Yu et al. Journal of Nanobiotechnology (2024) 22:497
https://doi.org/10.1186/s12951-024-02774-0

Journal of Nanobiotechnology

REVIEW

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Ambient energy harvesters in wearable electronics: fundamentals, methodologies, and applications

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Abstract

In recent years, wearable sensor devices with exceptional portability and the ability to continuously monitor physiological signals in real time have played increasingly prominent roles in the fields of disease diagnosis and health management. This transformation has been largely facilitated by materials science and micro/nano-processing technologies. However, as this technology continues to evolve, the demand for multifunctionality and flexibility in wearable devices has become increasingly urgent, thereby highlighting the problem of stable and sustainable miniaturized power supplies. Here, we comprehensively review the current mainstream energy technologies for powering wearable sensors, including batteries, supercapacitors, solar cells, biofuel cells, thermoelectric generators, radio frequency energy harvesters, and kinetic energy harvesters, as well as hybrid power systems that integrate multiple energy conversion modes. In addition, we consider the energy conversion mechanisms, fundamental characteristics, and typical application cases of these energy sources across various fields. In particular, we focus on the crucial roles of different materials, such as nanomaterials and nano-processing techniques, for enhancing the performance of devices. Finally, the challenges that affect power supplies for wearable electronic products and their future developmental trends are discussed in order to provide valuable references and insights for researchers in related fields.

Keywords Wearable electronics, Biosensors, Energy harvesters, Self-powered sensors, Nanomaterials, Health monitoring

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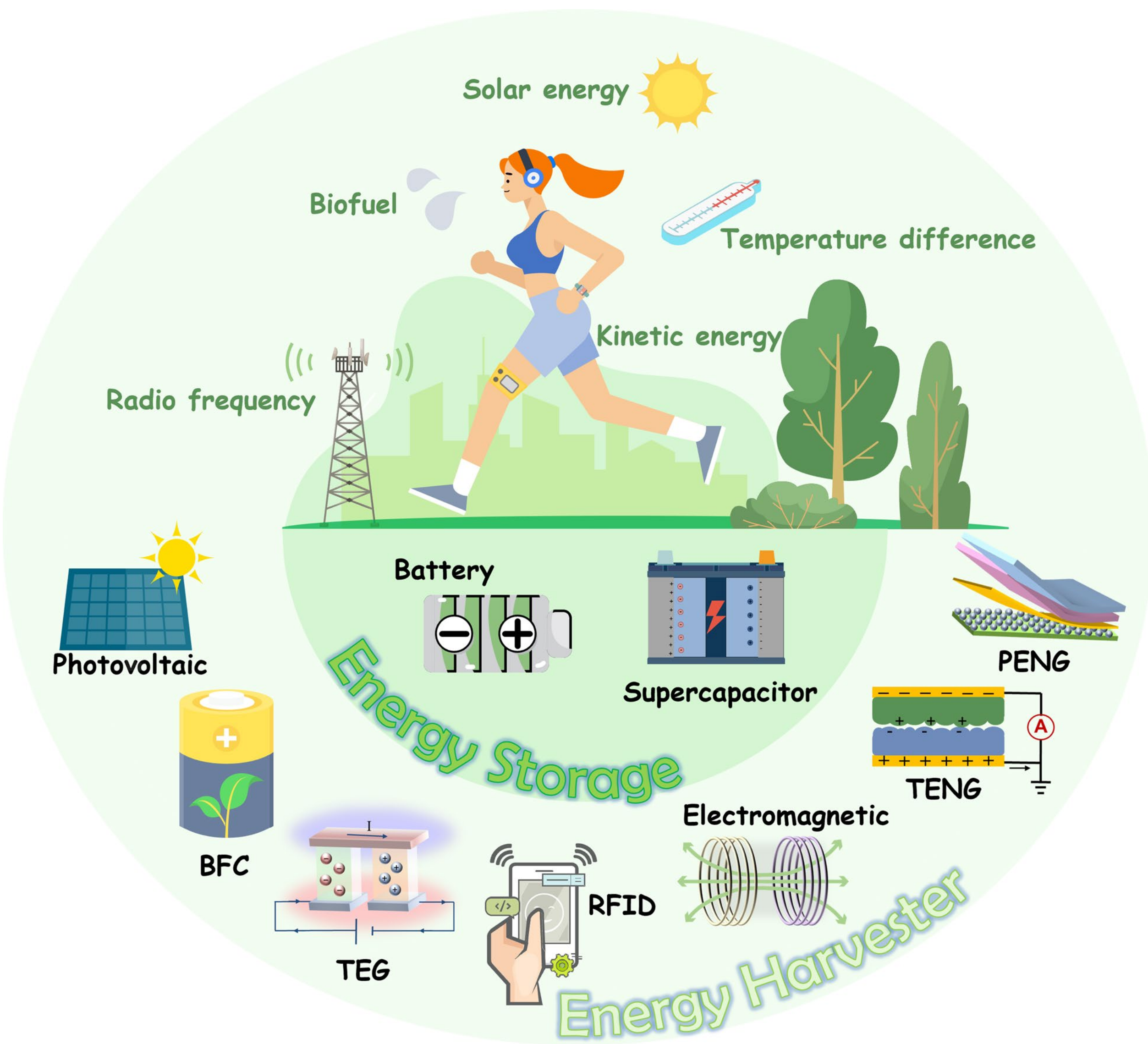
Graphic Abstract



Introduction

In recent years, significant theoretical and applied progress has been made in wearable sensors, which have advantages in terms of their light weight, portability, consistency, and comfort, as well as the ability to perform various functions when worn on the human body [1]. Wearable sensors can be embedded in products such as wristbands [2], eyeglasses [3], masks [4], and clothing [5], and used for real-time monitoring and collecting data for physiological indicators, including temperature [6], blood glucose [7], and blood pressure [8], as well as movement status data, such as acceleration [9], gait [10], and fall detection [11]. These data can be applied to help users comprehensively understand their health status and athletic performance. Subsequently, wearable sensors can establish communication connections with mobile terminals such as smartphones via Bluetooth or wireless networks [12], receive and analyze these data through applications, and finally upload them to the cloud for easy access by users and doctors at any time, thereby providing users with precise data support and a personalized experience.

Due to their capacity to continuously collect physiological data in real time, wearable sensors provide valuable insights to facilitate personalized health management and precision medical diagnosis, thereby changing the traditional monitoring model in healthcare [13]. However, a high-performance wearable sensing device cannot be operated in a stable and efficient manner without a suitable energy supply. An adequate, continuous, and stable supply of power is essential for the operation and reliable performance of devices. Due to technological development, demands for miniaturization, comfort, and user-friendly designs for wearable devices have become increasingly important in addition to pursuing functional diversity and superior performance, which are challenging problems for power supply module operation. To address these demands, the power supply module requires meticulous design and optimization in terms of its structure, size, power density, and energy output, and it is also necessary to consider critical factors, such as biocompatibility, weight, stability, and toxicity to humans.

Nanomaterials and nanotechnologies play crucial roles in addressing the challenge of producing flexible wearable sensors. The nanoscale size and high specific surface area of nanomaterials confer high sensitivity and rapid response capabilities [14]. Therefore, nanomaterials and nano-processing technologies have become popular solutions for improving the sensing performance of sensors, including the sensitivity, linearity, selectivity, and sensing range. In addition, nano-catalysts, nano-enzymes, and nanostructured membranes and interfaces can help address the instability of biological receptors and provide a viable approach for specific gas sensing through precise structural and chemical control [15]. The special electrical properties of some nanomaterials may facilitate the development of high-performance energy harvesting and storage devices. The high specificity surface areas and electrochemical activities of nanomaterials promote energy conversion at the material's interface, and they have been widely used in power supply modules for sensing systems in recent years.

Several previous excellent review articles have considered the topic of energy supply methods for wearable sensors [16–19]. However, they either focus on a few aspects, have not yet comprehensively summarized the power supply modes of wearable devices, or only emphasize on the application while lacking the introduction of the basic power conversion principle. In the present review, we systematically examine various power supply technologies applied in wearable sensing devices by focusing on the energy conversion principles of each power supply mechanism and the critical roles played by diverse materials (especially nanomaterials) in the power supply system, as well as typical applications. In addition, we summarize and explain the hybrid energy supply mode mixed with multi-source energy conversion and its application. In addition, we analyze and compare the characteristics of various power supply modes in order to provide reliable insights to facilitate the future design of power supply modules for wearable sensing systems. Finally, the main challenges and future development trends are summarized.

Power supply modules for wearable sensors

The early wearable sensing devices mostly used batteries as their power supply units. Due to the development of various battery technologies, they have become relatively mature and numerous power management strategies have been proposed to prolong the lifespan of batteries [20] and reduce their size [21]. However, the use of batteries imposes constraints on the volume and weight of wearable devices, thereby limiting their potential application range and comfort to a certain extent. In addition, the continuous monitoring of physiological parameters will be interrupted when the battery's charge is depleted, which will affect the accuracy of the data collected. Consequently, there is an urgent need to develop innovative power supply technologies to overcome the limitations of traditional batteries and provide a more durable, efficient, and stable energy supply. In recent years, various innovative power supply technologies have emerged to replace traditional batteries for wearable sensors, such as solar cells, supercapacitors (SCs) biofuel cells (BFCs), thermoelectric generators (TEGs), piezoelectric or triboelectric nanogenerators, and radio-frequency energy harvesting technologies.

Batteries and supercapacitors

Currently, batteries are still among the most widely used power supply methods for wearable devices. The structure of a battery generally comprises a positive/negative electrode, electrolyte, and diaphragm. The battery charging and discharging process is often accompanied by chemical reactions in the electrolyte, which convert chemical energy into electrical energy [22]. In particular, Li-ion batteries are commonly used, which are lightweight, with high energy storage density and good safety, where Li^+ is mainly embedded and de-embedded between the two electrodes [23]. Hou et al. [24] covalently coupled the transition metal sulfide ZnS with carbon nanotubes (CNTs) to prepare the anode material for Li-ion batteries. The ZnS nanoparticles in the composite and the compact ZnS-CNT heterogeneous interfaces were highly beneficial to promote electron/ion transfer and ensure structural stability (Fig. 1a), thereby leading to superior long-term stability and an excellent rate capability. The flexibility of Li-ion batteries is also an important research consideration in the field of wearable

