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Topical Review

Self-powered flexible sensors: from fundamental mechanisms toward diverse applications

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Abstract
Today, energy is essential for every aspect of human life, including clothing, food, housing and transportation. However, traditional energy resources are insufficient to meet our modern needs. Self-powered sensing devices emerge as promising alternatives, offering sustained operation without relying on external power sources. Leveraging advancements in materials and manufacturing research, these devices can autonomously harvest energy from various sources. In this review, we focus on the current landscape of self-powered wearable sensors, providing a concise overview of energy harvesting technologies, conversion mechanisms, structural or material innovations, and energy storage platforms. Then, we present experimental advances in different energy sources, showing their underlying mechanisms, and the potential for energy acquisition. Furthermore, we discuss the applications of self-powered flexible sensors in diverse fields such as medicine, sports, and food. Despite significant progress in this field, widespread commercialization will necessitate enhanced sensor detection abilities, improved design factors for adaptable devices, and a balance between sensitivity and standardization.

Keywords: self-powered, energy harvesting, applications, flexible sensing

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1. Introduction

Over the past decades, flexible wearable electronics have received significant focus due to their portable, flexible properties and their potential applications in the fields of movement sensing, medical detection, electronic skin, and human-computer communication [1–5]. The optimal functionality of wearable electronics is contingent upon the dependable performance of their corresponding power sources. Nevertheless, most wearable sensors depend on bulky external power sources [6, 7], like commercial secondary power cells, to operate. The power system in question exhibits rigidity and is inherently susceptible to issues such as vulnerability to washing, inadequate biocompatibility, and the possibility of electrolyte leakage or contamination [8–10]. This not only limits the large-scale application and lifespan of flexible sensors, but also significantly reduces sensitivity, safety, and comfort [11, 12]. Therefore, it is imperative to create energy sources that are eco-friendly, adaptable, and enduring, with a lifecycle that is circular.

Currently, fossil fuels, primarily utilized for generating power, are confronting the issue of depleting reserves. The development and utilization of sustainable energy sources are a must in order to satisfy the huge energy needs of contemporary society while maximizing environmental protection. The mechanical energy produced by the motion of humans is a sustainable and environmentally friendly source of energy. Among all bioenergy sources, mechanical power, which is widely distributed in the living condition, is clean, renewable, and is regarded as a significant and sufficient power source [13]. Mechanical power can be realized both through daily human activities (e.g. clapping, blinking, knocking, running, walking, jumping, striking, friction, touching, etc) and through any other mechanical movement [14–19]. In addition, the use of natural forces to generate electricity can also alleviate the expanding energy demand on a sustainable basis. For example, water currents [20], which harbour huge reserves of kinetic energy, magnetic fields [21], which provide safe and effective drives, solar energy [22], wind energy [23] and thermal energy [24]. Numerous endeavors have been dedicated to the development of energy harvesting technologies, including photovoltaic devices, piezoelectric, thermoelectric (TE), and triboelectric nanogenerator (TENG), to facilitate the conversion of renewable energy sources into electricity [25–28]. When it comes to the materials used in device construction, flexible sensors typically employ inorganic materials (such as quantum dots, zinc oxide, carbon nanotubes (CNTs), and carbon-based nanomaterials like graphene) along with organic polymer materials (such as poly (vinylidene fluoride) (PVDF) -co-hexafluoropropylene and conductive polyaniline polymers, etc) in order to develop energy harvesting devices that exhibit superior performance in terms of output [29–32]. In addition, the researchers have integrated different types of energy conversion methods with energy harvesting techniques to improve electrical output performance [33, 34].

Although several reviews have been written about self-powered flexible electronic equipment, most of them are TENG-related and the rapid development of the field requires constantly updated data. We hope that a thorough overview of energy collection technologies on self-powered flexible systems will provide readers with a holistic perspective and foster a global comprehension of the subject for those who are interested and want to delve deeper into it.

This article presents a selection of representative work from various research directions, detailing recent developments in the areas of self-driven flexible sensors. Starting from typical energy harvesting technologies (triboelectric effect, electromagnetic power generation, fuel cells, etc) and energy storage (batteries, capacitors), the transmission methods for obtaining the data, including wireless, cellular, Bluetooth, etc, are further described, along with several means of maintaining data security. Then, a completely integrated self-powered sensing system is prepared by integrating the circuit system and energy harvesting devices. Next, the working mechanisms and materials of various flexible self-powered sensors are discussed. Finally, some current problems and possible solutions in this field are summarized.

2. Energy harvesting technologies

2.1. Triboelectric effect

TENGs have emerged as a potent means of harnessing mechanical energy owing to their cost-effectiveness, lightweight nature, superior energy conversion efficiency, extensive material options, and diverse device structures [35–37]. On the basis of the coupling of triboelectrification and electrostatic induction [38–40], TENG is able to harvest different forms of mechanical energy at any location and any time [41], and efficiently convert the ubiquitous mechanical and human kinetic energy into electrical energy. It typically operates in four distinct modes: vertical contact-separation, lateral sliding, single-electrode, and freestanding triboelectric layers, where single electrode triboelectric sensors (TESs) are simple to fabricate [42–45]. Nowadays, various materials (metals and their compounds, carbon-based fillers, conductive polymers, liquid electrodes, composites, and degradable or green materials, such as chitosan, silk, and cellulose) were extensively employed in TENGs for biomechanical energy harvesting and self-powered sensing [43, 46–48]. In order to enhance the electrical performance of TENGs, various structural designs and fabrication methods have also been investigated, including surface modification, ion implantation, and the design of novel friction electric materials [49–54].

2.1.1. Lateral sliding mode. A self-powered active vibration sensor (SPAVS) based on TENGs was introduced by Liang *et al* [55], as illustrated in figure 1(a). The SPAVS, comprising a slider and a stator, exhibits peaks or valleys in the output current signal as the slider traverses individual gap electrodes. The linear motor's horizontal sliding was employed to simulate the vibration mechanism of the SPAVS. This involves a relative movement between the aluminum and the fluorinated ethylene propylene membrane, facilitating the transfer of electrons between electrodes A and B via an external circuit to

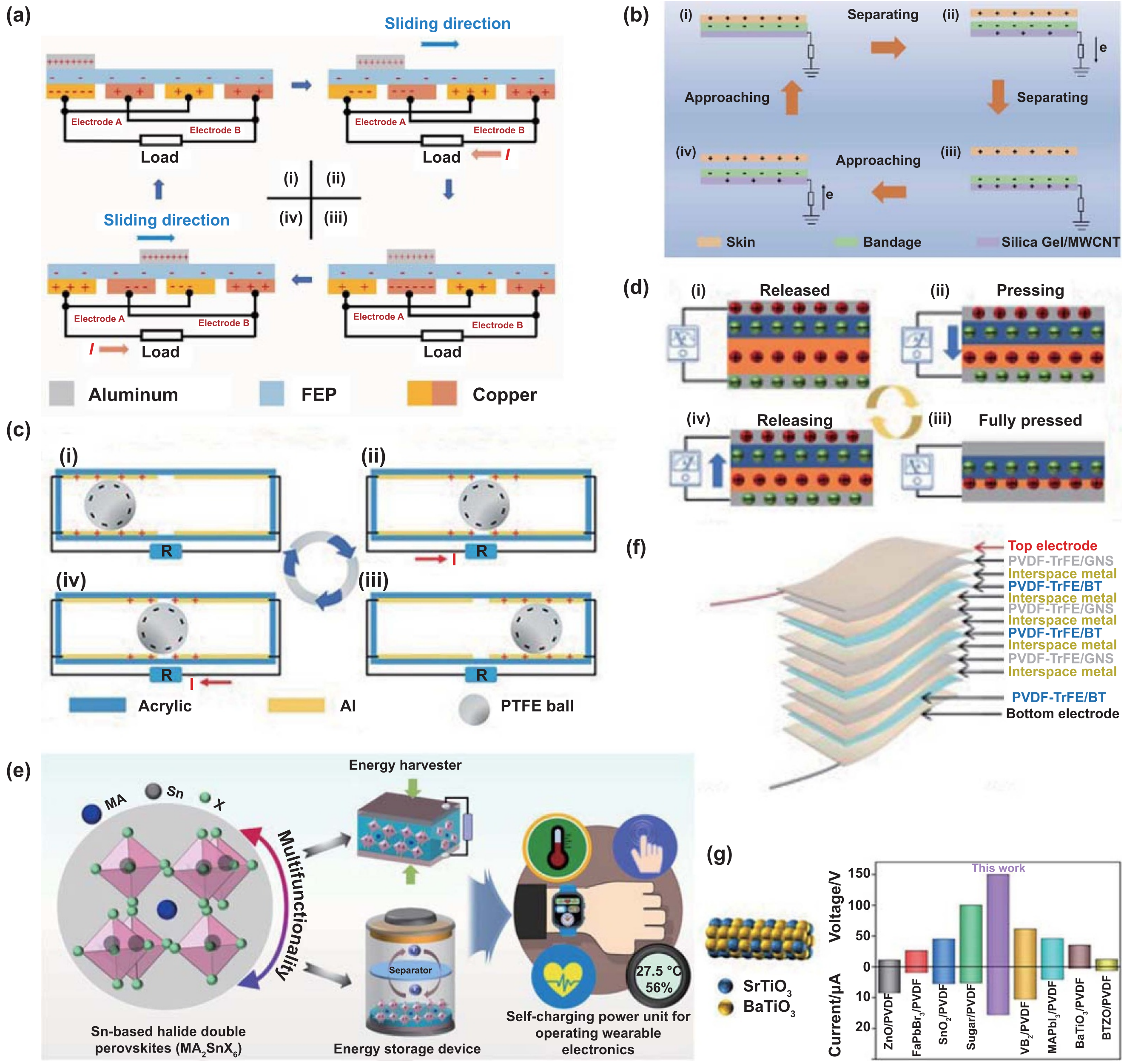

Figure 1. Sensing detection mechanism based on triboelectric effect and piezoelectric effect. (a) Operational mechanism of TENG in lateral slide mode. Reprinted from [55], © 2023 Elsevier Ltd. All rights reserved. (b) Operating principle of BMS-TENG in single electrode mode. Reprinted from [56], © 2023 Elsevier Ltd. All rights reserved. (c) Operating principle of TEWEH in stand-alone friction layer mode. [57] John Wiley & Sons.© 2023 Wiley-VCH GmbH. (d) Illustration depicting the operational mechanism of TENG. Reproduced from [58]. CC BY 4.0. (e) Theoretical illustration of tin-containing halide double-clad crystals for applications in energy harvesting and storage devices. Reprinted from [59], © 2022 Elsevier Ltd. All rights reserved. (f) The diagram illustrating the layer-by-layer heterostructure PENG with an interspace metal sheet. [60] John Wiley & Sons.© 2023 Wiley-VCH GmbH. (g) Schematic representation of $BaTiO_3$-$SrTiO_3$ nanofibers. Reprinted from [61], © 2023 Elsevier B.V. All rights reserved.

generate a complete electrical signal cycle. The corresponding potential distribution between the two electrodes of the freestanding sliding TENG was also simulated using COMSOL simulation. In addition, the SPAVS is efficient in overcoming the operating environment (temperature and humidity) dependency.

2.1.2. Single-electrode mode. After that, based on silica gel, self-adhesive bandages and highly conductive multi-walled CNTs, Zheng *et al* [56] developed a self-powered sensor known as BMS-TENG, characterized by exceptional stretchability (502%) and breathability. The principle of operation is shown in figure 1(b). Initially, the bandage and skin carry heterogeneously charged particles (i). When the separation of skin and bandage occurs (ii), the negative charge moves from the electrodes to the ground due to the electric field. Until the separation distance reaches a maximum (iii), the charge transfer stops. As the body skin approaches the bandage (iv), electrons flow from the ground to the electrodes. This process generates alternating electrical signals. It is noteworthy that the BMS-TENG is easy to fix on the skin and is less irritating to the skin.

2.1.3. Freestanding triboelectric layers mode. The triboelectric-electromagnetic wave energy harvester (TEWEH) has a potential application in the realm of wave energy collecting and ocean self-powered Internet of Things (IoT). Zhu *et al* [57] investigated and demonstrated a TEWEH capable of effectively harvesting broad-band wave energy. The power generation process of TENG is shown in figure 1(c). The polytetrafluoroethylene ball (negative charge) moves backwards and forwards inside the acrylic tube under wave excitation. The ball repeatedly contacts and separates from the aluminium electrode (positive charge), and electrons are transferred between the left and right electrodes, which generates alternating current (AC) in an external circuit. Remarkably, the output power of the TEWEH can light navigation lights and power thermometers. TEWEH also successfully powered a Bluetooth temperature module in an actual marine environment and wirelessly transmitted the ocean temperature in real time to a receiver on land, achieving a major milestone.

2.1.4. Vertical contact-separation mode. Quantitative analysis of gait parameters is necessary to optimize human physical activity. A study [58] developed a self-powered real-time step speed gait analysis system based on TENGs with electrostatically spun nanofibers. Considering the motion characteristics of the sole when walking, the TENG was designed as a classical contact separation mode, and its structure is shown in figure 1(d). When the user walks on the ground, pressure is generated in the vertical direction, the elastomer deforms, the distance between the composite fiber membrane (in the middle position) and the silver fabric (at the top and at the bottom) gradually decreases, and free electrons flow from the bottom to the silver fabric electrodes at the top. Once the foot leaves the ground, the shape of the elastomer gradually recovers. The potential difference at this point induces a reverse flow of electrons (from the top to the bottom). When the foot is periodically trampled and moved, a periodic alternating current is generated. The introduction of square hole array Ecoflex elastomers between the positive and negative friction materials effectively promotes contact separation movement while balancing comfort for human wear. Similarly, Li *et al* [62] developed a micro-topping structures enhanced TENG (MT-TENG) with high accuracy, efficiency and uniformity using inkjet printing. The MT-TENG has good sensitivity (0.031 $k \cdot Pa^{-1}$), instantaneous peak power density ($0.25\ W \cdot m^{-2}$), and output voltage (76.15 V) at an operating frequency of 4 Hz and an external force of up to 20 N.

Although TENGs have a broad array of applications in energy collection and self-charging sensing, their commercialization is still limited by the intermittent generation of electrical energy and low power output. An effective approach to mitigate this challenge involves integrating TENGs with a high-performance energy storage system to enable immediate storage of electrical energy.

