Tang *et al. Soft Sci.* **2025**, *5*, 11
DOI: 10.20517/ss.2024.62

Soft Science

Review Article

Open Access

Check for updates

Recent progress of biosensors based on thermoelectric effects for monitoring physical activity and environment monitoring

Xinyuan Tang[1,2], Cai Qi[1,3], Qiang Sun[1,3,*]

[1]State Key Laboratory of Oral Diseases, National Center for Stomatology, National Clinical Research Center for Oral Diseases, West China Hospital of Stomatology, Sichuan University, Chengdu 610041, Sichuan, China.
[2]Pittsburgh Institute, Sichuan University, Chengdu 610041, Sichuan, China.
[3]Sichuan Provincial Engineering Research Center of Oral Biomaterials, Chengdu 610064, Sichuan, China.

[*]**Correspondence to:** Prof. Qiang Sun, State Key Laboratory of Oral Diseases, National Center for Stomatology, National Clinical Research Center for Oral Diseases, West China Hospital of Stomatology, Sichuan University, 14, 3rd section, Renmin South Road, Chengdu 610041, Sichuan, China. E-mail: qiangsun@scu.edu.cn

How to cite this article: Tang, X.; Qi, C.; Sun, Q. Recent progress of biosensors based on thermoelectric effects for monitoring physical activity and environment monitoring. *Soft Sci.* **2025**, *5*, 11. https://dx.doi.org/10.20517/ss.2024.62

Received: 1 Nov 2024 **First Decision:** 25 Nov 2024 **Revised:** 16 Dec 2024 **Accepted:** 27 Dec 2024 **Published:** 13 Feb 2025

Academic Editors: Renkun Chen, Huanyu Cheng **Copy Editor:** Ting-Ting Hu **Production Editor:** Ting-Ting Hu

Abstract

Thermoelectric (TE) materials and sensors have emerged as a frontier in health and environmental monitoring, offering a silent, simple, and reliable alternative to traditional power generation methods by harnessing waste heat into usable electrical energy. They also offer superior stability and longevity, making them ideal for long-term monitoring applications. Furthermore, when compared to other self-powered biosensors, TE sensors excel in their ability to operate in a wide range of temperatures and environmental conditions, providing a more reliable and consistent power source for sensor operation. This review delves into the recent advancements in TE-based sensors, highlighting their multifunctional capabilities in real-time health monitoring and environmental sensing. We explore the fundamental principles of TE conversion, including the Seebeck effect, and assess the performance metric, specifically the figure-of-merit (*ZT*). The integration of TE materials with flexible and wearable electronics is discussed, emphasizing flexible materials for their high efficiency and mechanical robustness. Applications in self-powered wearable devices and internet of things (IoT)-integrated environmental monitoring systems are underscored, particularly in fire detection and personal health monitoring. Challenges in material limitations, miniaturization, and scalability are addressed, with a focus on future research directions to enhance the sustainability and longevity of TE sensors. This review provides a comprehensive overview of the development of TE sensor technology and its future trajectory, emphasizing the importance of ongoing research to address current challenges and realize the capabilities of these innovative devices.

Keywords: Thermoelectric sensors, health monitoring, environmental sensing, wearable technology, energy harvesting, internet of things (IoT)

INTRODUCTION

The miniaturization and integration of electronic devices have spurred the swift evolution of implantable and wearable electronics[1-3]. Those electronics are promising tools for detecting or monitoring various signals for healthcare and environment awareness because of their potential for sensing applications. The performance of sensors can be achieved by their intrinsic awesome characteristics such as their sensitivity and wide detecting range. However, their novelty and comprehensive performance can be accomplished by the combination of material science, energy efficiency, and integration with cutting-edge technologies. Self-powered technologies including triboelectric, piezoelectric, photovoltaic, and thermoelectric (TE) sensors have made significant strides, offering strategies for eliminating the need for external power sources and frequent battery replacement[4-6]. Among them, TE materials and conversion systems are increasingly recognized for their distinct advantages over traditional power conversion methods, particularly in their silent operation, simplicity of design, and exceptional reliability. These systems have the potential to efficiently detect the heat fluctuations generated from various sources, such as industrial processes, vehicle exhaust systems, and even human body heat, and convert them into usable electrical energy without the need for complex mechanical parts, which can inherently increase their reliability[7-10]. Unlike triboelectric and piezoelectric sensors, TE sensors do not need mechanical motion and external force to operate and can function with a steadier and more consistent energy source - namely, a temperature gradient. Photovoltaic sensors convert light into electricity and are ideal for environments with ample light. However, they perform poorly in low-light conditions, whereas TE sensors can operate effectively with a steadier energy source[4-6,11]. Therefore, due to the capabilities of TE materials in thermal-electrical signal conversion, TE techniques have been explored for advanced application in biosensing[12,13].

Among the myriad scenarios, physiological signals monitoring for healthcare use stands out as a pivotal application for biosensors. Particularly, sensor technology has evolved from basic detection mechanisms to sophisticated, multifunctional devices capable of real-time health monitoring and environmental sensing[14-18]. With the surging development of sensor hardware and wearable sensors, biosensors could realize high-precision and highly comfortable monitoring[19-21]. Moreover, the combination of the internet of things (IoT) with wearable biosensors enables continuous and remote monitoring[22]. By perceiving physiological signals, analyzing data with algorithms, and even triggering alarms in extreme conditions, these biosensors could be used to inform healthcare decisions and improve patient care[15]. Recent progress of multi-channel sensors could track various human health parameters, allowing for a more comprehensive understanding of the users[23]. Additionally, the TE technique also offers a novel solution for continuous monitoring, providing energy for the sensors without occasionally replacing the power supply. Hence, detecting human signals is a promising issue for the application of biosensors[24].

In environmental monitoring, TE sensors are being used to detect changes in temperature and humidity, which are pivotal for assessing ambient conditions[14,16]. These sensors are particularly crucial in fire monitoring applications where early detection can be a matter of life and property safety[25,26]. Recent advancements in TE technology have enabled the development of self-powered, rapid-response fire warning systems that utilize the temperature gradients present during a fire event to generate an electrical signal, thereby enhancing detection efficiency and reliability.

The flexibility of these sensors is crucial for comfortable, long-term wear, and it is achieved using materials such as polyimide (PI) substrates and thin-film TE materials such as Bi_2Te_3[27]. However, their application in wearable sensors can be limited by mechanical brittleness and suboptimal performance under flexible

conditions. This is where materials such as Ag_2Se come into play, offering a tougher alternative to n-type Bi_2Te_3 TE material. Ag_2Se demonstrates not only high TE efficiency but also enhanced mechanical robustness, which is vital for wearable devices subjected to continuous mechanical stress[28-32]. Carbon-based materials, particularly carbon nanotube (CNT)-based and graphene-based, have also emerged as promising candidates for flexible TE sensors, maintaining flexibility and cost-effectiveness. CNTs can be tailored for both n- and p-type properties through different strategies, and their inclusion in polymer matrices has been shown to enhance both electrical conductivity and Seebeck coefficient, leading to improved TE performance[33]. Incorporating graphene into various matrices can also enhance the TE performance of composite materials[34]. However, their TE properties still need further optimization for commercial use. Additionally, the advancement of hydrogels and nanomaterials provides a promising material basis for wearable, flexible sensors, which can be used for designing disposable *in-situ* health monitoring sensory systems. Nanomaterials are widely used in soft electronics, including sensors, due to their excellent mechanical flexibility, and their certain properties for human utilization such as ultralight weight and high breathability. Hence, such materials can be utilized as the substrates for TE-based sensors, thus ensuring their flexibility and practicality. However, due to the intrinsic rigidity of semiconductors, though the substrates are flexible, the device cannot meet the demand for its comfortability. That is what hydrogel based on thermogalvanic effect or Soret effect comes into play. Compared with traditional metal or semiconductor materials, hydrogels such as polyacrylamide (PAM)/carboxymethyl cellulose (CMC)-LiCl and polyvinyl alcohol (PVA)/tempooxidized bacterial cellulose (TOBC) are soft and often exhibit rather high thermopower, which allows for the utilization of wearable biosensors[35,36].

In summary, by integrating biosensors with TE materials, a novel approach to energy recycling is achieved, which extends device autonomy and reduces the need for frequent battery replacement. In this review, we aim to provide a comprehensive overview and analysis of recent advances in TE-based sensors for health and environmental monitoring applications [Figure 1]. Firstly, we discuss the fundamental principles of TE conversion. Additionally, we assess the practical applications of these sensors in real-world settings, particularly emphasizing their role in self-powered, wearable devices and IoT-integrated environmental monitoring systems. Finally, we address the current challenges facing TE sensor deployment, such as material limitations, miniaturization requirements, and scalability issues, and explore future research directions to maximize the potential of TE sensors for sustainable, long-term monitoring solutions.

TE EFFECTS FOR SENSING

Seebeck effect

The TE effect, including the Seebeck effect, was first reported by Thomas Johann Seebeck in 1821. This phenomenon occurs when there is a temperature gradient in conductive materials, leading to the differential migration of charge carriers[7,37-39]. To specify, when materials are exposed to a temperature gradient, there is a tendency for high-energy charge carriers, which are more prevalent in the hotter regions, to diffuse toward the colder regions, resulting in the development of an electrostatic potential difference across the material [Figure 2A][40]. Under open-circuit conditions, this process continues until the drift and diffusion currents reach equilibrium, leading to the establishment of a Seebeck voltage. Thus, we can conclude that Seebeck effect allows for the direct conversion of temperature gradient into electrical energy.

The figure-of-merit (ZT) is a dimensionless parameter that quantifies the efficiency of TE materials, given by[38,40,41]:

$$S = \frac{\Delta V}{\Delta T} \quad \text{Eq (1)}$$

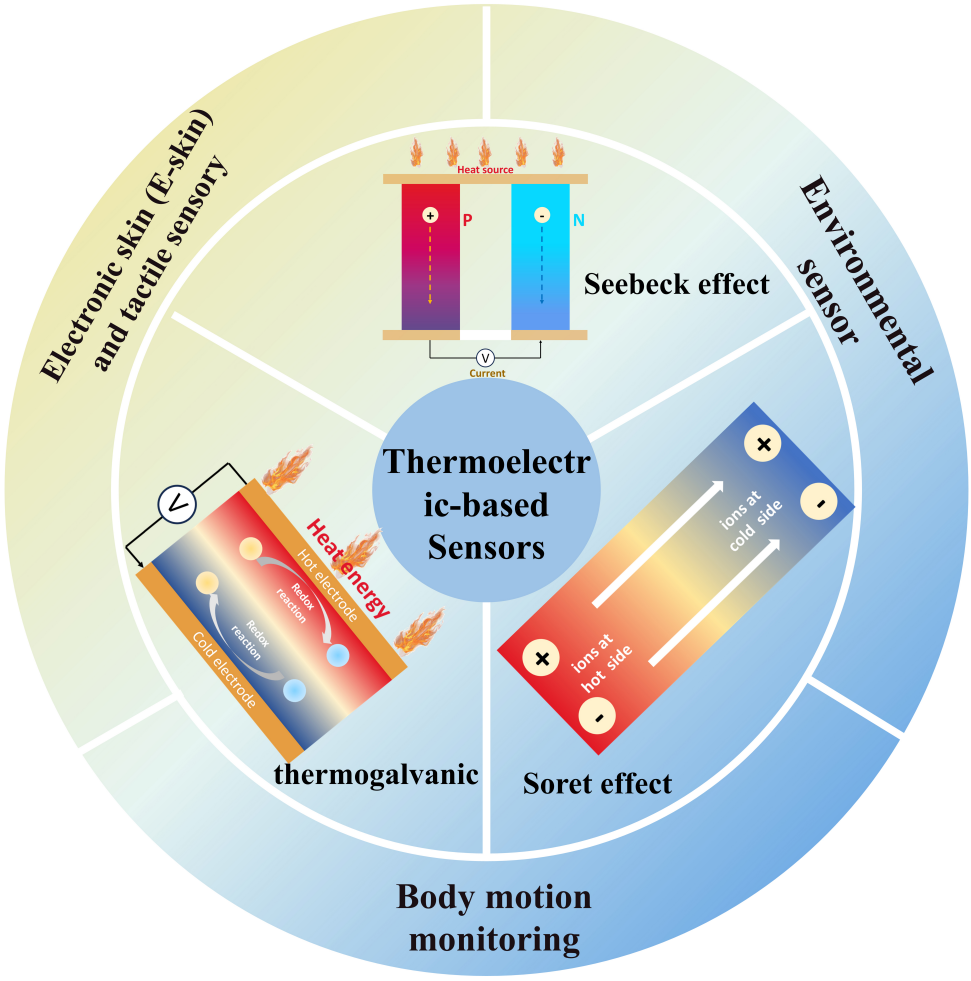

Figure 1. An overview of self-powered mechanisms and applications for monitoring.