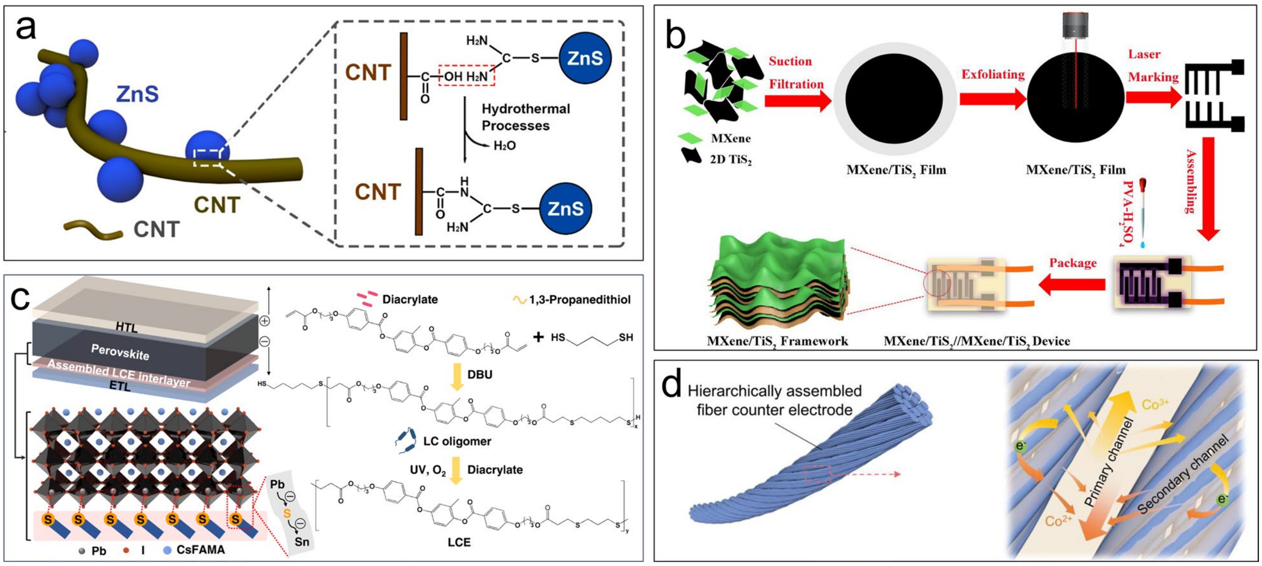


Fig. 1 The preparation or structural composition of batteries, SCs and solar cells. **a** Schematic illustration of the CC-ZnS/CNT preparation and its synthetic mechanism. The picture was reproduced from article published by Hou, Liu and co-workers in ACS Nano in the year 2021 [24]. **b** The schematic illustrations for technology process of flexible self-powering MXene/TiS_2-based device. The picture was reproduced from article published by Wang, Tang and co-workers in ACS Applied Materials and Interfaces in the year 2022 [30]. **c** Structure diagram and synthesis route of liquid crystal elastomeric oriented interface layer. The picture was reproduced from article published by Huang, Li and co-workers in Nature Communications in the year 2023 [35]. **d** Schemes of the hierarchically assembled CNT fiber (left) and enlarged view of hierarchical channels for rapid ion diffusion and charge transport (right). The picture was reproduced from article published by Kang, Zhu and co-workers in Advanced Functional Materials in the year 2022 [36]

electronics. He et al. [25] achieved the scalable production of high-performing woven lithium-ion fibrous batteries, with an energy density of 85.79 Wh/kg. The fabric woven from this fiber allowed the wireless charging of mobile phones as well as providing a power supply for health management jackets integrated with fiber sensor displays. In addition to Li-ion batteries, a small number of wearable sensing devices have used alkaline batteries [26] with simple processes and low costs, as well as fuel cells [27] characterized by fast response and environmental friendliness.

The capacity of batteries gradually decreases with usage and frequent charging is required. In addition to enhancing the capacity of conventional batteries, alternative power supply solutions are gradually being developed based on the trend toward miniaturization and lightweight wearable sensing devices. Supercapacitors (SCs) are characterized by a high power density, wide operating temperature range, and long cycle life [28]. Representative SCs are double layer capacitors, which usually consist of positive and negative electrodes, electrolyte, and diaphragm. The double layer structure can store more charge and the operating process only involves physical migration, so the electrolyte is not consumed, thereby resulting in a long cycle life. In addition, the electrodes are mostly made from carbon-based materials with high specific surface areas to further enhance the charge carrying capacity [29]. Wang et al. [30] designed an interdigitated MXene/TiS_2-based self-powered intelligent pseudocapacitive sensor system (Fig. 1b). Intercalation of the TiS_2 nanosheet effectively prevented the self-stacking of MXene to yield a mesoporous cross-linked framework, thereby exposing more active sites and broadening the channels for electron/ion transportation in the electrode material. An asymmetrical micro-SC prepared using this material exhibited a satisfactory energy density of 31.6 Wh/kg and retained 79.8% of the capacitance after 10,000 cycles. Jiang et al. [31] fabricated a flexible all-solid-state SC using hydrogel as the electrolyte, which also functioned as a strain sensor that could respond to various body movements and facial expressions. The hydrogel electrolyte was further assembled with an activated carbon/CNTs composite membrane electrode into an SC, with a high specific capacitance of 186.1 mF/cm^2, where it which exhibited a remarkable energy storage capacity and energy utilization efficiency.

SCs are characterized by a high power density and fast charging and discharging rates. However, their energy density is relatively low [32], and thus a larger mass is required to store the same amount of electricity. Their high cost also limits large-scale production and commercialization. Furthermore, both ordinary batteries and SCs may contain harmful metal substances that pose threats to human health and the ecological environment. Therefore, it is of great interest to develop harvesters that capture and convert energy from the environment to power wearable devices.

Photovoltaics and solar cells

Given the need for sustainable development, solar energy has become one of the most common energy sources used in wearable sensors because it is a clean energy source with abundant reserves [33]. Min et al. [34] reported an autonomous multimode wearable sweat sensor powered by a flexible quasi-two-dimensional perovskite solar cell module, with a conversion efficiency exceeding 31% under indoor light conditions. By dynamically adjusting its power consumption, the device maintains high power output under variable light conditions, ensuring continuous multimodal physiological data acquisition for over 12 h. In recent years, to enhance the flexibility of power supply modules, researchers have developed fibrous solar cells that are lightweight and flexible, and they can be readily matched to different parts of the body. For example, Huang et al. [35] introduced a reinforcement technique that involved building a structured charge transport pathway utilizing a liquid crystal elastomeric oriented interface layer (Fig. 1c). By enhancing charge collection efficiency and reducing interface charge recombination, they succeeded in boosting the efficiency of flexible solar cells to 22.10%. These solar cell chips were subsequently integrated into a wearable haptic device, showcasing their potential for use in pain sensation system. Kang et al. [36] prepared a hierarchically assembled CNT fiber counter electrode with high strength and conductivity. The hierarchically aligned channels with different sizes provided high-throughput channels and abundant active regions for the rapid diffusion of ions and charge transport (Fig. 1d). Moreover, the catalytic activity of the electrode was further enhanced through the electrodeposition of Pt nanoparticles. The resulting fiber dye-sensitized solar cell exhibited a power conversion efficiency of 11.94% and a power output of up to 22.7 mW.

The output performance of solar cells depends greatly on the intensity of sunlight and it is challenging to apply this technology to power wearable devices in low-light environments. However, efforts have been made to address this issue, where Surendran et al. [37] proposed a self-powered organic electrochemical transistor using carbon electrode-based perovskite solar cells, with a relatively low and tunable bandgap to allow sufficient spectral matching to drive electronic devices under variable light conditions.

Biofuel cells

Biofuel cells (BFCs) are special fuel cells that utilize biocatalysts such as microorganisms or enzymes instead of metal inorganic catalysts, and they can be basically classified into two types [38]. The first type comprises "secondary" or "indirect" cells where the biocatalysts simply facilitate the production of simple fuels (e.g., hydrogen or methane) from complex biochemical substrates (e.g., sugar). Subsequently, these simple fuels are oxidized by inorganic catalysts on the electrode's surface to generate electricity. The second type comprises "primary" or "direct" cells where the biocatalysts are directly involved in the redox reactions that generate electricity [39]. The current intensity and the electrical energy generated by BFCs are proportional to the fuel's concentration [40], so BFCs can be used to power biosensors and act as self-powered biosensors through various mechanisms, i.e., by using biofuels as target analytes or reaction inhibitors/activators and their concentration can be measured in this manner.

As an application of the first type of BFC, Wang et al. [41] developed a wearable BFC by using human sweat, urine, and glucose-containing soft drinks as biofuels (Fig. 2a). The main component of this system comprised a nano-engineered BFC with three functional layers of flexible and specially-patterned graphene electrode arrays induced by serpentine laser. This nanostructure was conducive to loading with a large amount of dense enzyme, and it also provided a continuous and unobstructed path for electron penetration and transport, which was beneficial for electron transfer at the interface of the bioanode and biocathode, thereby promoting the generation of electricity. Yin et al. [42] produced a BFC bracelet based on human sweat by using lactate from sweat as the biofuel, a lactate oxidase/CNT-based fiber for lactate oxidation, and a bilirubin oxidase/CNT-based fiber for oxygen reduction. The fiber-based BFCs were woven into a hydrophilic textile for sweat storage, and further fabricated into a bracelet for easy wearing, where it could produce an output voltage of 2.0 V. Yuan et al. [43] developed a highly self-adhesive polyvinyl acetate (PVA)-based hybrid BFC, where the PVA/succinic anhydride-polydopamine hydrogel exhibited high conductive properties, with an open circuit voltage of 0.50 V and maximum power density of 128.76 $\mu W/cm^2$.

In applications of the second type of BFC where biofuels are used as target analytes, the concentration can be detected while simultaneously generating electricity. Veenuttranon et al. [44] reported the first examples of screen-printable nanocomposite inks for energy harvesting devices and glucose driven self-powered biosensors. The anode and cathode ink were modified with naphthoquinone/multiwalled CNTs (MWCNTs) and Prussian

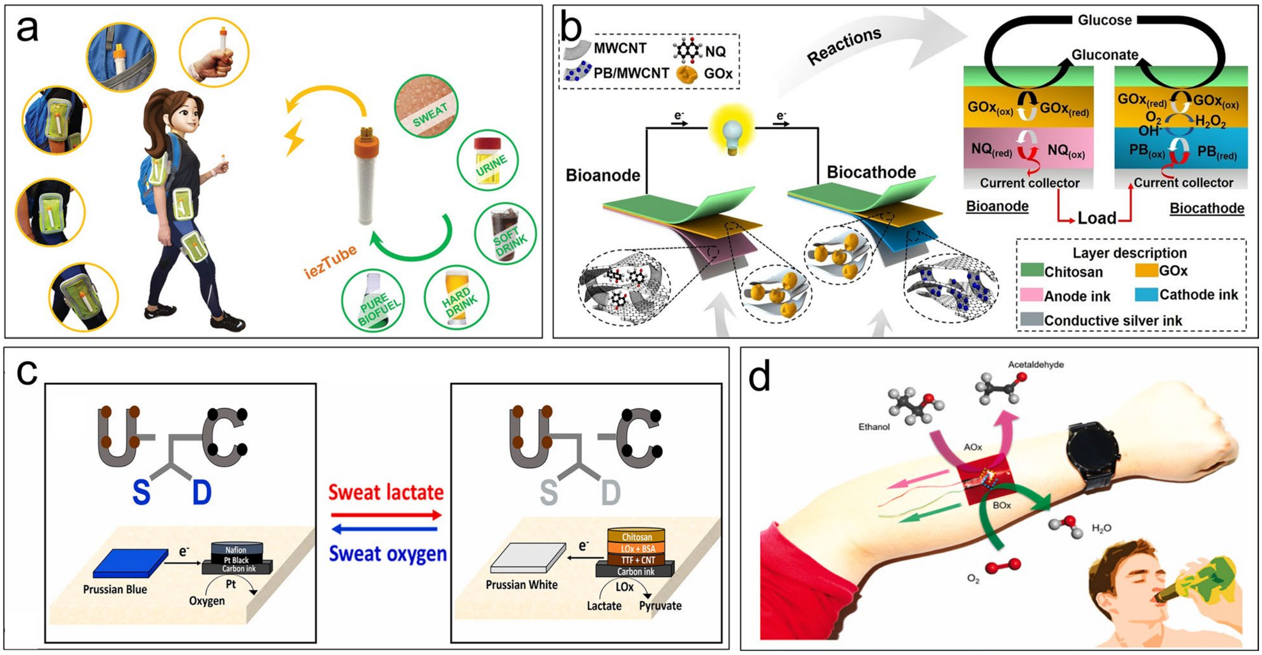


Fig. 2 Schematic illustration of the mechanism and structure of various BFCs. **a** Nanostructured biofuel cells can be worn on different body parts and utilizes various easily accessible green biofuel fluids for bio-energy harvesting. The picture was reproduced from article published by Wang, Sun and co-workers in Advanced Functional Materials in the year 2022 [41]. **b** The components of a screen-printed glucose BFC along with redox reactions occurring on the bioanode and the biocathode. The picture was reproduced from article published by Veenuttranon, Kaewpradub and co-workers in Nano-Micro Letters in the year 2023 [44]. **c** Working principle of self-powered and fully printed electrochromic self-powered sensor. The picture was reproduced from article published by Hartel, Lee and co-workers in Biosensors and Bioelectronics in the year 2022 [45]. **d** Illustration of an epidermal ethanol BFC that on-body and real-time harvests bioenergy from human sweat of people who consume alcohol. The picture was reproduced from article published by Sun, Gu and co-workers in Nano Energy in the year 2021 [46]

blue (PB)/MWCNT hybrid, respectively (Fig. 2b). The incorporation of MWCNT provided a more stable site for enzyme adsorption, and the combination with PB increased the charge transfer rate, thereby improving the electrical properties and stability of the electrodes. The BFC prepared using this ink exhibited an open circuit voltage of 0.45 V and a maximum power density of 266 μW/cm^2. When coupled with a wireless wearable device, the system could convert chemical energy into electrical energy using glucose from sweat, and detect glucose concentrations as low as 10 mM. Hartel et al. [45] developed a self-powered fully printed electrochromic sensor for in situ sweat lactate monitoring, which integrated a BFC module fueled by lactate and a reversible PB electrochromic display. The BFC anode was modified with tetrathiafulvalene and MWCNT for lactate oxidation, and the cathode was modified with Pt black for oxygen reduction (Fig. 2c), where the MWCNT also contributed to enzyme immobilization as well as the electrical properties. The device had a power density of 13 μW/cm^2 and it was powered entirely autonomously by lactate from human sweat.

