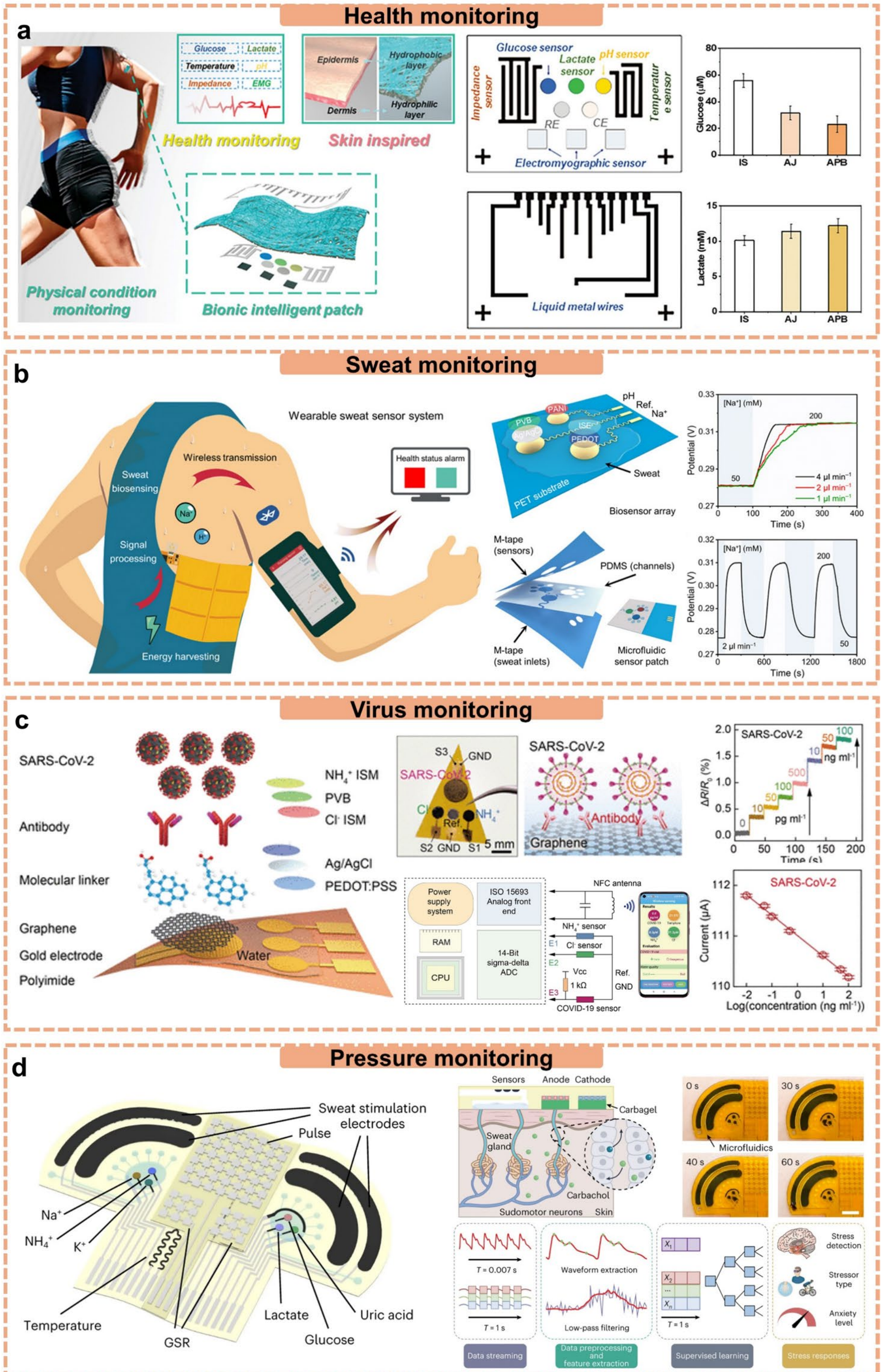


**Fig. 4** Representative health monitoring sensors and devices. **a** Bionic e-skin structure distribution and in situ health monitoring before/after sports; reproduced with permission from Ref. [105], Copyright © 2024 Wiley–VCH. **b** Biosensor patch for sweat collection, sensing, and analysis; reproduced with permission from Ref. [108], Copyright © 2020 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **c** Virus monitoring devices for pathogen contamination detection; reproduced under the CC BY 4.0 license from Ref. [111], Copyright © 2024 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **d** Flexible e-skin patch for monitoring human stress responses; reproduced with permission from Ref. [107], Copyright © 2024, Springer Nature

applied in wound healing, bone and cartilage regeneration, and fibrosis prevention [138, 139]. Furthermore, microorganisms can serve as biological engines embedded within microneedles to generate gas, hence propelling drug molecules to penetrate up to 1000 μm beneath the skin for deep tissue therapeutic delivery (Fig. 5a) [115]. A recent study introduced a digitally controlled automated transdermal drug delivery system. This system employs an electrotriggered mechanism to achieve high-precision ($< 1\ mm^2$) and rapid-response ($< 30$ s) melatonin release. This system enables on-demand drug delivery and allows for the personalized customization of drug formulations tailored to different diseases [140]. The wireless-controlled drug delivery system integrates remote modulation capabilities, enabling physicians to dynamically adjust drug release dosage and timing in response to disease progression. Simultaneously, flexible sensors facilitate real-time monitoring of tissue regeneration by measuring critical physiological parameters such as local pH levels, temperature, and electrical conductivity [141–143]. By leveraging feedback-driven optimization, treatment strategies can be refined to enhance therapeutic efficacy. The convergence of remote monitoring and personalized regulation allows patients to receive precise and necessary treatment without the need for frequent hospital visits, significantly improving both convenience and clinical outcomes.

Noninvasive flexible devices focus mostly on health monitoring. In addition to health monitoring capabilities, noninvasive flexible devices can also be used in therapeutic applications. In recent years, a noninvasive device combining monitoring and therapeutic functions has been developed (Fig. 5b). In addition, noninvasive sensor can be used to detect human motion, or pathogens, or to capture subtle electrophysiological signals for medical diagnosis of diseases and dysfunctions [145–147]. Some kinds of sensors can also provide UV protection, extending their operational lifespan. In one type of sensor, MXene and tannic acid are incorporated, and the antibacterial properties of the sensor are excellent. It can effectively cover irregularly shaped wounds and provide efficient hemostatic functionality [148]. Noninvasive therapeutic technologies significantly increase patient comfort while minimizing the side effects associated with conventional treatment methods.

Implantable devices can be directly placed within the body to treat diseases or regulate bioelectrical signals, such as cardiac implants and neural interfaces. With advancements in microelectronics and nanofabrication technologies, implantable sensors are evolving toward higher sensitivity, lower power consumption, and multifunctional integration. The introduction of flexible electronics allows these sensors and devices to better conform to tissue surfaces, minimizing mechanical irritation and enhancing biocompatibility. Furthermore, by integrating wireless power transfer and data communication technologies, implantable devices enable long-term data acquisition and remote monitoring, offering new possibilities for personalized medicine and intelligent health management. For instance, battery-free implantable sensors have been developed for real-time physiological signal monitoring (Fig. 5c) [116, 149]. In addition to sensing, implantable sensors can facilitate neural function restoration through electrical stimulation while precisely modulating the intensity and location of stimulation [116, 150]. A recent study proposed a temperature-sensitive implantable sensor array capable of dynamically locating inflamed regions and triggering drug release [151]. These devices and sensors typically require biocompatibility and long-term stability. Notably, biodegradable implantable devices can autonomously degrade after tissue healing, eliminating the need for surgical removal and significantly improving patient comfort.

### 3.4 Microbial Fuel Cells, Self-Powered Flexible Devices, and Enzymatic Fuel Cells

Microbial fuel cells (MFCs) are bioelectrochemical systems that directly convert chemical energy into electrical energy through microbial catalytic reactions. Based on their core catalytic mechanisms, MFCs can be broadly classified into two main types. The first type utilizes electroactive bacteria or photosynthetic organisms such as *cyanobacteria* and microalgae to facilitate biological catalytic reactions, hence driving electron transfer and generating electricity. Another type of MFC does not rely on intact microbial cells; rather, they use extracted biocatalysts such as enzymes, enzymatic cascades, or mitochondria to increase electron transfer and improve energy conversion efficiency. Integrating biofuel cells with flexible electronics enables the development of both energy harvesters [152] and self-powered wearable devices [153], ensuring an efficient and sustainable energy supply. These MFCs can generate electricity in situ with high efficiency by utilizing human body fluids and metabolic byproducts as fuel [154]. In addition, self-powered devices can simultaneously monitor biomarkers present in epidermal sweat or exudates from wounds, offering dual functionality of energy generation and real-time health monitoring.

Bacteria- and algae-catalyzed fuel cells typically employ a double-chamber structure (Fig. 6a) to optimize electron transfer and oxygen reduction reactions through Eqs. (1) and (2), hence enhancing the overall energy conversion efficiency.

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (1)$$

$$CO_2 + H_2O + Sunlight \rightarrow O_2 + Organicmatter \quad (2)$$

Equation (1) is the anode reaction and Eq. (2) is the cathode reaction.

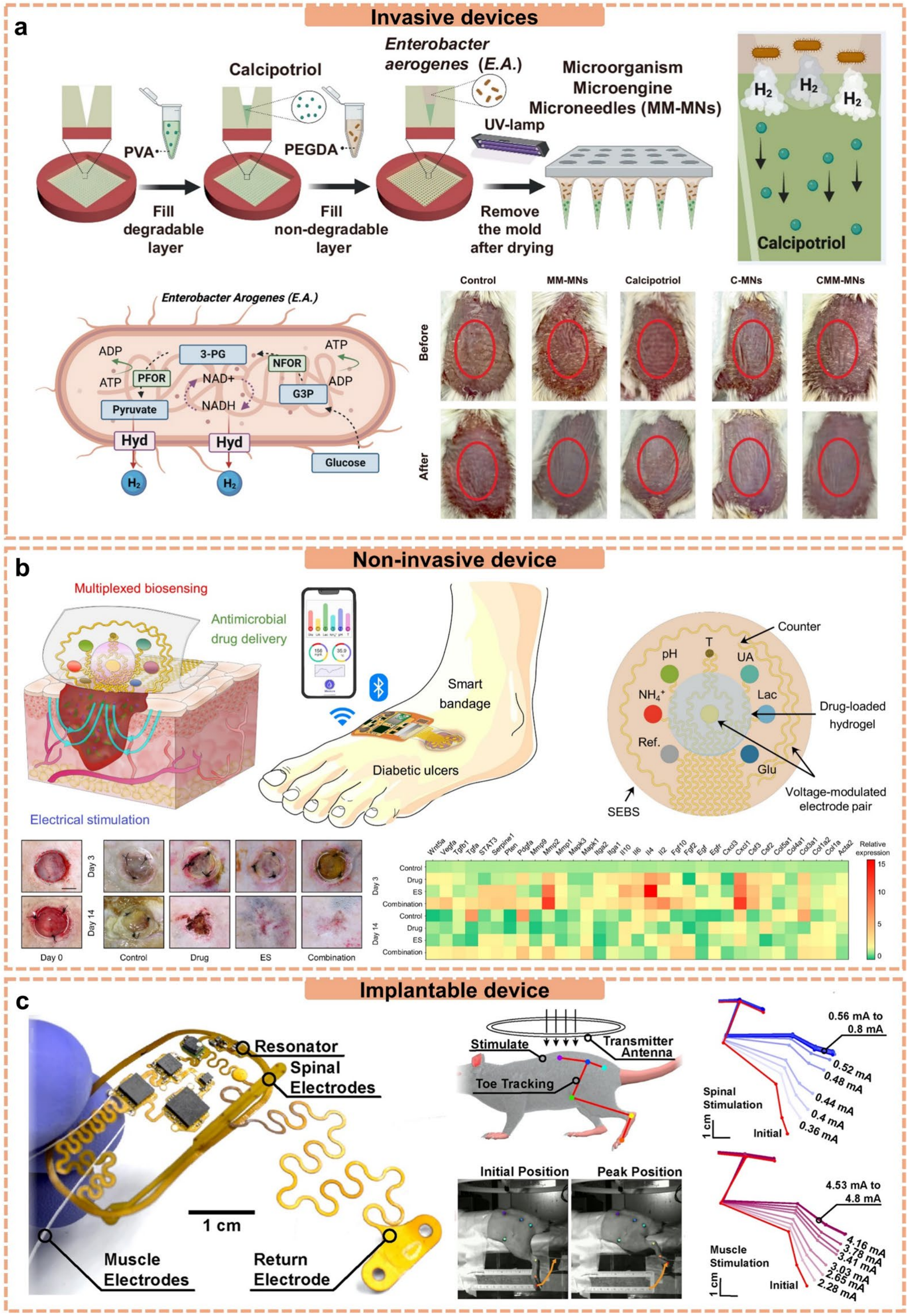


**Fig. 5** Representative invasive, noninvasive, and implantable devices. **a** $H_2$ generating living microneedles for deep tissue repair; reproduced with permission from Ref. [115], Copyright © 2024, The Author(s), Springer Nature. **b** Noninvasive device for wound monitoring and treatment; reproduced under the CC BY 4.0 license from Ref. [144], Copyright © 2023 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **c** Implantable device for spinal channel and muscle channel stimulation; reproduced under the CC BY 4.0 license from Ref. [116], Copyright © 2023, The Author(s), Springer Nature