2.2. Piezoelectric effect

Piezoelectric materials (polyvinylidene fluoride (PVDF), gallium nitride, zinc oxide, etc) [63–65] are materials based on the conversion of mechanical energy and electricity, and exhibit significant promise for utilization in the advancement of autonomous electronic devices. Zinc oxide (ZnO) is a typical piezoelectric material due to its characteristics as a wide bandgap semiconductor. ZnO exhibits favorable attributes such as strong chemical stability, exceptional optical transparency, high conductivity, and various other properties [66, 67], making it a popular choice for applications involving transparent electrodes and conductive films. Moreover, ZnO is readily available in abundance as raw materials, environmentally safe, and easily disposable, aligning with the principles of sustainable and eco-friendly material development [68, 69]. When a piezoelectric material is subjected to pressure, it generates a potential difference (called the positive piezoelectric effect), and vice versa when a voltage is applied, it generates a mechanical stress (called the reverse piezoelectric effect). The positive and reverse piezoelectric effects are collectively known as the piezoelectric effect. Flexible piezoelectric nanogenerators (PENGs) based on the piezoelectric effect have high power output and excellent mechanical stability to power self-powered microelectronic equipment, which are widely used in wearable electronic devices, energy harvesting and self-powered respiratory system monitoring [70, 71].

Self-powered wearable sensors have garnered significant interest within the realms of tactile perception, motion analysis, and monitoring of biomedical signals. A recent study [72] has introduced a durable superhydrophobic antimicrobial energy-autonomous wearable piezoelectric nano sensor utilizing electrostatically spun nanofiber membranes and CNT electrodes. The initiated chemical vapor deposition (iCVD) nanocoatings offer effective sensor protection through self-cleaning properties, super-hydrophobicity and over 90% bacterial fouling resistance. The hydrophobic iCVD nano-coating, which is conformal in nature, enhances the mechanical robustness and chemical resistance of the sensor, allowing it to function effectively in challenging conditions like elevated humidity levels, exposure to chemicals, and mechanical impacts. It is highly resistant to humidity, liquids and bacterial fouling compared to other PENGs in the literature. In addition, a nanofiber membrane of poly(vinylidene fluoride) was made [73]. The increase of the β-phase content in the electrospun nanofiber membrane ensured its piezoelectric properties. A piezoelectric elastomer (LBPE) based on a synthetic poly (butanediol/lactate/sebacate/itaconate) base was designed by introducing flexible chain segments in the lactate to generate the piezoelectric effect [74]. The device has large lattice distortions and asymmetries and produces significantly higher current densities (short-circuit current density of 19.75 $\mu A \cdot cm^{-2}$).

In recent years, metal halide perovskites (MHPs) have been considered as a potential material for energy harvesting and memory gadgets because of their outstanding optoelectronic, ferro/piezoelectric, and ion migration characteristics. But MHPs are highly toxic and have poor physicochemical stability. Therefore, Ippili *et al* [59] utilized the inherent stability of halide (Cl, Br, and I) double perovskite thin films in ambient conditions to synthesize vacancy-ordered lead-free Sn-based perovskite (MA_2SnX_6) PENGs. These devices exhibit a notable output power density of 7.33 $\mu W \cdot cm^{-2}$ and demonstrate exceptional mechanical robustness (figure 1(e)). In the absence of applied strain, no current is generated. However, upon the application of strain, the piezoelectric layer undergoes compression and deformation, resulting in the creation of a dipole and a piezoelectric potential disparity between the nanogenerator's two electrodes. This discrepancy induces the movement of electric charge between the electrodes through an external circuit. Upon the removal of the force, electrons flow in the reverse direction, thereby generating an electrical signal with an opposing polarity.

PENGs that are both flexible and transparent demonstrate the capability to capture diverse forms of mechanical energy, offering promising prospects for supplying power to portable devices and wearable electronic systems. To overcome the bottleneck of epitaxy of 3D crystalline materials, a study designed and prepared a PENG utilizing a structure composed of two-dimensional (2D) hexagonal boron nitride (h-BN) and zinc oxide (ZnO) nanorod arrays deposited on polycrystalline copper paper [75]. The introduction of h-BN in 2D intercalation processes alters the existing compressive strain within ZnO films and mitigates the presence of unbound charge carriers within the device. The ultra-thin thickness and high potential barriers suppress free carrier motion in this sensor, increasing the output voltage. The energy conversion efficiency was effectively improved by utilizing h-BN monolayers and multilayers as extremely thin dielectric layers.

The constrained operational efficiency of PENGs poses a barrier to their effective utilization in self-powered electronic devices. In order to overcome these constraints, a study developed the structure consisting of a blend of conductive nanoparticles, which made from barium titanate (BT) and composite nanofibers of poly(vinylidene fluoride-co-trifluoroethylene), known as P(VDF-TrFE)/BT. Additionally, this structure included the integration of conductive graphite nanosheets (GNS) with P(VDF-TrFE) composite nanofibers (P(VDF-TrFE)/GNS) in a staggered, non-uniform arrangement (figure 1(f)) [60]. The utilization of composite nanofibers consisting of P(VDF-TrFE)/BT and P(VDF-TrFE)/GNS has been found to enhance the piezoelectric coefficient and decrease the internal impedance of the device. This cumulative effect ultimately leads to an improvement in the power output of the device.

The efficiency of piezoelectric energy harvesters is contingent upon the energy conversion factor ($d_{33} \times g_{33}$). Nevertheless, the development of piezoelectric materials possessing simultaneously high piezoelectric voltage constant (g_{33}) and substantial piezoelectric coefficient (d_{33}) presents a significant obstacle. To achieve equilibrium in the energy transconductance coefficient of flexible piezoelectric energy harvester, Wang *et al* [61] designed one-dimensional heterostructured $BaTiO_3$-$SrTiO_3$ nanofibers with the aim of enhancing the output efficiency of the $d_{33} \times g_{33}$ parameter by coupling the pristine piezoelectricity with the flexoelectricity (figure 1(g)). The findings from simulation and multi-angle characterization indicate that the combined impact of piezoelectricity and strain gradient-induced flexoelectricity is notably enhanced in the heterostructure BT-ST nanofibers in comparison to the unmodified BT-ST nanofibers. This provides a new avenue for designing high-efficiency lead-free one-dimensional piezoelectric additives. A similar study constructed lead zirconate titanate (PZT) piezoelectric composites using a phase-inversion method. The piezoelectric composites PZT/PVDF&CNTs were prepared by mixing the low dielectric material PVDF and CNTs utilized as additives [76]. A sequence of examinations and characterization assessments demonstrated that the PZT/PVDF&CNTs composites had good piezoelectric properties and low dielectric properties, yielding an ultra-high $d_{33} \times g_{33}$ with a high dielectric constant of 24 942 $\times 10^{-15}$ $m^2 \cdot N^{-1}$.

2D ferroelectric materials have garnered significant interest due to their potential applications in the advancement of flexible energy-autonomous nanogenerators. Niobium oxide diiodide ($NbOI_2$) exhibits electrical properties that are anisotropic in-plane and possesses significant lateral piezoelectric coefficients, contributing to its exceptional performance and distinctive flexible sensing characteristics. Based on this, Sun *et al* [77] prepared a multidirectional PENG based on $NbOI_2$ sheets. The device is capable of extracting biomechanical energy from different joints of the human body and effectively capturing acoustic signals. This study expands the utilization of 2D materials in nanoenergy and introduces novel concepts and perspectives for the advancement of nanoenergy and intelligent wearable nanoelectronic devices.

2.3. TE and pyroelectric effects

The TE effect [78] is the phenomenon whereby a material produces a potential difference in the presence of a temperature difference and is an attractive energy conversion technique. The pyroelectric effect [79] refers to the phenomenon that certain materials produce a voltage difference in the presence of a temperature change. Both are related to temperature changes and have broad outlook for application in the development of flexible TE devices. The TE efficiency is established by the TE figure of merit (ZT), which is calculated as $ZT = S^2\sigma T/K$ [80]. The materials involved are usually single crystals, organic materials, polymers and composites [81–85].

One of the most typical materials is Bi_2Te_3 with high electrical conductivity. Chen's group [86] successfully synthesized Bi_2Te_3 using a solvothermal method and produced polycrystalline Bi_2Te_3 particles through discharge plasma sintering. These particles exhibit a low thermal conductivity of 0.1 $W\cdot m^{-1}\cdot K^{-1}$ due to an optimized grain boundary recrystallization process. The material boasts not only low thermal conductivity but also enhanced texture, optimized bipolar effect, and near-ideal carrier concentration. Additionally, the enhanced texture, optimized bipolar effect, and near-ideal carrier concentration further highlight the favorable characteristics of Bi_2Te_3 synthesized by Chen's group. The state-of-the-art TE material is low-toxicity GeTe [87] with good mechanical properties. A research project [88] effectively developed GeTe-based TE substances enriched with Cu within the lattice. These substances displayed enhanced carrier mobility (80 $cm^2\cdot V^{-1}\cdot s^{-1}$), reduced thermal conductivity within the lattice (0.48 $W\cdot m^{-1}\cdot K^{-1}$), and increased TE efficiency through the combined improvement of phonon scattering, reduction of carrier scattering, and optimization of carrier concentration. As a result, these materials demonstrated outstanding TE characteristics and promising practical implementations.

For the past few years, real-time wireless monitoring of human physiological information has become particularly important in health analysis. He *et al* successfully designed a non-contact pyroelectric sensor based on a wireless Bluetooth sensing circuit and a PVDF film [89]. Zeng *et al* [90] proposed a molecular TE capable of achieving broadband photo-pyroelectric effect, N-isopropylbenzylaminium trifluoroacetate (N-IBATFA) (figure 2(a)). As a simple organic binary salt, N-IBATFA has excellent TE properties, i.e. large polarization ($\sim$9.5 $\mu C\cdot cm^{-2}$), high pyroelectric coefficients ($\sim$6.9 $\mu C\cdot cm^{-2}\cdot K^{-1}$) and ZTs ($F_V = 187.9 \times 10^{-2}$ $cm^2\cdot\mu C^{-1}$; $F_D = 881.5 \times 10^{-5}$ $Pa^{-0.5}$), comparable to the state-of-the-art pyroelectric materials. In addition, it has a photoexcited pyroelectric effect in the ultrawide spectral range of UV-vis (266 nm–1950 nm). Similarly, ceramics composed of 0.5 Ba ($Zr_{0.2}Ti_{0.8}$) O_3-0.5($Ba_{0.7}Ca_{0.3}$) TiO_3 (BZT-BCT) exhibited notable pyroelectric properties at room temperature. Wang *et al* [91] developed a pyroelectric apparatus utilizing the lead-free ferroelectric BZT-BCT ceramics for applications in infrared sensing and energy harvesting. The device demonstrated a significantly enhanced photoluminescent pyroelectric response due to the elevated pyroelectric coefficient and improved photothermal (PT) conversion capacity, while maintaining resistance to external interference. Subsequent research introduced a high-performance pyroelectric photoconductive diode designed for the detection of deep ultraviolet light, showcasing exceptional sensitivity levels [92].

The spread of non-biodegradable waste destroys our natural habitats. To simplify this problem, a study prepared a pyro-piezoelectric hybrid nanogenerator based on titanium carbide-MXene (TiC-$Ti_3C_2O_2$) by converting plastics in a simple way [97]. The combined pyro-piezoelectric impact of $NiSnO_3$-PVA-KOH and $FeSnO_3$-PVA-KOH in a nitrate environment resulted in the transformation of mechanical energy input into electrochemical energy within the system. This process was accompanied by a rise in the open-circuit voltage (18 mV–222 mV) and temperature levels (25 °C–125 °C).

Hou *et al* [98] proposed an ultra-flexible fabric TE generator (uf-TEG) using conductive fabric electrodes and a flexible fabric substrate. However, the energy harvested using the uf-TEG is not sufficient for a fully self-driven sensor based on the device's internal resistance hindrance. To enhance the power density of the wearable TE generator (TEG), Fan *et al* [93] prepared a high-performance scalable TE device for harvesting heat from the human body by assembling high-performance TE units, scalable copper electrodes, and Ecoflex material in a modular assembly reminiscent of the Lego building system (figure 2(b)). The device can generate high enough power from the human body to efficiently operate a commercial light-emitting diode (LED) and consistently operate an ECG module in real-time without the need for supplementary power sources.

A study was conducted to create a versatile self-sustaining electronic skin capable of monitoring temperature and pressure simultaneously, utilizing a combination of triboelectric and TE mechanisms [80]. The thermocouple film demonstrates sensitivity to temperature along the horizontal axis, whereas the self-powered triboelectric pressure sensor exhibits its sensitivity to pressure along the vertical axis. This characteristic eliminates the necessity for the creation of supplementary algorithms or the execution of intricate decoupling computations. A self-chargeable textile device was prepared based on the thermionic effect (figure 2(c)). This study marks the initial utilization of common cotton fabric as the base material, multi-walled CNTs as the primary electrode substance, and PVA/H_3PO4 solid gel polyelectrolyte [94]. The device is capable of converting thermal energy into electrical energy output and storing the captured energy. The Soret coefficient of 1.85 $mV\cdot K^{-1}$ is the highest Soret coefficient reported in the literature for thermally-charged supercapacitors (SCs) developed on non-conductive fabric substrates, and is about 10 times higher than that of conventional TE devices (the output potential of conventional inorganic TE materials is $\sim$200 $\mu V\cdot K^{-1}$).