$$ZT = \frac{S^2\sigma}{\kappa}T = \frac{S^2\sigma}{\kappa_e + \kappa_l}T \quad \text{Eq (2)}$$

Here, S represents the Seebeck coefficient, also called thermopower, which is the ratio of the voltage (ΔV) generated by the TE device to the temperature gradient across it. The symbol σ represents the material's electrical conductivity. The total thermal conductivity, denoted by κ, consists of two parts: the electronic thermal conductivity (κ_e) and the lattice or phonon thermal conductivity (κ_l). The absolute temperature is represented by T. $S^2\sigma$ is termed power factor, a crucial parameter for evaluating the performance of TE materials, which describes the conversion efficiency of certain materials converts thermal energy into electrical energy. Among these factors, S, σ, and κ are the key factors relevant to the thermal exchange between objects, thereby necessitating extra attention for selecting proper TE sensing materials [Figure 2B][42].

Traditional strategies for enhancing ZT are maximizing $S^2\sigma$ including carrier concentration manipulating[43-46]. However, due to the inverse correlation between S and σ, increasing S always leads to the reduction of σ. Hence, $S^2\sigma$ would reach an optimal value of ZT with certain S and σ, making the ZT maintain a small value[47,48]. Any changes in those two parameters would degrade the performance of TE material. Other methods such as introducing nanostructures focus on scattering phonons, thus reducing κ_l[49].

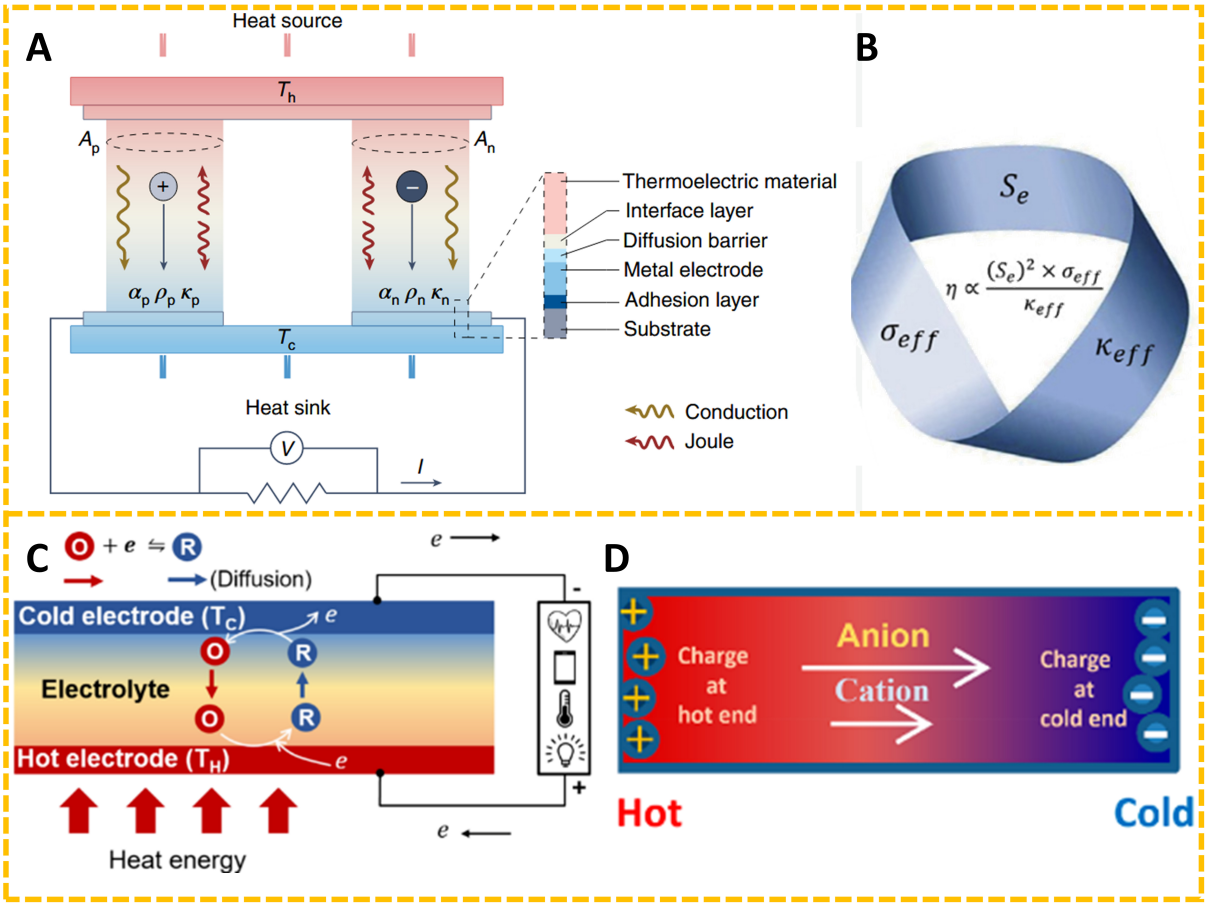

Figure 2. TE device working principle (A) Working principle of TE device based on Seebeck effect[40]. Copyright 2022, Springer Nature; (B) dependence of its efficiency on three strongly interdependent parameters including Se, S_{eff}, and κ_{eff}[42]. Copyright 2021, Elsevier; (C) Working principles of TGCs[62]. Copyright 2022 American Chemical Society; (D) Soret effects of cations and anions of an n-type ionic material under temperature gradient. The two arrows in the image signify the migrations of both cations and anions from the hot end to the cold end, but the anions migrate faster than the cations[70]. Copyright 2022 American Chemical Society. TE: Thermoelectric; TGCs: thermogalvanic cells.

However, scattering phonons also leads to the decline of σ, limiting the optimization of ZT. Overall, σ, S, and κ are strongly coupled, making it challenging to optimize them independently. This coupling complicates the ability to achieve a high ZT value[50,51]. Till now, researchers have found multiple ways to decouple those properties to cope with this challenge, which would be a promising breakthrough point for enhancing ZT[52-56].

Thermogalvanic effect

Thermogalvanic cells (TGCs), also known as thermocells, are devices that can turn heat into electricity using a principle called thermogalvanic effect. Unlike Seebeck effect, TGCs work by taking advantage of certain chemical reactions that change with temperature. To specify, the thermogalvanic effect allows for the direct conversion of low-grade heat into electrical energy by exploiting the temperature-dependent electrochemical properties of redox couples[57-61]. TGCs convert heat to electricity based on an electrochemical thermogalvanic effect via two critical processes: redox reactions on the electrodes and mass transport in the electrolytes [Figure 2C][62]. Two electrodes are submerged in an electrolyte containing a redox-active species. The creation of a temperature gradient between the two electrodes results in an electrochemical potential difference across the redox couple, leading to redox reactions, thereby generating

an electromotive force (EMF). This potential difference is what drives the flow of electrons through an external circuit, enabling electrical energy generation for sensing.

The conversion efficiency of thermocells is determined by three interconnected factors: the thermopower (Se), the effective electrical conductivity (σ_{eff}), and the effective thermal conductivity (κ_{eff}). The thermal power for materials utilizing the thermogalvanic effect is determined by[61,63]:

$$Se = \frac{\Delta V}{\Delta T} = \frac{\Delta S}{nF} \quad \text{Eq (3)}$$

Where ΔV represents the operating voltage of the ionic TE (iTE) material; ΔS denotes the difference in partial molar entropy of the redox couple; n signifies the number of electrons involved in the redox process; and F is the Faraday constant. The equation indicates that redox couples with a high absolute charge and complex structures exhibit greater differences in the partial molar entropy of ions, which correlates with a higher Seebeck coefficient.

Based on the ability of thermogalvanic hydrogel (TGH) to convert thermal energy into electrical signals, it is an ideal candidate for self-powered sensing, eliminating the need for external power sources and extending the operational life of sensors in remote or hard-to-reach locations. For instance, a TGH-based electronic skin (E-skin) can harness temperature differences to generate electricity for self-powered on-body dual-modal temperature and strain sensing[64]. Meanwhile, TGCs can also be utilized to monitor environmental conditions such as temperature gradients, which are crucial in various applications, including climate change studies and industrial processes. For example, a TGH sensor can be used for temperature monitoring of edibles, providing a safe and non-toxic method for self-powered sensing in food temperature detection[65].

Soret effect

Recent studies have reported that redox-free electrolytes can exhibit substantial Seebeck coefficients due to the thermo-diffusion of ions, a phenomenon driven by the Soret effect, also known as the ionic Seebeck effect[66-69]. The Soret effect, or thermodiffusion, occurs when a temperature gradient applied to a fluid containing multiple atomic or molecular species results in a nonuniform composition within the fluid [Figure 2D][70]. The difference between Seebeck effect is that the carriers are cations/anions and the materials are ionic liquids or polymers. This effect was first observed in the 19th century by Ludwig and Soret, who noted that in an electrolyte solution within a tube, the concentration of salt was higher on the cold side[71]. The Soret effect is characterized by the accumulation of solute particles, such as ions, towards the colder end of a temperature gradient, leading to a separation of components within a mixture. This generates a thermovoltage that is determined by the thermal gradient across the electrolyte. The ionic Seebeck coefficient describes the magnitude of the TE voltage produced by iTE materials under a certain temperature gradient.[72-74]. Consequently, the Soret effect plays a crucial role in sensing applications by enabling the conversion of thermal gradients into electrical signals, which can be harnessed for energy storage and sensing purposes[75].

ADVANCED SENSING APPLICATIONS BASED ON TES

The integration of TE materials into advanced sensing applications has transcended its traditional energy harvesting applications, opening new avenues for self-powered wearable biosensing, environmental monitoring, and health diagnostics. This section explores the cutting-edge applications of TE materials in creating sensors that can broaden our interaction with the environment and our bodies.