This configuration consists of an anode chamber and a cathode chamber, separated by a proton exchange membrane or other ion-conducting membranes. This separation ensures efficient electron and ion transport within the system, facilitating stable and effective energy generation [155]. Bacteria-catalyzed fuel cells primarily utilize electroactive bacteria such as *Pseudomonas*, *Geobacter*, and *Shewanella* [156]. These microorganisms facilitate extracellular electron transfer, enabling the transport of electrons generated during metabolic processes to the anode, thus driving current generation (Fig. 6b). These kinds of bacteria such as *Pseudomonas aeruginosa* PAO1 can be integrated into textiles to generate power. This textile-based MFC can generate a maximum power and density of 1.0 μW/cm$^2$ and 6.3 μA/cm$^2$, respectively (Fig. 6c). In addition, some MFCs are employed in wastewater treatment. Bacteria not only degrade organic pollutants but also generate electricity, achieving the dual functions of pollutant removal and energy recovery [157]. In contrast, algae-catalyzed fuel cells rely on photosynthetic organisms to increase electron transfer by releasing oxygen during photosynthesis and increasing the current output of fuel cells. For example, microalgae can absorb carbon dioxide and produce oxygen, simultaneously serving as electron donors to improve the overall efficiency of the fuel cell system. The self-powered mechanism is the same as that of the first kind of MFC and power can be supplied for flexible sensors and devices. In a recent study, *Geobacter sulfurreducens* biofilms were used as core elements to supply power. The biofilm contacts the water from the air and generates a humidity gradient that facilitates the directional transport of water molecules and ions to establish an internal electrical field (negative surface potential of approximately 41.96 mV). This microbial self-powered sensor can maintain stability during 30 000 s tests. (Fig. 6d and e).

Enzymatic fuel cells (EFCs) utilize specific redox enzymes such as glucose oxidase (GOx), bilirubin oxidase (BOD), and laccase to catalyze the oxidation of organic fuels (including glucose, ethanol, and lactate) to generate electrons (Fig. 6f and g). To increase efficiency, multiple enzymes can be integrated into a cascade reaction network. For instance, glucose can be oxidized to gluconic acid via GOx, and in conjunction with nicotinamide adenine dinucleotide (NADH)-dependent enzymes, the electron transfer pathway can be further optimized [160, 161]. Moreover, the mitochondrial electron transport chain inherently exhibits highly efficient energy conversion capabilities [162]. The respiratory chain within mitochondria sequentially transfers electrons derived from NADH to molecular oxygen, facilitating ATP synthesis while simultaneously releasing electrons to the electrode [163]. EFCs can directly harness glucose from biological fluids as self-powered devices. They are particularly suitable for powering implantable and wearable bioelectronic devices, such as cardiac pacemakers and continuous glucose monitoring systems [164, 165]. Owing to their ability to function at the microscale, enzymatic fuel cells also hold significant potential for driving microrobots, nanoelectronic devices, and medical devices [166–168].

### 3.5 Others

In addition to the above applications, advancements in skin-based flexible sensors and devices for olfactory processing and filtration have enabled their use in odor detection, deodorization, and the filtration of viruses and bacteria. When dermal-interfaced flexible systems are worn for extended periods, they often develop an unpleasant odor. This odor primarily originates from the accumulation of sweat, sebum, and other organic compounds secreted by the skin, which are subsequently decomposed by skin-surface microorganisms [169]. During this process, microorganisms metabolize these organic substances into volatile and irritating molecules such as ammonia, sulfur compounds, and organic acids, exacerbating body odors, particularly in hot and humid environments [170]. The latest miniaturized electronic noses can rapidly identify and classify odor sources [171], which is important in odor analysis and microbial community modulation. Moreover, newly developed olfactory feedback systems have the potential to release customizable scents [172], offering a novel approach to deodorization. In addition, intelligent filtration systems can effectively filter out viruses and bacteria [118], mitigating health risks while preventing excessive odor formation.

## 4 Smart Textile Design, Fabrication, and Health Management Applications

### 4.1 Materials Used for Smart Textiles

Material selection is crucial in smart textile development, as it underpins the integration of functions across various applications. The common types of materials for textiles, substrates, and flexible devices are summarized in Fig. 7. Materials for smart textiles are primarily categorized into natural and synthetic polymers. Natural polymers are derived from natural sources, including wool, silk, chitosan, collagen, and cellulose. Wool is a naturally occurring type of fiber, that features a unique structure composed of microscopic scales that effectively trap air and form an intrinsic insulation layer. This structure endows wool with superior thermal retention properties [173]. In addition, its inherent elasticity allows it to recover its original shape after deformation, enhancing the durability and wrinkle resistance of the fabric [174]. Excellent moisture absorption of wool further contributes to thermoregulation and perspiration management, making it highly suitable for outdoor apparel and garments requiring

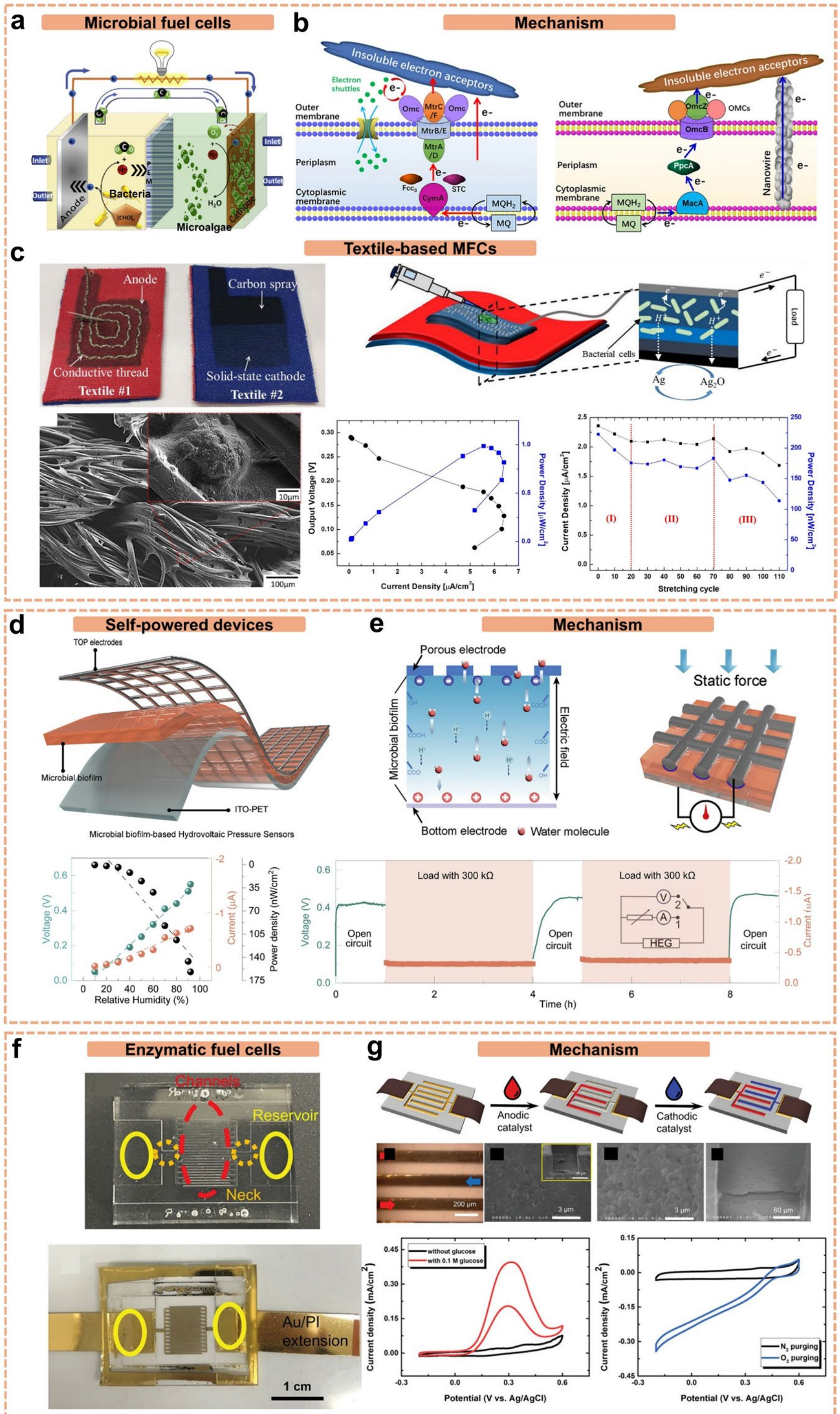


**Fig. 6** Representative MFC, self-powered flexible devices, and EFC. **a** Bacteria and microalgae for a double-chamber MFC; reproduced with permission from Ref. [158], Copyright © 2020 Elsevier B.V. **b** Extracellular electron transfer mechanism of the typical EAB stains *Shewanella oneidensis* and *Geobacter sulfurreducens*; reproduced with permission from Ref. [159], Copyright © 2021, The Author(s), Springer Nature. **c** Textile-based flexible microbial fuel cell; reproduced with permission from Ref. [119], Copyright © 2017 Elsevier B.V. **d** Composition of self-powered flexible electronics. **e** Self-powered MFCs work as a mechanism of bacteria with dynamic water; reprinted with permission from Ref. [120], Copyright © 2025 Elsevier B.V. **f** Demonstration of enzymatic biofuel cells. **g** Catalyst loading and reactions at the anode and cathode; reprinted with permission from Ref. [121], Copyright © 2023 Wiley–VCH

advanced thermal insulation [175]. Silk is renowned for its distinctive luster, smooth texture, and exceptional mechanical strength. It consists of elongated fibers with a tightly packed molecular structure. This structural arrangement imparts outstanding tensile strength and flexibility [176]. Moreover, the natural protein composition of silk provides excellent moisture absorption and breathability, facilitating effective body temperature regulation [177]. Consequently, silk is typically employed in medical textiles that demand high biocompatibility and skin-friendliness. Chitosan is a natural polysaccharide extracted from the exoskeletons of crustaceans and exhibits remarkable bioactivity. It possesses excellent biodegradability and biocompatibility while inherently exhibiting antimicrobial properties, effectively inhibiting bacterial and fungal proliferation [178, 179]. These characteristics make chitosan a valuable additive for functional coatings or composite materials in smart textiles, particularly for applications in skin health management, sportswear, and antimicrobial odor-resistant textiles. As a fundamental protein in human skin and connective tissues, collagen possesses a three-dimensional (3D) structure closely resembling that of endogenous tissues, making it highly promising for functional textiles and biomedical applications [180]. Incorporating collagen fibers into textiles enhances skin-friendliness and softness while promoting cellular repair and regeneration [181]. The strategic incorporation of natural polymers enables smart textiles to exhibit multifunctional properties that are adaptable to diverse application domains, such as health care, biomedicine, sports, and outdoor performance. Cellulose is among the most abundant natural polymers and is obtained from natural sources such as cotton, flax, and wood. Certain bacteria are capable of synthesizing bacterial cellulose, such as *Gluconacetobacter xylinus* [182]. Compared with plant-derived cellulose, bacterial cellulose is inherently free of lignin, hemicellulose, and other impurities. Therefore, the need for extensive purification processes is eliminated [183]. Cellulose exhibits excellent mechanical properties, moisture absorption, breathability, and biodegradability, making it highly promising for advanced applications in biomedical textiles, wearable sensors, and functional fabrics.