Kim *et al* [99] developed a self-healing polymer with tremendous ionic TE effect: poly(3,4-ethylenedioxythiophene) (PEDOT):(poly(2-acrylamido-2-methyl-1-propanesulfonic acid) (PAAMPSA): phytic acid (PA) PAAMPSA-doped PEDOT with PA. The findings indicate that the combination of the flexible PEDOT:PAAMPSA complex with the physical cross-linker results in superior tensile properties when compared to other sophisticated ionic TE materials. Despite undergoing numerous self-repair and stretching processes, the film maintains its ionic TE characteristics, indicating promise for sustained utilization in real-world scenarios. Significantly, the film demonstrates remarkable ionic TE characteristics, boasting an ionic ZT of 12.3% at 70% relative humidity (RH), which represents a 70% increase compared to previously documented values. Ternary composites with good tensile properties were prepared by introducing lysine and aqueous polyurethane into single-walled CNTs, as shown in figure 2(d) [95]. Utilizing the superior TE and stretchable properties of

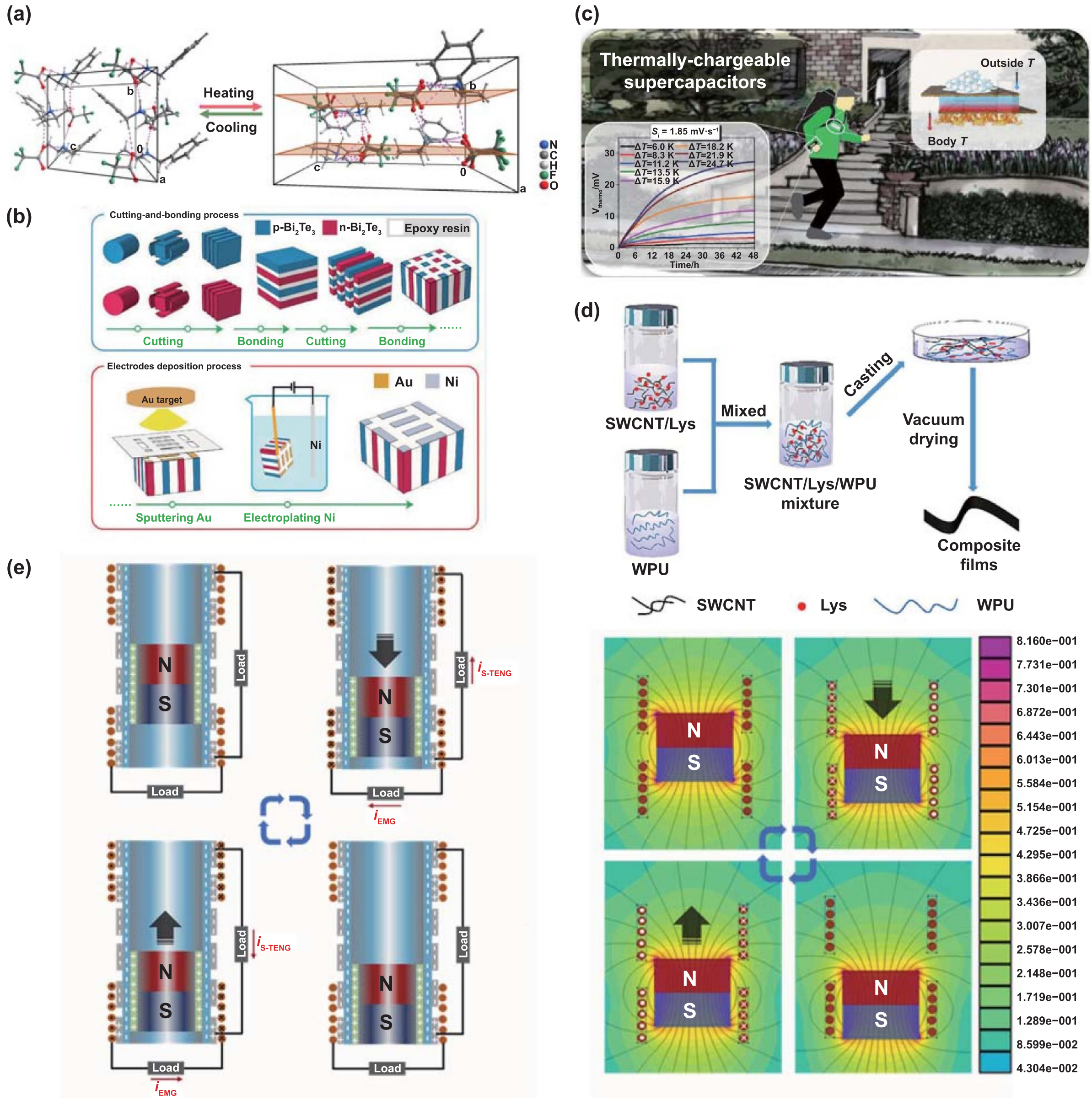

Figure 2. Sensing and detection mechanisms based on thermoelectric, pyroelectric and electromagnetic generation. (a) Crystal structure of N-IBATFA (reversible phase transition between low-temperature and high-temperature phase structures). Reproduced from [90]. CC BY 4.0. (b) Diagram showing the step-by-step process of assembling the TE unit. Reproduced from [93]. CC BY 4.0. (c) Schematic diagram of self-charging textile equipment. Reproduced from [94]. CC BY 4.0. (d) Fabrication process of composites. Reprinted from [95], © 2023 Elsevier B.V. All rights reserved. (e) Mechanism of operation of NLHN and finite element analysis of electromagnetic generator. Reprinted from [96], © 2023 Elsevier Ltd. All rights reserved.

the composite material, a flexible sensor was developed comprising five pairs of *p*-*n* junctions. The sensor demonstrated significantly enhanced maximum output power (0.13 μW) and sensitivity compared to previously reported stretchable composite materials. Yuan *et al* [100] proposed and developed a wearable system totally self-driven by a high-efficiency flexible TEG (f-TEG). The f-TEG device harnesses energy from the heat generated by the human body and is employed for continuous monitoring and assessment of various health parameters through multiple modes. This technology demonstrates a remarkably effective TE conversion capability, reaching levels of up to 1600 MW.

In the field of smart wearables, there has been significant research and advancement in the study of f-TEGs in recent years. There is an increasing focus on the investigation of stretchable conductive composites for use in flexible electronic applications. However, *n*-type organic materials with high TE and mechanical properties are scarce. In addition, multicomponent single crystals involve toxic heavy elements during the growth process. To address these limitations, we can work in the future on the development of new *n*-type organic materials as well as the selection of inorganic metal complexes as alternatives to overcome these drawbacks through appropriate design strategies.

2.4. Electromagnetic power generation

A variety of widely available radiofrequency sources (such as Wi-Fi, microwave ovens, 4G and 5G) generate magnetic energy [101]. Magneto-mechano-electric energy conversion is an efficient method of converting some form of external magnetic field (e.g. gradient, oscillating, rotating, or periodically varying) [102, 103] into electrical energy, and is excellent for gas and motion monitoring, harnessing low-frequency vibrations, and water quality monitoring [104–106].

A study [107] designed and fabricated a magneto-mechano-electric coupled energy harvester (MMEC-EH) based on $0.025Pb(Mn_{1/3}Nb_{2/3})O_3$-$0.525Pb(Ni_{1/3}Nb_{2/3})O_3$-$0.135P_bZ_rO_3$-$0.315PbTiO_3$ (PMNN-PZT) ceramics. The MMEC-EH showed a 60 $mW_{RMS}\cdot Oe^{-2}\cdot g^{-2}\cdot cm^{-3}$ power density, and one to two orders of magnitude higher than piezoceramic MMEC-EH power densities. Flexible magnets have received increasing attention as core components of motion sensors. However, most of the reported materials for flexible magnets are non-degradable substrates. Here, Chen *et al* [108] synthesized $CoFe_2O_4$ magnetic nanoparticles with a reticular structure for flexible composite magnetic membranes using magnetic bacterial cellulose as a material. The sensing process of the flexible magnetic film relies on the change of magnetic flux through the copper coil. It is significant to highlight that the device may undergo complete degradation within a timeframe of 56 h. Furthermore, the flexible electromagnetic sensor that has been developed is eco-friendly, and the $CoFe_2O_4$ nanoparticles utilized in its construction can be readily recycled.

A noise-less hybrid nanogenerator (NLHN) was developed by rationally combining an electromagnetic generator with a separate dual-mode nanofriction electric generator [96]. Using a finite element simulation, figure 2(e) shows the magnetic induction strength generated by the reciprocating motion of the magnet. Figure 2(e) illustrates the initial positioning of the magnet between the upper and lower coils. Upon exposure to external vibration, the magnet descends, causing the induced current in the coil to circulate in a clockwise direction. Conversely, as the magnet ascends, the current in the coil flows in an anti-clockwise direction. This reciprocating movement of the magnet within the coil results in the generation of AC that subsequently passes through the external load. The NLHN achieves its peak output power of 101 milliwatts when operating at a frequency of 6 Hertz and an acceleration of 1.5 g. In addition, the NLHN operates with a noise level of only 41 dB. Another study [109] reported a triboelectric-electromagnetic hybrid generator (TEHG). The TEHG addresses the issue of not having individual charging for the EMG and the TENG by reaching saturation levels exceeding 8 volts even when operating at a low frequency of 90 revolutions per minute. At a rotational speed of 600 revolutions per minute ($r\cdot min^{-1}$), the saturation voltage of the combined charge was observed to be 33.3% greater compared to the saturation voltage of EMG charging alone.

The implementation of energy recovery and adaptive vibration control remains challenging due to space and power constraints. Cui *et al* [110] designed a magnetic-suspension energy harvesting apparatus featuring a honeycomb configuration to facilitate energy extraction and mitigate passive vibrations. The magnetic levitation structure suppressed low-frequency random vibration. The levitation coil current signal and vibration supporter control adaptive signal tracking control algorithm achieved active vibration suppression and high power output.

2.5. Hydrovoltaic technology

Water covers about 72% of the Earth's surface [111]. As a green energy source, various forms of water movement (water flow, waves, natural water evaporation and humidity, etc) [20, 112–114] contain enormous amounts of energy. For example, the kinetic energy of raindrops is about 3000 terawatt-hours per year, which is equivalent to 5% of the annual global energy consumption. The hydrovoltaic effect is a phenomenon in which water obtained from various environments generates electricity by interacting with nanomaterials. Many hydroelectric devices utilizing hydrovoltaic technology have been created. Their power generation principles are divided into two main categories: water-induced power generation and evaporation-induced power generation based on classical flow potentials [115, 116].

High indoor humidity/temperature poses a serious threat to public health. In order to address the aforementioned issues, Zhang *et al* [117] first reported a zero-energy multimode fabric combining continuous indoor dehumidification, power generation driven by evaporation and radiative cooling functions. It generates electricity by a transpiration-driven electrokinetic effect. A single self-powered fabric produced a maximum open-circuit voltage (Voc) of 0.83 V, a peak short-circuit current of 5.51 μA, and a power density of up to 1.13 $\mu W\cdot cm^{-3}$. In addition, a configuration of four interconnected fabrics could provide zero-energy input to a miniature electronic timer. This offers a sustainable, energy-efficient framework for attaining the 2050 objective of achieving net-zero carbon emissions. Bionic textiles are unique in that they are soft, lightweight, porous and biodegradable [118]. As illustrated in figure 3(a), Min *et al* [119] assembled a textile-based TENG (B-TENG) and droplet electricity generator (DEG) into a leaf-shaped multi-path energy harvester that harvests energy from wind and rain. The device emulates the hydrophobic properties of a lotus leaf, known as the 'lotus effect', in order to create a textile surface with exceptional water-repellent characteristics. At a flow rate of 300 $ml\cdot h^{-1}$ and a drop height of 11 cm, the DEG demonstrates the ability to produce substantial output voltages and currents, measuring at 113 V and 67 μA respectively, which are utilized to supply power to a set of 10 LEDs.

Water wave energy is an important renewable energy source, but it is less exploited due to the low and variable frequency characteristics of water waves. Figure 3(b) shows a bifilar-pendulum coupled hybrid nanogenerator (BCHNG) installed on a ship for harvesting wave energy [120]. Thanks to the two oscillating degrees of freedom of the bilinear pendulum, the BCHNG module can capture both kinetic and gravitational potential energy of the waves. In addition, Dai *et al* [123] proposed a wave energy collecting system for unmanned

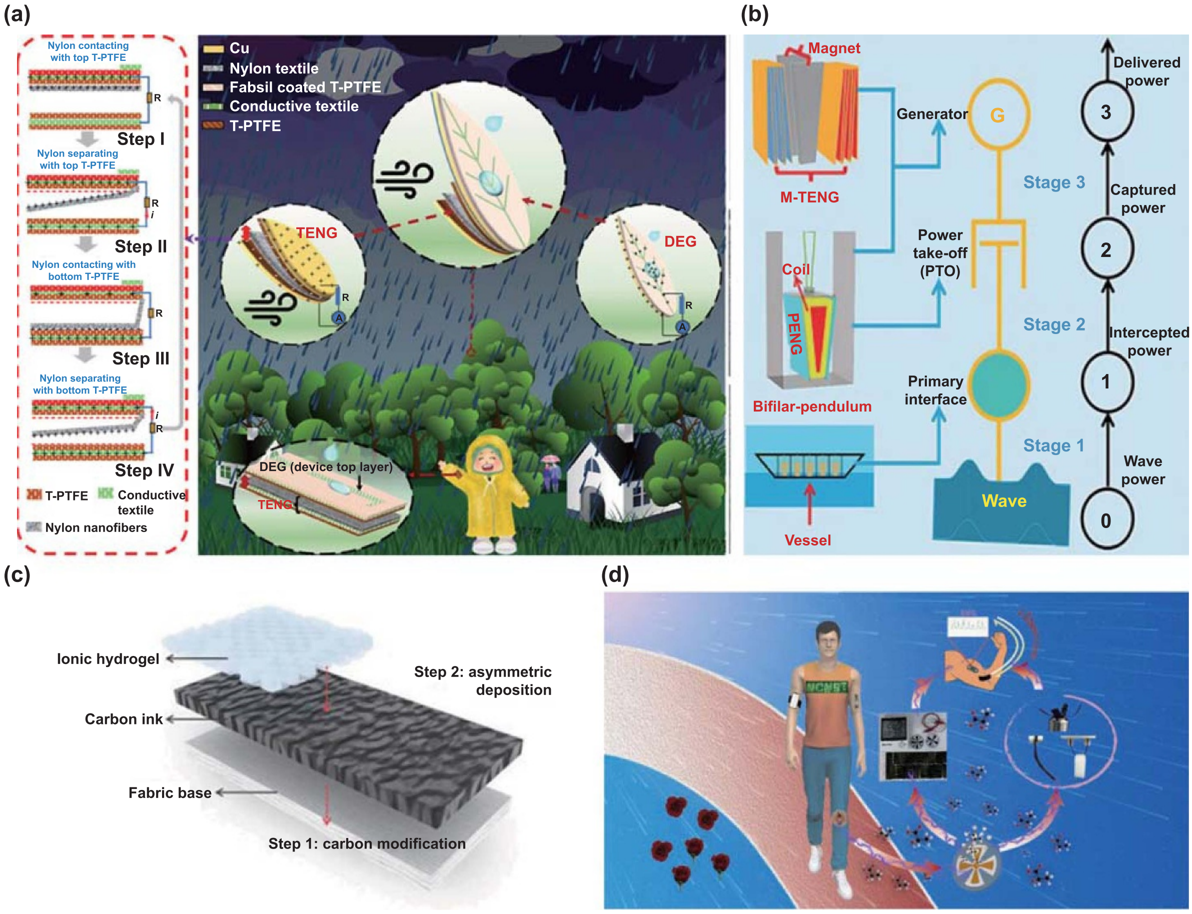

Figure 3. Self-powered devices based on hydrovolt technology. (a) Artificial leaves assembled by TENG and DEG devices. Reproduced from [119]. CC BY 4.0. (b) Power transmission chain and BCHNG module for ships. [120] John Wiley & Sons.© 2022 Wiley-VCH GmbH. (c) AHS structure and manufacturing process in 3D. [121] John Wiley & Sons.© 2022 Wiley-VCH GmbH. (d) Application of wearable sweat energy generators. Reprinted from [122], © 2023 Elsevier Ltd. All rights reserved.

surface ships based on a biplane flywheel. Compared with the energy harvesting device lacking mechanical motion rectifier, the energy harvesting power of the MTS was increased by 51.64%. To overcome the corrosive nature of seawater, Zaw *et al* [124] fabricated a waterproof TENG to capture blue energy.