E-skin and tactile sensory

E-skin is a flexible and stretchable electronic device that mimics the functions of human skin, capable of converting external mechanical or thermal stimuli into electrical signals. These signals can then be processed and interpreted by connected devices or systems, allowing for numerous applications in fields including robotics and wearable technology[64,76-81]. For E-skin, which requires durable power sources, TE generators (TEGs) could provide a means of self-sustaining energy. By incorporating TEGs, E-skin could benefit from a continuous and autonomous power supply, enhancing its functionality and extending its usage without the need for frequent recharging[82,83]. For instance, Yuan *et al.* have engineered a hand-shaped flexible TEG (f-TEG) that utilizes p-type ($Bi_{0.5}Sb_{1.5}Te_3$) and n-type ($Bi_2Te_{2.8}Se_{0.2}$) TE grains on a flexible PI substrate [Figure 3A][84]. This system demonstrates a maximum output power of 190 μW and a power density of 3 $\mu W \cdot cm^{-2}$. The f-TEG, optimized for high power density and load matching, exhibits a figure of merit (*ZT*) of about 0.9 even after bending. To protect the device from environmental factors, it is encapsulated with a 5 μm perylene film, providing waterproof and dustproof properties. This self-powered e-skin is highly sensitive to conductive and convective heat transfer between the TEG and its external environment. Similar to human skin, which senses different materials, such as metal and wood, based on their thermal conductivity, and detects fluid flow due to convective heat transfer, this e-skin can perceive material type and wind stimuli through the output response of the f-TEG. Similarly, the research conducted by Ma *et al.* also utilized the tactile perception of temperature changes upon contact with objects to enable material identification through thermal cues. Their E-skin, which leverages the TE properties of Ag_2Se films, can discern the thermal characteristics of various materials. This capability is illustrated in Figure 3B[85], where the e-skin's response to different materials is indicative of their distinct thermal profiles. To achieve more flexibility, Han *et al.* have made ultrasensitive flexible thermal sensor arrays based on a high-thermopower iTE hydrogel, able to detect spatial temperature distribution with a sensitivity of 2.7 $mV \cdot K^{-1}$. This hydrogel, derived from polyquaternium-10 (PQ-10) and sodium hydroxide (NaOH), stands out for its exceptional TE performance, boasting a thermopower of 24.17 $mV \cdot K^{-1}$, which is remarkably high for biopolymer-based iTE materials. The high p-type thermopower arises from the selective thermal diffusion of Na^+ ions under a temperature gradient. Integrated into a smart glove, the sensor arrays enable precise detection of temperature and touch, showing potential for enhancing human-machine interaction and E-skin applications[86].

For e-skin applications, the importance of real-time and high spatial resolution detection and mapping of external temperature stimuli has been underscored by recent research. Kang *et al.* have demonstrated the temperature monitoring capabilities of self-powered temperature E-skin (STES) across various scenarios, as presented in Figure 3C[87]. By attaching STES to a robotic finger, the technology's potential in human-machine interaction scenarios is realized. The STES-enabled robotic hand can accurately perceive and image temperature distributions when in contact with a human finger at body temperature, cold water, and hot water, showcasing its real-time sensing capabilities.

Guo *et al.* presented a flexible and wearable infrared detector based on the photothermoelectric (PTE) coupling of tellurium-based TE multilayer films and an infrared-absorbing PI substrate. The spatial distribution of photovoltage in a PI-based Te/CuTe multilayer PTE detector was characterized using a spatially resolved photovoltage mapping technique, as depicted in Figure 3D-F[88]. The high reflectivity of the Pt/Ni electrode led to a notable reduction in photovoltage response when exposed to infrared laser illumination, which facilitated the delineation of the electrode and Te/CuTe multilayer boundaries. Employing a 4 × 4 array as well, the thermopile array was affixed to the human skin, utilizing a TE Peltier module with an emissivity of approximately 0.95 as a variable-temperature thermal source. When the Peltier module, in heating mode, was positioned above one corner of the thermopile array, it detected a nonuniform infrared radiation distribution, manifesting a stair-step-like photoresponse pattern. The

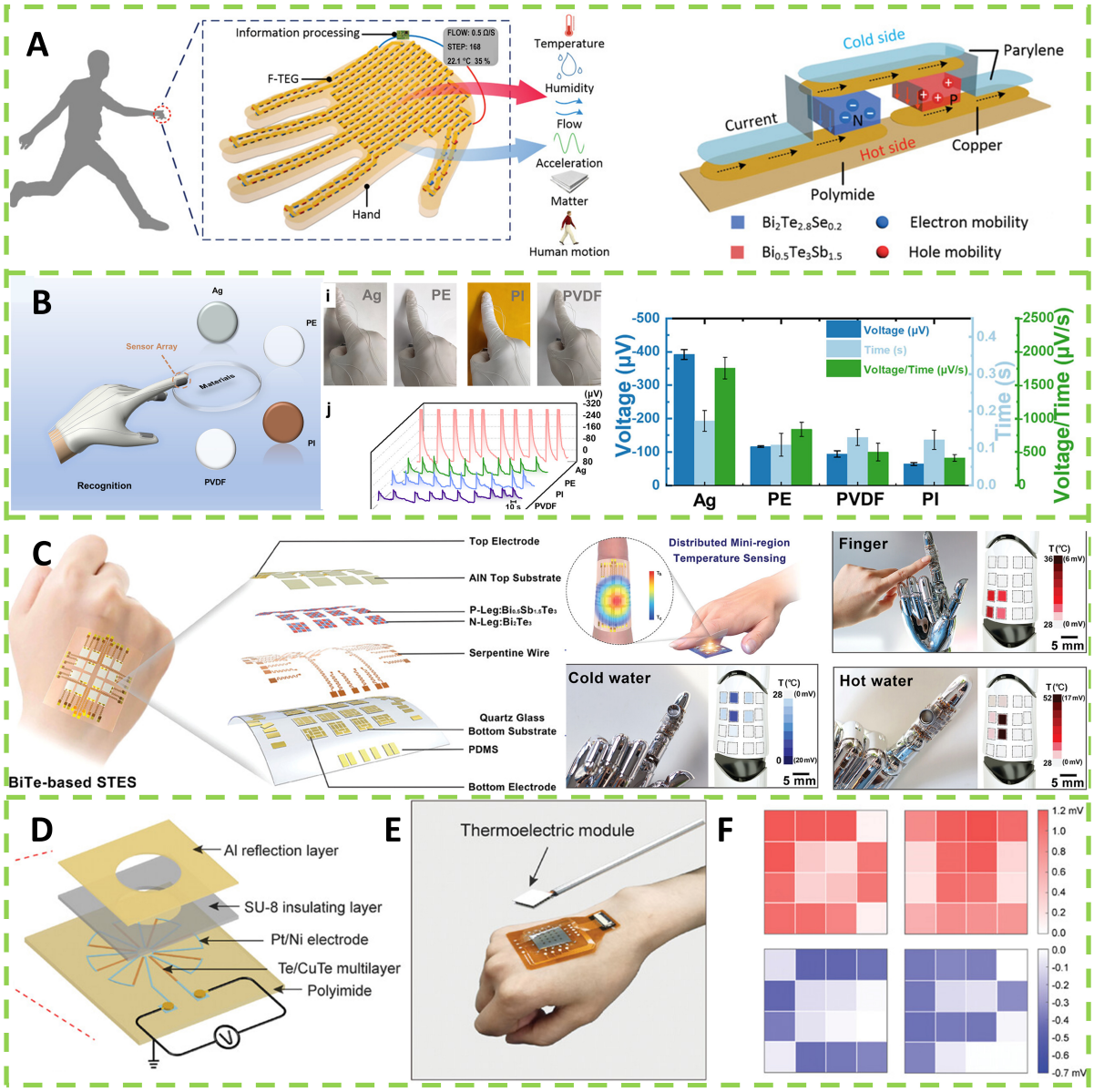

Figure 3. (A) Self-powered multifunction hand-shaped e-skin system(left) and A magnified and exploded view of a TE unit[84]. © Wiley 2020; (B) Schematic illustration, Digital photographs, and Voc response of the E-skin of E-skins for material recognition[85]. Copyright 2024 American Chemical Society; (C) Schematic illustration of STES in self-powered distributed mini-region sensing[87]. © Wiley 2023; (D) Photograph of the flexible thermopile array attached to a human hand, acting as a wearable e-skin to sense the radiation distribution emitted by a Peltier module; (E) Schematic for illustrating the structure of Te/CuTe multilayer-based thermopile with the asymmetric reflection structure; (F) Demonstration of radiation distribution sensing ability, by inserting the hollow masks with letters of "D", "I", "C", and "P" between the Peltier module and the thermopile array (upper panel: heating mode; lower panel: cooling mode)[88]. © Wiley 2024. STES: Self-powered temperature electronic skin; f-TEG: flexible thermoelectric generators; PI: polyimide; PVDF: polyvinylidene fluoride; STES: self-powered temperature electronic skin.

distinct contrast patterns observed using hollow masks with letters "D", "I", "C", and "P" between the Peltier module and the thermopile array, in both heating and cooling modes, were attributed to the significant response voltage difference for pixels at on and off states. These findings suggest that the development of artificial skin that can perceive thermal stimuli without physical contact eliminates the risk of physical damage during temperature sensing, especially when dealing with noxious thermal stimuli. Such innovation

is crucial for the implementation of touchless thermal sensation.

E-skin composed of sensor arrays also has considerable prospects in motion monitoring. Du *et al.* demonstrate an innovative self-powered TE wearable sensor, employing the reduced graphene oxide/poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (rGO/rPEDOT:PSS) composite as the active sensing element of TE devices [Figure 4A][89]. To specify, the researchers have proposed a TE sensing glove that leverages the superior TE properties, stability, and mechanical flexibility of rGO/rPEDOT:PSS composites for device-level applications, with a maximum power factor of 107.5 ± 5.5 $\mu W \cdot m^{-1} \cdot K^{-2}$ and a Seebeck coefficient of 29.5 ± 1.7 $\mu V \cdot K^{-1}$. The glove is equipped with fourteen micro TE sensors, each corresponding to a knuckle in the five fingers, mounted on a nitrile glove. The sensors are fabricated by sandwiching a film of rGO/rPEDOT: PSS between two copper electrodes, and their TE sensing capabilities are assessed based on the voltage signals produced due to the temperature gradient between the exterior (contacting an object) and interior (in contact with human skin) surfaces of the glove. The device achieved an average recognition accuracy of over 90% for various hand motions, indicating its effectiveness in precision motion monitoring.

Recent advancements have also shown that TE sensing systems can be effective interfaces for human-machine interaction within artificial perception systems, offering a new dimension to security and authentication mechanisms. Li *et al.* have developed an innovative TGH e-skin that addresses the limitations of existing self-powered E-skins, such as complex fabrication, stiffness, signal distortion under deformation, and inadequate performance [Figure 4B][90]. The e-skin in this study, integrated with deep learning technology, has been demonstrated for self-powered signature recognition and biometric authentication, achieving an impressive accuracy of 92.97%. The study of Ma *et al.* presents an innovative strategy utilizing a dual-network PVA/Ageterar hydrogel in an H_2O/glycerol binary solvent with $[Fe(CN)_6]^{3-/4-}$ as the redox couple [Figure 4C][91]. This TGH array, through its thermogalvanic effect, actively discerns the biometric characteristics of fingers by capturing intrinsic thermal signatures from five distinct locations. With the integration of machine learning, this approach achieves an impressive average accuracy of 97.6% in recognizing different users. Tian *et al.* present a novel TE hydrogel e-skin that transcends the limitations of traditional E-skins by offering passive multimodal sensing without the need for external power supplies [Figure 4D][92]. It could actively perceive multimodal physiological signals, including body temperature, pulse rate, and sweat content, in real-time without the need for decoupling. The ability of the e-skin to wirelessly transmit physiological signals for remote health monitoring highlights its potential in advanced intelligent medicine. The work of Li *et al.* involves the creation of conductive hydrogels that not only maintain their functionality in adverse environmental conditions but also enhance the sensitivity and responsiveness of E-skins [Figure 4E][93]. The anti-freezing properties and long-term storage stability of the hydrogel (> 1 week) at -20 °C were maintained due to the binary solvent system of water and ethylene glycol, which also contributed to its flexibility and stability. Moreover, these materials exhibit a high gauge factor of 0.725 and endurance to repetitive stress, making them suitable for the precise monitoring of various human motions and physiological signals. This hydrogel, when integrated into E-skins, allows for the monitoring of human motion with high sensitivity and could be instrumental in applications requiring gesture recognition and motion tracking. Ma *et al.* present a wearable smart glove device that integrates Ag_2Se-based E-skins, designed to replicate the diverse sensory functions of human hands. Each finger of the glove is equipped with e-skin sensors, enabling the collection of individual signals in response to environmental stimuli [Figure 4F][85]. The sensors capture the open-circuit voltage (V_{oc}) during activities such as keyboard typing and finger motion tracking, showcasing the device's responsiveness to varying stimuli. These systems are no longer limited to simple touch responses but now include complex sensory feedback, enhancing the capabilities of prosthetics, health monitoring devices, and interactive technologies.