The synthetic polymers commonly used in textiles include PET, nylon, polyurethane (PU), polylactic acid (PLA), and polycaprolactone (PCL). PET is not only cost-effective for large-scale production but can also be engineered with advanced functionalities such as water repellency, strain resistance, physical shielding effects, and UV protection by specialized treatments [184, 185]. Nylon fibers are known for their high strength, excellent wear resistance, and superior elasticity. Their tightly packed molecular chain structure ensures stability under significant tensile and flexural stress [186]. These outstanding mechanical properties and durability make nylon ideal for use in sportswear, outdoor gear, and other smart textiles that require high strength and long-term resilience. PU features alternating hard and soft segments within its molecular structure, imparting excellent stretchability and fatigue resistance [187]. Due to its remarkable softness and elasticity, PU is generally used in elastic fabrics, compression garments, and athletic wear. Moreover, PU fibers serve as an ideal substrate for integrating sensors and conductive elements in smart textiles, enhancing flexibility and wearability and providing greater freedom of movement for users [188]. PLA is a classical green and sustainable material. It offers an excellent balance of mechanical performance and biodegradability, and can be chemically modified to introduce functionalities such as antibacterial properties, electrical conductivity, and stimulation responsiveness [189, 190]. PCL is characterized by a low melting point, high flexibility, and superior biodegradability and is also a U.S. Food and Drug Administration-approved biomaterial [191]. It can be blended with other polymers to fine-tune the softness and mechanical properties of the fabric [192].

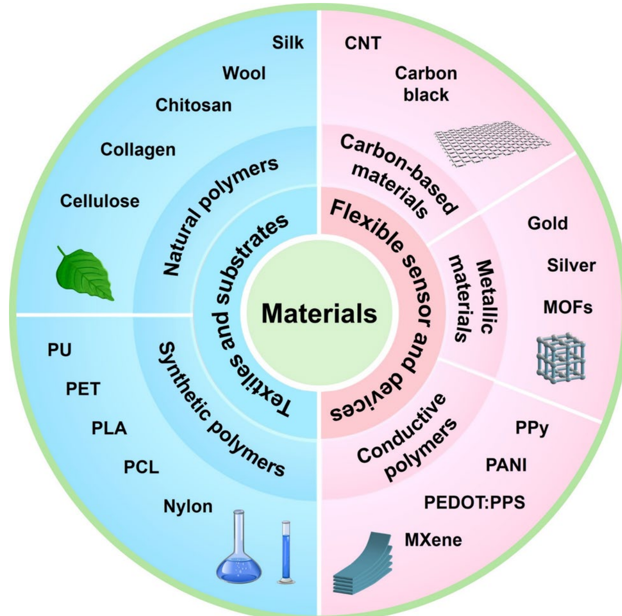


**Fig. 7** Classification of materials used for smart textiles, soft substrates, flexible sensors, and devices

Furthermore, flexible substrates and electrodes are essential components in imparting intelligent functionalities to smart textiles. To achieve superior electrical conductivity, flexibility, durability, and multifunctionality, various functional materials including metals, conductive polymers, carbon-based materials, and electroactive materials are typically used. Metallic materials (e.g., silver, copper, gold, and titanium) and metal–organic frameworks are typically utilized in flexible electronic sensors because of their exceptional conductivity and chemical stability [193, 194]. Silver nanowires and gold nanoparticles serve as primary components for flexible electrodes owing to their outstanding electrical performance [195, 196]. Conductive polymers such as polyaniline, polypyrrole, MXene, and PEDOT:PSS offer a unique combination of flexibility, stretchability, and tunable electrical conductivity, making them ideal for applications in flexible pressure and humidity sensors [197–199]. Carbon-based materials including graphene, carbon nanotubes (CNTs), and carbon black are highly valued for their ultrahigh conductivity, light weight, high-strength properties, and thermal regulation capabilities [200]. These attributes make them well-suited for applications in electrically heated garments and intelligent protective textiles. Electroactive materials endow smart textiles with self-powering, color-changing, and responsive actuation capabilities. For instance, piezoelectric materials (e.g., PVDF and barium titanate) facilitate motion monitoring and self-powered sensing textiles [201]. Electrochromic materials (e.g., liquid crystals) enable the development of color-changing garments [202]. Moreover, shape-memory materials are employed in environment-responsive clothing and adaptive dermal-interfaced flexible systems [203]. Other materials with outstanding electrical properties, such as black phosphorus, also meet the needs of flexible electronics [204, 205].

### 4.2 Structures and Design of Smart Textiles

The overall performance and specific functionalities of smart textiles are determined by not only material selection, but also their structural design. Textile structures significantly impact mechanical properties, breathability, elasticity, and comfort while determining their applicability in smart applications, such as sensing, conductivity, responsiveness, and durability [206, 207]. Consequently, a comprehensive understanding for the structural properties of textiles is crucial to optimizing their performance in targeted applications. Fundamentally, textile structures are composed of fibers or yarns, which are organized and processed using various techniques to form different types of fabrics. Common textile structures include weaving, knitting, braiding, nonwoven, and 3D textile structures (Fig. 8), each possessing unique properties and application potential.

Woven fabrics are formed by interlacing warp and weft yarns in a systematic pattern, resulting in high stability, abrasion resistance, and shape retention. Owing to their tightly woven structure, they typically exhibit superior mechanical strength and allow adjustments in breathability and softness through weaving techniques. Woven fabrics are frequently utilized in smart textile applications when high structural stability is needed, such as in smart protective clothing and medical textiles [211]. Compared with woven fabrics, knitted fabrics are characterized by interloped yarn structures that offer greater elasticity, softness, and breathability [212]. These properties make knitted fabrics more suitable for body-conforming applications, such as smart sportswear, intelligent socks, and smart gloves. In addition, knitting structures allow stretchable conductive pathways for e-textiles, ensuring adaptability to body movements and enhancing the comfort and durability of smart devices [213]. Braiding structures are typically formed by interlacing multiple yarns in a crisscross pattern, resulting in high flexibility and high wear resistance. This structure is relatively uncommon and is primarily utilized for the fabrication of fiber-shaped supercapacitors [214]. Nonwoven fabrics are produced through physical or chemical bonding of fibers without traditional weaving or knitting. They possess unique properties such as low weight, high absorbency, and high porosity [215]. These features make nonwoven fabrics applicable in smart filtration materials, intelligent medical dressings, and biodegradable textiles. 3D textile structures provide enhanced dimensionality, mechanical performance, cushioning ability, and functional integration. Therefore, 3D textiles are extensively applied in smart protective gear, aerospace composites, and wearable devices. For instance, 3D weaving techniques enable the creation of multilayered, multifunctional fabrics with integrated sensing capabilities and make smart textiles more effective at pressure detection, thermal regulation, and energy storage [215, 216]. Based on advanced 3D fabrication techniques, 4D textiles can be developed using transformable polymers that respond to external stimuli. These innovative textiles are capable of dynamically changing their shape when exposed to specific triggers, such as variations in temperature [208]. 4D textiles offer programmable and reversible shape transformations [217]. They can be used to create self-adaptive garments that adjust their fit, insulation, or ventilation in response to environmental changes. In the field of responsive fashion, 4D textiles can enable clothing that reacts to temperature, humidity, or body movement, enhancing both comfort and functionality. In addition, owing to their lightweight and flexible properties, they can serve as adaptive substrates for wearable electronic devices, enabling better integration of sensors or interactive components.

### 4.3 Methods for Fabricating Smart Textiles

The fabrication of smart textiles relies primarily on six key technologies: electrospinning, 3D printing, thermal drawing, surface coating, chemical vapor deposition (CVD), and embroidery. Each technique offers unique advantages in imparting specific functionalities to textiles.

Electrospinning employs a high-voltage electric field to elongate polymer solutions, resulting in the formation of continuous fibers with diameters ranging from the micro- to nanoscale (Fig. 9a). The underlying mechanism involves the generation of a Taylor cone at the tip of the spinneret under

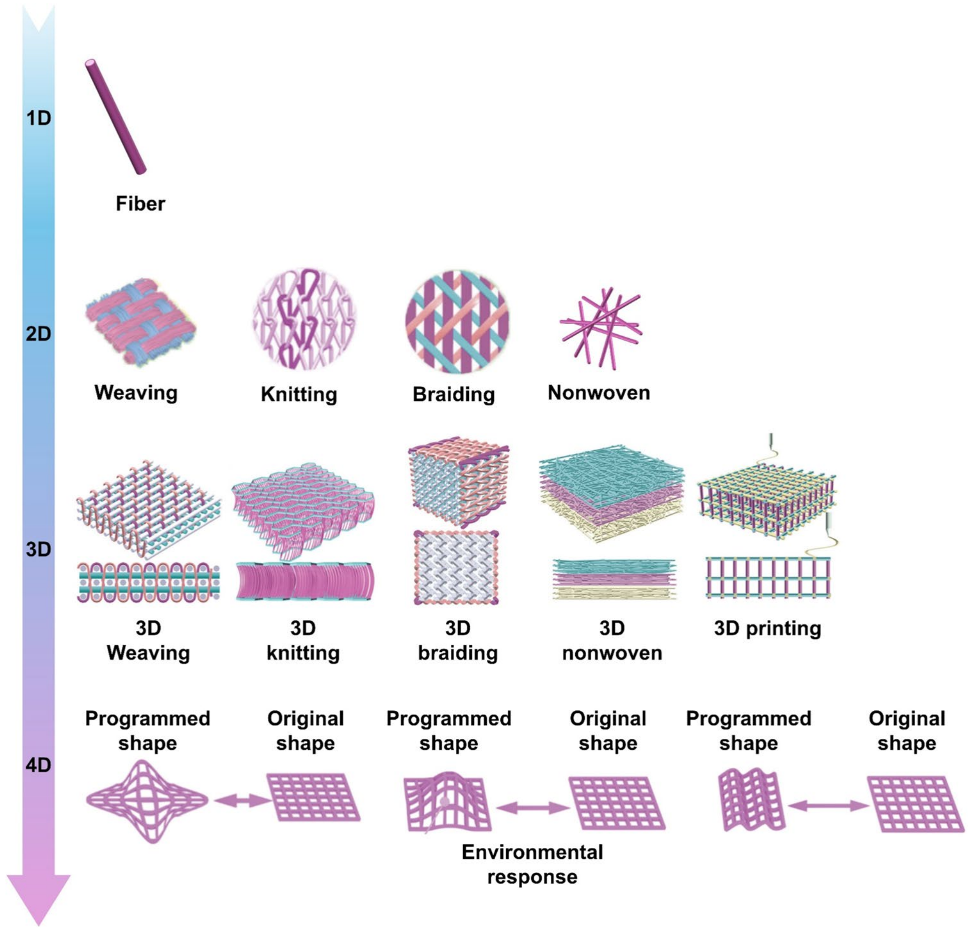


**Fig. 8** Classification of smart textiles from a 1D single fiber structure to a 4D response structure; reprinted (adapted) with permission from Ref. [208]. Copyright 2020 American Chemical Society. Reproduced with permission from Ref. [209], Copyright © 2019 Wiley–VCH. Reproduced with permission from Ref. [210], Copyright © 2022 Wiley–VCH

the influence of an electrostatic field. Once the electrostatic force overcomes the surface tension of the polymer solution, a charged fluid jet is ejected and undergoes rapid stretching and solvent evaporation during its flight. The solidified ultrafine fibers are subsequently deposited onto a grounded collector, forming a nonwoven nanofibrous membrane with a high surface-area-to-volume ratio and tunable porosity [218]. Electrospinning is typically used for the fabrication of breathable textiles, filtration membranes, and medical fabrics [219–222]. However, precise control of fiber functionality remains challenging for electrospinning. In addition, the process is highly sensitive to environmental conditions (e.g., humidity and temperature), leading to inconsistencies in fiber quality and performance.