The BFCs mentioned above all utilized endogenous substances from the human body (such as glucose or lactate) as the fuel source. Sun et al. [46] developed a noninvasive exogenous ethanol/oxygen BFC based on human sweat after alcohol ingestion (Fig. 2d) for the first time. The enzymatic screen-printed electrode arrays utilized three-dimensional (3D) coralloid N-doped hierarchical-micro-mesoporous carbon aerogels as the substrate in the core of the BFC module. This morphology allowed high-mass enzyme loading and provided unobstructed channels for species transport. The results obtained based on in vivo experiments indicated that the peak power collected by the system on the skin was 1.01 μW/cm^2. The power generation level did not match that of other BFCs that utilized glucose or lactate as fuel, but it overcame the limitations imposed by endogenous substances, thereby providing a novel approach for bioelectronics research. Thus, from the perspective of the design of wearable sensors, BFCs can utilize the body's own reactants such as glucose and lactate, which can also serve as target analytes. Therefore, integrating BFCs with biochemical sensors can simplify their design. However, the output power of BFCs depends greatly on the fuel concentration, thereby necessitating stringent fuel supply mechanisms (such as the design of rational microfluidic channels for sufficient sweat infiltration). The energy conversion efficiency of BFCs also needs to be improved.

Thermoelectric generators

The human body continuously generates heat during its daily metabolism. According to statistics, the power of body heat ranges from 100 to 525 W [47], thereby allowing the application of thermal energy collection techniques to convert body heat into electricity, which is rapidly becoming a novel approach for powering wireless and portable sensor devices. The fundamental principle of thermoelectric conversion devices is the Seebeck effect, which is a thermoelectric conversion phenomenon where a voltage difference is induced by a temperature difference between two different electrical conductors or semiconductors. Solid-state devices that utilize this effect are known as TEGs, where they typically exploit the temperature difference between the human body and the surrounding environment to capture energy and convert it into a useful electrical output.

Standard TEG modules typically employ tellurium (Te), bismuth (Bi), antimony (Sb), or selenium (Se) as their crucial component comprising the thermoelement (TE). Bi_2Te_3 and Sb_2Te_3 alloys are the most commonly used thermoelectric materials due to their high thermoelectric conversion efficiency at room temperature [48]. The presence of nanostructures (quantum wells or quantum dots) alters the transport of electrons or phonons in the material to significantly enhance the ZT value for the material and improve the thermoelectric conversion efficiency [49]. Du et al. [50] deposited Bi_2Te_3 nanocrystals in a conductive porous poly (3,4-ethylenedioxythiophene) (PEDOT) nanowire scaffold to prepare a flexible sandwich-like TE film (Fig. 3a). The particle sizes of Bi_2Te_3 nanocrystals were concentrated in the range of 100–250 nm and introducing nano/micro-structured Bi_2Te_3 nanocrystals promoted the carrier transport and electrical performance. The Bi_2Te_3@PEDOT nanowire film exhibited a record Seebeck coefficient of 266.4 mV/K with a power factor of 740.2 mW/m/K^2 at room temperature, and the corresponding maximum output power density of the TEG at a temperature difference of 17.8 K was 3.48 μW/cm^2, and thus the constructed temperature sensor arrays exhibited excellent stability and thermal sensitivity. Li et al. [51] prepared conductive and stretchable graphene/polymer TE threads for energy harvesting

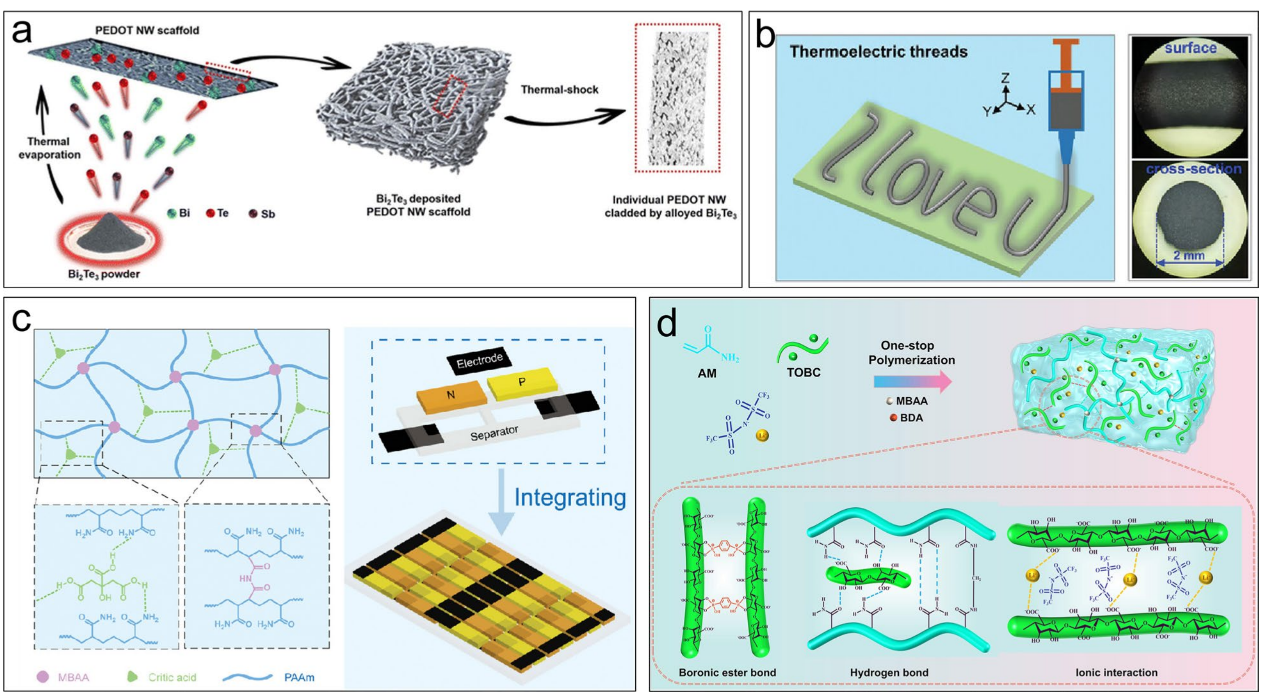


Fig. 3 The preparation process or material structure of various TEGs. **a** Schematic illustration of the preparation process of Bi_2Te_3@PEDOT nanowire sandwich-like films. The picture was reproduced from article published by Du, Ouyang and co-workers in Journal of Materials Chemistry A in the year 2023 [50]. **b** The preparation schematic diagram (left) and the optical micrograph of the TE threads (right). The picture was reproduced from article published by Li, Zhang and co-workers in Small in the year 2023 [51]. **c** Schematic illustration of the structure of PAAm hydrogel (left) and the integration of stretchable thermocell device (right). The picture was reproduced from article published by Xu, Sun and co-workers in Advanced Energy Materials in the year 2022 [52]. **d** Schematic of the fabrication process and chemical structure for the ionic thermoelectric hydrogel. The picture was reproduced from article published by Chen, Lou and co-workers in Carbohydrate Polymers in the year 2023 [54]

and wearable sensing by using the 3D extrusion method (Fig. 3b). Graphene has a large specific surface area, and diverse boundary structures, which promote the synergistic regulation of electrical and thermal properties. After regulating the graphene content, the optimized TE threads had a Seebeck coefficient of 37.2 μV/K, which allowed the self-powered monitoring of physiological signals, such as the respiratory and pulse rates, as well as the bite frequency and force of the teeth during feeding.

A thermoelectric hydrogel is a quasi-solid material with excellent thermoelectric properties and it is widely used in thermoelectric conversion devices. Due to its flexibility and stretchability, thermoelectric hydrogels can be designed as flexible materials with variable degrees of hardness and thickness, but also fabricated into thin films that conformally adhere to the skin surface. For example, Xu et al. [52] developed a wearable thermocell and used polyacrylamide (PAAm) with good mechanical properties as the crosslinked network. The hydrogel with a 3D crosslinked network structure formed by further combining the crosslinker N,N′-methylenebisacrylamide and citric acid is illustrated in Fig. 3c. After integrating with graphite paper electrodes, the hydrogel thermoelectric device achieved a voltage output of 0.16 V ($\Delta T = 4.1$ K) and it could potentially be used in wearable sensing systems. In order to achieve efficient thermoelectric conversion of low-grade heat energy in the human body, Kong et al. [53] reported a PEDOT:PSS/polyvinyl alcohol hydrogel composite using Te nanowires doping. The incorporation of Te nanowires can provide more paths for the transport of electrons and holes, and by modulating its content, the optimized hydrogel achieved a Seeback factor of 878 μV/K. When fabricated into a wearable thermoelectric module and applied to the arm, the output voltage can reach 138 mV. Chen et al. [54] used PAAm as a crosslinked network to prepare a super-stretching ionic thermoelectric hydrogel based on a double interpenetrating network structure (Fig. 3d). Lithium bis(trifluoromethane) sulfonimide (Li TFSI) was utilized as the ion provider for thermal diffusion and its interaction with the hydrogel matrix facilitated the selective transport of conducting ions, resulting in a high Seebeck coefficient of 11.53 mV/K. The self-powered sensor based on this ionic thermoelectric hydrogel was capable of identifying and monitoring physiological motions of human body.

In recent years, great progress has been made in the research of thermoelectric fibers/yarns, which further improves the stretchability of thermoelectric devices. He et al. [55] loaded CNT and PEDOT:PSS on each nanofiber through electrospinning and self-assembly strategies, greatly enhancing the interaction between the thermoelectric material and the nanofiber, and the obtained thermoelectric yarns showed good thermoelectric properties and stretchability. The self-powered strain sensors composed of the yarns can be used to optimize a basketball player's hit rate, and integrating the yarn into a mask can also enable breathing monitoring. In conclusion, TEGs have a longer lifespan compared with other power generation systems and they do not rely on moving parts or light illumination, while they are also environmentally friendly with no harmful pollutant emissions or environmental chemical reactions. In addition, TEGs are capable of harnessing low-grade thermal energy from the human body without the need for tester movement, thereby making them particularly suitable for daily care of the elderly, disabled individuals, and prolonged monitoring of vital signs and chronic diseases.

Radio frequency identification

Radio frequency (RF) refers to the oscillatory frequency of an alternating current or voltage, as well as the associated electric, magnetic, or electromagnetic fields [56]. RF identification (RFID) is a reliable method for powering wireless wearable sensors, thereby allowing the transmission of sensing signals and providing a power supply through wireless information and power transfer [57]. The principle is mainly based on collecting RF energy from an interrogator using a high-frequency antenna and retransmitting information in the tag back to the interrogator [58]. This method can provide green, stable, and continuous power for wireless sensor networks, and thus it is of great interest for wearable sensing.