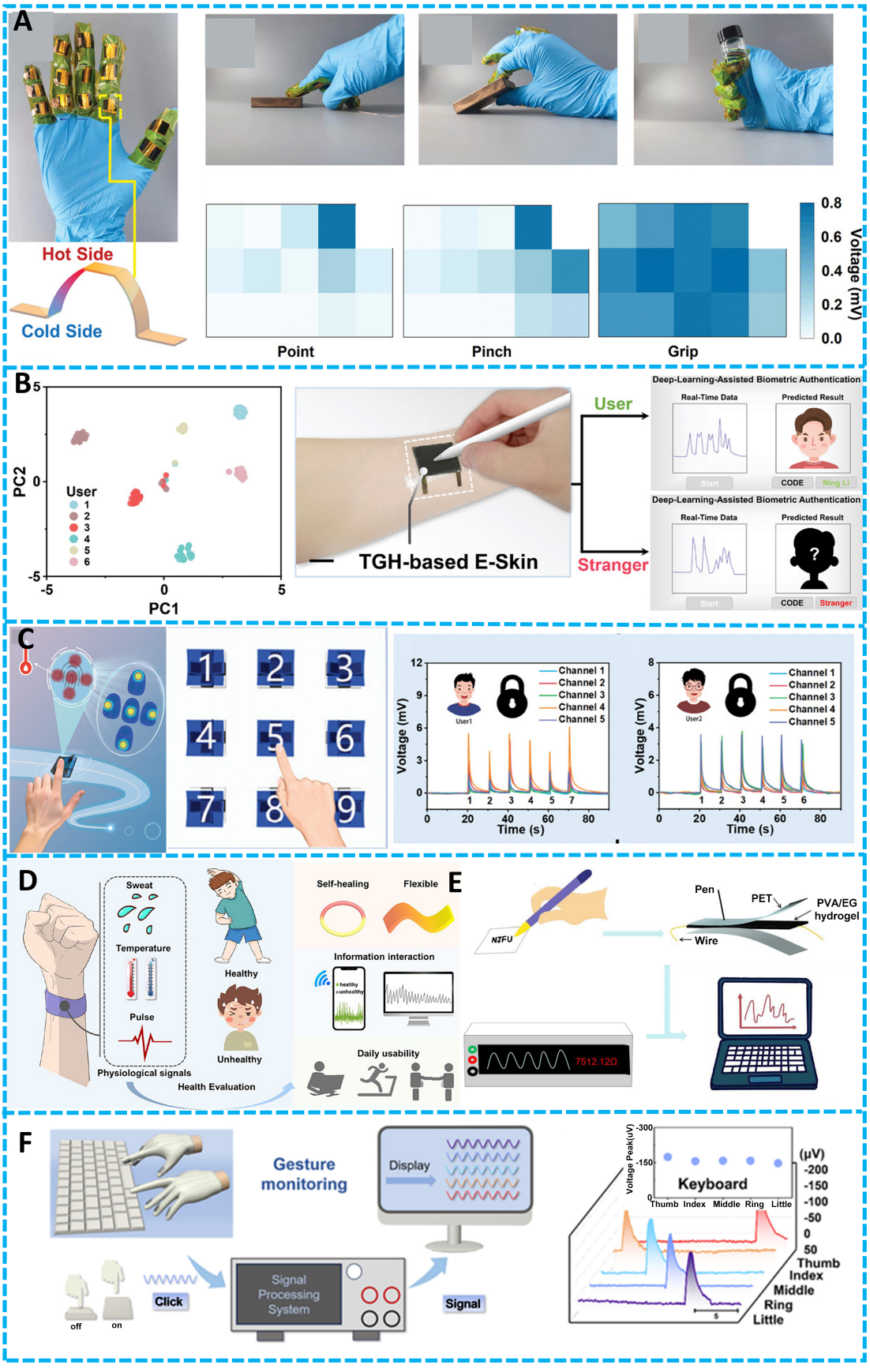
A
Hot Side
Cold Side
Point
Pinch
Grip
Voltage (mV)
0.8
0.6
0.4
0.2
0.0
B
PC2
PC1
User
1
2
3
4
5
6
TGH-based E-Skin
User
Stranger
Deep-Learning-Assisted Biometric Authentication
Real-Time Data
Predicted Result
Start
CODE
Ning Li
Deep-Learning-Assisted Biometric Authentication
Real-Time Data
Predicted Result
Start
CODE
Stranger
C
Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Voltage (mV)
Time (s)
User1
User2
D
Sweat
Temperature
Pulse
Physiological signals
Healthy
Unhealthy
Health Evaluation
Self-healing
Flexible
Information interaction
Daily usability
E
NTFU
Pen
PET
PVA/EG hydrogel
Wire
7512.12Ω
F
Gesture monitoring
Display
Click
off
on
Signal Processing System
Signal
Keyboard
Thumb
Index
Middle
Ring
Little
Voltage Peak(uV)
(μV)

Figure 4. (A) Thermoelectric sensors on the glove and the thermoelectric sensing diagram(left) and Map of voltages in the fourteen knuckles corresponding to the hand gestures (right)[89]. © Wiley 2022; (B) The distribution of datasets in a two-dimensional space composed of PC1 and PC2 axes (left) and demonstration of window display of user and stranger after writing down word "CODE" on the e-skin (right)[90]. © Wiley 2024; (C) Overview of the self-powered identity recognition based on the TGH[91]; (D) Application of multimodal e-skin PLG in health monitoring[92]. © Wiley 2024; (E) Schematic representing the device assembly during writing on the 25% PVA/EG hydrogel sensor. Copyright 2023, Elsevier; (F) Schematic illustration of the wearable device as a smart glove integrated with multiple E-skins and its sensing signal acquisition circuit[85]. Copyright 2024 American Chemical Society. PET: Polyethylene terephthalate.

The innovative integration of deep learning and machine learning algorithms in the studies represents a significant advancement in the field of smart materials and security systems, paving the way for more intelligent and interactive human-computer interfaces.

Body motion and respiration monitoring

TE sensing is a pivotal technology for its ability to harness body heat and convert it into electrical energy, facilitating self-powered systems[9,24,94-97]. This innovative approach is particularly significant for applications in personal health monitoring and energy harvesting, as it allows for the real-time detection of physiological parameters without the need for external power sources. He *et al.* have introduced a novel method for fabricating CNT/poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (CNT/PEDOT:PSS) TE nanofiber yarns. This method integrates coagulation-bath electrospinning with self-assembly techniques, as depicted in Figure 5A[98]. These yarns exhibit a high stretchability of approximately 350% and a Seebeck coefficient of 44 $\mu V \cdot K^{-1}$ and can be integrated into garments, such as gloves and masks, for applications in cold/heat source identification and human respiration monitoring in a self-powered mode. Wang *et al.* have made strides in this field by developing a novel class of iTE materials based on ionogels [Figure 5B][99]. The ionogel exhibited a giant ionic Seebeck coefficient of up to 28.43 $mV \cdot K^{-1}$, a superior ionic conductivity of 35.3 $mS \cdot cm^{-1}$, and an impressive power factor of 2.85 $mW \cdot m^{-1} \cdot K^{-2}$ at 90% relative humidity, resulting in a record high iTE figure of merit (ZT_i) of 6.9. Employing this material, smart masks integrating iTE sensors can monitor respiratory conditions by detecting temperature gradients between exhaled gas and the external environment. This results in distinct voltage signals that correspond to different respiratory states, enabling accurate monitoring of patient's breathing patterns. Building upon the advancements in TE sensing for personal health monitoring, the application of these materials in wearable devices extends beyond respiratory tracking. He *et al.* have fabricated durable, breathable, and enhanced-performance TE fabrics through a layer-by-layer self-assembly strategy [Figure 5C][100]. These fabrics are designed to maintain their TE properties even after extensive bending and washing cycles, showcasing their potential for long-term use in wearable applications. To specify, the fabrics exhibit a synergistic monitoring capability, combining facial respiration monitoring with knee joint motion tracking. This dual-mode sensing system provides a comprehensive assessment of an athlete's dynamic physical condition by capturing different signals from the body. The fabric's ability to convert thermal voltage changes into actionable data enables the real-time monitoring of respiratory rates and movement patterns, which is invaluable for sports performance analysis and injury prevention.

Additionally, there is a growing demand for devices that can provide continuous health monitoring and energy harvesting in particular scenarios. He *et al.* have introduced a novel TE fabric that is both waterproof and flexible, offering a practical solution for wearable devices that can operate in humid conditions, such as those caused by sweat or rain [Figure 5D][101]. This fabric, which combines thermoplastic polyurethane with CNTs (TPU/CNTs), is designed to be durable and sensitive, allowing it to function reliably even when exposed to moisture, unlike many electronic devices that can be compromised by water. One application is integrating the fabric into a mask, which can detect temperature changes caused by exhaled air, providing real-time data on breathing rates and patterns in multiple health conditions.