3D printing is a layer-by-layer additive manufacturing technique for creating 3D structures, enabling the production of complex smart textile configurations or their components (Fig. 9b). Based on computer-aided design models, digital designs are converted into layered instructions to guide the print head in depositing materials such as conductive polymers, biomaterials, and bio-based composites. This technology is primarily utilized for the fabrication of smart clothing, functional fabrics, bioactive textiles, and flexible substrates [224, 229, 230]. 3D printing offers precise fabrication of complex structures, but it is still limited by several factors. Producing multilayer structures with different materials is costly and technically complex. The printing of flexible, conductive materials lacks sufficient resolution and speed to meet the softness and comfort requirements of textiles.

Thermal drawing is an effective and scalable technique for fabricating functional fibers by heating and elongating thermoplastic polymers or composite materials in their molten state (Fig. 9c). This process has been adopted in the development of fiber-based electronic systems, enabling the integration of electronic, optical, and sensory components within flexible fiber architectures [231, 232]. Collectively, these technologies constitute a versatile platform for the design and production of next-generation smart textiles with multifunctional capabilities, thus facilitating considerable progress in wearable electronics, biomedical sensing, and energy-harvesting applications. This technique is primarily suited for fiber production rather than complex fabric processing. It requires high processing temperatures, and the process is complex and costly.

Coating involves the application of a functional material layer onto the surface of textiles, hence endowing them with novel smart properties such as conductivity, sensing capability, and waterproof breathability. Coating technology is widely employed in the preparation of protective textiles and energy-harvesting fabrics. Common coating materials include functional polymers, various nanomaterials, and conductive inks. These materials adhere to textiles via physical (Fig. 9d) or chemical (Fig. 9e) adsorption and are stabilized through deposition, thermal curing, or UV cross-linking [233, 234]. Surface coating enhances textile functionality but shares similar limitations with general coating techniques. It may compromise the breathability and softness of fabrics, reducing wearer comfort. Achieving a uniform coating on complex textile geometries is difficult, and long-term durability is a concern, as coatings may wear off or lose functionality after the textile is washed or placed under mechanical stress. Chemical vapor deposition enables the precise deposition of functional materials, but this process is complex and expensive and requires specialized equipment. Environmental and biocompatibility issues associated with certain coating materials further limit their applicability.

Embroidery is a commonly used technology to integrate flexible electronics into textiles (Fig. 9f), offering a simple, fast, and versatile approach to creating smart textiles [228, 235]. Using conductive fibers, threads or functional yarns, electronic components such as sensors can be stitched directly onto fabric surfaces without compromising their comfort or flexibility [236, 237]. This technique allows for precise patterning and customization, making it ideal for

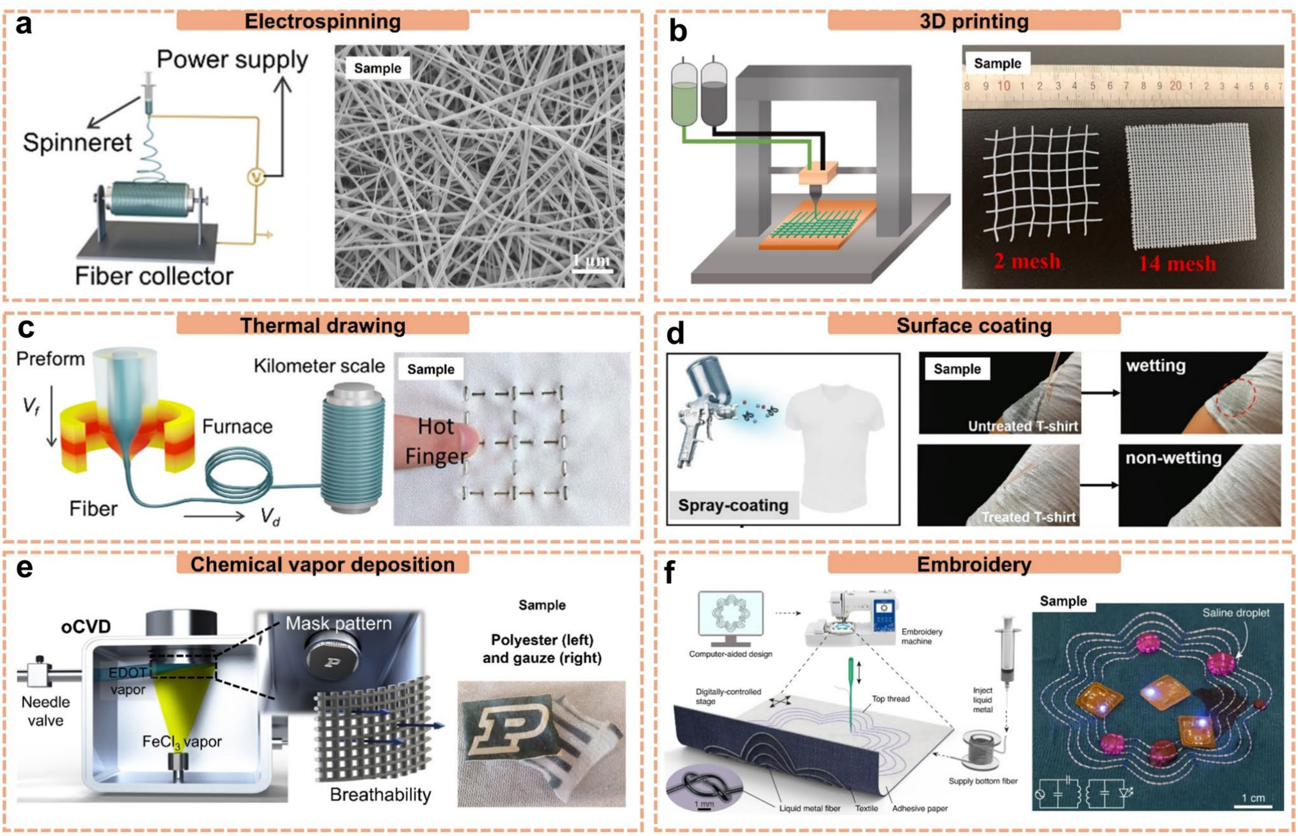


**Fig. 9** Smart textile fabrication methods and related samples. **a** Electrospinning and fibrous membrane captured by SEM; reproduced (adapted) with permission from Ref. [223]. Copyright 2024 American Chemical Society. Reproduced with permission from Ref. [4], Copyright © 2023 Elsevier B.V. **b** 3D-printed and printed textiles; Copyright 2024 American Chemical Society. Reproduced with permission from Ref. [224], Copyright © 2021 Elsevier B.V. **c** Thermal drawing and weaving into a textile; reproduced (adapted) with permission from Ref. [223]. Reproduced (adapted) with permission from Ref. [225]. Copyright 2019 American Chemical Society. **d** Surface coating and waterproofing before/after treatment; reproduced with permission from Ref. [226], Copyright © 2021 Elsevier B.V. **e** CVD process and image of a pattern on a fabric; reproduced with permission from Ref. [227], Copyright © 2021 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **f** Embroidery process and image of embroidered textiles with devices; reproduced under the CC BY 4.0 license from Ref. [228], Copyright © 2022, The Author(s), Springer Nature

wearable applications such as health monitoring, motion tracking, and communication. In addition, embroidery is compatible with existing textile manufacturing processes, which support mass production and enhance the durability and washability of integrated electronics in everyday garments. However, embroidered regions can increase localized stiffness, compromising patient comfort and esthetics. High stitch densities may cause fabric wear or breakage. Furthermore, the effectiveness of the application limits its ability to support large-scale production.

### 4.4 Smart Textiles Applied for Skin Health Management

As a pivotal intersection of future technology and fashion, smart textiles are reshaping traditional perceptions of textiles. This field encompasses a wide range of innovations, including smart gloves, smart clothing, intelligent pressure-sensitive socks, smart accessories, smart medical dressings, and wearable displays (Table 3) [47, 238–240]. Smart textiles are particularly well-suited for applications related to skin health, because of their prolonged and intimate contact with the human body (Fig. 10a and b). As a significant advancement in textile technology, smart garments are transforming conventional clothing beyond esthetic appeal, decoration, and basic protective functions, evolving toward higher intelligence and multifunctionality. The development of smart textiles is fundamentally dependent on the seamless integration of advanced technologies, including flexible electronics, high-performance materials, energy storage, and wireless communication systems. This constructive interaction enables promising applications in health monitoring, infection prevention, personalized therapy, and wound healing acceleration (Fig. 10c). In addition, functional fibers facilitate integration into textiles and electrical signal transmission and support various electronic functions. For example, self-charging fibers can supply power to sensors or devices in smart textiles (Fig. 10d). Intelligent sensors, such as temperature sensors, heart rate monitors, and accelerometers, enable real-time physiological data collection and analysis [241, 242]. Meanwhile, wireless communication technologies ensure seamless data transmission to external devices, such as smartphones or cloud-based systems [243]. Smart garments have demonstrated preliminary functionalities in Table 3, including temperature regulation, health monitoring, wound detection, and interactive features.

Furthermore, to enhance the functionality of smart textiles, researchers are considering the introduction of microbes into fabrics. In recent years, researchers have started to explore how daily human activities influence microorganisms and are considering incorporating these microorganisms into dermal-interfaced flexible systems. Temperature and genetic technologies have been used to regulate microbes, enabling them to serve as display interfaces in textiles or to increase the yield of sustainable materials synthesized by microbes [48, 259]. They have shown immense potential in terms of fiber fabrication and HMI in health management. However, several technical challenges such as energy supply, durability, washability, comfort, and the development of intelligent therapeutic capabilities still need to be addressed. Overcoming these challenges will be crucial for advancing the next generation of smart textiles, paving the way for broader adoption and enhanced user experiences.

## 5 Advanced Technologies for Next-Generation Smart Textiles

### 5.1 Microbes for Living Smart Textiles

Smart textiles integrate advanced flexible electronic technologies to create fabrics with enhanced functionalities. These innovations allow textiles to perform a variety of functions beyond traditional uses, such as self-cleaning, energy harvesting, and biosensing [260, 261]. By leveraging these capabilities, smart textiles can interact effectively with the human body and its environment. Considering that skin microbes are particularly important for maintaining balanced microenvironment, skin health, and wound management, they are essential for the development of next-generation smart textiles focused on skin health management. They hold the potential to optimize skin health management through microbial regulation, real-time monitoring, and personalized interventions, offering novel solutions for both medical and daily care applications. For example, upon identifying pathogenic bacterial proliferation, these smart textiles can actively trigger antimicrobial mechanisms, such as photothermal, photocatalytic, or magnetically responsive technologies [262, 263], to eliminate harmful microbes in a targeted manner. Future smart textiles can be designed to regulate skin pH, humidity, and temperature, creating an optimal environment for beneficial microbial growth and maintaining microbiome homeostasis. For acute wounds, chronic wounds, and scar management, next-generation smart textiles can be engineered to incorporate antimicrobial agents, anti-inflammatory compounds, and proregenerative factors. These enhancements aim to reduce infection risks; provide smart regulation, wound monitoring and intelligence therapy; and promote scarless regeneration. This section describes some emerging technologies capable of achieving these advanced functionalities, laying the foundation for the development of living fabrics.