A study [125] utilizes thermal energy for the desalination of seawater or electricity generation to help alleviate the demand for limited natural water and energy sources. A novel dual-purpose device powered by solar energy has been developed for generating electricity through evaporation, utilizing asymmetrically structured blends of carbon black and PVDF@BFP. This innovative system aims to concurrently purify wastewater and produce environmentally friendly electricity. Another study [126] developed a self-powered silicon nanowire arrays (SiNWs) wet electrical generation system based on the direct moisture-directly triggered electricity generation effect. The functionality of the moisture sensor is based on the selective movement of charges within the nano-channels of SiNWs, which is facilitated by a gradient in water content. This process enables the sensor to generate electrical signals autonomously, eliminating the requirement for an external power source. The sensor has the advantages of fast response/recovery time (∼0.10 s–0.17 s), high sensitivity, and a wide RH operating range (0%–95.7%). These characteristics surpass those of previously developed state-of-the-art humidity sensors. In addition, a non-contact controller was constructed using SiNWs sensors, effectively stopping virus transmission and bacterial infection.

The potential for power generation through the interaction of water with materials is presented. Zhang *et al* [121] reported an asymmetric hygroscopic structure (AHS) capable of simultaneous energy harvesting and storage. The AHS absorbs water from the air and creates a dry-wet asymmetry, which results in the formation of an in-plane electric field. It is remarkable that even after saturated water is absorbed, the asymmetry remains intact. The AHS can be recharged either by itself or by external electrical means (e.g. PV source and TENG). After rational optimization, the AHS achieves an ultra-high peak power density (70 $\mathrm{uW \cdot cm^3}$ or 226 $\mathrm{uW \cdot g^{-1}}$) (figure 3(c)). In addition, bacteria cellulose nanofiber (CNF) is also hydrovoltaic material for the production of efficient energy [127].

To overcome the challenges of a rigid and bulky battery drive, Chen *et al* [122] demonstrated a wearable sweat energy generator (SEG). A redox reaction was performed using sweat

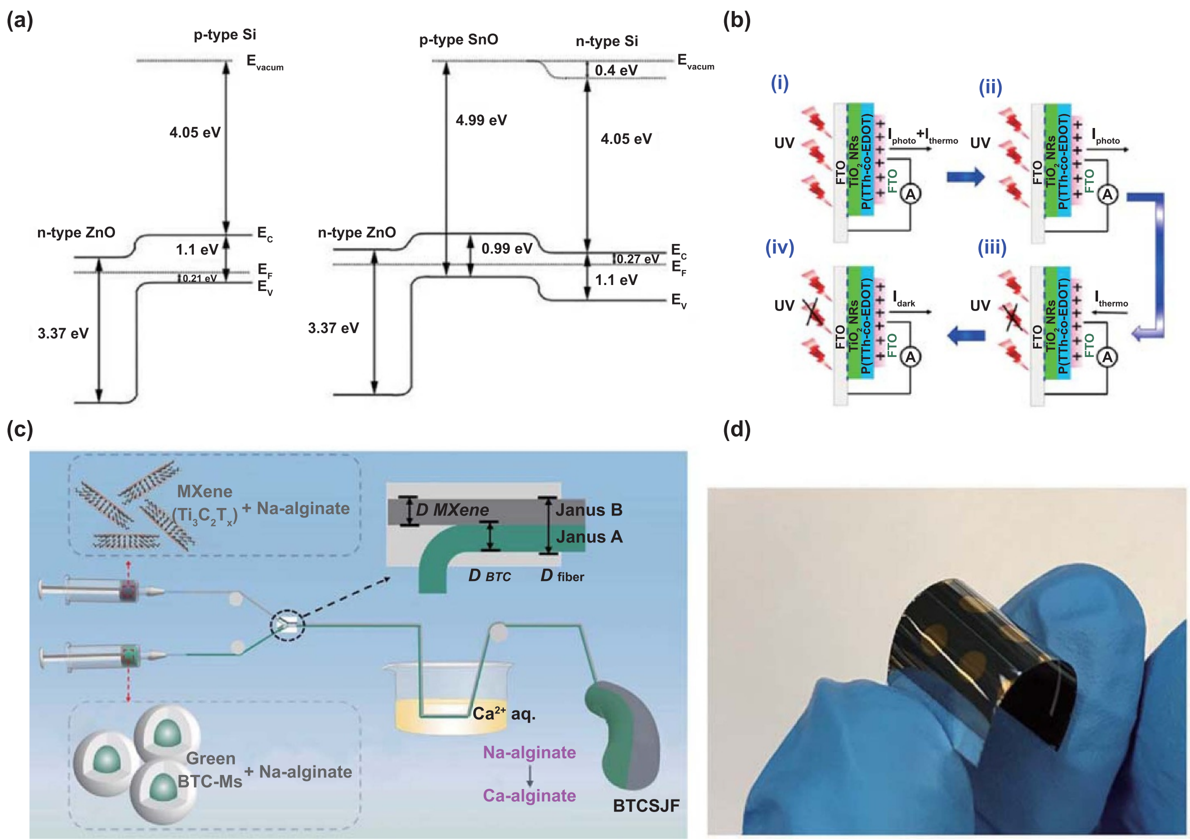

Figure 4. Self-powered sensing mechanism based on photovoltaic technology. (a) Band diagrams illustrating the heterojunctions of p-Si/ZnO and n-Si/SnO/ZnO, and the generation of photocarriers. Reproduced with permission from [139]. © 2023 The Authors. Small published by Wiley-VCH GmbH CC BY-NC-ND 4.0. (b) Mechanism of operation of a self-powered ultraviolet detector with P-n heterojunction. Reprinted from [140], © 2023 Elsevier B.V. All rights reserved. (c) Diagrammatic representation of the procedure employed in the production of BTCSJF. Reproduced from [141], with permission from Springer Nature. (d) Image of the Sb_2Se_3 photodetector with flexibility, placed on an SU-8 substrate and subjected to bending with a radius of 5 mm. Reprinted from [142], © 2023 Elsevier B.V. All rights reserved.

(0.2 ml) and achieved a maximum power density of 18.3 watts per square meter under 0.3 kV. This was sufficient to activate artificial muscles. Moreover, the high-performance SEG shows good charging performance and has been shown to charge timers, hygrometers, calculators, and mobile phones (figure 3(d)).

2.6. Photovoltaic technology

The process of converting solar energy directly into electrical energy is known as the photovoltaic effect [128]. Photovoltaic technology has been developed in the country for more than sixty years since 1958, with perovskite solar cells receiving widespread attention due to their advantages. Photovoltaic materials are capable of achieving specific functions by manipulating photons and electrons and are the basis for achieving efficient output from wearable photovoltaic generators, which mainly include semiconductor structures, dye sensitized, and 2D materials (graphene, carbon nitride, WS_2, chalcogenide, etc) [129–137].

For visual detection of UV light, a study [138] developed an energy-autonomous UV photodetector (PD). In it, a thin film of ZnO nanoparticles acted as the photo-resistive substance and electrode. The variable resistance and output voltage (0.5 V–1.1 1 V) of the ZnO film at 375 nm varied with light intensity due to impedance matching effect. Afterwards, Vieira *et al* [139] used the epyro-phototronic effect to successfully prepare an energy-autonomous, sensitive Al/Si/SnO/ZnO/ITO PD. The Si/SnO/ZnO/ITO device showed a 3 067% increase in responsivity over the Al/Si/SnO/ZnO/ITO device. The PD has a fast response time (rise time 2.2 us and fall time 2.0 us). In comparison to existing ZnO self-powered PDs documented in literature, it demonstrates superior performance (figure 4(a)). In a study [140], a high-efficiency *p-n* heterojunction self-powered UV detector was realized for the first time by combining conjugated copolymer P(TTh-co-EDOT) (a copolymer of trithiophene (TTh) and 3,4-ethylenedioxythiophene (EDOT)) as the photosensitive layer with TiO_2 nanorrays (NRs). As shown in figure 4(b), in the first stage, when 365 nm UV light is present, the temperature of the P(TTh-co-EDOT) increases and the detector undergoes thermal polarization, generating additional carriers. This favours the production and transport of photogenerated carriers. In the second stage, the pyroelectric effect disappears. Both the current generated by the photovoltaic effect and the temperature of the film stabilize. In the third stage, the UV light disappears and the current decreases instantaneously, producing a thermally polarized current in the opposite direction. In the fourth stage, the transient thermal effect stabilizes, the pyroelectric effect disappears and the temperature drops to room temperature. Importantly, the TE effect between TiO_2 NRs and P(TTh-co-EDOT) improved the UV PD (ultraviolet PD) efficiency of TiO_2 NRs/P(TTh-co-EDOT)-3c.

The sun is a huge reservoir of energy. There are two types of solar power generation: photo-thermal-electric conversion and direct photoelectric conversion. A study [143] demonstrated the first Mxenes-based bifunctional photovoltaic chip without the use of any additional photovoltaic device using $Ti_3C_2T_x$ and Te/$Ti_3C_2T_x$ as active materials for in photocathode. In another study [144], $Cu_2ZnSn(S,Se)_4$ (CZTSSe) self-powered PDs were prepared using conventional photovoltaic devices. In the absence of any bias, the CZTSSe PD exhibits rapid response characteristics (0.576/1.792 μs) and a broad dynamic range (103 decibels). Given the notable combined impact of utilizing green solar heating in conjunction with energy storage systems, Wang *et al* [141] designed and fabricated a PD using dual-channel microfluidic technology with excellent solar thermal performance of Janus (Janus A/B) optical fiber (BTCSJF) and used it for multifunctional smart textiles. BTCSJF can collect and store solar energy without blocking bright colors. When exposed to solar radiation at an intensity of 1000 $W\cdot m^{-2}$, the self-heating temperature of the material is elevated by 36.6 °C compared to bistable thermochromic fiber and by 35.6 °C compared to traditional fibers. (figure 4(c)).

In recent times, antimony selenide (Sb_2Se_3) has demonstrated promising prospects for use in flexible photovoltaic technologies owing to its distinctive one-dimensional crystalline structure, cost-effectiveness, and exceptional photovoltaic characteristics. On this basis, Wen *et al* [142] fabricated flexible PDs based on highly [001]-oriented Sb_2Se_3 films. Under near-infrared (NIR) light (940 nm), the flexible Sb_2Se_3 PD exhibits a responsivity of 0.74 aW^{-1}, a detectivity of (5.1×10^{13}) Jones, and a linear dynamic range spanning of 102 dB. The PD demonstrates superior performance compared to previously reported Sb_2Se_3 PDs and exhibits similar capabilities to commercially available rigid silicon PDs (figure 4(d)). A wearable TE generator capable of functioning in various weather conditions was developed, incorporating a highly efficient NIR absorbing photo-thermal harvesting layer known as $Cs_{0.32}WO_3$ nanofiber membrane as the interlayer [145]. The PT conversion efficiency of the $Cs_{0.32}WO_3$ membrane achieves a level of 42.7% following 10 consecutive operations without any decline in performance. Notably, the peak output voltages recorded were 225 mV under artificial solar illumination and 200 mV during midday exposure to natural light.

Dye-sensitized solar cells (DSSCs) have garnered interest due to their superior capability to capture indoor light compared to alternative photovoltaic technologies. Laser-induced graphene has the potential to serve as an environmentally friendly alternative for the counter electrode in DSSCs, enabling its utilization as a versatile self-sustaining system for energy harvesting and storage in indoor settings. A flexible laser-induced flexible counter electrode for graphene-based DSSCs was firstly reported by Speranza and coworkers [146]. Organic photovoltaics (OPVs) and PD (OPDs) are viewed as viable sustainable electronic devices for indoor applications. Nevertheless, the manufacturing procedure for individual OPVs and OPDs is intricate and expensive, resulting in elevated production expenses and restricted scalability. Therefore, Kim *et al* [147] used a multicomponent photoactive structure to develop a self-powered bifunctional sensor. The optimized rigid and flexible OPVs have output power densities of 81 $\mu W\cdot cm^{-2}$ and 76 $\mu W\cdot cm^{-2}$, respectively, and demonstrate a linear dynamic range exceeding 130 dB in photovoltaic operation without the need for external bias.

Solar energy has been widely reported for its easy accessibility, opening up opportunities for optoelectronic devices, energy conversion, IoT and other related fields. However, some challenges remain, such as significantly lower power generation efficiency indoors, light energy dependent on climatic conditions, and quality defects in photovoltaic materials that impair device efficacy. In order to further develop photovoltaic technology and expand its application in self-powered wearables, such unfavourable conditions must be wisely taken into account in the design process.

2.7. Fuel cells

Microbial fuel cells (MFCs) present a favorable avenue for investigating self-charging biopower systems. A microbial energy harvesting and energy storage device based on bacterial spores is shown in figure 5(a). Gao *et al* [148] successfully combined sweat-driven three MFCs and a solid-state SC in a paper-based platform. In the paper-based self-charging power patch, non-toxic, storable bacterial spores serve as biocatalysts, which use human sweat to germinate and generate electricity. The hybrid self-powered system not only generates 4 $\mu W\cdot cm^2$ and 37 $\mu A\cdot cm^2$ and stores 9.81 mF of energy, but also produces a constant discharge of 5.53 μAh and exhibits stable capacitive behaviour over 100 cycles. The study shows that the integrated paper-based self-charging power patch is capable of lighting up the LEDs on the chip. The paper system can be incinerated and disposed of after use, which eliminates the potential risk of bacterial infection.