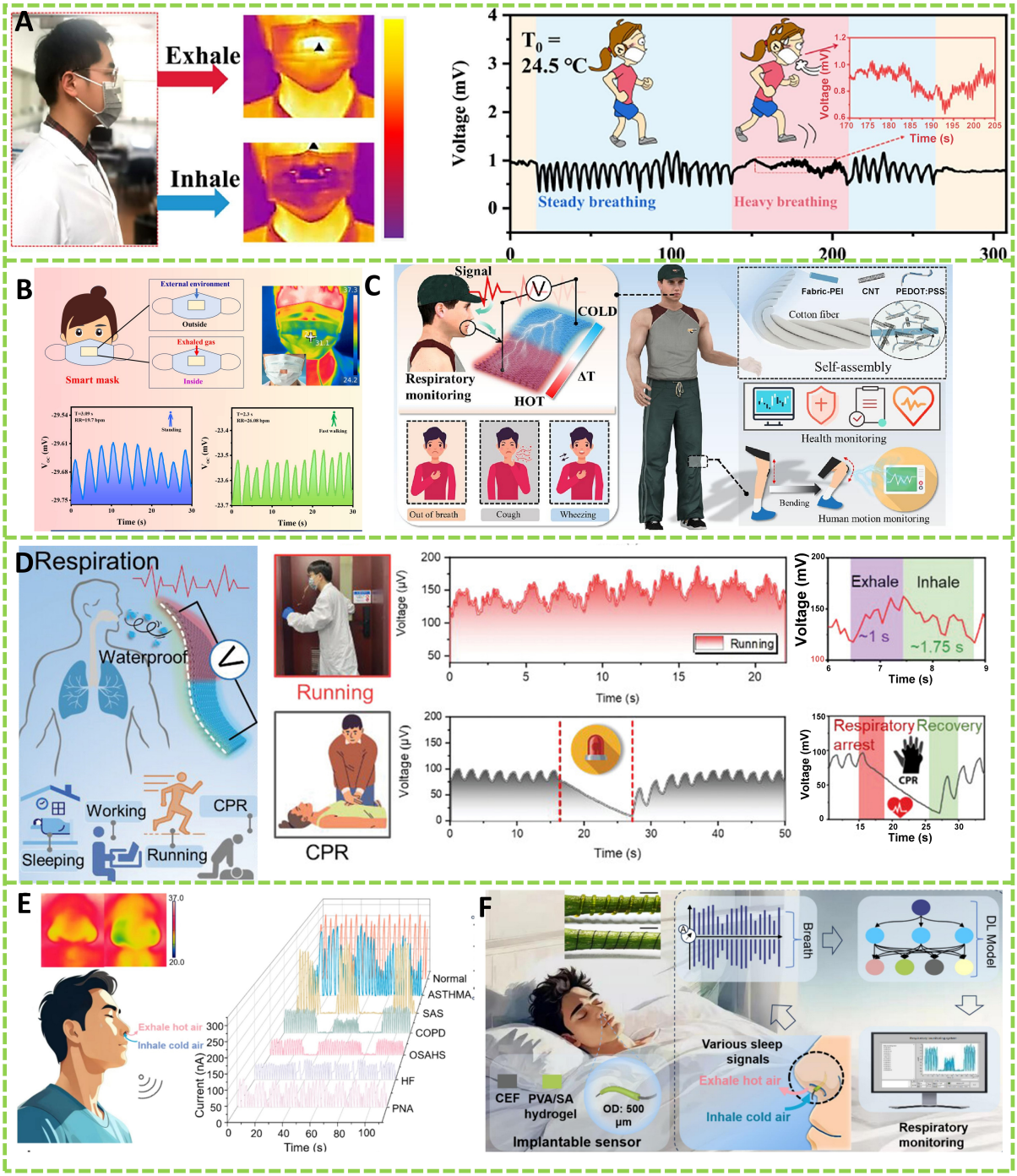

Figure 5. (A) Flexible wearable thermoelectric device composed of eight thermoelectric nanofiber yarns in series and its applications in human energy harvesting and respiration monitoring[98]. Copyright 2022, Elsevier; (B) Schematic illustration of the thermoelectric sensing mask for detecting respiratory rate[99]. Copyright 2024, Elsevier; (C) The thermoelectric fabric and its application in self-powered wearable products. Copyright 2024, Elsevier; (D) Temperature sensing applications of fabrics integrated into daily wear masks[101]; (E) Demonstration of a deep-learning-assisted self-powered in-nostril respiratory monitoring strategy. © Wiley 2022; (F) Design of the P-THF-based self-powered in-nostril thermoelectric sensor for respiratory monitoring[102]. Copyright 2025, Elsevier. CNT: Carbon nanotube; CPR: cardiopulmonary resuscitation; CEF: conductive elastomer film; PVA/SA: composite material of polyvinyl alcohol and sodium alginate.

Furthermore, the integration of deep learning with TE sensor technology represents a significant leap

forward in the field of wearable health monitoring and environmental sensing. Deep learning algorithms enhance the capability of TE sensors to not only detect but also interpret complex physiological and environmental data with high accuracy. Zhang *et al.* have contributed with their deep-learning-assisted TGH fiber sensor for self-powered in-nostril respiratory monitoring [Figure 5E][102]. This novel sensor leverages the TE effect to convert temperature differences within the nasal cavity into electrical signals, which are then processed using deep learning to identify distinct respiratory patterns with remarkable accuracy. Using deep learning, the hydrogel fiber-based respiratory monitoring strategy could actively identify seven respiratory patterns with an accuracy of 97.1%. Based on the sensor's TE capabilities, the hydrogel fiber sensor, with thermogalvanic properties, provides a non-invasive and comfortable method for long-term monitoring of respiratory health [Figure 5F][102]. This is particularly significant for individuals with conditions such as sleep apnea or asthma, where continuous monitoring is crucial for disease management and prevention of complications.

Temperature sensor for environmental monitoring

Environmental sensing is pivotal in the realm of smart living and industrial automation, providing critical data that informs decisions on safety, comfort, and energy efficiency[4,103,104]. The ability to accurately monitor environmental parameters such as temperature, humidity, and gas concentrations is not just a matter of convenience but is essential for maintaining optimal living conditions and preventing health hazards[105]. Advancements in material science have led to the development of innovative self-powered temperature monitoring systems that harness TE and thermogalvanic effects, offering a new frontier in environmental sensing technology. These systems are designed to be highly responsive and adaptive to varying conditions, making them invaluable tools for enhancing the precision and reliability of environmental sensing applications. Li *et al.* have crafted a gel electrolyte-based flexible thermogalvanic device that incorporates the I^-/I_3^- redox couple. This device demonstrates remarkable temperature resilience, operating effectively between -20 and 80 °C, and shows excellent resistance to drying under low vapor pressure conditions, as illustrated in Figure 6A[106]. This innovation allows the hydrogel to maintain its mechanical properties even in subzero temperatures, thus enhancing its resistance to environmental interference. The advancement is attributed to the weakening of hydrogen bonds between water molecules through a binary solvent strategy, enhancing the device's performance in harsh temperature environments. The high thermal sensitivity and stretchability of the TGH make it an ideal candidate for wearable E-skins, enabling real-time and continuous monitoring of environmental temperatures without the need for external power sources. The hydrogel can be embedded in smart windows, known as H-windows, for self-powered monitoring of indoor and outdoor temperatures, with the potential to trigger alarms in case of abnormal temperature changes, such as those indicating a fire or a malfunctioning refrigeration system.

The incorporation of TE materials into wearable textiles represents an innovative approach to early fire warning systems in harsh environments. He *et al.* have developed a self-powered, wearable fire warning electronic textiles (e-textile) that leverages the TE properties of $Ti_3C_2T_x$ MXene, silver nanowires (Ag NWs), and aramid nanofibers (ANFs) within an aerogel fiber matrix [Figure 6B][107]. This e-textile, crafted through wet spinning and weaving techniques, demonstrates a wide-range temperature sensing capability from 100-400 °C, indicating its reliability in different temperature scenarios. The output voltage of the e-textile increased with temperature, fitting a linear model with a high correlation coefficient ($R2 = 0.957$), which is attributed to the TE properties of Mxene. This linear relationship between TE voltage and temperature allows the e-textile to function effectively across varying temperature conditions, making it suitable for real-time temperature monitoring during firefighting operations. Additionally, the e-textile showed only a slight decrease in conductivity after a 500-cycle bending test, indicating its exceptional TE stability under mechanical stress. The rapid and repeated fire warning capability of the e-textile, which can initiate an alarm in less than 1.6 seconds upon exposure to flame, is significantly improved by the three-dimensional

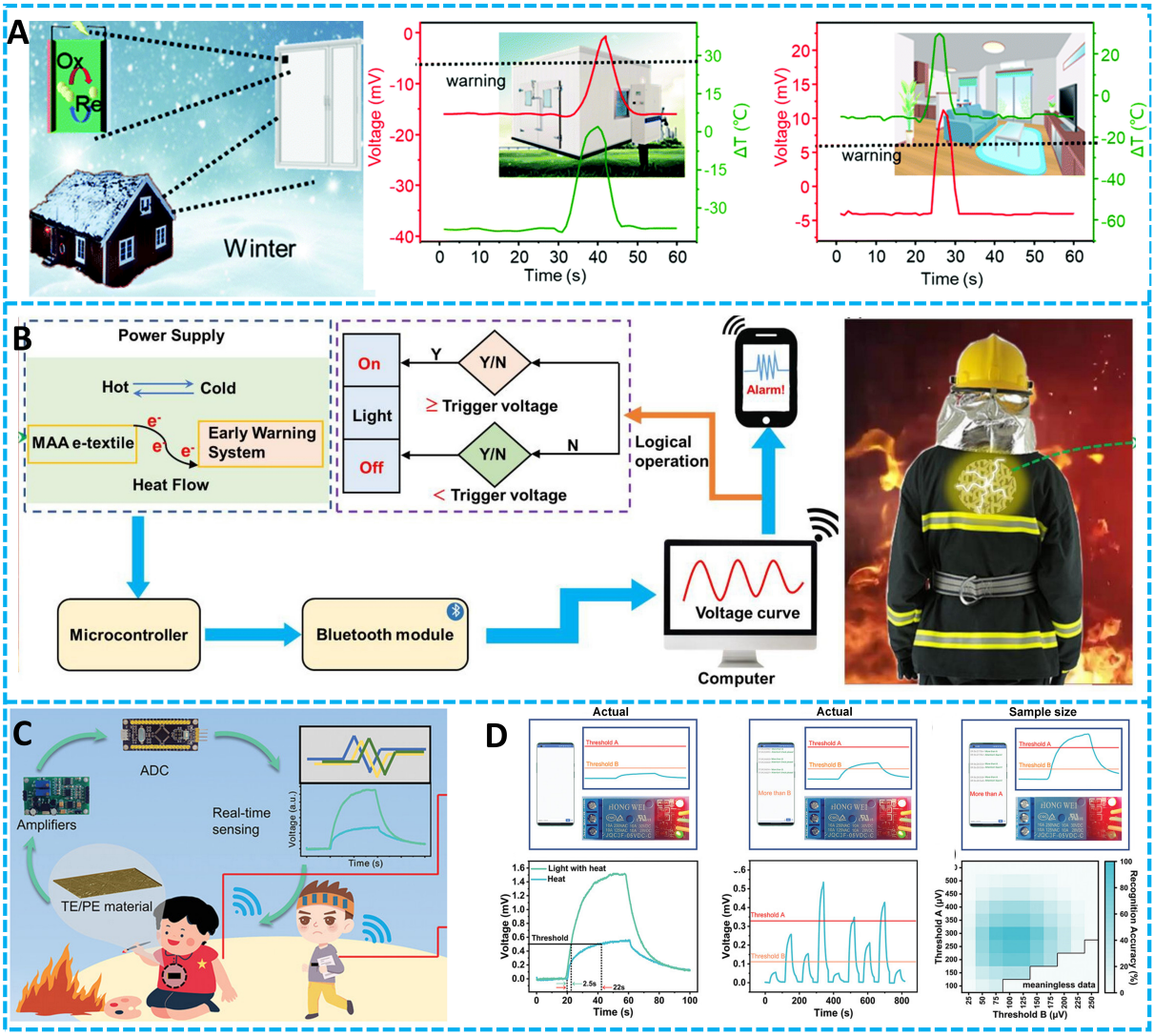

Figure 6. (A) Self-powered temperature monitoring using the PVA/GL thermogalvanic hydrogel of the H-window for outside temperature monitoring[106]. © Royal Society of Chemistry 2022; (B) The working mode of the MAA e-textile in the fire warning system[107]. Copyright 2023, Elsevier; (C)Thermoelectric and photoelectric dual modulated sensors for accurate fire recognition and warning; (D) V-T plots with light with heat and heat alone; the settings of threshold A and threshold B with output voltages (up) and the improvement of alarming accuracy by adjusting the settings of threshold A and threshold B (down)[108]. © Wiley 2023. ADC: Analog-to-Digital Converter; TE: thermoelectric; PE: piezoelectric.

conductive network formed by the bridging of 1D Ag NWs between 2D MXene nanosheets.