**Table 3** Summarization of skin-related smart textiles with their components, performances, and applications

| Smart textile and substrate materials | Structure | Fabrication method | Breathability | Washability | Application | Refs. |
|---|---|---|---|---|---|---|
| Gloves | | | | | | |
| Multiwall CNT and chitin carbon with silk fibroin | Braiding | Electrospinning | AP > 90 mm/s | > 50 washing cycles | Noncontact voltage detection glove | [244] |
| Cu, parylene, and polyacrylonitrile | Knitting | Surface coating | WVTR > 1.2 kg/$m^2$/day | > 20 washing cycles | Grip posture detection | [245] |
| Graphene and silk sericin | Knitting | Cross-linking | WVTR > 8.4 kg/$m^2$/day | > 2 h | Recognizing complex activities | [246] |
| Chest strap | | | | | | |
| Polypropylene | Nonwoven | Melt blowing | AP ~ 215 mm/s | > 8 washing cycles | Respiratory monitoring | [247] |
| Sensing fabrics | | | | | | |
| Semiconducting glass and polyetherimide | Weaving | Thermal drawing | – | – | Temperature-sensing fabrics | [225] |
| Clothes | | | | | | |
| PVDF, PTFE, and PET | Weaving | Electrospinning and electrospray | WVTR = 8.837 kg/$m^2$/day | > 12 h | Self-powered monitoring | [248] |
| Ag/$MoS_2$/HfAlOx/CNT | Weaving | CVD | – | – | Warm fabric | [249] |
| Chitosan aerogel fiber and TPU | Weaving and knitting | Freeze-spinning | – | > 1 washing cycle | Thermal insulation | [250] |
| TPU, ZnS phosphors, nylon | Weaving | 3D printing | – | > 100 washing cycles | Displays | [47] |
| Boron nitride and poly(vinyl alcohol) | Weaving and knitting | 3D printing | – | – | Thermal regulation | [251] |
| Bedsheet | | | | | | |
| PET and silicone | 3D fabric | Manual fabrication | – | > 8 washing cycles | Sleep-monitoring | [252] |
| Soft prosthesis | | | | | | |
| Thermoplastic elastomers | Weaving | Thermal drawing | – | > 6 washing cycles | Rehabilitation medical applications | [253] |
| Smart bandage | | | | | | |
| TPU and polyether sulfone | Nonwoven | Electrospinning | AP > 70% | – | Chronic wound management | [254] |
| Fiber battery | | | | | | |
| $TiO_2$ nanotube, carboxymethyl cellulose, and CNT sheet | Weaving | Surface coating | – | > 50 washing cycles | Self-charging | [255] |
| Firefighting suits or energy-saving curtains | | | | | | |
| PET, TPU, PEG | 3D fabric | Surface coating | WVTR = 3.27 kg/$m^2$/day | > 100 washing cycles | Thermal management and fire protection | [256] |
| Solar control coatings | | | | | | |
| Zinc oxide, cotton | Weaving | Surface coating | AP > 6 mL/s/$cm^2$ | > 50 washing cycles | UV shielding | [257] |
| Conformal textile skin patches | | | | | | |
| Galinstan (Ga68.5/In21.5/Sn10) | 3D fabric | Embroidery | WVTR = 7.2 ± 0.1848 kg/$m^2$/day | > 10 h | Electronic textiles | [228] |

*AP* air permeability, *WVTR* water vapor transmission rate

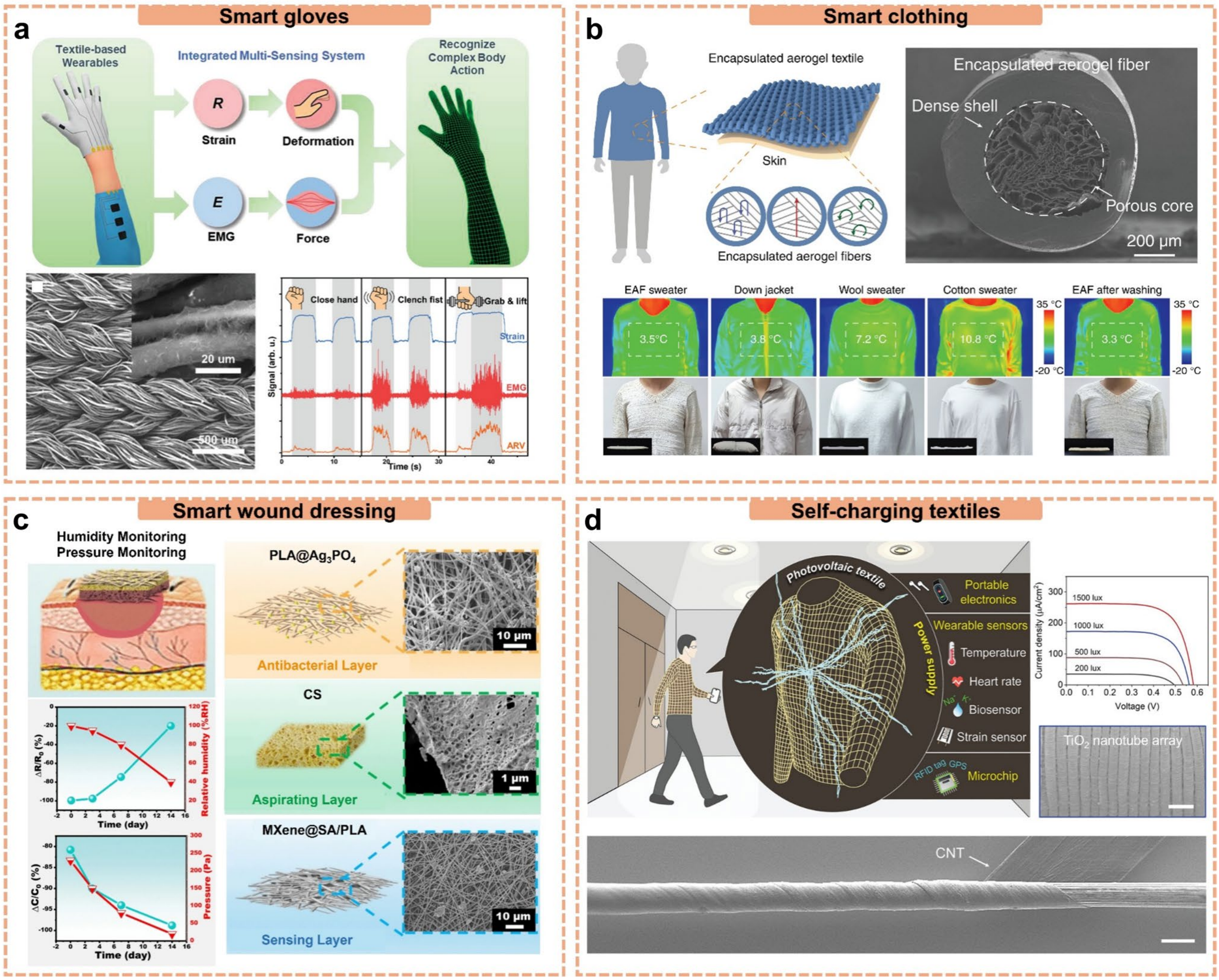


**Fig. 10** Representative current smart textiles for skin health management. **a** Smart gloves for monitoring and recognition of hand activities; reproduced with permission from Ref. [246], Copyright © 2022 Wiley–VCH. **b** Polar bear hair mimetic encapsulated aerogel fiber for thermal insulating clothing; reproduced with permission from Ref. [250], Copyright © 2023 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. **c** Smart dressing for wound humidity and pressure monitoring and acceleration of the healing process; reproduced with permission from Ref. [258], Copyright © 2024, Springer Nature. **d** Self-charging textiles can supply energy for commercial electronic devices under light. Reproduced with permission from Ref. [255], Copyright © 2023 Wiley–VCH

## 5.2 Microencapsulation Technology

Textiles have the largest contact area with skin and serve as highly convenient carriers for delivering therapeutic agents and bioactive substances for skin health management and wound healing. However, directly introducing beneficial microorganisms onto textile surfaces presents significant challenges. Their activity can be compromised by washing, elevated temperatures, and UV radiation. These environmental factors may also lead to reduced efficacy or complete deactivation. Therefore, ensuring the protection, stability, and controlled release of these microorganisms are crucial issues that must be addressed to maximize their therapeutic potential.

Microencapsulation is an advanced technique that involves the encapsulation of active substances or engineered microorganisms within micro/nanoscale carrier materials to increase stability (Fig. 11a), regulate release, improve biocompatibility, facilitate textile processing, and detection [264]. These encapsulating carriers, which are typically composed of polymers, lipids, or inorganic materials, shield bioactive agents from external environmental stressors while enabling precise and controlled release [265]. Current applications of microencapsulation include the encapsulation of dyes, proteins, fragrances, monomers, and catalysts [266]. This technique allows the immobilization of active substances (e.g., microorganisms, enzymes, and bioactive compounds) within microcapsules, which can be incorporated into textiles through coating, impregnation, spraying, or fiber blending [267]. Microencapsulation has significant potential for enhancing microbial stability, ensuring controlled release, prolonging functional durability, and allowing engineered microorganisms to detect specific microenvironmental conditions. A recent study [268] demonstrated that engineered bacteria can be encapsulated within miniature biomedical devices and can detect biomarkers of inflammation in the body as a biosensing tool (Fig. 11b). Furthermore, stimuli-responsive microencapsulation enables the intelligent release of active agents under specific conditions. For instance, pH-, temperature-, or humidity-responsive encapsulating materials can ensure that microorganisms are release only under optimal conditions, maximizing their effectiveness and minimizing unnecessary loss at the same time. For functional clothing, antibacterial dressing, and wound dressings (Fig. 11c and d), encapsulated commensal microbes can be released in response to triggers such as inflammation, perspiration, pathogen infection, or other external environmental stimuli. When encapsulated microbes are released under certain conditions, they can regulate the microbiome balance and improve the skin barrier; premature deactivation can be prevented during dry storage. In antimicrobial applications, microencapsulation can be used to increase the efficacy of beneficial microbes while reducing the potential toxicity of traditional antimicrobial agents to humans. Encapsulation of *Staphylococcus epidermidis* can enable competitive inhibition of pathogenic bacteria and reduce the risk of skin infections [269]. In addition, *Bacillus subtilis* can produce natural antimicrobial peptides [270]. This kind of microbe can be encapsulated to provide long-lasting antimicrobial protection and avoid rapid activity depletion due to premature release. In the context of sustainable textile development, microencapsulation can drive innovations in eco-friendly and functional textiles. Encapsulating pollutant-degrading microorganisms can impart air-purification properties to textiles, while encapsulated enzymes can enable self-cleaning capabilities, reducing the washing frequency and water consumption.