Biofuel cells (BFCs) are being extensively investigated as an energy autonomous sensor. Hartel *et al* [152] developed a resettable electrochromic self-powered sensor driven by the biocatalytic reaction of BFCs. The device was continuously powered exclusively by sweat biofuel, and the BFC could achieve up to 13 $\mu W\cdot cm^{-2}$ of power generation, compared to half the power generation required to fully bleach an electrochromic display in 2 min. They incorporated a BFC anode, a BFC cathode, and a reversible electrochromic display onto a completely printed epidermal wearable patch for the purpose of non-invasive biomarker monitoring and visualization of sensing data. In another study [153], utilizing human biofluidic energy, a BFC harvested electrical energy from lactate in sweat. Metal–organic framework (MOF) derived carbon nano-arrays with gold and cobalt nano-ions form a multifunctional electrode. A microfluidic system integrating a SC and a

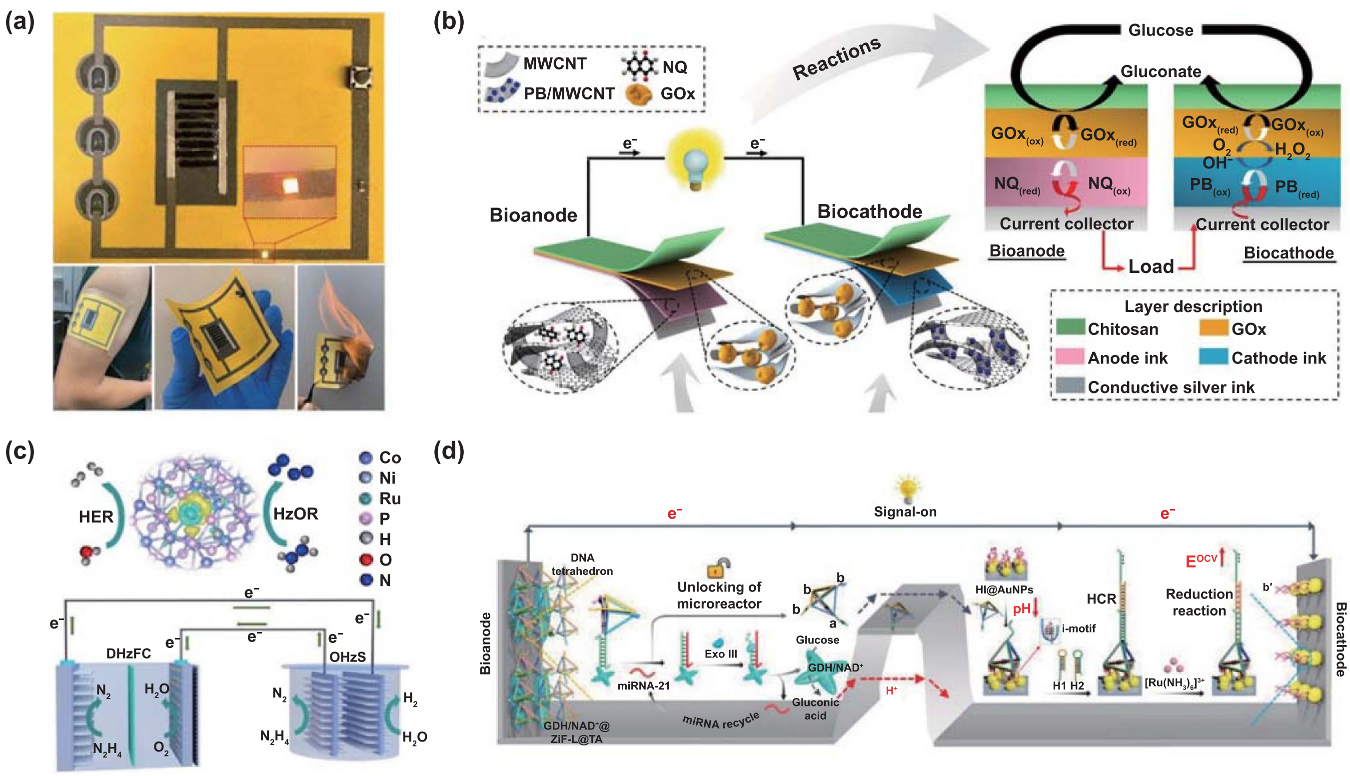

Figure 5. Sensing principles based on fuel cells. (a) Paper-based self-charging power supply patch schematic. Reprinted from [148], © 2022 Elsevier Ltd. All rights reserved. (b) Introduction to the concept of flexible single-enzyme biofuel cells. Reproduced from [149]. CC BY 4.0. (c) Self-powered hydrogen production system driven by fuel cells. [150] John Wiley & Sons.© 2023 Wiley-VCH GmbH. (d) Diagram illustrating an energy-autonomous biosensor utilizing MOF technology and cascade amplification techniques. [151] John Wiley & Sons.© 2023 Wiley-VCH GmbH.

BFC was developed based on the multifunctional electrodes. The multiplexed microfluidic system has been engineered to facilitate the pumping and storage of natural sweat in order to sustain an uninterrupted provision of biofuel. A single SC-BFC can self-charge with a power of about 0.8 V and stabilized energy and power of 7.2 mJ and 80.3 μW, respectively.

Enzymatic BFC is a promising power source. Veenuttranon *et al* [149] developed a flexible single enzyme BFC based on glucose oxidase (biocatalyst) (figure 5(b)). This BFC has a peak power density of 266 uW·cm^{-2} at 20 mm glucose, a maximum current density of 1.3 mA·cm^{-2}, and an open-circuit voltage of 0.45 V. Electrons derived from the oxidation of glucose, a type of biofuel, and the reduction of hydrogen peroxide (H_2O_2) are directed towards the bioanode and biocathode, respectively, in order to establish a self-sustaining electrical circuit. This energy harvesting device is distinct from traditional fuel cells due to its ability to function in moderate conditions, including physiological environments and room temperature [154].

However, there are problems of limited loading efficiency, diminished catalytic activity, and inadequate stability bio-enzymes in enzymatic BFCs. To address the aforementioned issues, Yan *et al* [151] synthesized a multilayered porous metal-organic skeleton co-encapsulated with glucose dehydrogenase (GDH) and nicotinamide adenine dinucleotide (NAD^+) through the utilization of tannic acid (TA) for structural etching, which was used as a biocatalytic microreactor to modify the bioanode (figure 5(d)). The one-pot method was used to co-encapsulate GDH and NAD^+ into a zeolitic imidazolate skeleton (ZIF-L) with high loading capacity. As a result, the biocatalytic effect of the cofactor-dependent enzyme was enhanced compared to the homogeneous solution. TA-controlled etching not only accelerated the diffusion of substrates in ZIF-L, but also enabled the reorientation of the enzyme in a lower surface energy form, which enhanced the biocatalytic effect of the cofactor-dependent enzyme, resulting in a 10.2-fold increase in the biocatalytic performance.

In recent years, hybrid enzymatic BFCs have demonstrated good performance. Nevertheless, enzymatic BFCs are limited to functioning effectively at glucose levels of 100 mm or more, a significantly greater concentration than the typical physiological glucose levels observed in diabetic individuals. In order to address these challenges, Debasis *et al* [155] designed a mediator-free glucose-powered metabolic fuel cell using a new flexible three-dimensional inorganic nanocomposite. During hyperglycemia, the cell is able to transform surplus glucose into electrical energy, producing a sufficient amount of energy (0.7 mW·cm^{-2}, 0.9 V, 50 mm glucose) to facilitate the prompt release of insulin from modified human cells. In addition, a closed-loop metabolic control model for type 1 diabetes was developed. The findings indicate that the metabolic fuel cell has the ability to monitor glucose levels, remove excess glucose, and independently restore glucose balance, as well as autonomous restoration of glucose homeostasis.

Table 1. An overview of research on coupling technology, highlighting the various equipment manufacturing methods discussed herein.

Device	Device fabrication	Performance	References
SPAVS	The system comprises a stator composed of an FEP film and a slider consisting of an aluminum film.	Good stability	[55]
MA_2SnX_6 based PENGs	MA_2SnX_6 chalcogenide precursor prepared by depositing on ITO-PET film	With an output power of 7.33 μW·cm^{-2}	[59]
UF-TEG	The apparatus comprises a stiff TE rectangle, a flexible fabric backing, and electrodes made of conductive fabric tape.	Peak power of 64.10 μW	[98]
MMEC-EH	MMEC-EH is derived from trapezoidal metal plates, PMNN-PZT ceramics, or commercially available ceramics in conjunction with NdFeB magnets.	Maximum magnetoelectric coefficient of 307 V·cm^{-1}·Oe	[107]
DEG	Manufactured from PTFE and nylon nanofiber mats.	Capable of generating a voltage of 252 V and a current of 57.6 μA	[119]
TiO_2 NRs/P(TTh-co-EDOT) heterojunction UV PD	The device was assembled from deposited TiO_2 NRs/P(TTh-co-EDOT) copolymer films.	The responsivity and detectivity were 2.252 mA·W^{-1} and 3.413 × 10^{10} jones, respectively.	[140]
Blood glucose power metabolism fuel cells	The cell was prepared from flexible graphite felt anode, platinum nanoparticle cathode and CuOMWCNTs-PEDOT:PSS complex.	With an output power of 0.7 mW·cm^{-2}	[155]
FB-PTEM	The device consists of a TE layer and an insulating nanofiber membrane (substrate).	The open-circuit voltage at 100 mW·cm^{-2} was 0.52 V	[158]

The electrolytic hydrogen production process is constrained by the sluggishness of the oxygen evolution reaction (OER). The use of the thermodynamically more favorable basic hydrazine oxidation reaction (HzOR) to replace OER has garnered growing interest. Here, Hu *et al* [150] reported a Ru single-atom (Ru_1-NiCoP) immobilized array of twisted NiCoP nanowires (figure 5(c)). The NiCoP nanowire arrays demonstrated exceptional electrocatalytic performance for HzOR and hydrogen evolution reaction (HER) due to the distinctive atomic Ni(Co)-Ru-P interface sites present on the matrix. These arrays exhibited bifunctional activity, achieving remarkably low working potentials of 60 mV and 32 mV for HzOR and HER, respectively, at a current density of 10 mA·cm^{-2}. Encouragingly, a hydrogen generation system that operates autonomously by utilizing a direct hydrazine fuel cell to power the hydrazine cracking unit demonstrated a hydrogen production rate of 24.0 mol·h^{-1}·m^{-2}.

Water splitting is a cost-effective and green alternative to direct solar hydrogen production. A super-hydrophilic MOF-driven Billy-button flower ZnP_2@CoP was developed in situ on a highly conducting porous carbon nanotube/carbon cloth substrate [156]. The hetero-structured composition of the device was powered by a 6 V standard silicon solar panel for uninterrupted generation of green hydrogen in a water electrolyzer. The overall water splitting efficiencies were 98.81% and 9.94%, respectively.

Semiconductor photoelectrochemical (PEC) fuel cells offer a promising approach for the generation of sustainable and eco-friendly energy through the conversion of solar and chemical energy into electrical power. Nevertheless, the limited performance of PEC fuel cells is attributed to the rapid recombination of electron-hole pairs and the sluggish rate of the interfacial reaction hinders their practical application. To solve this problem, Tan *et al* [157] developed an innovative dual photoelectrode PEC fuel cell using ascorbic acid as an organic fuel. The bifunctional iron monoatomic catalyst combined with photoactive materials has been shown to significantly enhance both the interfacial reaction kinetics and the efficiency of photoelectric conversion. The PEC fuel cell that was constructed demonstrated the capability to convert both solar and chemical energy into electrical energy concurrently. It achieved a peak power output density of 82.82 μW·cm^{-2} when exposed to visible light, with open-circuit potentials recorded at 0.39 V and 0.78 V.

2.8. Coupling effects

In addition to standalone energy harvesting technologies, self-powered sensing arrays are often combined with technologies that complement each other, such as the photo-TE effect (table 1). Ma *et al* [158] created a photo-TE integrated membrane (FB-PTEM) that has a high conversion capability for photo-TE and air permeability. This membrane merges PT and TE properties to decrease overall energy consumption. The concept behind it is that the PT nanofiber membrane absorbs light energy and swiftly transforms it into heat energy. Due to its naturally low thermal conductivity, the PT nanofiber membrane hinders downward heat conduction, resulting in a notable temperature contrast between its upper and lower surfaces. With the 'self-temperature difference' effect caused by light, the carrier-generated potential difference (electron and hole) inside the

TE material moves under the temperature gradient. This membrane can perform photo-TE conversion not only under solar energy but also under LED light sources, broadening its potential applications.

Furthermore, alongside photo-TE, there exists a fusion of the TE and piezoresistive phenomena. A recent investigation [159] introduced a novel TE gel, termed dynamic crystalline ion-injected TE gel. The operational principle involves the alteration of temperature distribution within the gel upon contact with a finger, resulting from the temperature differential between the finger and the surroundings, and the ensuing heat transfer upon contact. This temperature gradient induces the TE effect, prompting directional migration of TE ions within the gel to establish a thermal voltage. Simultaneously, the applied pressure induces a variation in the gel's resistance, further modulating the current intensity. The integration of thermal voltage and resistance alterations leads to a modification in the ultimate output current signal, facilitating the recognition of gestures and objects. Similarly, a separate investigation devised a self-powered intelligent pen by effectively combining the TE and piezoresistive effects elicited by finger temperature and pressure on the gel [160]. This intelligent pen can monitor both finger temperature and pressure, offering robust support for analyzing handwriting patterns, user authentication, and correcting pen-holding techniques.

Following their research, Huang *et al* [161] conducted an investigation on a new versatile flexible textile material (PCP) that leverages piezoelectric and piezoelectronic effects. This innovative material was developed through the combined action of polydopamine-coated cerium oxide (CeO_2@PDA) nanoparticles and PVDF. The CeO_2@PDA nanoparticles served as localized nucleating agents and photosensitizers for PVDF, facilitating the integration of piezoelectric effects, semiconductors, and optical processes within the PCP textiles. This advancement paves the way for the creation of comprehensive self-powered sensing systems. Furthermore, the material exhibits a combined photovoltaic-TE effect with logic processing capabilities [162], as well as a combined friction initiation-electrostatic induction effect for harnessing the energy generated by cardiac motion [163].

3. Energy storage

One of the key constituent elements of self-fed energy systems is energy storage devices (batteries and capacitors). Among them, lithium-ion batteries are already commercially available. However, lithium-ion batteries are rigid and bulky and cannot meet the needs of the rapidly evolving self-powered wearable sensors. In order to develop flexible, lightweight, stable and safe energy storage components, there has been significant interest in the advancement of wearable batteries and high-power capacitors, and novel structures such as island bridges, origami and textiles have been developed [164], as well as novel materials with energy storage, flexibility and stretchability properties.