Moreover, providing early fire warnings before ignition can mitigate fire hazards. Li *et al.* have made significant strides in this field by developing a smart sensing system that leverages a light/heat dual-parameter-responsive single-walled CNT/poly(3-hexylthiophene-2,5-diyl) (SWCNT/P3HT) composite [Figure 6C][108]. The composite demonstrated excellent thermal stability with an onset decomposition temperature of 713 K and a maximum weight loss rate temperature of 748 K, as determined by thermogravimetric analysis (TGA), suggesting its robustness against high temperatures. Moreover, after a 7-day ambient exposure, its Seebeck coefficient and electrical conductivity remain constant with the power factor retaining above 97% of its initial value, indicating its ideal TE stability and consistent performance for

sensing applications. This system is designed to operate within the realm of human applications, offering enhanced precision in fire detection before ignition. The SWCNT/P3HT composite, integrated with a circuit microcontroller and a message transmission system, forms an intelligent fire source sensing device. It has been observed that the synergistic effect of light and heat significantly amplifies the output voltage and response time of the composite under concurrent stimuli, surpassing the performance under heating alone. This advancement is crucial for the accurate identification of fire sources and the initiation of alarm systems, which can be adjusted to detect fire hazards effectively. This system employs a sensing module that communicates with a mobile phone and a relay system, as illustrated in Figure 6D, accomplishing the accurate identification of fire sources and effective detection of fire hazards[108]. Jiang *et al.* presented a multifunctional ionic hydrogel [flame-retardant ionic hydrogel (HTIG)] with high thermopower for intelligent fire protection. This novel material, synthesized through free-radical polymerization, exhibits exceptional properties such as high thermopower (up to 3.35 $mV \cdot K^{-1}$) based on Soret effect, sensitive fire warning and strain sensing capabilities, and outstanding flame retardancy. The HTIG demonstrates a rapid response to fire, triggering an alarm in approximately six seconds and generating a voltage exceeding 100 mV upon exposure to flames. This rapid response time is critical for early fire detection and can greatly assist in evacuation and firefighting efforts. Moreover, the HTIG significantly enhances the fire safety of materials it is applied to, such as increasing the limiting oxygen index (LOI) of wood from 27% to over 80%, indicating a substantial improvement in flame resistance. In addition to its outstanding fire protection capabilities, the HTIG also shows great self-adhesive properties, which allows it to apply to various substrates[109].

Chemical sensors (chem-sensors) are another popular application for environmental sensing. Based on TE effect, self-powered chem-sensors are a promising candidate for pollutant detection. For example, Tsao *et al.* have developed a novel self-powered mercury ion (Hg^{2+}) nanosensor, harnessing the TE effect and chemical transformation mechanism for the detection of mercury ions[110]. Experiments have revealed that the output voltages of the TE nanosensor increased linearly as the concentration of Hg^{2+} ions in the water samples varied from 0 to 10 nM and 100 nM, indicating the sensor's capability to distinguish even small concentrations of Hg^{2+} ions from the presence of various other species in environmental samples.

CONCLUSION AND OUTLOOK

As the field of TE-based sensors for health and environmental monitoring continues to evolve, it is clear that significant strides have been made in recent years. However, there are several areas that require further attention and innovation to fully realize the potential of these technologies. The performance of TE sensors is intrinsically linked to the properties of the materials used. Hence, future research would continuously focus on the development of novel materials with enhanced TE *ZT*. One key challenge that biosensors face is their biocompatibility, which is influenced by the selection of materials (such as their natural abundance and non-toxicity) and structural design. Any changes in those parameters would degrade the performance of TE material. For some wearable sensors, the choice of substrate is particularly important, as they are directly attached to the user's skin. Polymers films including Polyethylene Terephthalate (PET), Polyethylene naphthalate (PEN), Polyimide (PI), and Polydimethylsiloxane (PDMS) are often utilized as the substrates for biosensors due to their biocompatibility and their biocompatibility and other key properties are summarized by Jia *et al.*[111]. Similarly, the biocompatibility of hydrogel-based sensors also matters. For current research, it is significant to choose the target material according to their particular application scenarios.

Meanwhile, the sensitivity, precision, fast response, and high sensing range of biosensors are desired. However, there are unavoidable trade-offs between those properties, which require further optimization

towards commercial applications. Researchers are now delving into probing techniques and methods to enhance the overall properties of those sensors. For example, Wang *et al.* introduce an innovative intronic pressure sensor that achieves both high sensitivity and a wide sensing range, partly addressing a critical bottleneck in the development of sensors for E-skins and wearable electronics[112].

Moreover, integrating TE sensors into wearable and implantable biosensors requires innovative design approaches that prioritize both functionality and comfort. However, though existing sensors could somewhat integrate materials such as semiconductors and hydrogels, they still faced some challenges that impede border and commercial applications. When ensuring the biocompatibility, adaptability, and comfortability of biosensors through encapsulation, their thermal efficiency is sacrificed to some extent. Wu *et al.* present an innovative approach to enhance the output of flexible TEGs (FTEGs) by leveraging the infrared reflection effect, which addresses the challenges of heat loss limitations, ensuring sufficient power for sensing[113]. For TE hydrogel, there is unavoidable dehydration in dry conditions and hydration in humid environments, which would negatively affect their original sensing performance. Hence, the encapsulation also matters for the TE hydrogel, and some researchers have delved into those areas. For instance, enlightened by mammals' skin, Huang *et al.* have reported a novel surface-encapsulating method to enhance the stability of hydrogel sensors by preventing dehydration and swelling. The researchers developed a chemical approach to create an elastic coating on the hydrogel surface, resulting in less than 6% weight loss when exposed to air at 28 °C for 20 days and no significant weight increase when immersed in water for 60 days[114]. Meanwhile, the integration of anode/hydrogel interfaces presents a significant challenge due to side reactions of anodes. Recent scientific research has provided valuable insights into this issue. The development of an *in-situ* physical/chemical cross-linked hydrogel electrolyte has been reported to stabilize the zinc anode-electrolyte interface, thereby preventing side reactions and dendrite growth in zinc-ion batteries[115]. To ensure long-term wearability and reliability, The developing self-healing materials and self-assembly strategies could also contribute to the creation of more robust and adaptable TE devices. IoT also offers vast opportunities for enhancing the capabilities of TE sensors. By integrating these sensors with IoT platforms, real-time data can be collected and analyzed more effectively, leading to more accurate health monitoring and environmental sensing.

When it comes to manufacturing, scaling up production methods while maintaining or improving material quality would be a significant task. This includes the exploration of low-cost fabrication techniques and the use of abundant, non-toxic materials. Additionally, the optimization of device architectures to require fewer materials or simpler manufacturing processes can significantly reduce costs. Meanwhile, as the demand for miniaturized and flexible TE sensors grows, particularly for wearable applications, there is a need for scalable manufacturing processes that can produce high-quality devices in large quantities. Advances in printing and flexible electronics technologies could play a crucial role in meeting this demand.

In conclusion, the future of TE-based sensors for health and environmental monitoring is promising but requires a concerted effort to address the challenges in materials optimization, device design, cost reduction, and integration with emerging technologies. By tackling these issues, we can pave the way for the next generation of TE sensors that are not only more efficient and reliable but also more accessible and sustainable.

DECLARATIONS

Acknowledgments

The authors acknowledge the support from Mr. Huangshui Ma and Miss. Shiyu Jia.

Authors' contributions

Manuscript structuring and writing: Tang, X.
Manuscript editing: Qi, C.
Manuscript structuring and editing: Sun, Q.

Availability of data and materials

Not applicable.

Financial support and sponsorship

This work was supported by Sichuan Science and Technology Program (Grant Nos. 2023YFG0220 and 2023ZYD0064) and the Fundamental Research Funds for the Central Universities and Research Funding from West China School/Hospital of Stomatology Sichuan University (No. QDJF2022-2).

Conflicts of interest

All authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Nguyen, A. T.; Tjulkins, F.; Aasmundtveit, K. E.; Hoivik, N.; Hoff, L.; Imenes, K. Miniaturization of package for an implantable heart monitoring device. *Microsyst. Technol.* **2015**, *21*, 1813-26. DOI
2. Sun, B.; Huang, X. Seeking advanced thermal management for stretchable electronics. *npj. Flex. Electron.* **2021**, *5*, 109. DOI
3. Linh, V. T. N.; Han, S.; Koh, E.; Kim, S.; Jung, H. S.; Koo, J. Advances in wearable electronics for monitoring human organs: bridging external and internal health assessments. *Biomaterials* **2025**, *314*, 122865. DOI PubMed
4. Dong, B.; Shi, Q.; Yang, Y.; Wen, F.; Zhang, Z.; Lee, C. Technology evolution from self-powered sensors to AIoT enabled smart homes. *Nano. Energy.* **2021**, *79*, 105414. DOI
5. Xu, C.; Song, Y.; Han, M.; Zhang, H. Portable and wearable self-powered systems based on emerging energy harvesting technology. *Microsyst. Nanoeng.* **2021**, *7*, 25. DOI PubMed PMC
6. Ahn, J.; Cho, S.; Wu, L.; et al. Innovations in self-powered sensors utilizing light, thermal, and mechanical renewable energy. *Nano. Energy.* **2024**, *129*, 110045. DOI
7. Twaha, S.; Zhu, J.; Yan, Y.; Li, B. A comprehensive review of thermoelectric technology: materials, applications, modelling and performance improvement. *Renew. Sustain. Energy. Rev.* **2016**, *65*, 698-726. DOI
8. Jaziri, N.; Boughamoura, A.; Müller, J.; Mezghani, B.; Tounsi, F.; Ismail, M. A comprehensive review of thermoelectric generators: technologies and common applications. *Energy. Reports.* **2020**, *6*, 264-87. DOI
9. Wu, Z.; Zhang, S.; Liu, Z.; Mu, E.; Hu, Z. Thermoelectric converter: strategies from materials to device application. *Nano. Energy.* **2022**, *91*, 106692. DOI
10. Hou, C.; Zhu, M. Semiconductors flex thermoelectric power. *Science* **2022**, *377*, 815-6. DOI PubMed
11. Riffat, S.; Ma, X. Thermoelectrics: a review of present and potential applications. *Appl. Therm. Eng.* **2003**, *23*, 913-35. DOI
12. Wang, Y.; Zhu, W.; Deng, Y.; et al. High-sensitivity self-powered temperature/pressure sensor based on flexible Bi-Te thermoelectric film and porous microconed elastomer. *J. Mater. Sci. Technol.* **2022**, *103*, 1-7. DOI
13. Jia, Y.; Zhang, S.; Li, J.; et al. Wearable device with high thermoelectric performance and long-lasting usability based on gel-thermocells for body heat harvesting. *Small* **2024**, *20*, e2401427. DOI PubMed
14. Liu, Z.; Tian, B.; Zhang, B.; et al. A thin-film temperature sensor based on a flexible electrode and substrate. *Microsyst. Nanoeng.* **2021**, *7*, 42. DOI PubMed PMC
15. Paganelli, A. I.; Mondéjar, A. G.; da, S. A. C.; et al. Real-time data analysis in health monitoring systems: a comprehensive systematic literature review. *J. Biomed. Inform.* **2022**, *127*, 104009. DOI PubMed