Liu et al. [59] prepared a wearable RF energy-localized harvester with multiple antennas and spoof surface plasmon structure (Fig. 4a) for multibeam radiation to power a Bluetooth sensor module. The device was made entirely from flexible conductive fabrics, which were readily integrated with rectifier and power management units that could be further integrated into clothing and worn on the human body, with an output power density of 2.75 μW/cm^2, and thus exceptional potential for powering wearable electronic devices. Li et al. [60] screen-printed innovative RF resonator circuits using MXene ink. Due to the reliable mobility and conductivity of the MXene ink, it can be patterned on different flexible substrates with high resolution, good conductivity, and robust mechanical strength. Moreover, the use of MXene-reduced palladium nanoparticles facilitates the response to ethylene and reduces the detection limit. When used in combination with a portable vector network analyzer, this plant wearable sensor tag with integrated RF antenna and gas sensor can allow the in situ wireless detection of ethylene and further transmit the data to a mobile terminal for dynamic display and analysis (Fig. 4b).

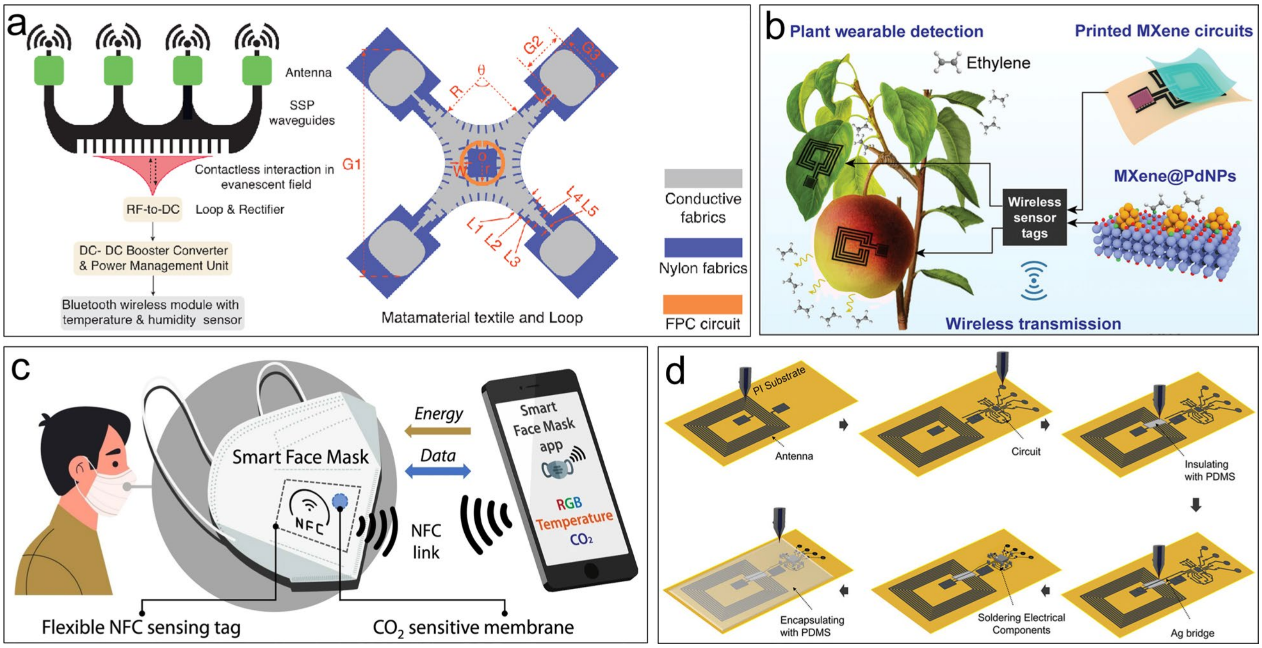


Fig. 4 Application scenarios or preparation processes of different RFID devices. **a** Block diagram of the complete wearable RF energy harvester (left) and the structure and geometry of the RF energy-localized harvester (right). The picture was reproduced from article published by Liu, Wu and co-workers in IEEE Internet of Things Journal in the year 2022 [59]. **b** Scheme of the all-MXene printed plant wearable sensors for wireless ethylene detection. The picture was reproduced from article published by Li, Sun and co-workers in Small in the year 2023 [60]. **c** Scheme of the NFC-based smart facemask for wireless CO_2 real-time determination. The picture was reproduced from article published by Escobedo, Fernández-Ramos and co-workers in Nature Communications in the year 2022 [65]. **d** Schematic diagram of the manufacturing process of 3D printed wireless pH sensor patch. The picture was reproduced from article published by NajafiKhoshnoo, Kim and co-workers in Advanced Materials Technology in the year 2023 [68]

Near field communication (NFC) is a technology derived from RFID that utilizes near-field inductive coupling at a fundamental frequency of 13.56 MHz to transmit and receive energy as well as information [61]. Compared with traditional RFID, NFC does not require expensive and bulky readers because most readers are now integrated into smartphones. When operating in wireless charging mode, NFC can achieve a transmission power of up to 1 W [62], which is sufficient to power small wearable devices. Due to its small size and simple operation, NFC has been widely used in the design of wearable devices in recent years. For example, the sweat detection patch designed by Shi et al. [63] and the wearable sensor for nicotine gas detection prepared by Rahman et al. [64] used NFC chips for wireless energy collection and data interaction with a smartphone. In addition, the CO_2 sensing platform inside the facemask developed by Escobedo et al. [65] comprised an opto-chemical sensor combined with a flexible NFC tag (Fig. 4c), and a customized smartphone application was implemented for wireless powering, data analysis, results display and alert management.

The NFC antenna parameters (e.g., resonance frequency, input reflection coefficient, bandwidth, and quality factor) are crucial determinants of the effectiveness and distance of communication [66]. In particular, the use of nanomaterials allows the production of antennas with superior flexibility, adjustability, and durability. For instance, Scidà et al. [67] prepared NFC devices based on flexible antennas composed of stacked graphene multilayers. Graphene possesses high conductivity comparable to single-crystal graphite but with superior flexibility and processability. After hundreds of thousands of bending cycles, minimal variation was observed in the antenna's self-resonance frequency, and it outperformed the standard commercial metal antennas. NajafiKhoshnoo et al. [68] developed a flexible 3D-printed system with an integrated non-invasive pH sensor and NFC-based communication circuitry for real-time, wireless, in-situ pH monitoring. The NFC coil in the system with a width of 400 μm and spacing of 400 μm was made by 3D printing using nanoparticle silver ink (Fig. 4d), and the output voltage remained stable at approximately 2.17 V, with good mechanical properties. In general, NFC is compatible with smart devices to allow convenient and efficient usage. However, it requires precise alignment between the transmitting and receiving coils (typically < 2 cm). The associated power transfer efficiency drops sharply when the coils are separated, which make it unsuitable for continuous data recording.

Compared with other energy supply methods, RF energy harvesting is unaffected by the lighting, physical motion, or temperature conditions. However, it is often necessary to consider the alignment, matching, and transmission distance between the transmitting and receiving ends. Inaccurate alignment between these ends may lead to signal attenuation or distortion, which affects the efficiency of energy harvesting. Moreover, different devices have various requirements for RF signals, and thus it is necessary to match the parameters between the two ends to ensure the transmission of signals and collection of energy. Finally, the limited transmission distance is also a challenge that affects this technique. Therefore, it is imperative to conduct a thorough evaluation and analysis of the application scenario and select appropriate technical solutions accordingly.

Kinetic energy harvesters

The human body can generate a large amount of thermal energy and mechanical energy while performing daily activities. Kinetic energy harvesters work by converting kinetic energy produced by the human body, such as electromagnetic energy harvesters that operate on the basis of Faraday's law. In recent years, due to the rapid development of nanotechnology, the emergence of piezoelectric nanogenerators (PENGs) [69]and triboelectric nanogenerators (TENGs) [70] has led to revolutionary changes in the power supply for wearable electronic devices. All of these methods can effectively convert the kinetic energy generated by human activities into electrical energy to provide a reliable power supply for wearable sensors.

Electromagnetic energy harvesters

According to Faraday's Law of Electromagnetic Induction, variations in the external magnetic field generate an electric current in the induction coil of the wearable device (Fig. 5a), enabling wireless power supply. For instance, Wu et al. [71] investigated an electromagnetic resonance wearable energy harvester. The resonant generator is composed of a permanent magnet connected by two elastic strings, housed inside a rectangular box. This configuration provides the resonator with three degrees of freedom, aligning well with the frequency range of human motion. The study demonstrated that the developed harvester can be attached to a shoe to continuously power wearable sensors. In the wearable respiratory monitoring sensor developed by Bošković et al. [72], the electromagnetic energy harvested from the human body reaches up to 100 mV, which is further modulated using nanostructured electrochemically activated aluminum fork-finger capacitors. This signal is rectified by a set of Schottky diodes and finally measured by a voltmeter. Electromagnetic harvesting can serve as a power source in applications with low power requirements. However, in most scenarios, it is used in conjunction with other power supply modes, as detailed later.

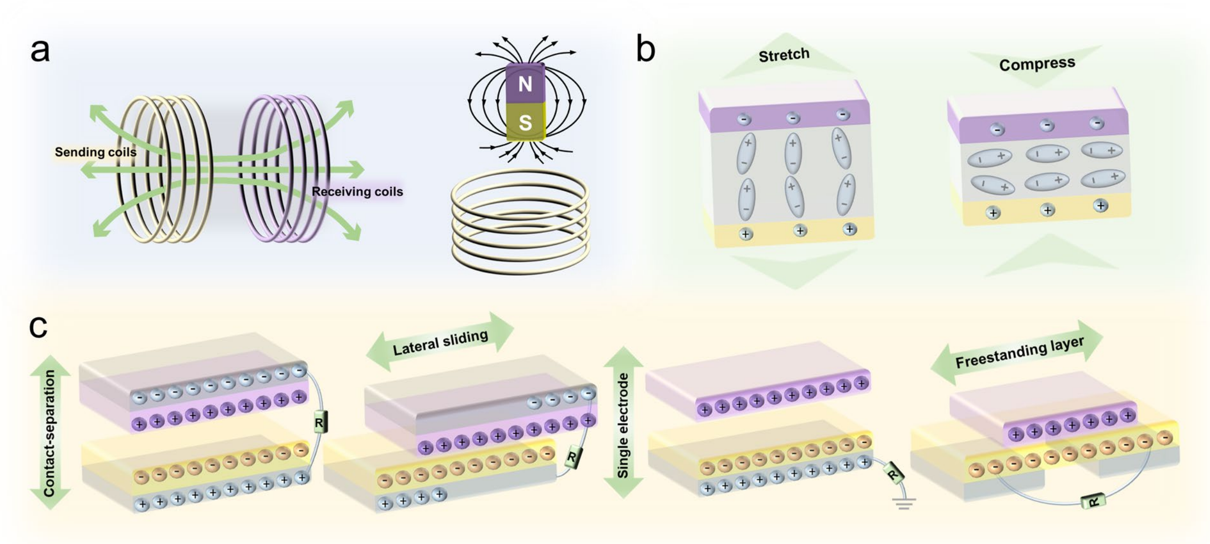


Fig. 5 The working principle of **a** electromagnetic energy harvesters, **b** PENGs, and **c** TENGs