3.1. Battery

The sweat-activated battery is an electronic power source characterized by a consistent energy output, as well as being environmentally friendly and devoid of toxic substances. Xiao *et al* [165] demonstrated a human sweat-activated textile-retractable cotton yarn-based Zn-air battery (ZAB). The carbon black segment, pristine yarn, and zinc foil segment serve as the cathode, salt bridge, and anode of the battery, respectively (figure 6(a)). Upon the introduction of a sodium chloride (NaCl) solution, the air cell undergoes swift activation, leading to a redox reaction and resulting in an open-circuit voltage potential of up to 1.0 V. Experiments showed that sweat secreted by volunteers while cycling could activate energy supplying hair bands to power the headlight of the LED. Paper electronics offer an environmentally sustainable option for flexible wearable systems and are compatible with existing printing processes. Here, Yang *et al* [166] designed a new fabrication technique for paper batteries. Biodegradable hydrogel reinforced cellulose paper acts as an isolator and solid electrolyte for zinc-based paper batteries. Combining the properties of cellulose paper and hydrogel, this work offers good strain performance, high volumetric energy density (26 $mW{\cdot}h^{-3}$) and cuttability, and is biodegradable in the natural environment. Unlike previous reports, it is possible to print the anode and cathode materials on distinct front and back sides of the paper. Figure 6(b) shows a self-powered high-performance Zn^{2+}/AI^{3+} electrochromic battery based on complex niobium tungsten oxide ($Nb_{18}W_{16}0_{93}$) [167]. The device utilizes a novel electrolyte combination that allows for the real-time visualization of energy storage levels. The experimental results show that $Nb_{18}W_{16}0_{93}$ has good electrochromic performance in Zn^{2+}/AI^{3+} aqueous solution, including fast self-coloring response (10.8 s), high discharge capacity (160 $mAh{\cdot}m^{-2}$), high optical modulation in mixed electrolyte (90.5%), and outstanding cycling stability (93.13% retention after 5000 cycles). Self-charging SC power cells (SCSPC) have great potential in the micro (e.g. electronic skin and biosensors) and macro (e.g. electric vehicles and health monitoring systems) sectors. A SCSPC device was assembled using ZnO@Mo-Fe-MnO_2 NA electrodes and PVDF-l Trfe/CNTs/BTO($BaTiO_3$) piezoelectric films [168]. This work demonstrated for the first time the self-charging phenomenon of electrode- and film-driven electrolyte ion migration. Moreover, the findings from the experiment indicated that the connection of three SCSPCs in series effectively illuminated LED. Subsequently, Li *et al* [169] proposed a well-performing zinc-ion thermally charging cell based on a rational heterostructure engineered hydrated vanadium pentoxide cathode material.

3.2. Capacitors

Bio-SCs [172], which integrate BFCs with capacitors, serve as a dependable energy source system for wearable electronic devices. However, the deep embedding of enzyme active

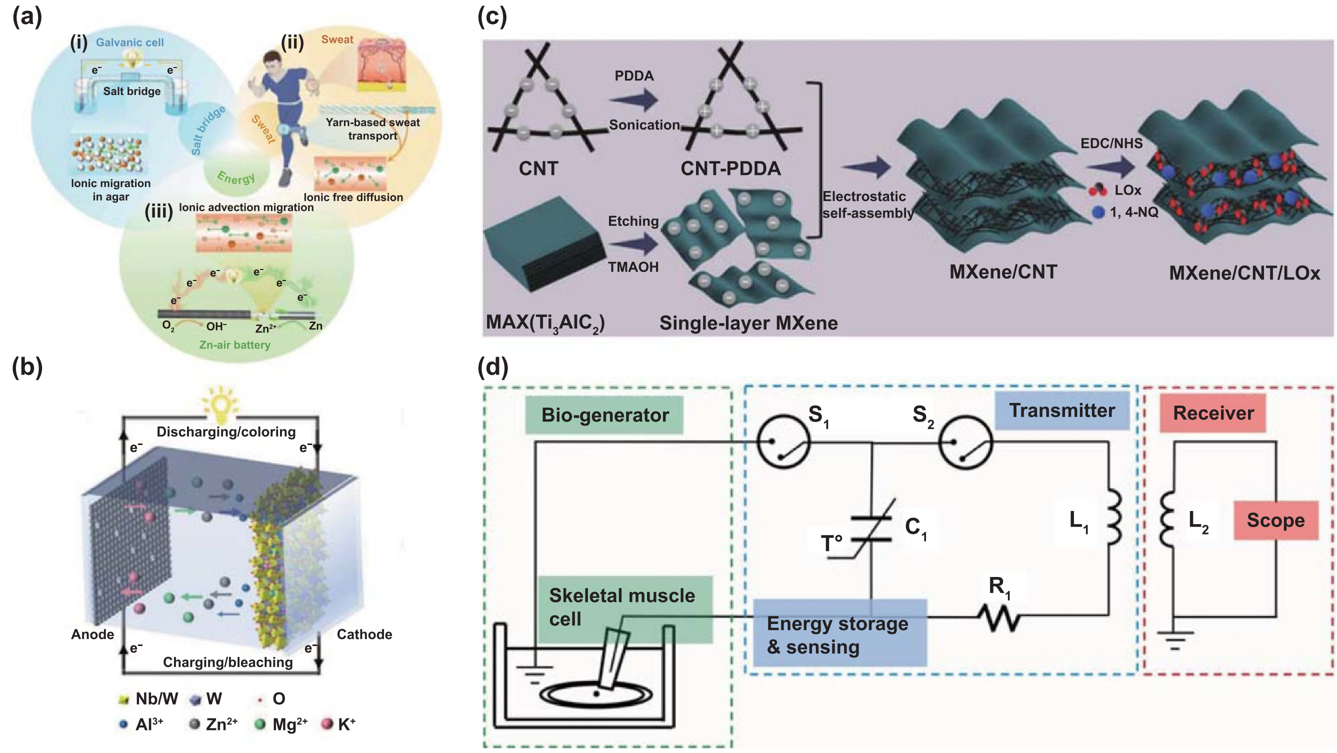

Figure 6. Examples of self-powered energy storage. (a) The composition and operational mechanism of a perspiration-triggered battery. Reproduced from [165]. CC BY 4.0. (b) Schematic structure of electrochromic battery. [167] John Wiley & Sons.© 2023 Wiley-VCH GmbH. (c) Schematic of the synthesis of MXene/carbon nanotube/liquid oxygen bioanodes. [170] John Wiley & Sons.© 2023 Wiley-VCH GmbH. (d) Illustration depicting the components of an energy-autonomous system. Reproduced from [171]. CC BY 4.0.

sites on the bioelectrodes and the extensive preparation process limit the energy harvesting, especially during complex in vivo motions, hindering the actual power supply. Therefore, Guan *et al* [170] designed a three-dimensional layered structure comprising MXene, single-walled carbon nanotubes, and lactate oxidase, serving as a bifunctional bioanode. Wearable self-charging bio-SC of 'island-bridge' type with composite bioanode, activated carbon/platinum cathode, hydrogel substrate and liquid metal conductor (figure 6(c)). The activated carbon and Pt composites avoided the over polarization of MXene. The MXene/CNT composite exhibited a well-defined hierarchical structure that created a stable catalytic microenvironment. The bioanode possessed a significant specific surface area, a plentiful presence of surface functional groups, and demonstrated superior capacitance performance. As an energy storage device, it can recharge itself to the open-close state after discharging to 0 V.

Skeletal muscle fibers are present in every part of the mammalian body, providing a possible solution for pathology monitoring. Therefore, Clementi *et al* [171] developed an embedded autonomous biosensing device based on electrical energy collected from membrane potentials of living cells (figure 6(d)). The capacitor presents in the device functions as both a means of storing energy and a sensor for monitoring temperature. Importantly, tests were conducted using soleus muscle isolated from rats, and experimental data demonstrated the feasibility of converting chemical energy to electrical energy in cell membranes, and skeletal muscle was found to outperform our previous oocytes [173, 174]. This solution presents notable benefits compared to rechargeable batteries and holds considerable promise for utilization in distant passive sensing scenarios.

In the forthcoming period, we expect to be able to create different heterojunctions or promising electrode materials, electrode structures and energy storage substances, which in turn will lead to high-power, deformable and multifunctional energy storage platforms in lightweight systems.

4. Data processing and transmission

Data processing is a key aspect of self-powered sensors and contains data processing algorithms such as algorithmic learning and peak detection. It not only calibrates the data, but also enables personalized healthcare. With the development of IoT communication technology, the data transmission methods between sensing devices are more and more diversified, and the application prospect is broader.

4.1. Wireless transmission

In recent years, self-powered sensing has become increasingly utilized in various applications and shows promising potential for the advancement of wireless transmission technologies (Zig-Bee, Bluetooth, Wi-Fi, NFC, and so on).

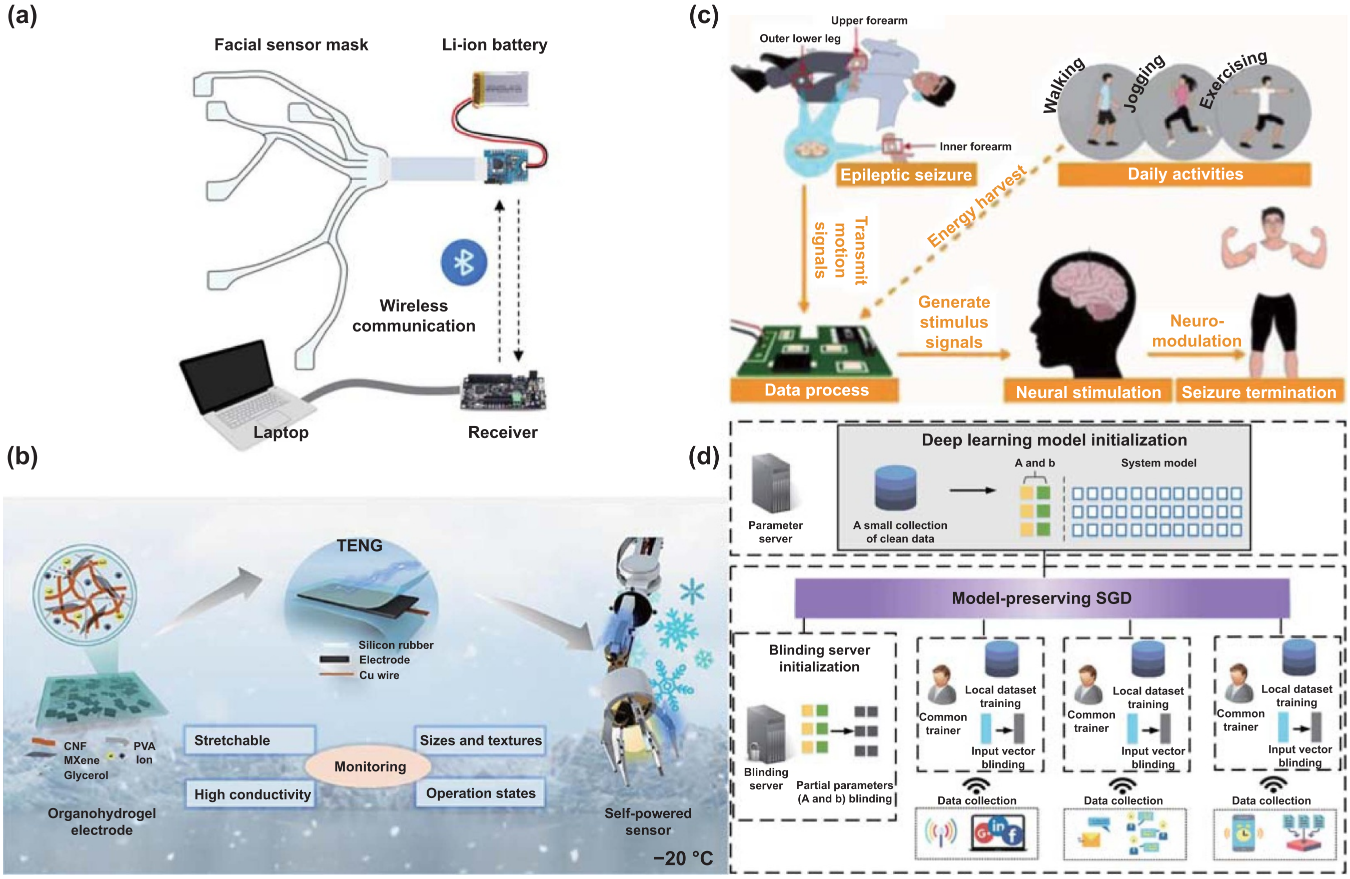

Figure 7. Examples on data transmission and processing. (a) Schematic diagram of a wireless system for personalized skin-integrated facial interfaces. Reproduced from [175]. CC BY 4.0. (b) Self-powered temperature monitoring platform. Reprinted from [179], © 2023 Elsevier B.V. All rights reserved. (c) Illustration of an energy autonomous wearable system for epilepsy detection and treatment. Reprinted from [180], © 2022 Elsevier Ltd. All rights reserved. (d) Composition of MP-CLF. Reprinted from [181], © 2023 Published by Elsevier B.V.

A study [175] made a personalized facial skin detection system with an integrated data processing unit. The test accuracy can reach an acceptable standard in the presence of occlusion. As shown in figure 7(a), data acquisition from the skin-integrated face mask was started. The circuit board acts as a signal transmitter, the miniature portable battery is powered to transmit the received data wirelessly through the motherboard, and the receiver is connected to a laptop to store the data as a dataset for machine learning. In order to overcome the problem of redundant data and large power consumption limiting sustainable wireless sensing, a study [176] proposed a wearable bending automatic wake-up wireless sensing method. This contrasts with the process of continuously recording and transmitting data. The TENG signal is recorded for the trigger, the piezoelectric generator voltage is transmitted wirelessly as angle sensing data, and Zigbee is used as the wireless transmitter and receiver. The implementation of sleep mode and a straightforward and accurate autonomous start-up system is anticipated to lessen the operational workload and decrease the power consumption of wireless sensing by 4 mW. Subsequently, another study [177] reported an ecosystem of amphibious epidermal body area networks capable of data transfer between wearable sensors. This represents the inaugural medium-range underwater wireless power and data transmission platform that is designed to be interoperable with current commercial electronic devices. The system enables artificial near-field electromagnetic wave propagation via magnetically induced magneto inductive metamaterials and is capable of providing uninterrupted, self-driven communication in harsh environments where far-field propagation (e.g. Bluetooth, WiFi, or cellular) is not possible. In addition, alternating-current-powered compliant circuits have been developed using organic electronics, and stand-alone devices have been implanted in free-moving rodents for acquiring, processing, and wirelessly transmitting neurophysiological brain signals [178].

An autonomous personalized detection system incorporating a Bluetooth module is capable of relaying real-time monitoring data to a mobile phone interface to track temperature changes in the lower limbs and surroundings of a pregnant woman during exercise in real time, and issue the necessary alarms when she is exposed to a hot environment [182]. This provides ideas for the development of biocompatible and reliable temperature monitoring platforms for complex health diagnostics and protection of at-risk populations. Zhou *et al* [179] have shown an energy-autonomous sensor for signal acquisition and Bluetooth real-time transmission of electrical signals in extremely cold environments (figure 7(b)).

4.2. Data security

A novel energy-autonomous epilepsy detection and treatment system was developed in a study [180]. Figure 7(c) shows the schematic diagram of the system. The sensor generates piezoelectric signals in response to physical activity, such as exercise, which are then sent to a data processing center for analysis. The data analysis center processes the signals in real time (analog-to-digital conversion), generates neuroelectric stimulation signals and transmits them to the brain to suppress seizures. This creates a closed loop of behavior-system-brain.