16. Kim Tuoi T, Van Toan N, Ono T. Thermal energy harvester using ambient temperature fluctuations for self-powered wireless IoT sensing systems: a review. *Nano. Energy.* **2024**, *121*, 109186. DOI
17. Chen, P.; Wang, J.; Xue, Y.; et al. From challenge to opportunity: revolutionizing the monitoring of emerging contaminants in water with advanced sensors. *Water. Res.* **2024**, *265*, 122297. DOI PubMed
18. Zhang, J.; Huang, L.; Chen, M.; et al. Highly sensitive self-powered biosensor for real-time monitoring and early warning of human health and motion state. *Nano. Energy.* **2024**, *131*, 110213. DOI
19. Smith, A. A.; Li, R.; Tse, Z. T. H. Reshaping healthcare with wearable biosensors. *Sci. Rep.* **2023**, *13*, 4998. DOI PubMed PMC
20. Erdem, A.; Eksin, E.; Senturk, H.; Yildiz, E.; Maral, M. Recent developments in wearable biosensors for healthcare and biomedical applications. *TrAC. Trends. Anal. Chem.* **2024**, *171*, 117510. DOI
21. Kulkarni, M. B.; Rajagopal, S.; Prieto-Simón, B.; Pogue, B. W. Recent advances in smart wearable sensors for continuous human health monitoring. *Talanta* **2024**, *272*, 125817. DOI PubMed
22. Assaad, R. H.; Mohammadi, M.; Poudel, O. Developing an intelligent IoT-enabled wearable multimodal biosensing device and cloud-based digital dashboard for real-time and comprehensive health, physiological, emotional, and cognitive monitoring using multi-sensor fusion technologies. *Sens. Actuators. A. Phys.* **2025**, *381*, 116074. DOI
23. Wang, J.; Zhu, Y.; Wu, Z.; et al. Wearable multichannel pulse condition monitoring system based on flexible pressure sensor arrays. *Microsyst. Nanoeng.* **2022**, *8*, 16. DOI PubMed PMC
24. Xue, Z.; Gai, Y.; Wu, Y.; liu, Z.; Li, Z. Wearable mechanical and electrochemical sensors for real-time health monitoring. *Commun. Mater.* **2024**, *5*, 658. DOI
25. Ding, Z.; Du, C.; Long, W.; et al. Thermoelectrics and thermocells for fire warning applications. *Sci. Bull.* **2023**, *68*, 3261-77. DOI PubMed
26. Lv, L.; Cao, C.; Qu, Y.; et al. Smart fire-warning materials and sensors: design principle, performances, and applications. *Mater. Sci. Eng. R. Rep.* **2022**, *150*, 100690. DOI
27. Yu, H.; Hu, Z.; He, J.; et al. Flexible temperature-pressure dual sensor based on 3D spiral thermoelectric Bi_2Te_3 films. *Nat. Commun.* **2024**, *15*, 2521. DOI PubMed PMC
28. Li, J.; Liu, Y.; Wang, Z.; Chen, L.; Cai, K. Ultra-flexible self-supporting Ag_2Se/nylon composite films for wearable thermoelectric devices. *Compos. Part. B. Eng.* **2023**, *265*, 110946. DOI
29. Wu, H.; Shi, X.; Duan, J.; Liu, Q.; Chen, Z. Advances in Ag_2Se-based thermoelectrics from materials to applications. *Energy. Environ. Sci.* **2023**, *16*, 1870-906. DOI
30. Liu, Y.; Zhang, Q.; Huang, A.; et al. Fully inkjet-printed Ag_2Se flexible thermoelectric devices for sustainable power generation. *Nat. Commun.* **2024**, *15*, 2141. DOI PubMed PMC
31. Liu, M.; Zhang, X.; Zhang, S.; Pei, Y. Ag_2Se as a tougher alternative to n-type Bi_2Te_3 thermoelectrics. *Nat. Commun.* **2024**, *15*, 6580. DOI PubMed PMC
32. Chen, Y. X.; Shi, X. L.; Zhang, J. Z.; et al. Deviceization of high-performance and flexible Ag_2Se films for electronic skin and servo rotation angle control. *Nat. Commun.* **2024**, *15*, 8356. DOI PubMed PMC
33. Wang, X.; Wang, H.; Liu, B. Carbon nanotube-based organic thermoelectric materials for energy harvesting. *Polymers* **2018**, *10*, 1196. DOI PubMed PMC
34. Li, D.; Gong, Y.; Chen, Y.; et al. Recent progress of two-dimensional thermoelectric materials. *Nanomicro. Lett.* **2020**, *12*, 36. DOI PubMed PMC
35. Qian, W.; Jia, S.; Yu, P.; et al. Highly stretchable, low-hysteresis, and antifreeze hydrogel for low-grade thermal energy harvesting in ionic thermoelectric supercapacitors. *Mater. Today. Phys.* **2024**, *49*, 101589. DOI
36. Chen, L.; Rong, X.; Liu, Z.; et al. Negative thermopower anisotropic ionic thermoelectric hydrogels based on synergistic coordination and hydration for low-grade heat harvesting. *Chem. Eng. J.* **2024**, *481*, 148797. DOI
37. Zhu, X.; Yu, Y.; Li, F. A review on thermoelectric energy harvesting from asphalt pavement: configuration, performance and future. *Constr. Build. Mater.* **2019**, *228*, 116818. DOI
38. Beretta, D.; Neophytou, N.; Hodges, J. M.; et al. Thermoelectrics: from history, a window to the future. *Mater. Sci. Eng. R. Rep.* **2019**, *138*, 100501. DOI
39. d'Angelo, M.; Galassi, C.; Lecis, N. Thermoelectric materials and applications: a review. *Energies* **2023**, *16*, 6409. DOI
40. Zhang, Q.; Deng, K.; Wilkens, L.; Reith, H.; Nielsch, K. Micro-thermoelectric devices. *Nat. Electron.* **2022**, *5*, 333-47. DOI
41. Snyder, G. J.; Toberer, E. S. Complex thermoelectric materials. *Nat. Mater.* **2008**, *7*, 105-14. DOI PubMed
42. Duan, J.; Yu, B.; Huang, L.; et al. Liquid-state thermocells: opportunities and challenges for low-grade heat harvesting. *Joule* **2021**, *5*, 768-79. DOI
43. Zhang, Q.; Song, Q.; Wang, X.; et al. Deep defect level engineering: a strategy of optimizing the carrier concentration for high thermoelectric performance. *Energy. Environ. Sci.* **2018**, *11*, 933-40. DOI
44. Ma, Z.; Wei, J.; Song, P.; et al. Review of experimental approaches for improving zT of thermoelectric materials. *Mater. Sci. Semicond. Process.* **2021**, *121*, 105303. DOI
45. Sun, Y.; Zhu, Y.; Wu, H.; et al. Rational design from materials to devices enables an efficiency of 10.5% based on thermoelectric $(Bi, Sb)_2Te_3$ and $Mg_3(Bi, Sb)_2$ for power generation†. *Energy. Environ. Sci.* **2024**, *17*, 738-47. DOI
46. Lyu, W.; Liu, W.; Li, M.; et al. Efficient stepwise carrier concentration optimization in $Ge_{(1+x)}ySbyTe$†. *J. Mater. Chem. C.* **2024**, *12*, 18004-8. DOI

47. Hicks, L. D.; Dresselhaus, M. S. Thermoelectric figure of merit of a one-dimensional conductor. *Phys. Rev. B.* **1993**, *47*, 16631-4. DOI PubMed
48. Oxandale, S. W.; Reinke, C.; Das, S. R.; El-kady, I. Enhanced thermoelectric performance via quantum confinement in a metal oxide semiconductor field effect transistor for thermal management. *Commun. Mater.* **2023**, *4*, 397. DOI
49. Ma, J.; Delaire, O.; May, A. F.; et al. Glass-like phonon scattering from a spontaneous nanostructure in $AgSbTe_2$. *Nat. Nanotechnol.* **2013**, *8*, 445-51. DOI PubMed
50. Liu, F.; Zhang, M.; Nan, P.; et al. Unraveling the origin of donor - like effect in bismuth -telluride-based thermoelectric materials. *Small. Science.* **2023**, Epub ahead of print. DOI
51. Mathew, S. S.; Sangeeta; Kumar, R.; Singh, M.; Kashyap, M. K. Optimizing carrier concentration for enhanced thermoelectric performance in $AgSbS_2$ monolayer. *Ionics* **2024**, *30*, 8647-57. DOI
52. Musah, J.; Ilyas, A.; Novitskii, A.; et al. Effective decoupling of seebeck coefficient and the electrical conductivity through isovalent substitution of erbium in bismuth selenide thermoelectric material. *J. Alloys. Compd.* **2021**, *857*, 157559. DOI
53. Shalini, M.; Nanthini, S.; Veluswamy, P.; et al. Facet dependent ultralow thermal conductivity of zinc oxide coated silver fabric for thermoelectric devices. *Sci. Rep.* **2024**, *14*, 27210. DOI PubMed PMC
54. Qi, X.; Kang, T.; Yang, L.; et al. Simultaneous suppression of phonon transport and carrier concentration for efficient rhombohedral GeTe thermoelectric. *Adv. Sci.* **2024**, *11*, e2407413. DOI PubMed PMC
55. Gong, Y.; Dou, W.; Lu, B.; et al. Divacancy and resonance level enables high thermoelectric performance in n-type SnSe polycrystals. *Nat. Commun.* **2024**, *15*, 4231. DOI PubMed PMC
56. Jia, B.; Wu, D.; Xie, L.; et al. Pseudo-nanostructure and trapped-hole release induce high thermoelectric performance in PbTe. *Science* **2024**, *384*, 81-6. DOI PubMed
57. Wang, X.; Huang, Y. T.; Liu, C.; et al. Direct thermal charging cell for converting low-grade heat to electricity. *Nat. Commun.* **2019**, *10*, 4151. DOI PubMed PMC
58. Dong, S.; Cabral, D. M.; Pringle, J. M.; Macfarlane, D. R. Exploring the electrochemical properties of mixed ligand Fe(II) complexes as redox couples. *Electrochim. Acta.* **2020**, *362*, 137109. DOI
59. Han, C. G.; Qian, X.; Li, Q.; et al. Giant thermopower of ionic gelatin near room temperature. *Science* **2020**, *368*, 1091-8. DOI PubMed
60. Li, Z.; Xu, Y.; Wu, L.; et al. Zinc ion thermal charging cell for low-grade heat conversion and energy storage. *Nat. Commun.* **2022**, *13*, 132. DOI PubMed PMC
61. Liu, Y.; Cui, M.; Ling, W.; et al. Thermo-electrochemical cells for heat to electricity conversion: from mechanisms, materials, strategies to applications. *Energy. Environ. Sci.* **2022**, *15*, 3670-87. DOI
62. Qian, X.; Ma, Z.; Huang, Q.; Jiang, H.; Yang, R. Thermodynamics of ionic thermoelectrics for low-grade heat harvesting. *ACS. Energy. Lett.* **2024**, *9*, 679-706. DOI
63. Duan, J.; Feng, G.; Yu, B.; et al. Aqueous thermogalvanic cells with a high Seebeck coefficient for low-grade heat harvest. *Nat. Commun.* **2018**, *9*, 5146. DOI PubMed PMC
64. Wang, Z.; Li, N.; Yang, X.; Zhang, Z.; Zhang, H.; Cui, X. Thermogalvanic hydrogel-based e-skin for self-powered on-body dual-modal temperature and strain sensing. *Microsyst. Nanoeng.* **2024**, *10*, 55. DOI PubMed PMC
65. Yang, K.; Bai, C.; Liu, B.; Liu, Z.; Cui, X. Self-powered, non-toxic, recyclable thermogalvanic hydrogel sensor for temperature monitoring of edibles. *Micromachines* **2023**, *14*, 1327. DOI PubMed PMC
66. Li, T.; Zhang, X.; Lacey, S. D.; et al. Cellulose ionic conductors with high differential thermal voltage for low-grade heat harvesting. *Nat. Mater.* **2019**, *18*, 608-13. DOI PubMed
67. Zhao, D.; Martinelli, A.; Willfahrt, A.; et al. Polymer gels with tunable ionic Seebeck coefficient for ultra-sensitive printed thermopiles. *Nat. Commun.* **2019**, *10*, 1093. DOI PubMed PMC
68. He, Y.; Li, S.; Chen, R.; et al. Ion-electron coupling enables ionic thermoelectric material with new operation mode and high energy density. *Nanomicro. Lett.* **2023**, *15*, 101. DOI PubMed PMC
69. Kjelstrup, S.; Kristiansen, K. R.; Gunnarshaug, A. F.; Bedeaux, D. Seebeck, Peltier, and Soret effects: on different formalisms for transport equations in thermogalvanic cells. *J. Chem. Phys.* **2023**, *158*, 020901. DOI PubMed
70. Cheng, H.; Ouyang, J. Soret effect of ionic liquid gels for thermoelectric conversion. *J. Phys. Chem. Lett.* **2022**, *13*, 10830-42. DOI PubMed
71. Rahman, M.; Saghir, M. Thermodiffusion or Soret effect: historical review. *Int. J. Heat. Mass. Transf.* **2014**, *73*, 693-705. DOI
72. Zhao, D.; Würger, A.; Crispin, X. Ionic thermoelectric materials and devices. *J. Energy. Chem.* **2021**, *61*, 88-103. DOI
73. Song, D.; Chi, C.; An, M.; et al. Ionic Seebeck coefficient and figure of merit in ionic thermoelectric materials. *Cell. Rep. Phys. Sci.* **2022**, *3*, 101018. DOI
74. Kim, D. H.; Akbar, Z. A.; Malik, Y. T.; Jeon, J. W.; Jang, S. Y. Self-healable polymer complex with a giant ionic thermoelectric effect. *Nat. Commun.* **2023**, *14*, 3246. DOI PubMed PMC
75. Tian, Y.; Yang, X.; Li, K.; et al. High-performance ionic thermoelectric materials and emerging applications of ionic thermoelectric devices. *Mater. Today. Energy.* **2023**, *36*, 101342. DOI
76. Wu, M.; Yao, K.; Li, D.; et al. Self-powered skin electronics for energy harvesting and healthcare monitoring. *Mater. Today. Energy.* **2021**, *21*, 100786. DOI
77. Yuan, F.; Wang, W.; Liu, S.; et al. A self-powered three-dimensional integrated e-skin for multiple stimuli recognition. *Chem. Eng. J.*