### 5.3 Synthetic Biology

Synthetic biology allows researchers to precisely design and modify microorganisms. This technology offers revolutionary support for next-generation smart textiles in skin health management. Current smart textiles face limitations including unreliable durability, poor battery life, and inability to sustain bioactive substances for extended periods. The integration of synthetic biology enables microorganisms to actively sense, regulate, and improve the skin microenvironment, while also providing a biologically driven sustainable energy source for smart textiles. Synthetic biology enables the programming of microorganisms, which can impart these engineered microbes with the ability to manage skin health, therapeutic ability, and other applications, such as skin status monitoring and increased therapeutic factor release. (Fig. 12a). With the use of CRISPR and other gene editing technologies, microbes can be engineered to express customized functional genes under specific conditions [274, 275]. Engineered microorganisms can be modified to secrete bioactive compounds, such as antimicrobial peptides, antioxidants, probiotics, or anti-inflammatory proteins, to protect skin health. For example, genes encoding leptin, α-MSH, and BDNF have been cloned and inserted into expression vectors, lactobacillus-compatible promoters have been used to drive gene expression, and signal peptide sequences have been incorporated to ensure extracellular protein secretion. The weight of mice can be reduced using these engineered microbes. [276] (Fig. 12b). These bioactive agents inhibit pathogenic bacterial growth, reduce skin inflammation, and enhance skin barrier function. Moreover, engineered bacteria can be designed to produce beneficial compounds or improve the effectiveness of the production of biomaterials such as cellulose, hyaluronic acid, and collagen precursors [277–279], potentially providing long-lasting hydration or supporting tissue repair (Fig. 12c). In addition, engineered *Komagataeibacter rhaeticus* has been used to produce alternative polymers such as self-pigmenting bacterial cellulose for use as potential biomaterials in textiles and fashion [280].

Synthetic biology can also be leveraged to develop living biosensors or gain efficiency for microbe-based devices such as MFCs. By optimizing genetic circuits, engineered microorganisms can detect changes in sweat composition, pH levels, temperature, or inflammatory markers. Microbes can provide health feedback through bioluminescence, color changes, or electrical signals and ultimately offer immediate therapy in specific areas [284]. For example, engineered *Lactobacillus species* can respond to skin microbiome imbalances by sensing the overgrowth of pathogenic bacteria or abnormal skin pH and subsequently triggering the synthesis of antimicrobial agents or protective factors to restore skin homeostasis [285]. Meanwhile, flexible biosensing devices enable remote health monitoring and personalized skin

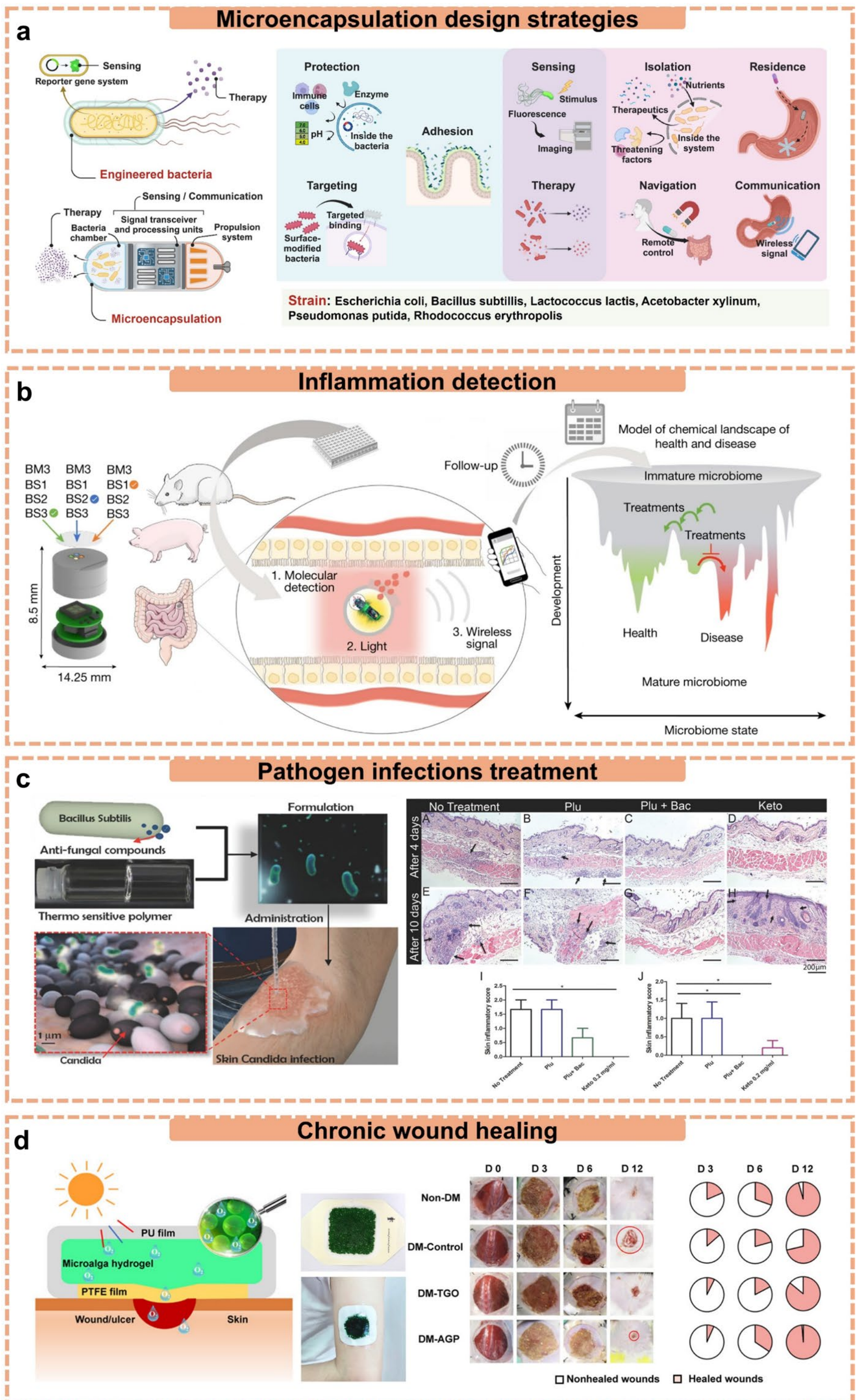


**Fig. 11** Microencapsulation for microbes integrated into smart textiles and related applications. **a** Design strategies of microencapsulation for microbes; reproduced with permission from Ref. [271], Copyright © 2024 Elsevier B.V. **b** Probiotic bacteria-encapsulated biosensor for inflammation detection in situ; reproduced with permission from Ref. [268], Copyright © 2023, Springer Nature. **c** Encapsulated microbes for pathogen infection treatment; reproduced with permission from Ref. [272], Copyright © 2018 Wiley–VCH. **d** Chronic wound therapy involving oxygen generation from encapsulated bacteria; reproduced with permission from Ref. [273], Copyright © 2020 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science

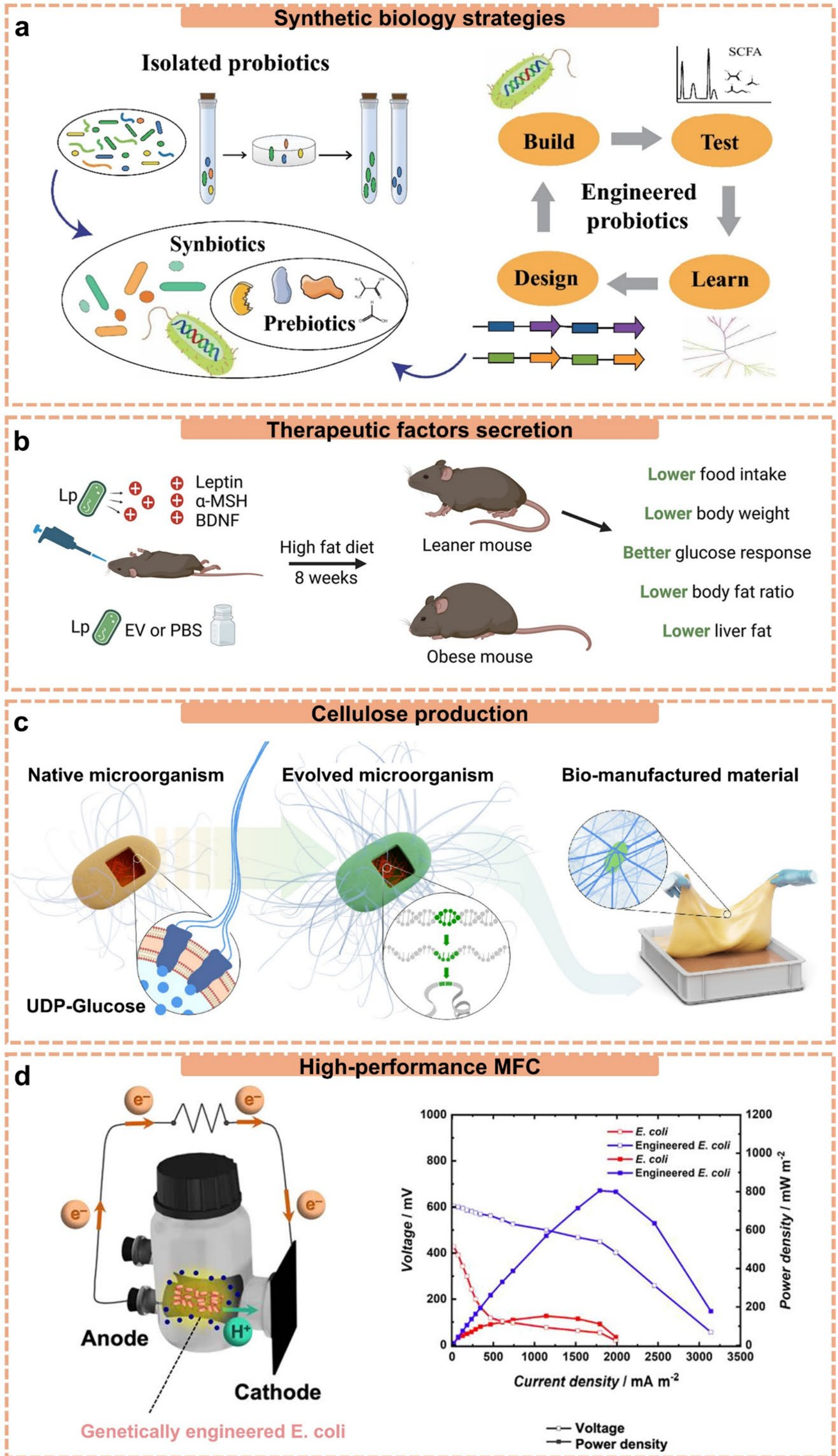


**Fig. 12** Synthetic biology strategies for microbes used in smart textiles. **a** Synthetic biology processes for functionally engineered microbes; reproduced under the CC BY 4.0 license from Ref. [281], Copyright © 2022, The Author(s), Springer Nature. **b** Engineered microbes can secrete therapeutic factors or growth factors to assist in health management; reproduced under the CC BY 4.0 license from Ref. [276], Copyright © 2025, The Author(s), Elsevier B.V. **c** Improving cellulose production with engineered bacteria; reproduced under the CC BY 4.0 license from Ref. [282], Copyright © 2024 the Author(s). National Academy of Sciences. **d** Engineered bacteria for high-performance MFCs. Reproduced (adapted) with permission from Ref. [283], Copyright 2023 American Chemical Society

health management [286]. In addition, engineered microbes can be programmed to respond to humidity or temperature changes [287, 288], dynamically modulating textile breathability and moisture retention for better wearer comfort. For instance, genetically modified bacteria can be designed to synthesize thermoresponsive proteins [289], which alter the hydrophilicity of textile surfaces under high temperatures, hence improving the evaporation efficiency of sweat and increasing thermal comfort. Furthermore, synthetic biology facilitates the integration of bioenergy conversion and self-repair functionalities into smart textiles. The incorporation of MFC technology allows engineered microbes to generate more electricity from organic matter on the skin surface and textiles [290], providing sustainable and efficient energy for smart sensing systems or low-power electronic components. Engineered bacteria-triggered MFC provides maximum current and power densities that are approximately fourfold to sixfold greater than those of mediator-based MFCs reported previously (Fig. 12d). In terms of the self-repair property of smart textiles, certain engineered microbes can be programmed to activate self-repair mechanisms [291], producing biopolymer-based repair agents in response to microdamage or exposure. This self-healing potential enhances the durability of microbe-based smart textiles. With the genetic engineering of microbes, synthetic biology empowers next-generation smart textiles with initiative-taking regulation, real-time monitoring, and personalized skin management.