Piezoelectric nanogenerator

The operation of a PENG is based on the piezoelectric effect. When a piezoelectric material deforms under mechanical force, it becomes polarized inside to generate positive and negative charges on the two opposing surfaces, thereby converting mechanical energy into electrical energy (Fig. 5b). Piezoelectric ceramics are a typical class of inorganic piezoelectric materials, and they usually have wurtzite or perovskite crystal structures. The inherently brittle nature of piezoelectric ceramics makes them unsuitable for bending deformation during wear on the human body [73], so nanoparticles are typically incorporated into organic polymer matrices (e.g., polyvinylidene fluoride (PVDF) or polydimethylsiloxane (PDMS)) to create PENGs that combine both piezoelectricity and mechanical flexibility. Shao et al. [74] constructed fabric piezoelectric energy harvesters by introducing $BaTi_2O_5$ nanorods into PVDF nanofibers with dual orientation structure through electrospinning (Fig. 6a). Due to the strong piezoelectric activity of $BaTi_2O_5$ nanorods and the bi-oriented architectures of the composite nanofibers, the device exhibited excellent output performance, with a maximum output voltage of 31.2 V and a high sensitivity of 5.22 N/V as a self-supplied pressure sensor, and it could be used for multimodal human motion monitoring. Another commonly used perovskite-type piezoelectric ceramic is lead zirconate titanate (PZT), which is one of the most widely applied piezoelectric materials [75]. PZT can be employed in various forms (e.g. nanowires, nanorods, or nanofibers) to produce high-performance flexible nanogenerators. For example, Guan et al. [76] developed a self-powered wearable PENG for physiological monitoring based on a composite film of PZT nanoparticles, micro-fibrillated cellulose, and PVA. The piezoelectric property of the composite material was primarily attributed to the PZT nanoparticles, and the principles of polarization and voltage output are shown in Fig. 6b. PZT formed domains after polarizing spontaneously and the direction of the internal domain was changed indirectly by external force through the conduction of the matrix to generate the piezoelectric potential. The PENG made of this material had a maximum output voltage of 16.5 V and power of 3.3 μW. ZnO with a wurtzite structure is also a very commonly used piezoelectric conversion material. Mahapatra et al. [77] grew ZnO nanorods via the hydrothermal method and incorporated them into PVDF matrices, and then sandwiched the ZnO:PVDF composite film between Al electrodes to prepare flexible free-standing PENGs. The nanofiller ZnO had a high dipole moment, which improved the polarization strength of the composites. The PENGs could also act as nucleation sites to form polarized domains in the PVDF matrices and enhance the piezoelectric properties. At present, due to environmental and safety concerns, lead-free piezoelectric

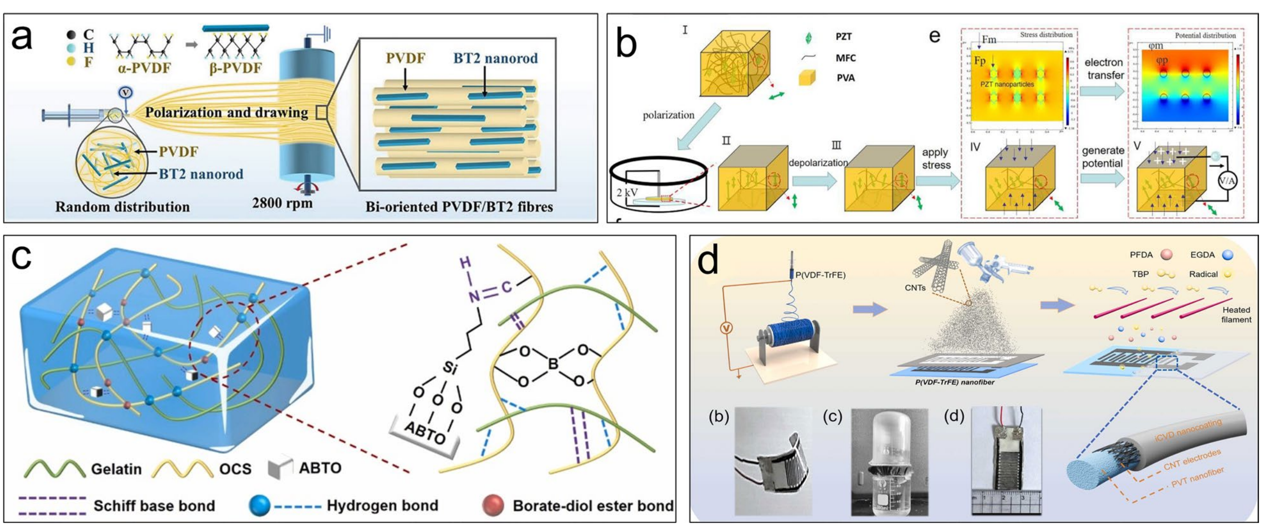


Fig. 6 Schematic representation of the preparation or structure of various PENGs. **a** Diagram of the electrospinning process of bi-oriented PVDF/$BaTi_2O_5$ nanofibers. The picture was reproduced from article published by Shao, Zhang and co-workers in Small Methods in the year 2023 [74]. **b** The polarization (left) and working principle (right) of PENG. The picture was reproduced from article published by Guan, Bai and co-workers in Chemical Engineering Journal in the year 2023 [76]. **c** Molecular interaction among gelatin, oxidized chondroitin sulfate and surface-aminated piezoelectric barium titanate nanoparticles. The picture was reproduced from article published by Fu, Zhong and co-workers in Nano Energy in the year 2023 [80]. **d** Preparation process of self-powered PENG sensor. The picture was reproduced from article published by Su, Huang and co-workers in Nano Energy in the year 2023 [81]

ceramic potassium sodium niobate (KNN) has gradually gained popularity among researchers and industry professionals. Athira et al. [78] incorporated ferroelectric KNN nanoparticles into the host PVDF matrix via a facile solid-state route accompanied by high energy ball milling. Due to the synergistic association between the ferroelectric KNN nanoparticles and PVDF, the electroactive β-phase and crystallinity increased significantly to enhance the piezoelectric properties of the prepared material.

Organic polymers comprise another class of piezoelectric materials, which are generally flexible and can withstand large mechanical strains [79], but their piezoelectric strain coefficients and electromechanical coupling factors are not very high. Therefore, other nanoparticles are often introduced to enhance their piezoelectric properties. For instance, Fu et al. [80] utilized surface-aminated piezoelectric barium titanate nanoparticles, gelatin and oxidized chondroitin sulfate to prepare a composite piezoelectric hydrogel with good stretchability, biocompatibility, and self-powered capability. The surface-aminated piezoelectric barium titanate nanoparticles were bonded on the oxidized chondroitin sulfate through Schiff base bonds (Fig. 6c), which improved the mechanical properties of the matrix and conferred piezoelectric properties, with output voltages of up to 85–90 mV and sensitivity of up to 49.61 mV/Kpa. Su et al. [81] reported a PENG sensor consisting of an electrospun poly (vinylidene fluoride-co-trifluoroethylene) piezoelectric nanofiber membrane and spray-coated interdigitated CNT electrodes. Chemical vapor deposition was further applied to encapsulate the sensor in a hydrophobic nano-coating to ensure its chemical stability and mechanical durability (Fig. 6d). Dynamic pressure could be detected in a linear manner over a range of 5–200 × *g* with a sensitivity of 0.35 V/kPa, and the voltage generated under pressure could be used to power sensing recording devices.

Moreover, other classes of piezoelectric materials naturally occur in nature, such as fish scales [82], eggshell membranes [83], and spider silks [84]. Bairagi et al. [85] developed a piezoelectric energy harvester based on the membrane of pomelo fruit, and its piezoelectric properties were attributed to the complex network structure among cellulose, hemicellulose, and pectin. In conclusion, it is evident that the piezoelectric conversion mechanism can harness the mechanical energy generated by human motion to power wearable electronic devices, and reflect information regarding the pressure applied, such as its magnitude, location, and frequency. Therefore, PENGs can be used as power supply units as well as sensing components to directly detect the pressure or tactile signals, which reduces the system design complexity.

Triboelectric nanogenerator

The principle of TENG can be summarized as two steps comprising the generation of electrostatic charges through the contact electrification effect and the generation of external electrical current through the electrostatic induction effect [86]. When two triboelectric materials with different electronic gain and loss characteristics come into contact with each other, they generate equal amounts of different charges. During contact and separation, the change in the potential difference caused by electrostatic induction leads to rearrangement of the charges on the electrode. This rearrangement prompts the transfer of charges in the external circuit to achieve a new equilibrium [87], thereby generating a current. Figure 5c illustrates the four typical working modes of the TENG.

Triboelectric materials are usually required to be stretchable and self-healable for wearable applications. There has been some work in the past few years devoted to the development of such devices [88–91], demonstrating the TENG's ability as a next-generation soft power source. By dispersing conductive nanofibers or nanoparticles into stretchable matrices, composites with both conductivity and stretchability can be obtained, and the surface charge density and triboelectric properties are increased. In the flexible TENG based on bilayer structured films prepared by Kim et al. [92], one layer comprised parylene derivatives with diverse functional groups and the other was a PDMS composite layer embedded with MWCNTs (Fig. 7a). The differences in permittivity and conductivity between the two layers resulted in highly improved interfacial polarization, with substantially improved triboelectric performance, where the output power densities were 4.57 W/cm^2 and 10.28 W/cm^2 in the contact and separation phases, respectively. Han et al. [93] also used MWCNTs as fillers and chitosan as the matrix to prepare composite films, and constructed a TENG with high energy harvesting performance. Due to Maxwell–Wagner relaxation, the utilization of MWCNTs as the conductive filler significantly enhanced the dielectric constant of the films. Sardana et al. [94] synthesized a TENG with high output performance by pairing highly conductive MXene nanofibers and degradable cellulose acetate nanofibers as triboelectric layers. By integrating and assembling this TENG with an NH_3 monitoring module in an insole (Fig. 7b), the energy harvested from foot movements can be utilized to power the sensor for sensitive detection and early warning of environmental NH_3.

Hydrogels are highly stretchable and can also be made into fibrous mesh structures, which makes them very suitable for use as matrix materials for TENGs. Kim et al. [95] synthesized a self-healable biological hydrogel

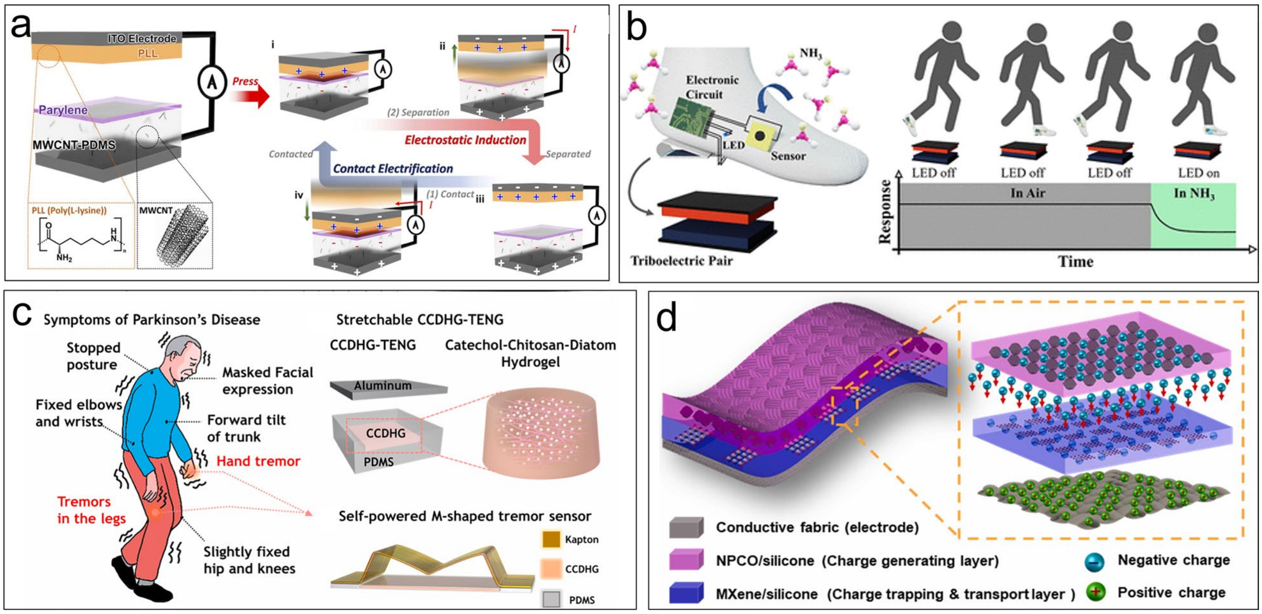


Fig. 7 The power generation mechanism or structural composition of the TENGs. **a** Schematic illustration of a TENG based on bilayer structured films and its working mechanism. The picture was reproduced from article published by Kim, Lee and co-workers in Nano Energy in the year 2024 [92]. **b** MXene/cellulose acetate TENG-powered smart insoles for NH_3 monitoring. The picture was reproduced from article published by Sardana, Kaur and co-workers in ACS Sensors in the year 2022 [94]. **c** Schematic diagram of the structure of the integrated tremor sensor for Parkinson's monitoring. The picture was reproduced from article published by Kim, Lee and co-workers in Nano Energy in the year 2021 [95]. **d** Schematic illustration of fabric-type TENG based on composite nanomaterials. The picture was reproduced from article published by Rahman, Rana and co-workers in Nano Energy in the year 2022 [96]

electrode based on three naturally occurring marine biomaterials comprising catechol, chitosan, and diatoms. The TENG device based on this electrode had a maximum open circuit voltage of 110 V, short circuit current of 3.8 μA, and instantaneous power density of 29.8 mW/m^2. The device was integrated with M-shaped Kapton film to prepare a highly sensitive self-powered tremor sensor (Fig. 7c), and combined with a machine learning algorithm for the real-time health monitoring of Parkinson's patients.