2023, *451*, 138522. DOI

78. Chugh, V.; Basu, A.; Kaushik, A.; Basu, A. K. E-skin - based advanced wearable technology for health management. *Curr. Res. Biotechnol.* **2023**, *5*, 100129. DOI
79. Chen, J.; Chen, X.; Li, H.; Ma, C.; Yu, P.; Zhang, Y. A large-area less-wires stretchable robot electronic skin. *Sens. Actuators. A. Phys.* **2024**, *376*, 115618. DOI
80. Núñez C, Manjakkal L, Dahiya R. Energy autonomous electronic skin. *npj. Flex. Electron.* **2019**, *3*, 45. DOI
81. Yin, L.; Kim, K. N.; Lv, J.; et al. A self-sustainable wearable multi-modular E-textile bioenergy microgrid system. *Nat. Commun.* **2021**, *12*, 1542. DOI PubMed PMC
82. Sun, X.; Guo, X.; Gao, J.; et al. E-Skin and its advanced applications in ubiquitous health monitoring. *Biomedicines* **2024**, *12*, 2307. DOI PubMed PMC
83. Jabri, M.; Masoumi, S.; Kandukuri, T. R.; Occhipinti, L. G. Flexible thin-film thermoelectric generators for human skin-heat harvesting: a numerical study. *Nano. Energy.* **2024**, *129*, 110001. DOI
84. Yuan, J.; Zhu, R.; Li, G. Self-powered electronic skin with multisensory functions based on thermoelectric conversion. *Adv. Mater. Technol.* **2020**, *5*, 2000419. DOI
85. Ma, H.; Pu, S.; Wu, H.; et al. Flexible Ag_2Se thermoelectric films enable the multifunctional thermal perception in electronic skins. *ACS. Appl. Mater. Interfaces.* **2024**, *16*, 7453-62. DOI PubMed
86. Han, Y.; Wei, H.; Du, Y.; et al. Ultrasensitive flexible thermal sensor arrays based on high-thermopower ionic thermoelectric hydrogel. *Adv. Sci.* **2023**, *10*, e2302685. DOI PubMed PMC
87. Kang, M.; Qu, R.; Sun, X.; et al. Self-powered temperature electronic skin based on island-bridge structure and Bi-Te micro-thermoelectric generator for distributed mini-region sensing. *Adv. Mater.* **2023**, *35*, e2309629. DOI PubMed
88. Guo, X.; Lu, X.; Jiang, P.; Bao, X. Touchless thermosensation enabled by flexible infrared photothermoelectric detector for temperature prewarning function of electronic skin. *Adv. Mater.* **2024**, *36*, e2313911. DOI PubMed
89. Du, C.; Cao, M.; Li, G.; et al. Toward precision recognition of complex hand motions: wearable thermoelectrics by synergistic 2D nanostructure confinement and controlled reduction. *Adv. Funct. Mater.* **2022**, *32*, 2206083. DOI
90. Li, N.; Wang, Z.; Yang, X.; et al. Deep-learning-assisted thermogalvanic hydrogel E-skin for self-powered signature recognition and biometric authentication. *Adv. Funct. Mater.* **2024**, *34*, 2314419. DOI
91. Ma, X.; Wang, W.; Cui, X.; et al. Machine learning assisted self-powered identity recognition based on thermogalvanic hydrogel for intelligent security. *Small* **2024**, *20*, e2402700. DOI PubMed
92. Tian, C.; Khan, S. A.; Zhang, Z.; Cui, X.; Zhang, H. Thermoelectric hydrogel electronic skin for passive multimodal physiological perception. *ACS. Sens.* **2024**, *9*, 840-8. DOI PubMed
93. Li, Z.; Yin, F.; He, W.; et al. Anti-freezing, recoverable and transparent conductive hydrogels co-reinforced by ethylene glycol as flexible sensors for human motion monitoring. *Int. J. Biol. Macromol.* **2023**, *230*, 123117. DOI PubMed
94. Zhang, X.; Zhao, L. Thermoelectric materials: energy conversion between heat and electricity. *J. Materiomics.* **2015**, *1*, 92-105. DOI
95. Nozariasbmarz, A.; Collins, H.; Dsouza, K.; et al. Review of wearable thermoelectric energy harvesting: from body temperature to electronic systems. *Appl. Energy.* **2020**, *258*, 114069. DOI
96. Yang, S.; Li, Y.; Deng, L.; et al. Flexible thermoelectric generator and energy management electronics powered by body heat. *Microsyst. Nanoeng.* **2023**, *9*, 106. DOI PubMed PMC
97. Jin, J.; Hou, Y.; Li, C.; et al. High-performance waterproof flexible thermoelectric generators for self-powered electronics. *Nano. Energy.* **2024**, *132*, 110388. DOI
98. He, X.; Gu, J.; Hao, Y.; et al. Continuous manufacture of stretchable and integratable thermoelectric nanofiber yarn for human body energy harvesting and self-powered motion detection. *Chem. Eng. J.* **2022**, *450*, 137937. DOI
99. Wang, Z.; Lv, H.; Gao, Z.; Song, H. Stretchable and thermo-mechanical stable ionogels with high thermoelectric properties for respiratory sensing and energy harvesting. *Chem. Eng. J.* **2024**, *498*, 155789. DOI
100. He, X.; Li, C.; Zhu, S.; et al. Layer-by-layer self-assembly of durable, breathable and enhanced performance thermoelectric fabrics for collaborative monitoring of human signal. *Chem. Eng. J.* **2024**, *490*, 151470. DOI
101. He, X.; Li, B.; Cai, J.; et al. A waterproof, environment-friendly, multifunctional, and stretchable thermoelectric fabric for continuous self-powered personal health signal collection at high humidity. *SusMat* **2023**, *3*, 709-20. DOI
102. Zhang, Y.; Wang, H.; Ahmed, K. S.; et al. Deep-learning-assisted thermogalvanic hydrogel fiber sensor for self-powered in-nostril respiratory monitoring. *J. Colloid. Interface. Sci.* **2025**, *678*, 143-9. DOI PubMed
103. Dong, B.; Prakash, V.; Feng, F.; O'neill, Z. A review of smart building sensing system for better indoor environment control. *Energy. Build.* **2019**, *199*, 29-46. DOI
104. Narayana, T. L.; Venkatesh, C.; Kiran, A.; et al. Advances in real time smart monitoring of environmental parameters using IoT and sensors. *Heliyon* **2024**, *10*, e28195. DOI PubMed PMC
105. Wang, J.; Song, Y.; Yu, F.; et al. Ultrastrong, flexible thermogalvanic armor with a Carnot-relative efficiency over 8. *Nat. Commun.* **2024**, *15*, 6704. DOI PubMed PMC
106. Li, X.; Xiao, X.; Bai, C.; et al. Thermogalvanic hydrogels for self-powered temperature monitoring in extreme environments. *J. Mater. Chem. C.* **2022**, *10*, 13789-96. DOI
107. He, H.; Qin, Y.; Liu, J.; et al. A wearable self-powered fire warning e-textile enabled by aramid nanofibers/MXene/silver nanowires aerogel fiber for fire protection used in firefighting clothing. *Chem. Eng. J.* **2023**, *460*, 141661. DOI

108. Li, G.; Hu, Y.; Chen, J.; et al. Thermoelectric and photoelectric dual modulated sensors for human internet of things application in accurate fire recognition and warning. *Adv. Funct. Mater.* **2023**, *33*, 2303861. DOI
109. Jiang, C.; Lai, X.; Wu, Z.; et al. A high-thermopower ionic hydrogel for intelligent fire protection. *J. Mater. Chem. A.* **2022**, *10*, 21368-78. DOI
110. Tsao, Y.; Husain, R. A.; Lin, Y.; Khan, I.; Chen, S.; Lin, Z. A self-powered mercury ion nanosensor based on the thermoelectric effect and chemical transformation mechanism. *Nano. Energy.* **2019**, *62*, 268-74. DOI
111. Jia, S.; Ma, H.; Gao, S.; Yang, L.; Sun, Q. Thermoelectric materials and devices for advanced biomedical applications. *Small* **2024**, *20*, e2405019. DOI PubMed
112. Wang, J.; Xiong, Z.; Wu, L.; Chen, J.; Zhu, Y. Highly sensitive and wide-range iontronic pressure sensors with a wheat awn-like hierarchical structure. *J. Colloid. Interface. Sci.* **2024**, *669*, 190-7. DOI PubMed
113. Wu, B.; Wei, W.; Guo, Y.; et al. Stretchable thermoelectric generators with enhanced output by infrared reflection for wearable application. *Chem. Eng. J.* **2023**, *453*, 139749. DOI
114. Huang, X.; Zhang, L. Encapsulation of hydrogel sensors. *Chem. Eng. J.* **2024**, *484*, 149631. DOI
115. Li, C.; Wang, J.; Zhang, D.; et al. In-situ physical/chemical cross-linked hydrogel electrolyte achieving ultra-stable zinc anode-electrolyte interface towards dendrite-free zinc ion battery. *J. Energy. Chem.* **2024**, *97*, 342-51. DOI