At present, matters pertaining to information security have emerged as a prominent subject of interest and discussion. Blockchain technology is a 'decentralized network of trust'. A study [183] developed an innovative method to enhance the security of wireless sensing data through the integration of blockchain technology with IoT data, which effectively prevents data from being stolen or corrupted. Firstly, remote sensing data is data fused using wireless sensing network. The combined data is subsequently sent to the data processing center of the organic farm, where the blockchain technology data is encapsulated and encrypted. The system is packaged and sent to the cloud database for storage. Furthermore, personnel have the capability to remotely monitor and manage data stored in cloud storage. Researchers have also invested a lot of effort in privacy-preserving deep learning. Chen *et al* [181] proposed a model-preserving collaborative deep learning framework (MP-CLF) for resisting generative adversarial network (GAN) attacks. The scheme consists of three main phases: deep learning model initialization, blinding server initialization and collaborative training (figure 7(d)). MP-CLF uses matrix blinding to protect data. Breaking the local modelling of GAN attacks by encrypting specific model parameters and trainer data with a lightweight approach to security. Experimental results demonstrate that MP-CLF exhibits effective defense mechanisms against GAN attacks while maintaining the accuracy of the training model, thereby addressing the challenge of balancing data availability and privacy. The approach enables decentralized devices to engage in cooperative training to combat GAN attacks through the involvement of servers and reputable third parties, all while safeguarding the confidentiality of sensitive information.

With the proliferation of self-powered wearable devices, there are potential privacy and data security issues with Bluetooth- and Wifi-based data transmission devices, which have triggered consumer concerns about data misuse and leakage, and consequently sceptics towards wearable devices. In order to avoid this situation, the security of storage, transmission and use of private information should be properly considered during the development of wearable technologies.

5. Materials for self-charging flexible sensors

Self-charging has received much attention for its remarkable ability to harvest, convert and store energy without the need for an outside power source. Most self-charging systems are constructed using a combination of energy harvesting, energy storage and electrode components. So far, several interesting materials (hydrogels, flexible crystals, etc) have been used in smart homes, medicine, etc [184–188].

5.1. Energy harvesting materials

To date, a wide range of materials have been developed for harvesting environmental energy sources such as mechanics, chemical reactions, light energy, wind energy and rain energy. Depending on their intrinsic energy transfer mechanisms, these materials can be classified as piezoelectric, friction electric, hydrovoltaic, photovoltaic and so on.

As shown in figure 8(a), a flame-retardant and heat-insulating biomass-based triboelectric material (CNF@HAP composite film) was prepared [189]. The composite membrane consists of CNFs with triboelectric effect and hydroxyapatite nanowires (HAP NWs), capable of harvesting mechanical energy and converting it into electrical energy. The CNF@HAP composite film-B-TENG exhibited an open-circuit voltage of 102 V, a short-circuit current of 6.18 μA, and an output power of 1.6 W$\cdot$m^{-2} at a working area of 4 cm^2. These performance metrics surpassed those typically observed in cellulose-based triboelectric materials. In addition, 90% of the triboelectric performance is maintained at 100 °C, which provides a better idea for metallurgical operations, textile industry and fire rescue. Afterwards, in order to improve the detection accuracy of TENG sensors in complex real-world environments, a study prepared TENG based on ZnO, MoS_2 and rGO [190]. The photosensitive ZnO was used as an energy harvesting material with piezoelectric effect, superior liquid repulsion and mechanical strength properties, which significantly improved the sensitivity of the TENG sensor under light.

Mahapatra *et al* [194] synthesized 2D magnesiochromite, a flexible electrical energy harvesting material with high surface activity and used it for the preparation of a flexoelectric cell. In a small mechanical source, this 2D cell has the capability to achieve a peak voltage of approximately 3 V. This offers great potential for future energy production technologies. Shi *et al* [195] describe the design and fabrication of a novel shell-like ferroelectric metamaterial with programmable piezoelectric and pyroelectric properties for 3D printing through a customized additive manufacturing platform and multi-physical property optimization. In addition, CdTe for solar energy harvesting [196], TiO_2 nanoparticle for triboelectric harvesting [197], and telluride with TE effect [198], and polyvinylidene difluoride with piezoelectric and pyroelectric effect [199] also provide more options for energy harvesting.

5.2. Electrode materials

Bi_2CuO_4 (BCO) has excellent electrochemical display capabilities. Karnan *et al* [200] synthesized BCO nanosheets in one step hydrothermally based on the combination of bismuth and copper sources. At a current density of 3 amperes per gram,

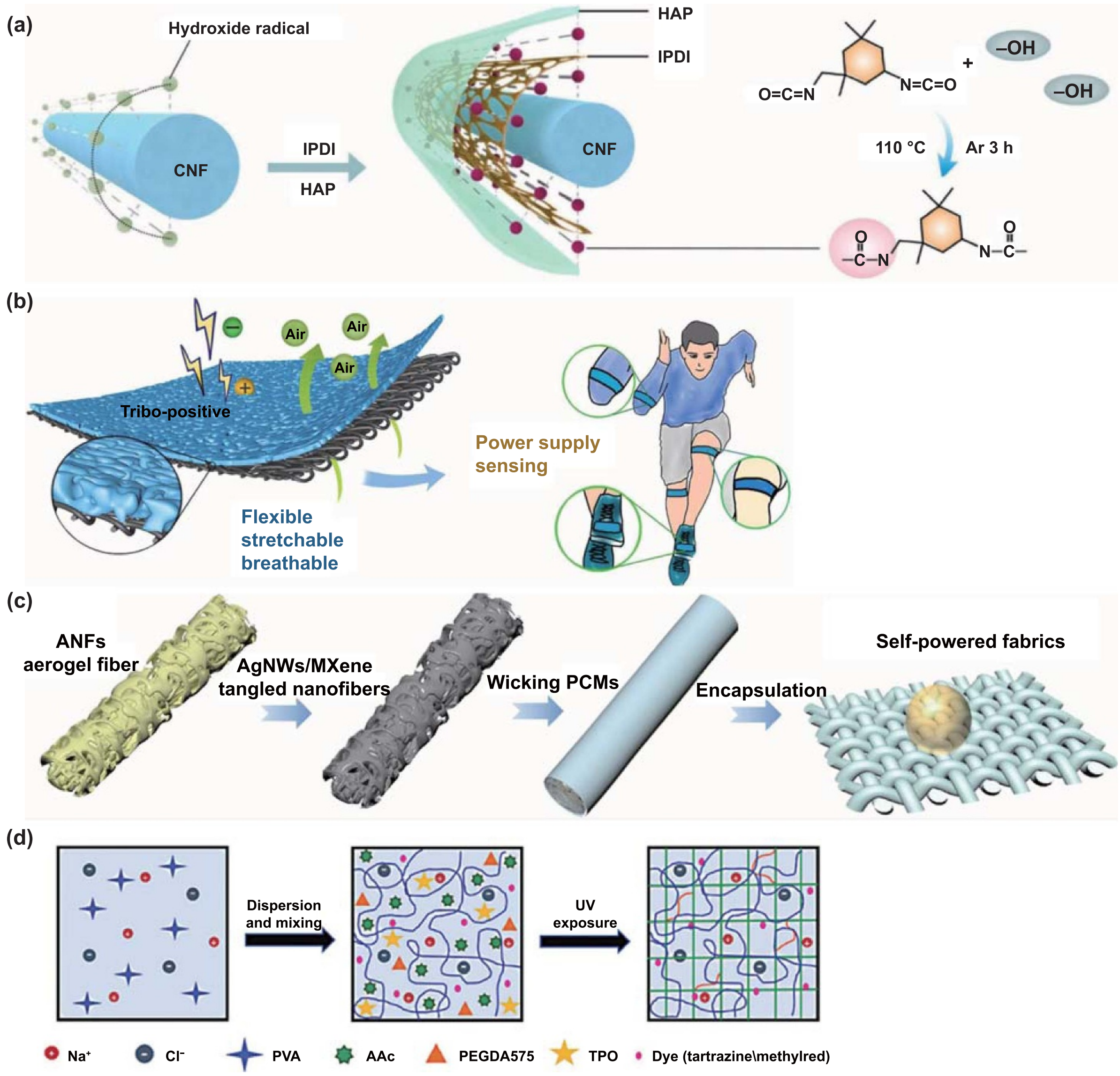

Figure 8. Different materials for self-powered flexible sensing. (a) Structure of CNF@HAP composite membrane. Reprinted from [189], © 2023 Elsevier Ltd. All rights reserved. (b) Stretchable and breathable friction electric fabrics. Reprinted from [191], © 2023 Published by Elsevier Ltd. (c) The process of preparing conductive aerogel fibers. Reprinted from [192], © 2022 Elsevier Ltd. All rights reserved. (d) Schematic diagram of PVA/AAc/NaCl hydrogel. Reproduced from [193]. CC BY 4.0.

this electrode material exhibits a specific volume of 1842 coulombs per gram, which leads to a high energy storage capacity. Carbon nanotube electrodes are a type of nanomaterials known for their strong mechanical properties and impressive electrical conductivity. They have a high aspect ratio and significant specific surface area, making them suitable for use in self-powered sensors, flexible electronic devices, and other applications. Xu *et al* [191] prepared a triboelectric fabric with excellent comfort and breathability properties using polyethyleneimine/carbon nanotube conductive nanomaterials as the electrodes. Its instantaneous power density reached 1.62 $W \cdot m^{-2}$, which was higher than most reported triboelectric fabrics. By optimizing the mass ratio of each component, the electrical performance was improved by 111%. Finally, the researchers also successfully used the fabric for garment production. (figure 8(b)). Later, Wang *et al* [201] constructed an oxygen-rich carbon electrode. Based on the autoxidation of catechols in air, phenolic resin-assembled copper oxygen-enriched carbon batteries confirmed the feasibility of energy autonomy in practical applications. During the charging process (20 min to 120 min), the potential of the oxygen-enriched carbon electrode gradually increased (0.28V/RHE–0.64V/RHE), which was mainly due to aerobic autoxidation of catechol groups to catechol groups on the oxygen-enriched carbon cathode. This carbon material integrates energy harvesting, conversion, and storage capabilities in a single entity, eliminating energy loss during transfer between various materials. Furthermore, flexible electrodes like Ag electrode [202], silver nanowire [203], indium tin oxide [204], and conductive polymers (polypyrrole, polyaniline) [205, 206] offer a wider range of options for electrodes in self-powered flexible sensors.

5.3. Energy storage materials

Graphene's exceptional mechanical and physical characteristics render it a prime candidate for energy capacity. Being a carbon nanomaterial in two dimensions, graphene possesses a generous specific surface area, along with effective electrical and thermal conductivities. Weng *et al* [207] incorporated graphene into polymer films derived from biomass, resulting in improved mechanical attributes. Furthermore, the research team developed multifunctional sensors that are lightweight and energy-efficient by combining polypyrrole with graphene-infused bacterial cellulose. These sensors exhibited capabilities such as light-driven, humidity-driven, intelligent gesture recognition, and multi-modal self-powered sensing functionalities.

A promising technology emerging in the field of self-powered energy is the additive manufacturing of conductive hydrogels, which act as basic components for energy storage, enabling robust, flexible and biocompatible sensor devices. Yang *et al* [208] demonstrated a printed conductive hydrogel with complex structure. It showed strong mechanical properties and was able to withstand compressive strains of more than 50%. Hydrogels are an ideal solution for solid-state SC electrolytes due to their good ionic conductivity. Being an electrolyte, it creates a dual electric layer on the electrode's surface. This results in the storage and release of energy while charging and discharging. Such characteristic allows hydrogel to serve as an electrolyte substance in SCs, actively involved in the energy storage process.

Building on previous research on 3D printed hydrogels, Mogli *et al* [193] synthesized polyvinyl alcohol/acrylic acid/NaCI (PVA/AAc/NaCl) hydrogels (figure 8(d)). This material has excellent mechanical deformation sensitivity, tensile strain (550%) and electrical response. These properties suggest a promising application of PVA/AAc/NaCI hydrogel sensing devices for multifunctional strain sensing. Organic hydrogels offer significant benefits compared to traditional liquid electrolyte solutions owing to the favorable biocompatibility and non-flammability of their components. Additionally, these hydrogels exhibit robust mechanical strength, tensile properties, and environmental stability, which allow them to work flexibly in a variety of open environments without safety hazards. A study presented a self-powered analytical sensing device to monitor H_2S using a stretchable organic hydrogel as a multifunctional energy storage materials [209].

Another study [192] developed a smart flexible fabric through aerogel nanofibers to achieve response to multiple external stimuli (light/electricity/temperature/stress, etc) (figure 8(c)). The aerogel fibers with their high porosity and pore channels provide a strong physical barrier for the organic phase change materials (PCMs) to prevent leakage issues that may arise from phase changes. The built-in conductive network enhances the containment of PCMs and keeps them securely attached to the fiber structure even under thermal cycling conditions. PCMs possess a natural capacity for storing and transforming thermal energy, allowing them to capture the energy from ambient radiant sources and excess heat. As a result, aerogels play a key role in storing and releasing latent heat. The sensor can be powered stably around the clock to drive continuous operation of electronic products. This has great potential for next-generation wearable systems and lunar exploration, among others. There are also bioenergy storage materials such as G. sulfurreducens biofilm. Ma *et al* [210] first assembled simple self-powered non-contact sensors using a G. sulfurreducens biofilm as the sensing layer. Microbial biofilms have unique advantages over traditional biomaterials: environmentally friendly, self-propagating, and second-by-second self-healing capabilities, and strong energy storage.

In this section, we provide an overview of the various types of materials designed for self-powered applications and summarize the preparation methods of the selected materials in table 2.

6. Energy-autonomy system in flexible sensing

6.1. Medical

Ongoing surveillance of essential physiological indicators and prompt intervention represent emerging directions in the development of self-powered wearable and implantable medical technologies. A study [211] designed a self-powered TES based on N-doped graphene quantum dot modified polyaniline nanocomposites (NGQDs/PANI) for non-invasive monitoring of glucose concentration in sweat (figure 9(a)). Under the enhanced charge transfer of NGQDs, the sensitivity of TES for glucose detection (23.52 mM^{-1}) was higher than that of pristine PANI/GOx (16.44 mM^{-1}). The superior performance of TES offers alternative medical approaches for the diagnosis and management of diabetes. Implantable devices that are self-powered hold promise in prolonging the operational lifespan of the device within the human body and diminishing the necessity for recurrent high-risk surgical interventions. Ryu *et al* [212] reported an inertia effect powered TENG (I-TENG) and implemented a self-powered cardiac pacemaker system. The I-TENG indirectly provides enough mechanical energy to be completely enclosed with the human implanted medical materials for complete containment. In addition, a proof-of-concept was performed to successfully demonstrate asynchronous V-pacing mode (VVO) and VVI mode using bradycardia in a mutt. Self-rechargeable implantable medical device. In forthcoming manufacturing endeavors, there is a potential to enhance the power efficiency of self-powered human implantable medical devices and health monitoring systems in order to enhance patient well-being. Battery discharge is detrimental to people's health. As shown in figure 9(b), a type 1 diabetes continuous healthcare system was constructed with a micropump, a biosensor and continuously powered power supplies [213]. The battery was charged for 790.1 s to obtain 100% energy conversion from body heat to electricity. The micropump and sensor used 54.5% and 18.5%, respectively, with the remaining 27.0% being stored in the

Table 2. Overview of research on the preparation of self-powered materials.