Many studies have investigated the development of fibrous TENGs (FTENGs) and fabric-based sensors, which have promising applications in the field of wearable sensing due to their good adherence to human skin. For example, Rahman et al. [96] prepared a new type of stretchable TENG using nanocomposite comprised of metal-organic framework-derived nanoporous cobalt oxide, silicone and MXene (Fig. 7d). The high nanoporosity of cobalt oxide induced high charge accumulation to increase the electronegativity of the nanocomposite, and MXene/silicone with the capacity for charge trapping and charge transport significantly improved the electronegativity of the nanocomposite. Due to the synergistic effects among the nanocomposites, the FTENG exhibited good stretchability and a high power density of up to 10.4 W/m^2, and it has been applied in plantar pressure distribution sensor arrays and wearable keyboards. Zhang et al. [97] fabricated a thermoplastic fiber from polyurethane/silver flakes by wet spinning, before further coating with a water-borne polyurethane thin layer and liquid metal coating to obtain a composite triboelectric fiber material. After PDMS packaging, the single-electrode FTENG produced a maximum output voltage, current, and transferred charge of 7.5 V, 167 nA, and 3.2 nC, respectively. The FTENGs could be used as self-powered sensors to detect joint bending, as well as for pressure and location identification. Recently, a high-performance and stretchable wearable nanogenerator based on polarization-induced ultra-stretchable micro/nano-fibers has been developed [98]. Due to the coupling effect of compositional engineering and polarization-induced surface charges and triboelectric-induced surface charges, it exhibited higher performance than other stretchable textile-based nanogenerators. It can be used as a self-powered pressure sensor and has proven potential in the field of machine learning-enabled intelligent sensing system.

In addition to the research into triboelectrification described above, the team led by Wang proposed the tribovoltaic effect [99] as the charge transfer generated by the mutual friction between semiconductors, thereby extending the triboelectric materials from organic polymers to semiconductors. With its direct-current output characteristics and significant current density, the tribovoltaic nanogenerators (TVNGs) have become emerging new devices for high entropy energy conversion [100]. In the past two years, many teams have begun to focus on the development of sensors based on TVNGs [101–103], and we look forward to the early application of this potential technology in the field of wearable electronics. In addition, according to the applications described above, there is great potential for the further development of fiber TENGs, especially electronic skin or flexible fabrics, as well as other uses. Moreover, due to the rapid development of the big data era, TENGs can be used in conjunction with AI for intelligent monitoring and control of the energy conversion process, and to improve the energy utilization efficiency and system performance.

Hybrid power supplies for wearable sensors

The overall power density and sustainability can be improved by using a hybrid power supply comprising a combination of different energy sources. A typical hybrid energy harvesting system consists of an energy harvester module and an energy storage module. In the following, we describe the hybrid power supply methods that are commonly used at present.

TENGs and PENGs

Both the triboelectric effect and piezoelectric effect utilize the mechanical energy generated by human activities to convert it into electricity, and thus they can be effectively combined to produce more efficient outputs in wearable sensors. Abdullah et al. [104] synthesized KNN particles using a wet ball milling technique and then incorporated them into a PVDF matrix together with MWCNTs, and the structural compositions of the TENG and PENG are shown in Fig. 8a. The MWCNTs promoted the conductivity of the composites by creating a 3D network within the matrix, which decreased the electron flow during triboelectric and piezoelectric actions. The output voltage was 28.8 V higher compared with those obtained in previous studies that used KNN and PVDF due to the combination of triboelectricity and piezoelectricity. Similarly, in Zhu et al. [105] study on stretchable PENG-TENG devices, the electrical performance of a single PENG, single TENG, and PENG-TENG coupler were compared, where the results showed that the average output voltages under the same conditions were 3.96 V, 3.08 V, and 8.6 V, respectively. Thus, the PENG-TENG coupler combined the advantages of the TENG and PENG to produce a higher output and allow more accurate detection under complex conditions. Wang et al. [106] proposed wearable bending wireless sensing by using piezoelectric and triboelectric hybrid nanogenerators, which harvested energy from finger bending motions while generating frequency and angle signals. In contrast to previous methods, this sensor used the response of the TENG as the trigger signal, the PENG voltage data measured at the trigger time as the finger bending angle, and the pulse time difference generated by bending and stretching was recorded as the finger movement time, and the sensing information was then wirelessly transmitted to an intelligent terminal (Fig. 8b). This sensing and communicating mode with an autonomous wake-up function can reduce the computation and power consumption of the system, thus providing more possibilities for wireless health monitoring.

Electromagnetic energy harvesters and TENGs and PENGs

Human movement is a combination of various low-frequency vibrations. Electromagnetic energy harvesters used in combination with TENGs or PENGs can broaden the frequency applicability range and improve the adaptability to various applications. For example, the power generating unit in the self-powered and superhydrophobic pressure sensor (Fig. 8c) developed by Cheng et al. [107] combined triboelectric and electromagnetic technologies, and this hybrid power generation system exhibited ideal complementary high voltage and high current characteristics, and wider operating bandwidth, thus provided more efficient vibration energy conversion. In addition, the device's inductive performance and electrical conductivity were significantly enhanced by the MXene materials and the bio-inspired dual Merkel's disk structure. Since the electrical energy conversion of both EMG and TENG is strictly dependent on mechanical motion, Wang et al. [108] developed a rotary hybrid nanogenerator driven by bicycle tires for self-powered ethanol and motion monitoring. The device was divided into two parts, stationary and rotating, in which the rotating part was connected to the wheel by a protruding rubber cylinder tip. With the flexible sensor based on MXene/Ag composite material, the self-powered sensing system was constructed to realize the assessment of cyclists' drinking and the monitoring of cycling movement.

In other studies, researchers even coupled a PENG, TENG, and EMG to greatly improve the energy harvesting capacity of hybrid power generation devices. Rodrigues et al. [109] developed a hybrid generator on the sole of shoes, which included a triboelectric component (an optimized parallel plate structure consisting of three friction pairs), electromagnetic component, and piezoelectric component, and used an all-diode rectifier to combine the outputs from the three energy harvesting units, thereby allowing energy harvesting from human walking. In the self-powered sensing microsystem based

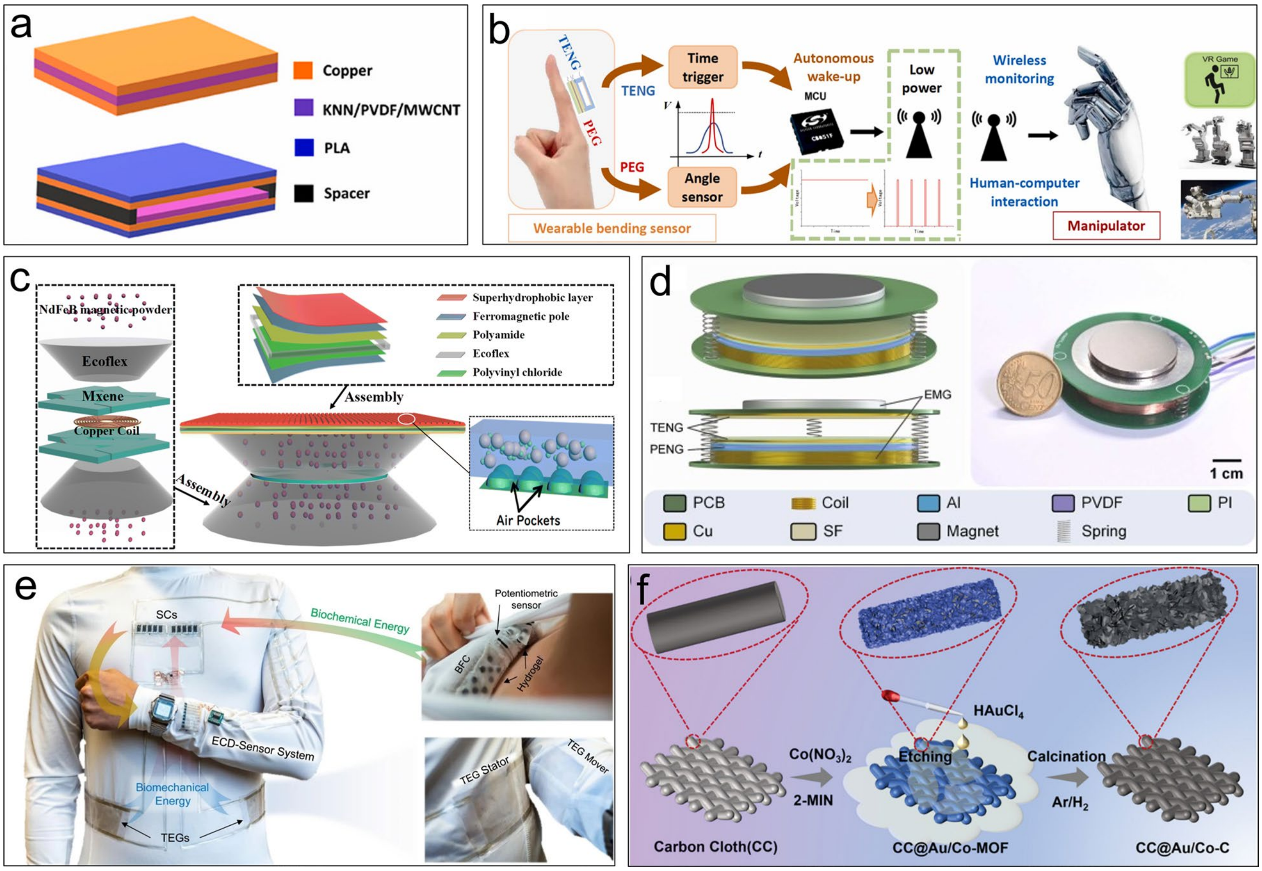


Fig. 8 The structure and application of various hybrid power supply systems. **a** The structural composition of TENG and PENG. The picture was reproduced from article published by Abdullah, Sadaf and co-workers in Nano energy in the year 2021 [104]. **b** Principle of self-powered wearable bending wireless sensing with autonomous wake-up. The picture was reproduced from article published by Wang, Fei and co-workers in Nano energy in the year 2023 [106]. **c** The self-powered and super-hydrophobic pressure sensor composed of a dual Merkel's disk pressure sensor and a superhydrophobic triboelectric–electromagnetic hybrid system. The picture was reproduced from article published by Cheng, Li and co-workers in Journal of Materials Chemistry A in the year 2024 [107]. **d** Structure diagram of high-performance triboelectric-piezoelectric-electromagnetic hybrid generator. The picture was reproduced from article published by Wen, Huang and co-workers in Nano Energy in the year 2023 [110]. **e** The arrangement of the individual modules of the wearable microgrid system on a shirt worn on-body. The picture was reproduced from article published by Yin, Kim and co-workers in Nature Communications in the year 2021 [114]. **f** Schematic illustration of the synthetic procedure for multifunctional electrode in the SC energy-storage module. The picture was reproduced from article published by Guan, Li and co-workers in Advanced Materials in the year 2023 [117]

on silk fibroin/Ag nanowire designed by Wen et al. [110], a high-performance triboelectric-piezoelectric-electromagnetic hybrid generator was used to supply energy to the system, and its schematic structure is shown in Fig. 8d. The electromagnetic part was composed of a 10,000-turn Cu coil and a neodymium iron boron-based permanent magnet. The triboelectric part was made of a polyimide film and silk fibroin film, combined with Cu film electrodes. The piezoelectric part comprised Al films with PVDF sandwiched between them. The whole hybrid power generation system contained stationary and movable parts, which were connected by springs, and the peak load power was up to 8.05 mW with a maximum power density of 189.6 W/m^3.