### 5.4 Optogenetics

In recent years, microbial engineering technologies such as synthetic biology and optogenetics have provided innovative design strategies for next-generation smart textiles. By harnessing engineered microorganisms, smart textiles can integrate antibacterial, protective, and reparative functions, paving the way for personalized and sustainable skin health management.

Optogenetics is a cutting-edge technology that combines genetic engineering and optical control. It allows precise light-driven regulation of microbial gene expression [292], enhancing the controllability and intelligence of smart textiles. This mechanism relies on light-sensitive proteins or photoreceptors that regulate gene activation or suppression, such as blue-light receptors and red-light receptors [293, 294]. By utilizing light of different wavelengths, precise control of microbial behaviors can potentially be achieved, enabling them to perform specific functions in different physiological states or conduct multitasking operations (Fig. 13a). Compared with traditional electrical stimulation and microbiota transplantation methods, the optogenetic regulation of engineered microbial secretion is more efficient and results in lower toxicity and side effects. By integrating optogenetic microbes with smart textiles, a wide range of innovative applications can be realized. For example, the pDusk and pDawn systems can control the MazEF toxin–antitoxin system with darkness and blue light. Under blue light, MazE-mediated inhibition of MazF enables bacterial growth and biofilm generation. Conversely, bacterial growth is inhibited by the repression of mazE and the expression of mazF in the dark (Fig. 13b) [295, 296]. When foreign pathogens invade, engineered bacteria can promote the growth of biofilms under light regulation, allowing them to occupy colonization sites, and compete for nutrients. This approach can effectively inhibit pathogen colonization and spread in situ. Once the pathogens are eliminated, the system can regulate biofilm degradation to prevent the risk of biofouling caused by excessive proliferation of the original bacteria. In addition, engineered microbes can serve as genetically encoded bactericidal and anti-inflammatory agents, eliminating bacteria under optical control [297]. In addition, engineered microbes can be used to pattern graphics on textiles (Fig. 13c) [298]. For detection and sensing, engineered microbes can be utilized to develop smart monitoring textiles. For instance, a light-sensitive biofilm of engineered *Escherichia coli* has been verified to adhere to various surfaces and maintain its responsiveness to light signals after being washed [299]. This property can be applied to detect volatile compounds or pathogens in sweat and body odor on textiles, enabling real-time health monitoring and early disease warning. Optogenetics may also be applied in the development of self-healing textiles in the future, where specific light exposure promotes volume expansion and deformation to fill damaged areas. This light-controlled repair technology can extend the lifespan of smart textiles and reduce material wear. Furthermore, engineered microbes may enable self-cleaning functionality for the surface of textiles, such as breaking down sweat, sebum, and stains on fabric surfaces under light activation. Overall, optogenetics technology endows engineered microbe-based smart textiles with enhanced functionality and controllability.

### 5.5 Artificial Intelligence

Rapid advancements in big data, bioinformatics, synthetic biology, and intelligent materials have expanded the applications of artificial intelligence (AI) beyond computer science into interdisciplinary fields such as life science, materials science, and engineering. AI has demonstrated remarkable capabilities in data analysis, pattern recognition, and predictive modeling [303, 304]. By leveraging big data analysis and computational simulations, AI provides powerful tools to facilitate the development of next-generation microbe-integrated smart textiles. The incorporation of microbes into smart textiles begins with selection of suitable microbial strains for specific textile environments. AI algorithms can identify optimal strains for specific applications by analyzing

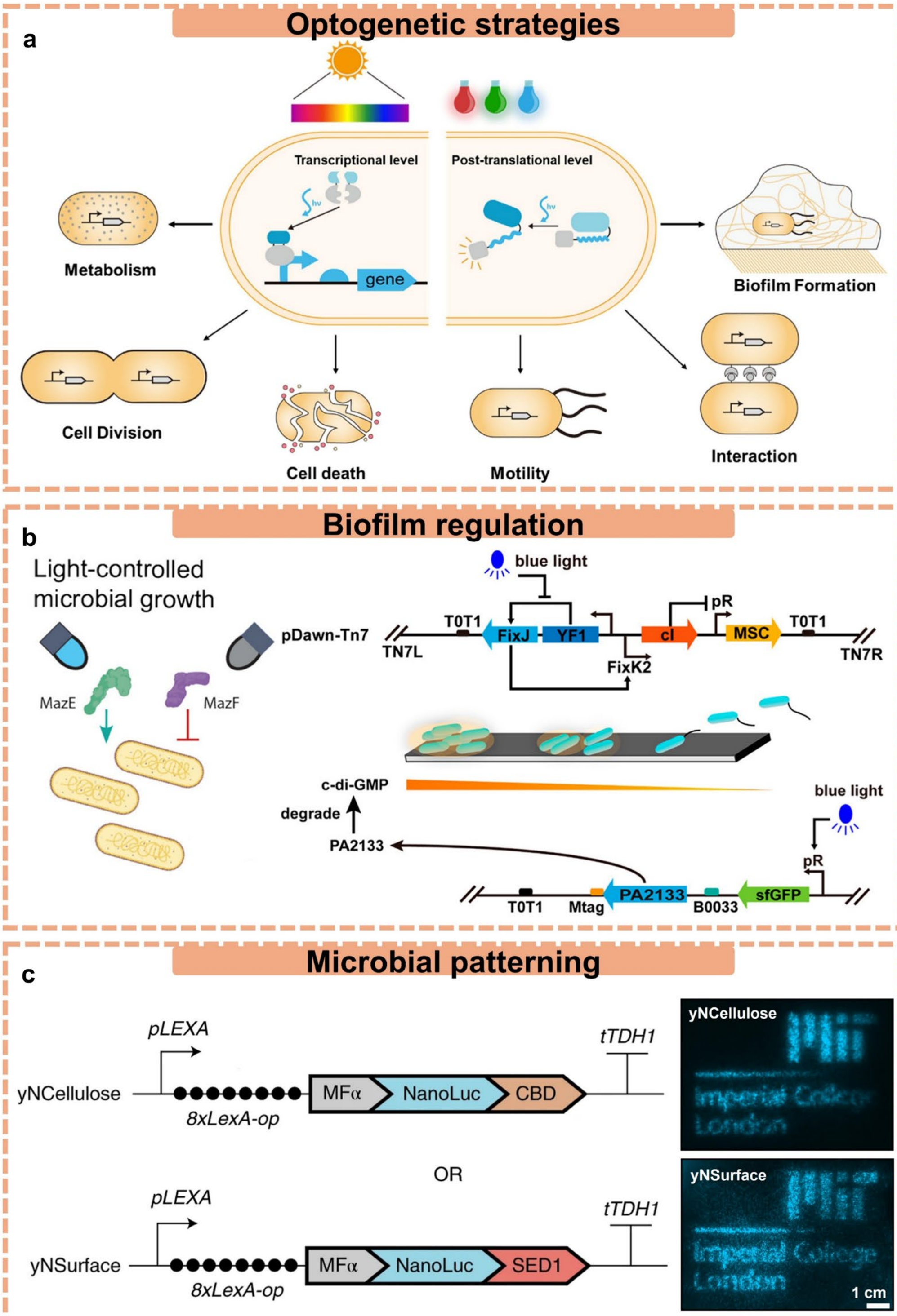


**Fig. 13** Optogenetics for microbial modulation and potential applications in smart textiles. **a** Optogenetic strategies for engineered microbes; reproduced with permission from Ref. [300], Copyright © 2022 Elsevier B.V. **b** Biofilms can be regulated by engineered bacteria under light control; reproduced (adapted) with permission from Ref. [301], Copyright 2018 American Chemical Society. Reproduced (adapted) with permission from Ref. [302], Copyright 2021 American Chemical Society. **c** Projecting patterns on different pellicles under light to obtain images. Reproduced with permission from Ref. [298], Copyright © 2021, Springer Nature

their genomic, proteomic, and metabolomic profiles, which are powered by large-scale datasets (Fig. 14a) [305, 306]. AI can predict the ideal growth conditions for microbes [307], and improve their long-term storage, and stable functionality during usage when embedded in textiles. For instance, machine learning models can simulate the interactions between microorganisms and textile fibers [308], optimizing surface properties to enhance microbial adherence and bioactivity. AI is also instrumental in enabling real-time monitoring and dynamic regulation of human activities within smart textiles. By integrating sensors into smart textiles, AI can continuously track changes in microbial activity and monitor environmental factors such as pH, temperature, and humidity [309]. In skin health management smart textiles, AI can monitor changes in the skin surface or microenvironment and adjust the activity of embedded microbes automatically to maintain the balance of the skin microbiome and prevent infection and dermatological disorders. Developers can track microbial functionality and textile performance in real time. Moreover, end-users can use mobile devices to access information about the status of textiles [310], such as humidity regulation, microbial activity, or filtration capabilities (Fig. 14b). This integration not only enhances user convenience but also promotes the development of intelligent textile ecosystems. One of the most transformative aspects of AI in smart textiles is its ability to deliver personalized solutions (Fig. 14c). When AI is combined with the Internet of Things (IoT), it enables personalized skin health monitoring and management by smart textiles [311, 312]. By analyzing user-specific data, such as health conditions, lifestyle habits, and environmental factors, AI can recommend tailored solutions with doctors in hospitals. For instance, AI can assist doctors in hospitals in quickly determining skin characteristics and specific patient issues and provide suggestions for related cases. Thus, doctors save time, and the probability of error decreases. In addition, AI can predict user preferences [313] for textile design and functionality and optimize product development to enhance the user experience. Personalization ensures that smart textiles meet diverse user needs while providing targeted health and wellness benefits. AI is driving the deep integration of microorganisms and smart textiles, enabling unprecedented levels of intelligence, bioactivity, and environmental adaptability. By empowering microbial selection, structural design, material optimization, intelligent monitoring, and personalized regulation, AI is redefining the capabilities of smart textiles in skin health management and beyond.

## 6 Conclusion and Future Perspectives

The advancement of smart textile technologies accelerates the development of textile systems with enhanced functionality and intelligence. Strikingly, applications in skin health management are driving smart textiles beyond the traditional roles of comfort and protection, toward real-time physiological monitoring, active therapeutic intervention, and adaptive microenvironmental regulation. The integration of microorganisms is a promising and innovative strategy for further enhancing the intelligence and multifunctionality of smart textiles.

Microbes that naturally interact with the skin microenvironment can be engineered or selectively introduced onto textile surfaces or within fiber matrices to enable functionalities such as health monitoring, environmental responsiveness, and antimicrobial defense. This review began by highlighting the pivotal role of microorganisms in both the human body and textile interfaces. As the primary barrier of the body, the skin hosts a diverse and dynamic microbial community that plays essential roles in barrier function, immune modulation, and disease prevention. Similarly, microbial colonization on textiles can yield both beneficial and adverse outcomes. The types, distributions, and functional mechanisms of skin-associated microbes, as well as their interactions with the human host, were systematically summarized. Beyond passive functions, the integration of microorganisms into flexible electronics provides new possibilities for active health monitoring and management. Dermal-interfaced flexible systems, such as electronic skin, flexible sensors, smart dressings, and intelligent garments enable real-time acquisition of physiological parameters, including skin temperature, humidity, sweat composition, and bioelectrical signals. The incorporation of living microorganisms into such systems can further expand their capabilities: Microbial metabolites can serve as diagnostic biomarkers or even generate bioelectricity to power on-body electronics. This review also provided a comprehensive overview of the development of microbially enabled smart textiles, encompassing material selection, textile architecture, fabrication techniques, and applications in skin health. To accelerate the development of next-generation smart textiles, several enabling technologies were discussed. Microencapsulation allows for the protection and controlled release of microorganisms on textile substrates, enhancing their stability and functionality. Synthetic biology offers tools to engineer microbes with tailored functionalities for specific textile applications. Optogenetics enables precise control over microbial activity via light stimuli, opening new avenues for dynamic and responsive systems. AI and big data analytics further support personalized microbiome regulation and real-time decision-making in intelligent textile platforms.