Material	Material preparation	Properties	References
CNF@HAP composite membrane	Preparation of HAP NWs by solvothermal method. Then CNF, HAP NW, isophorone diisocyanate, and dibutyltin dilaurate are fully reacted. Vacuum filtration yields CNF@HAP composite membranes.	High temperature resistance, flame retardant, thermal insulation, high surface roughness	[189]
2D magnesium chromite	Sol-gel synthesis method	High surface activity, electrically responsive	[194]
Ferroelectric materials	$BaTiO_3$ ceramic powder was fully reacted with PEGDA 250 and TPO. The sintered $BaTiO_3$ bulk ceramics were then polarized by contact polarization method. Finally, an electric field was applied to activate the ferroelectric properties of the 3D printed metamaterials.	Programmability, versatility	[195]
Bi_2CuO_4 nanosheets	One-step hydrothermal method	High cycling stability, high specific capacity, excellent electrochemical performance	[196]
Polypyrrole@graphene-bacterial cellulose	Graphene nanosheets and BC nanofibers are alternately stacked together through extensive hydrogen bonding interactions and van der Waals forces to form self-supported films. In situ polymerisation method to grow highly conductive PPy nanoparticles on thin films.	Flexibility	[207]
3D architected conductive hydrogel	3D printing preparation	Mechanical properties, stretchability, mechanical robustness, biocompatibility	[208]

battery. These results contribute to the future realization of a true continuous medical system.

The capacity of smart textiles to capture environmental energy and provide multiple sensing functions through the triboelectric effect has generated great interest in next-generation medical electronics. Borophene/ecoflex nanocomposites were prepared as fabric-B-TENGs for mechanical energy harvesting, medical assist systems, and wound healing applications [216]. The B-TENGs provided consistent output performance even under severe deformation. The designed B-TENG not only showcases the considerable potential of versatile self-powered medical sensors, but also holds great promise for wearable medical support and therapeutic systems.

6.2. Physical activity

Despite the rapid progress in the advancement of energy-autonomy triboelectric sensors, the creation of TESs that possess characteristics such as extreme flexibility, exceptional sensitivity, minimal weight, and prolonged energy remains a great challenge. A study [217] prepared a TENG (EC10S + PNy 11 TES) using a surface-modified nylon 11 electrostatically spun film (PNy 11) as the positive electrode and Ecoflex as the negative electrode. Not only can it power stopwatches and LED lights, but it can also detect joint movements such as fingers and knees. Similarly, a polymer fiber fabricated from carbon nanotubes and hydrogel with good stability, mechanical properties and biodegradability was reported and successfully used for a self-powered TENG that can be attached to the human body [214] (figure 9(c)). Fiber-B-TENGs can effectively monitor human movements such as walking, running and lifting hands, and have potential applications in the field of rehabilitation.

The objective of monitoring exercise is to monitor the current physiological condition of the human body live, thereby examining exercise performance, enhancing exercise effectiveness, and intelligently preventing exercise injuries. A study [218] reported a physiological monitoring sensor integrating different forms of technology (triboelectric generator and solar cells) to enable monitoring of the user's ECG and exercise parameters. The data was sent wirelessly to a user interface that allowed the user to modify the pace and level of physical activity as desired. The system has the ability to effectively capture mechanical and solar energy and utilize it for individualized health monitoring of the human body. Future power management and integration of multiple sensors may require fine circuit design and preparation of related materials. Flexibility and integration modes will largely influence the overall system's comfort level, all the while maintaining precision. Body area networks have garnered significant interest for their application in the next generation of personalized healthcare solutions for sports, medical, diagnostic, and rehabilitation training. Liu *et al* [215] described an energy-autonomy

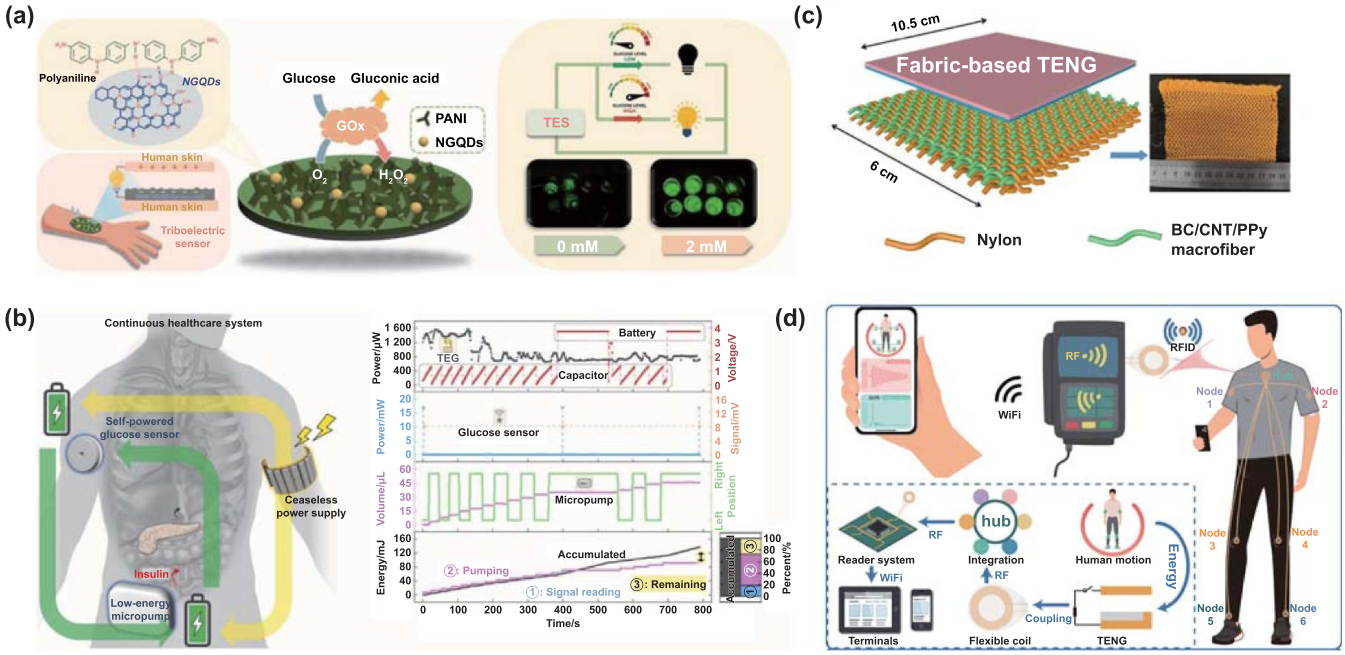

Figure 9. Self-powered systems for biosensing applications. (a) Demonstration of a non-invasive detection mechanism and alarm for triboelectric generators. Reprinted from [211], © 2023 Elsevier Ltd. All rights reserved. (b) Type 1 diabetes continuum of care. Reprinted from [213], © 2023 Elsevier Ltd. All rights reserved. (c) Cellulose-based conductive polymer fibers. Reproduced from [214]. CC BY 4.0. (d) Self-powered wireless body area network system. Reproduced from [215]. CC BY 4.0.

wireless body area network that utilizes contact-separation direct current TENGs to enable real-time monitoring of human movement across multiple joints (figure 9(d)). This work realizes a wearable TENG, which is conducive to the significant advance of smart healthcare, wireless sensors and human area networks.

A recent research project [219] successfully created a self-sustaining flexible motion sensor using semiconductor nanowires. The sensor was attached to various human joints like fingers, wrists, elbows, and knees to gather data on human movements, such as bending angles. It demonstrated strong long-term stability and is anticipated to enhance the range of applications for motion sensors. Similarly, another study [220] developed a self-powered flexible sensing array that visualized pressure changes and bending angles during knee flexion and extension, enabling real-time monitoring of sound vibration, radial artery pulse and finger movement. In this study, the pressure of 0.3 g of soybeans generated a voltage of 0.26 V.

6.3. Foods

Food safety has consistently been a major concern globally, and improper storage of raw materials and finished products can result in significant economic losses. Guo and colleagues [221] introduced an innovative energy-autonomy aptamer sensor driven by ZAB for hexestrol detection. The biosensor has high sensitivity (0.08 pg$\cdot$ml^{-1}) and a wide detection range (0.1 pg$\cdot$ml^{-1}–100 ng$\cdot$ml^{-1}). This work provides a new aptamer strategy for constructing self-powered aptamer sensors for food hazard analysis. In a similar manner, Jin and colleagues [222] introduced a novel self-sustaining electrochemical device that combines photocatalysis for detecting and breaking down aflatoxin B1 in maize. This device achieved an impressive degradation rate of 81.62%, with a photocurrent of 13.7 μA and an output power of 467.4 mV.

Food packaging plays a crucial role in ensuring food safety. Jin *et al* [223] developed a portable self-powered UV device called Tribo-sanitizer, inspired by lightning. This device utilizes a tribo-electric nanogenerator to convert mechanical energy into electricity, which powers a UVC lamp for disinfection. The effectiveness of the Tribo-sanitizer was tested on polyethylene, fresh apples, and lettuce, demonstrating successful decontamination of *E. coli* O157:H7 and *L. monocytogenes* to meet government guidelines for microbiological control. Furthermore, controlled atmosphere (CA) has been proven to be a successful method for preserving food freshness. Wu *et al* [224] introduced a self-sustaining flexible sensing system to monitor CA gases. This system utilizes an electromagnetic generator to harness wind energy for powering the sensing device. Additionally, a temperature and humidity sensing patch with real-time monitoring capabilities was developed. This innovative system not only addressed the issue of continuous power supply needed for the sensing system but also achieved minimal energy consumption for food preservation.

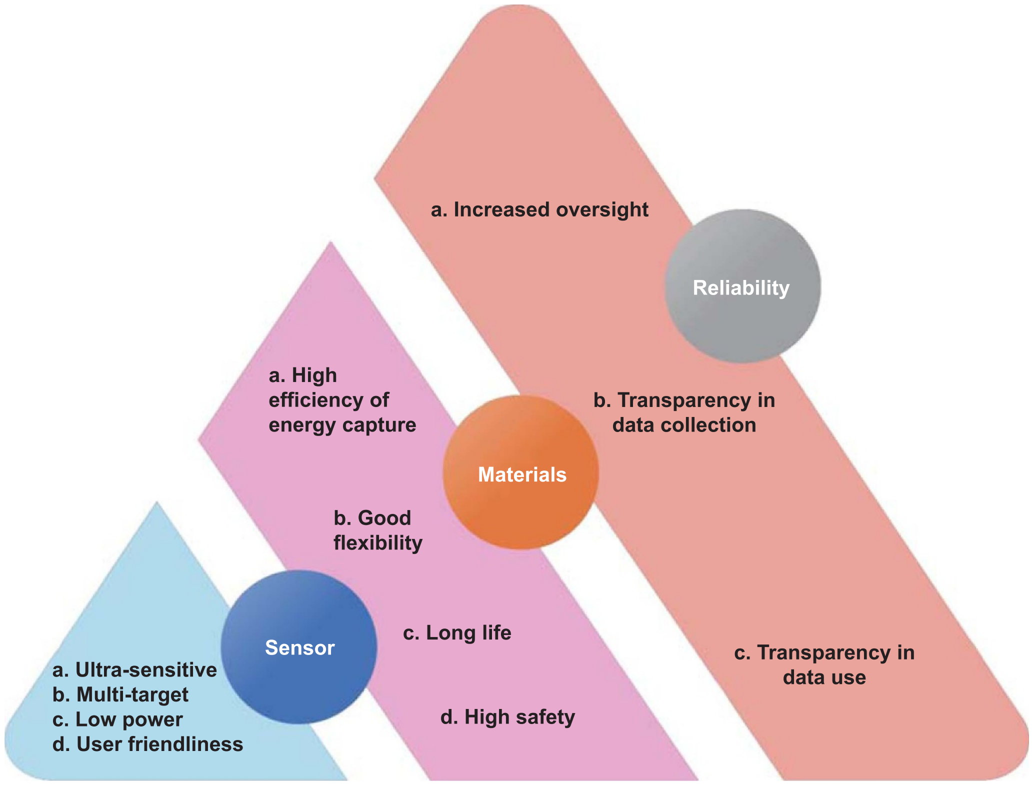

Figure 10. Outlook for self-powered flexible sensors.

7. Conclusions and outlook

This paper has reviewed and emphasized recent progress in self-powered flexible sensing systems through some representative work. The exposition covers different energy harvesting methods and describes novel structural designs and application materials in this field. As more and more wearable energy harvesters are developed, the key technical challenges hindering the development of self-powered wearable sensors become clearer (figure 10).

(1) Sensor performance. Some energy harvesting technologies are theoretically able to meet the application, but due to environmental and other factors, the power generation effect is not ideal in actual use, such as only being able to work with solar energy during the day, fast battery consumption in winter, and broken down trams in snow. Hence, it is advisable to integrate various signal amplification techniques in order to enhance the circuit's output power, enable highly sensitive and multi-target detection, and ultimately fulfill the detection requirements of diverse application scenarios. To optimize user comfort, new textiles or wearable materials can be developed that combine functionality with comfort as well as the seamless integration of multi-purpose wearable sensors in different environments of the human body. In addition, devices need to be subjected to complex environments and more research (large-scale human trials, mixing of multiple technologies, multilayering, arrays, etc) to optimize cyclic stability, compatibility and power continuity, which in turn will ensure that they are functional and user-friendly, thus increasing consumer confidence.

(2) Materials. Each element of a self-powered system (sensors, system circuits, energy storage and energy harvesting units) requires continuous material optimization and innovation. Currently, several energy-independent sensing technologies utilizing inorganic materials have been employed in various emerging fields such as public health, bionics, and environmental monitoring. Nevertheless, the restricted range of materials accessible and the reliance on external power supplies have impeded the practical implementation of these technologies. The development of functional materials (such as DNA nanomaterials) that capture energy with high efficiency, flexibility, longevity and safety is highly desirable.

(3) Reliability and standardization issues. Firstly, there should be increased supervision by regulatory bodies to ensure the safety and effectiveness of equipment as well as the strength of project design and implementation. Secondly, as the IoT becomes more widely used, a large amount of data is uploaded to the cloud and there is a risk of data leakage. Therefore, transparency should be ensured in how data is collected and used by users.

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