Solar energy and TEGs

Solar cells do not fully utilize the light beyond their bandgap energy, which is converted into waste heat [111]. Therefore, this part of the heat can be combined with the thermoelectric conversion mechanism to convert waste heat into electricity. In a wearable medical sensor system designed by Mohsen et al. [112], a hybrid photovoltaic-thermoelectric coupling energy harvester was developed to extend the system lifetime. The hybrid energy harvester comprised a flexible photovoltaic panel, TEG module, DC-DC boost converter, and two supercapacitors, which supported the sustainable and long-term monitoring operation of a medical monitoring system. De Fazio et al. [113] developed a smart shirt for hazardous workplace environmental monitoring by integrating a broad set of sensors to collect the user's vital signs and environmental parameters, before sending the data wirelessly to the cloud for display, processing, and storage. The smart shirt's energy was provided by a multi-source energy harvesting module containing thin-film solar panels, TEGs, and piezoelectric transducers. Tests showed that it could provide average power up to 216 mW, which completely fulfill the power requirements for the sensing, data processing and transmission in all possible scenarios.

TENGs and BFCs

Another reliable hybrid power strategy involves harvesting energy from the human body using TENGs and BFCs, which are then regulated and stored in a storage module, such as batteries or SCs. Yin et al. [114] proposed the combination of a TENG powered by torso oscillating motion and a BFC driven by sweat to form a complementary and synergistic wearable e-textile microgrid system (Fig. 8e). The TENG modules were initially activated by instant motion-induced charge generation to harvest biomechanical energy. Subsequently, the BFC harvested biochemical energy from electroenzymatic reactions with sweat metabolites for sustained power output. Thus, the complementary relationship between the two bioenergy harvesters compensated for the limitations posed by the BFC' s delayed perspiration response and the TENG' s lack of motion. This new method combines the mechanical and chemical energy of the human body to power wearable devices and efforts are being made to develop hybrid energy harvesting systems in the form of fibers to further improve the portability and comfort. For example, Park et al. [115] co-wove perspiration electric generator-based fibers and TENGs into stretchable and washable patch-type energy harvesting fabrics for harvesting energy from human movement and sweat to power wearable IoT devices. In addition, Zhuo et al. [116] prepared a breathable and woven hybrid energy harvester, which was knitted with a textile TENG and fiber BFCs, in order to sustainably power wearable electronics by harvesting biomechanical and biochemical energy.

Others

Researchers often flexibly design and combine power supply modules based on the requirements of specific application scenarios and working principles, thereby resulting in a variety of power supply modes. Therefore, a considerable number of power supply strategies used in applications are not described above. For example, in the wearable sweat energy harvesting-storage hybrid system proposed by Guan et al. [117], a BFC module was used to harvest electrical energy from lactate in sweat and a symmetric SC module was used to store the bioelectricity for subsequent utilization. In the SC energy-storage module, they developed a multifunctional electrode by incorporating metal–organic framework-derived and Au/Co nanoparticles embedded in carbon nanoarrays on flexible carbon cloth (Fig. 8f), which provided superior electrical conductivity and a high specific capacitance. The capture and storage of electrical energy from human skin were achieved by integrating the SC and BFC modules with a microfluidic system, where the voltage was 0.8 V and the power was 80.3 μW. Chen et al. [118] proposed a battery-free flexible solar energy harvesting node for powering low power medical wearable devices, which comprised a solar panel, SC, and supporting power management unit. Under illumination at 500 lx for 3 h per day, this system could power the sensing module without the need for recharging. Furthermore, in the self-powered wireless biochemical system designed by Yuan et al. [119] for continuous personal health status monitoring, a multi-source energy harvester and power management module were also employed to collect energy from RF, light, and heat sources. Due to the significant differences in the resistance values and output characteristics among various energy harvesting devices, each device was isolated using Schottky diodes and then connected to the power management chip to maximize the utilization of energy. In general, the energy sources in a hybrid power supply model complement each other to obtain better continuity and sustainability. However, the flexibility is reduced compared with a single energy source, and thus it is necessary to consider issues such as structural design and power matching among different levels, thereby leading to a corresponding increase in the cost.

Conclusions

Wearable sensors have developed significance, and they play important roles in human health monitoring and diagnostic assessment. The selection and design of energy supply methods are crucial steps in the design process for wearable sensing systems. In this review, we systematically analyzed the energy conversion mechanisms, basic characteristics, and potential applications of various technologies used in the power supply modules of wearable sensors, including batteries, SCs, photovoltaic technology, BFCs, thermoelectric, electromagnetic, piezoelectric, triboelectric, and radio-frequency energy harvesting, with a focus on the performance enhancements obtained by using these materials, especially nanomaterials. We also introduced the hybrid energy supply model involving mixing energy conversion from multiple sources. Table 1 summarizes some of the studies

Table 1 Comparison of typical power supply modes used for wearable sensors

Mechanism	Sensing function	Materials	Voltage	Current	Power	Size	Advantages & limitations	Ref
Li-ion Battery	/	ZnS nanoparticles, CNTs	/	/	(Capacity: 333 mAh/g)	d = 12 mm	Lightweight, high energy storage density Need recharge or replacement	[24]
Supercapacitor	Pressure	MXene/TiS_2 film	/	/	(Energy density: 31.6 Wh/kg)	1 × 2 cm	High power density, fast charging rates, long cycle life Low energy density	[30]
Solar Cells	Glucose, pH, Na^+, sweat rate	Perovskite, PEDOT:PSS, PCBM, TiO_x	/	/	~25 mW (PCE 31%)	27 × 20 × 4 mm	Environmentally friendly Require light, unstable	[34]
	Tactile sensing	Liquid crystal elastomer	1.17 V	24.79 mA/cm^2	(PCE 22.10%)	/		[35]
	/	CNT fibers	0.923 V	18.26 mA/cm^2	22.7 mW (PCE 11.94%)	17 × 22 cm		[36]
Biofuel Cells	Glucose	Naphthoquinone, MWCNT, PB	0.45 V	/	226 μW/cm^2 (glucose)	~4 × 2 cm	Integrated power generation and sensing Affected by the analyte concentration	[44]
	Lactate	Tetrathiafulvalene, MWCNT, Pt black	/	/	13 μW/cm^2 (lactate)	~5 × 5 cm		[45]
	Ethanol	Micro-mesoporous carbon aerogels	0.39 V	/	1.9 μW/cm^2 (ethanol)	~4 × 4 cm		[46]
Thermoelectric Generator	Temperature	Bi_2Te_3 nanoparticles, PEDOT nanowires	65.1 mV/cm^2 ($\Delta T = 17.8$ K)	208.8 μA ($\Delta T = 17.8$ K)	3.48 μW/cm^2 ($\Delta T = 17.8$ K)	14 × 6 × 5 mm	No need for motion, stable and sustainable Low output power	[50]
	Strain, Temperature	Graphene (TE threads)	1.1 mV ($\Delta T = 27.7$ K)	3.3 μA ($\Delta T = 27.7$ K)	0.7 nW ($\Delta T = 27.7$ K)	d = 2 mm		[51]
	/	PAAm hydrogel, graphene electrode	160 mV ($\Delta T = 4.1$ K)	40 μA ($\Delta T = 4.1$ K)	37 μW/cm^2 ($\Delta T = 4.1$ K)	20 × 10 × 1 mm		[52]
	Human movements	PAAm/TOBC/Li TFSI hydrogel	231 mV ($\Delta T = 20$ K)	9.28 μA ($\Delta T = 20$ K)	538 nW ($\Delta T = 20$ K)	30 × 10 × 3 mm		[54]
Radio frequency	Temperature, humidity	Conductive fabrics	0.2 ~ 0.355 V	/	2.75 μW/cm^2 (2.4 ~ 2.45 GHz)	/	Green, stable, and continuous Alignment, matching and transmission distance need to be considered	[59]

Table 1 (continued)

Mechanism	Sensing function	Materials	Voltage	Current	Power	Size	Advantages & limitations	Ref
NFC	CO_2	(commercial chip)	/	/	22.5 mW 13.72 MHz	/	Small size, good compatibility. Very limited transmission distance	[65]
	/	Graphene multilayers	4 V (13.56 MHz)	/	/	75 × 45 mm		[67]
	pH	Nanoparticle silver ink	2.17 V (13.56 MHz)	/	/	28 × 23 mm		[68]
Electromagnetic	/	Permanent magnet	/	/	0.5 ~ 2.28 mW	51 × 46 × 10 mm	High efficiency and simple structure. Limited transmission distance	[71]
	Breath monitoring	Electrochemically active aluminum–silicon alloy	100 mV	/	1 nW	d ≈ 15 mm		[72]
PENG	Pressure	$BaTi_2O_5$ nanorods, PVDF	31.2 V	0.52 μA	2.46 μW/cm^2	5 cm × 1 cm × 125 μm	No need for light or RF waves. Integrated power generation and sensing. Require body motion	[74]
	Facial activity and chest respiratory	PZT nanoparticles, microfibrillated cellulose, PVA	16.5 V	0.86 μA	3.3 μW	2 × 2 cm		[76]
	Shoe insole pedometer	ZnO nanorods, PVDF	14.6 V	0.6 μA	21.32 μW/cm^2	~4 cm^2		[77]
	Force	Electrospun PVDF-KNN nanofibers	~25 V	0.5 μA/cm^2	0.3 μW/cm^2	4 cm^2		[78]
	/	Membrane of pomelo fruit	~6.4 V	~7.44 μA	~12 μW/cm^2	2 × 2 × 0.045 cm		[85]
TENG	/	Parylene-deposited MWCNT-PDMS films	111.1 ±4.4 V (contact) 443.6 ± 14 V (separation)	17.8 ± 2.6 μA (contact) 37.1 ± 2.9 μA (separation)	4.57 W/cm^2 (contact) 10.28 W/cm^2 (separation)	1 × 1 cm	No need for light or RF waves Require body motion	[92]
	/	MWCNT, chitosan	85.8 V	8.7 μA	18 μW/cm^2	2 × 2 cm		[93]
	NH_3	MXene, cellulose acetate nanofibers	140 V	92 μA	136.1 μW/cm^2	3 × 3 cm		[94]
	Tremor	Catechol-chitosan-diatom hydrogel	110 V	3.8 μA	29.8 μW/cm^2	3 × 3 cm		[95]
	Pressure distribution	MXene/silicone nanocomposite	/	56 μA/cm^2	1040 μW/cm^2	/		[96]
TENG&PENG	Pressure and motion	KNN, MWCNT, PVDF	54.1 V	29.4 μA	0.164 W	/	/	[104]
EMG&TENG	Pressure, human gait	Mxene, MWCNTs-OH, high-purity iron, $Nd_2Fe_{14}B$ magnetic particles	13 V	30 mA	/	d = 50 mm h = 25 mm	/	[107]

Table 1 (continued)

Mechanism	Sensing function	Materials	Voltage	Current	Power	Size	Advantages & limitations	Ref
EMG&TENG &PENG	Pressure, temperature	Silk fibroin/silver nanowire composite film	/	/	189.6 μW/cm^3	d = 60 mm h = 15 mm	/	[110]
PV & TEG	Temperature, heartbeat, SpO_2, and acceleration	(Commercial chip)	PV: 4.6 V TEG:1.0 V	PV: 49.5 mA TEG:100 mA	PV: 207 mW TEG: 100 mW	/	/	[112]
BFC&TENG	/	Carbon fibers, rubber, CNT-fiber, PE-CNT fiber and PVA hydrogel electrolyte	1.2 V	/	16.6 μW	/	/	[116]
SCs & BFC	/	MOF-derived and Au, Co nanoparticles embedded carbon nanoarrays on the flexible carbon cloth	~ 0.8 V	/	80.3 μW	d = 35 mm	/	[117]
SCs & Solar cell	Heart rate and SpO_2	(Commercial chip)	/	/	0.45mW/500 lx 0.14mW/200 lx	/	/	[118]
RF&PV&TEG	Glucose	(Commercial chip)	/	/	> 5.8 mW	/	/	[119]

V – open-circuit voltage or output voltage; I – short-circuit current; P – output power or output power density; d – diameter; h – height

PCE power conversion efficiency, PCBM [6.6]-phenyl-C_{61}-butyric acid methyl ester, SpO_2 blood oxygen saturation, PV photovoltaic mentioned above and Fig. 9 more intuitively shows the performance of various power supply modes.