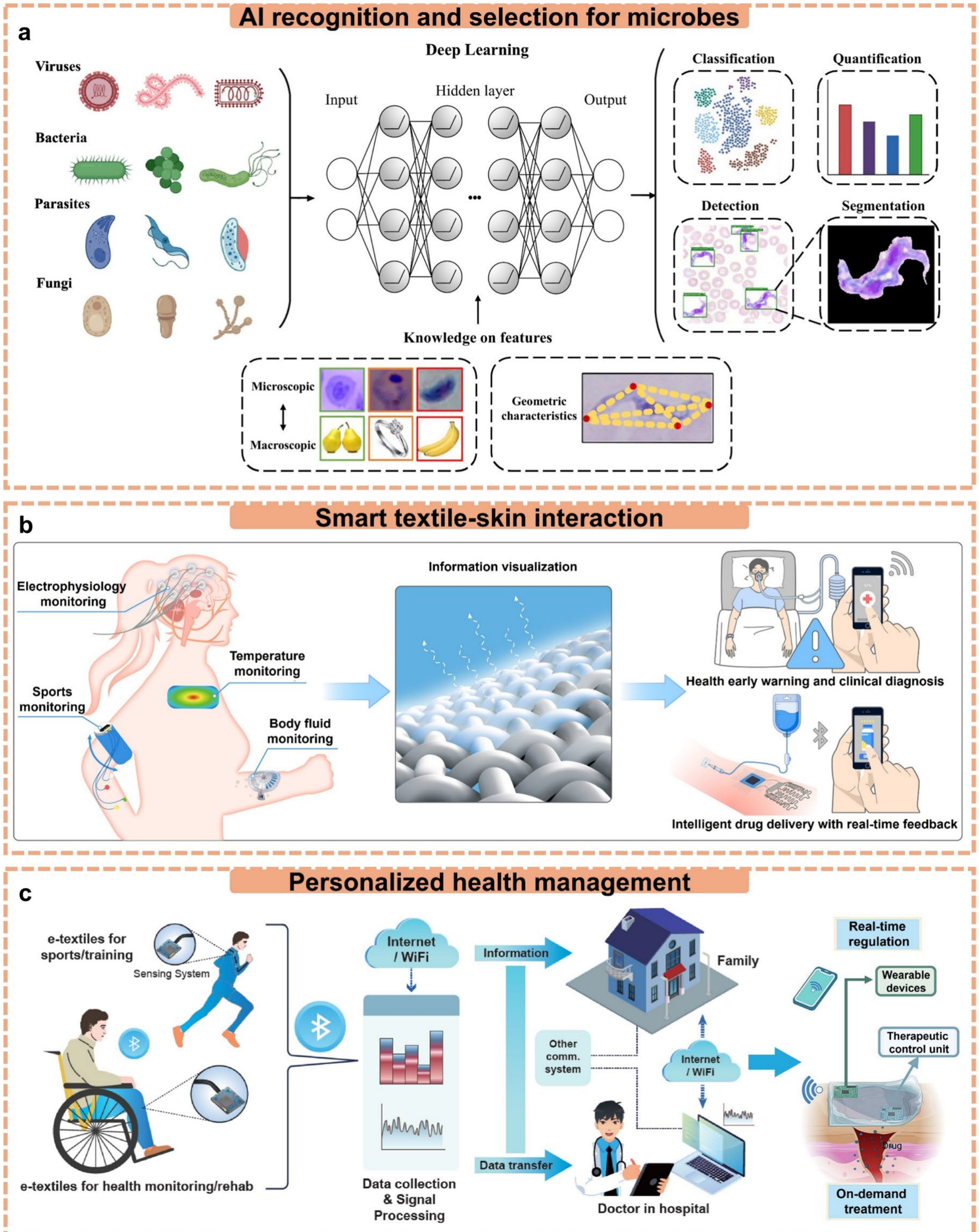


**Fig. 14** AI for next-generation living smart textiles. **a** AI recognition, classification, quantification, and selection for microbes that can be used in smart textiles; reproduced with permission from Ref. [314], Copyright © 2021 Elsevier B.V. **b** Smart textiles applied in the medical HMI field with AI; reproduced with permission from Ref. [315], Copyright © 2024, The Author(s), Elsevier B.V. **c** AI-based personalized health management system in smart textiles. Reproduced with permission from Ref. [316], Copyright © 2023, The Author(s), Elsevier B.V. Reproduced with permission from Ref. [317], Copyright © 2023, The Author(s), Elsevier B.V.

Despite the promising potential of integrating microencapsulation, biosynthesis, optogenetic technologies, and AI into next-generation smart textiles, several significant challenges hinder their commercial translation. First, the high cost and low scalability of current manufacturing processes remain major limitations. Microencapsulation techniques often do not achieve a high ratio in batch production, and ensuring uniformity, biocompatibility, and long-term stability across large textile surfaces is technically demanding. Although microbially enabled smart textiles hold transformative potential for future skin health management, several challenges remain particularly in terms of optimizing microbial stability, ensuring biocompatibility with textile matrices, and scaling from laboratory proof-of-concept to industrial production. Moreover, the use of genetically modified organisms (GMOs), particularly those with optogenetic modifications, introduces regulatory, biosafety, and ethical challenges, as there are currently no globally standardized frameworks governing the use of living engineered microbes in consumer textiles.

The evolution of next-generation smart textiles is being shaped by several key trends, including advanced material selection, biocompatibility, microbial viability, user comfort, integrated intelligent functionality, and commercial scalability (Fig. 15). The critical concerns in microbial-enabled textiles include biosafety and ethical considerations. Importantly, establishing safe-by-design standards and engaging in early dialog with regulatory bodies may accelerate approval pathways and build consumer trust. These strategies collectively pave the way for transformation of these cutting-edge biohybrid technologies into viable commercial textile products. The integration of microbes into textile systems, thus, requires the use of nontoxic, well-characterized strains, along with advanced bioencapsulation strategies to ensure functional stability and safety over time. In terms of functionality, real-time physiological monitoring represents one of the most compelling applications of microbe-integrated smart textiles. Leveraging the biosensing capabilities of engineered microbes, these systems can detect biomarkers such as sweat metabolites, temperature variations, and other physiological cues. In addition, sustaining microbial viability in textile environments remains a significant challenge, as microbial activity is highly sensitive to environmental factors such as temperature, humidity, pH, and nutrient availability. To address this issue, various immobilization techniques, such as hydrogel encapsulation, nanocarrier embedding, and controlled-release systems, are being investigated to prolong microbial functionality and maintain biosensing performance. The growing demand for lightweight, multifunctional, and user-friendly smart textiles imposes stringent design requirements. Traditional strategies often rely on surface coatings or embedded electronics to achieve functionality. In contrast, microbe-integrated smart textiles aim to integrate diverse capabilities including self-cleaning, thermoregulation, antimicrobial protection, and even bioelectricity generation directly through

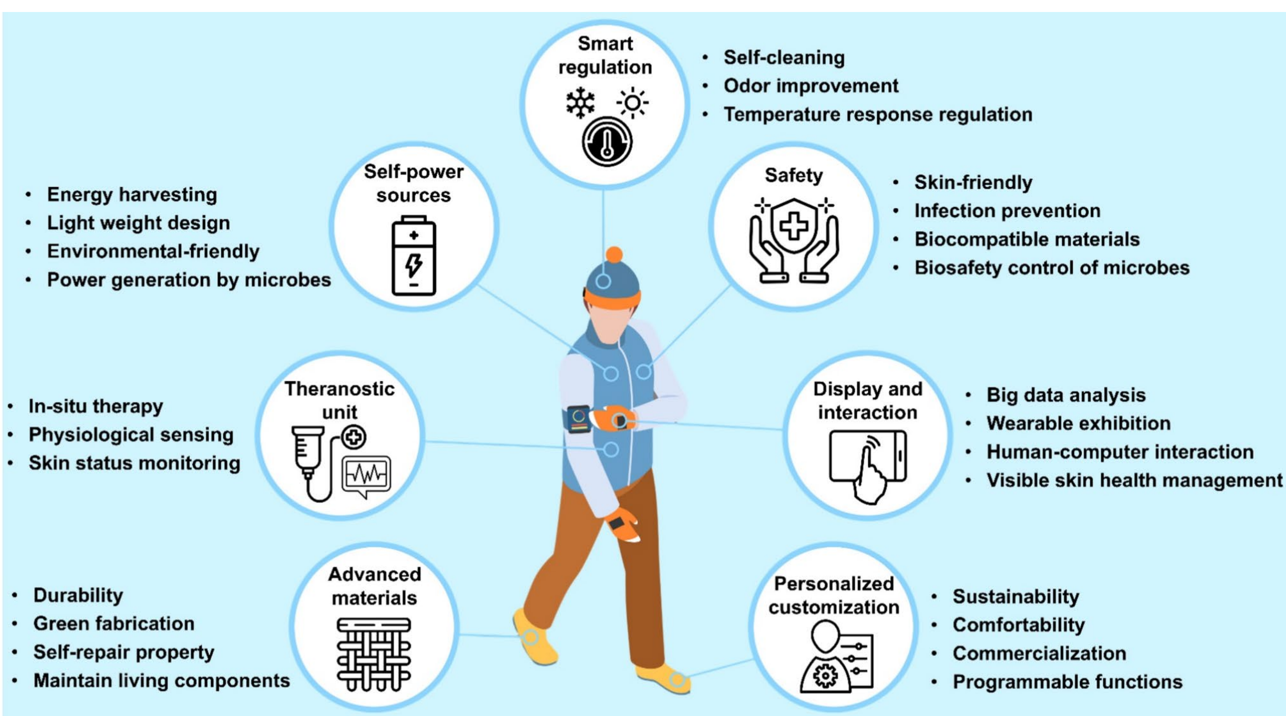


**Fig. 15** Characteristics and functions of next-generation smart textiles

microbial metabolic activity, without compromising flexibility or load. Genetic engineering approaches offer powerful tools to optimize microbes for multifunctionality. Engineered microbial consortia may be embedded into textiles to modulate the skin microbiome of wearers, reduce the use of conventional electronic components, or enhance overall comfort and wearability. Durability is another critical consideration. Repeated usage leads to mechanical abrasion, laundering, and UV exposure of smart textiles, all of which can impair microbial function and textile integrity. Future microbe-integrated smart textiles must incorporate robust design strategies to maintain functionality under real-world conditions. Advanced microbial engineering and regulatory systems may enable dynamic stabilization of the skin microbiome, real-time biomarker detection, personalized therapeutic responses, and enhanced wound healing. As research in this interdisciplinary field continues to advance, microbe-integrated smart textiles are poised to become powerful commercial products for improving human health.

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**Author Contributions** **HBW**: Conceptualization, investigation, writing original draft, writing—review, editing, and wiring—revision. **YM**: Investigation, writing original draft, writing—review, and editing. **SS**: Investigation, writing—review and editing. **CWZ**: Investigation, writing original draft. **DMC**: Writing—review and editing. **XH**: Writing—review and editing. **RJY**: Writing—review and editing. **SQ**: Investigation, writing—revision. **HML**: Supervision. **JLH**: Supervision. **JYK**: Writing—revision. **JY**: Writing—revision. **BF**: Supervision, writing—review and editing.

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

## Declarations

**Conflict of interest** The authors declare that they have no conflicts of interest.



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