Developments and applications

When designing wearable sensors at the system level, researchers often need to consider whether the output performance provided by the power supply module meets the required standards, which is typically related to the materials and structure of the power supply components. Nanomaterials with minute sizes and high specific surface areas exhibit unique physical and chemical properties. The use of nanomaterials as electrodes or dielectrics is an effective strategy for improving the output performance. For instance, carbon nanomaterials can enhance the utilization of active substances in electrodes and facilitate the transfer of electrons and ions due to their excellent conductivity, high specific surface area, and good chemical stability [120]. In addition, metal nanomaterials possess high electrical conductivity, good catalytic activity, and high energy conversion efficiency, and thus they have great potential for use in energy supply technologies. Furthermore, nanomaterials used as catalysts, electrodes, or as parts of transduction devices play important roles in improving the sensitivity of sensors to low concentrations of target substances [121]. In recent years, the development of fiber-based power-generating fabrics has emerged as a significant hotspot. These fabrics have the advantages of being lightweight and readily integrated with existing textiles, and thus they have promising broad application prospects in fields such as wearable devices and smart textiles, thereby aligning with the current scalable manufacturing trends and the potential for large-scale production. In addition, hydrogels with a modulus similar to skin and exceptional flexibility can seamlessly adhere to the human epidermis and provide excellent interfacial compatibility for sensors. Hydrogels can achieve multifunctional and highly sensitive detection by introducing different functionalized components. The incorporation of conductive fillers to form conductive networks within hydrogels can yield power supply devices with high electronic and mechanical performance [122]. We also highlighted the application of hybrid power supply modes. By coordinating the operation of various energy sources, the hybrid power supply mode can provide a stable and efficient energy supply under different environmental conditions, thereby enhancing the continuity and sustainability of the sensing system.

The development of energy technology has led to a wide range of applications for wearable energy harvesters. Each power supply method possesses unique characteristics, leading to varying applicable scenarios. Photovoltaic technology harnesses clean, renewable solar energy as a power source, reducing the reliance of wearable sensors on traditional energy sources and mitigating environmental pollution. The emergence of flexible solar cells in wearable settings has enhanced comfort for users and significantly broadened the range of potential applications [34, 123–125]. Biofuel cells, recognized for their biocompatibility, convert endogenous human substances like lactic acid and glucose into electricity through chemical reactions, making them valuable for concentration detection purposes [43, 44, 126] and streamlining wearable device design. Thermoelectric power supply leverages

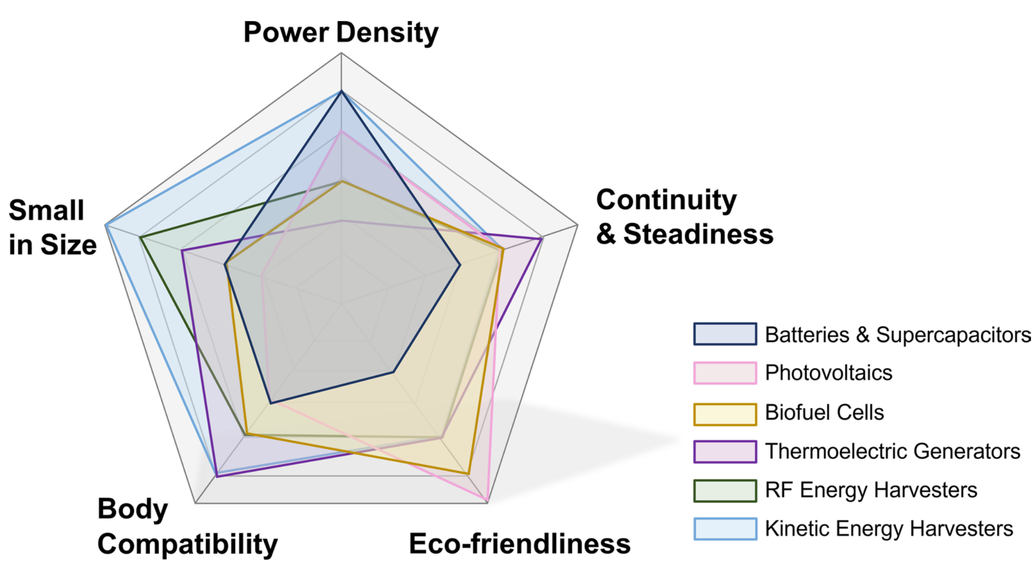


Fig. 9 Multi-dimensional performance comparison of various power supply modes

the temperature differential between human body heat and the surrounding environment to produce electrical energy, offering continuous powering capability as long as the temperature variance persists a feature beneficial for prolonged health monitoring applications [127–130]. RF energy harvesters and near-field communication technologies are unaffected by environmental factors like temperature and light, yet successful transmission distance and parameter matching are crucial for determining their applicable domains. Kinetic energy harvesters excel in efficiently capturing the mechanical energy from human movement, making them particularly well-suited for motion monitoring scenarios such as gait analysis [77, 96, 107], and gesture control applications [131–133]. Notably, the integration of new materials, such as hydrogels, has significantly elevated the flexibility and self-healing capacity of energy harvesters, rendering them more fitting for human wearable applications [95, 134].

Challenges and perspectives

It should be noted that previously described energy supply modules for wearable sensors have some limitations. First and foremost, the challenge lies in maintaining wearable characteristics while ensuring high output performance. This necessitates a multifaceted approach that includes optimizing materials and structures, along with the incorporation of power management techniques such as low-power design and adaptive adjustments. Secondly, the performance of most of these energy supply modes has only been validated under laboratory conditions, and these devices will be exposed to more complex body movement when applied in wearable sensors in practical scenarios. Therefore, avoiding possible structural damage and performance degradation is an issue that should be addressed in future research. Thirdly, the cost of producing these energy supply technologies must be considered, including the cost of the materials, especially more specialized nanomaterials and rare precious metals, and the costs of advanced equipment and technicians required to prepare complex devices, which are also important during the industrialization process. Finally, the use of nanomaterials can be challenging. Due to the diverse morphology and surface states of nanomaterials, more standardized synthesis and processing techniques are needed to achieve precise control over the structure, morphology, and size of nanomaterials [135], which is crucial for enhancing the stability and reproducibility of the devices. Moreover, there is a lack of legal and regulatory frameworks regarding the safety of nanomaterials, which is concerning for both human health and the environment. Thus, when applying nanomaterials in wearable devices for human use, it is necessary to consider the problems of nanotoxicology, recyclability of materials, and disposal of waste. In addition, given the inapplicability of photovoltaic technology at nighttime and the requirement of sufficient sweat for BFC, etc. How to expand the application conditions of the power supply module and improve the user wearing experience remains a research direction that requires sustained efforts and long-term dedication (Fig. 10).

Due to continuous technological advances, the wireless transmission of electricity and data are crucial considerations in the design of wearable sensor systems. As the components of wearable sensors become increasingly

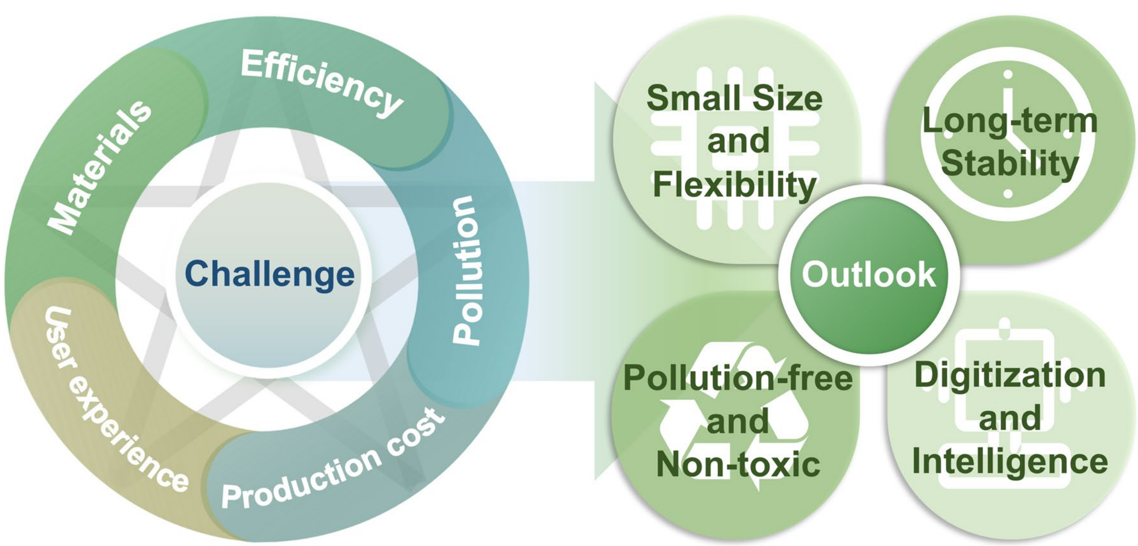


Fig. 10 An overview of issues related to power supply module in wearable sensors, including challenges (left) and the trend of development in the future (right)

small and portable, the power supply modules for wearable sensors generally need to be more flexible, miniaturized, and lightweight. This trend depends on the unprecedented prospects for high power energy harvesters, large capacity energy storage devices, and efficient wireless transmission equipment with flexible, stretchable, and miniaturized form factors. To meet the power module requirements of wearable devices, scientists are conducting intensive research and developing more suitable, efficient, and stable power supply devices. In addition to continuously optimizing performance, they are focusing on environmentally friendly concepts that are pollution-free and non-toxic. Moreover, as big data and digitization gradually permeate various fields of production and life, intelligent power sources and corresponding power management strategies are expected to play important roles in energy management and improvements in the efficiency of devices [136]. By analyzing power usage data in real-time, it is possible to achieve optimized power configurations, thereby ensuring the stability and efficiency of energy supplies. In conclusion, due to continuous breakthroughs in the performance of power supply modules and the increasing maturity of technology, we consider that wearable sensors will have broader development prospects. We expect that these technologies will play crucial roles in many fields and bring great benefits to human health and life.

Author contributions
RYY: Writing—original draft, Investigation. SQF: Writing—review & editing, Formal analysis. QWS: Writing—review & editing, Formal analysis. HX: Writing—review & editing. QXJ: Writing—review & editing. JHG: Funding acquisition, Supervision. BD: Funding acquisition, Conceptualization. DXC: Funding acquisition, Supervision. KW: Writing—review & editing, Methodology, Funding acquisition. All authors have read and approved the manuscript.

Funding
This work was supported by the National Key Research and Development Program of China (No. 2023YFF0724300), the National Natural Science Foundation of China (No. 32171373), the Projects of International Cooperation and Exchanges NSFC (No. 82020108017), the Natural Science Foundation of Shanghai (No.23ZR1414500), the Medical Engineering Cross Project of SJTU (No. YG2021QN141).

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 17 May 2024 Accepted: 14 August 2024
Published online: 20 August 2024

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