Triboelectric Nanogenerator Enabled Wearable Sensors and Electronics for Sustainable Internet of Things Integrated Green Earth

Yanqin Yang, Xinge Guo, Minglu Zhu, Zhongda Sun, Zixuan Zhang, Tianyi He, and Chengkuo Lee*

The advancement of the Internet of Things/5G infrastructure requires a low-cost ubiquitous sensory network to realize an autonomous system for information collection and processing, aiming at diversified applications ranging from healthcare, smart home, industry 4.0 to environmental monitoring. The triboelectric nanogenerator (TENG) is considered the most promising technology due to its self-powered, cost-effective, and highly customizable advantages. Through the use of wearable electronic devices, advanced TENG technology is developed as a core technology enabling self-powered sensors, power supplies, and data communications for the aforementioned applications. In this review, the advancements of TENG-based electronics regarding materials, material/device hybridization, systems integration, technology convergence, and applications in healthcare, environment monitoring, transportation, and smart homes toward the future green earth are reported.

1. Introduction

Moving toward the fifth-generation wireless network (5G) era, the world is rapidly adapting to innovative technological advancement. 5G technology gets to be the significant driving force for the blooming of the Internet of Things (IoT), enabling faster, more stable, and more secure connectivity.\[1\] It is estimated that 42 billion devices will be connected globally by 2025 as the components of the IoT network, and they will generate massive data with multi-dimensions, higher velocity, and improved heterogeneity.\[2\] Benefiting from this, our world is developing toward a smarter and more well-knit green earth, covering essential blocks like smart homes, smart agriculture, smart cities, smart industries as well as outer space and airlines.\[3\] In the green earth, the IoT systems are promising to be spread in every smart area, consisting of various sensing modules, signal processing modules, power management modules, power supply modules, etc. Sensing modules are applied to collect abundant information from the target objects or environment, such as temperature, humidity, light intensity, gas concentration, pressure, etc. And the signal processing modules help with the data transmission, processing, and analysis to connect and exchange information with other devices or systems to provide an optimal command to the target object or environment. In addition, the power management modules and power supply modules are to provide the most efficient solutions to reduce the overall power consumption in the operations of the IoT systems.\[4–6\] Thus, looking at the whole earth, it is to be closely connected with the IoT systems, enabling information transfer and communication over the strong network.

Narrowing down to a single object like the human body, a single animal, or a robot, wearable electronics have attracted increasing research interest owing to their promising applications in real-time and precious monitoring and tracking of user’s preferences and habits on the green earth.\[7–10\] Conventional wearable electronics involve smart watches, smart glasses, smart helmets, etc., while most of them are fabricated from nonflexible or rigid materials, resulting in limited wearable comfort, device lifetime, latency response, and loss of sensing information.\[11–13\] To address these issues, the current research focuses on the investigation of sensing materials with flexibility or even stretchability, breathability, washability, lightweight, adhesiveness, etc., enabling improved wearing comfort and long-term wearability.\[14–17\]

Besides the wearability of the modules in the IoT system, energy issue is within wide research interest and concern as one of the urgent issues contemporarily. Batteries, as the dominant choices for power supply modules, are now revealed as

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the stumbling block for the extensive applications of IoT systems, given their drawbacks including limited lifetime, high contamination, and requirement for frequent replacements or recharging. To compensate for this limitation, self-sustained systems with zero or nano external energy consumption have been developed with power supply modules, which include energy harvesters (EHs) and energy storage units. Specifically, mechanical energy or thermal energy in the ambient environment can be harvested and generated into electricity by devices like electromagnetic generators (EMGs), piezoelectric nanogenerators (PENGs), triboelectric nanogenerators (TENGs) or thermoelectric nanogenerators (TEGs).\[18–24\]

Afterward, the generated electricity can be stored in the energy storage units such as the lithium-ion battery, supercapacitor, etc., to power the other functional modules in the IoT systems. On the other hand, in terms of the sensing modules, researchers are also exploring the extensive potential of these EHs in self-powered sensing.\[25\] The self-generated electrical signals of the self-powered sensors vary with external stimulus levels so that they show promising prospects for temperature sensing, pressure sensing, strain sensing, tactile sensing, gas sensing, etc.\[21,26–28\]

Considering the sustainability of the IoT system, devices based on TENGs stand out in functionalities of both energy harvesting and self-powered sensing.\[29–34\] Specifically, TENGs are mainly composed of triboelectric layers and electrode layers and the working mechanism relies on the coupling effects of triboelectrification and electrostatic induction of any two materials with different electron affinities.\[15–18\] Hence, they possess additional advantages like vast material choices, easy fabrication, low cost, and versatile working modes. Many kinds of flexible materials like paper-based materials, textile-based materials, and even stretchable elastomers are widely utilized in the fabrication of wearable TENGs.\[39–44\] To improve the wearability of the flexible materials regarding e-textile and e-skirt, many efforts have been put to functionalizing the materials for TENGs with washability, lightweight, breathability, antibacterial capability, self-healing capability, biodegradability, biocompatibility, etc.\[20,45–50\] Although the output power of TENGs is limited compared with the EMGs, the portability and wearability are much more superior and TENGs also excel in harvesting low-frequency energy such as mechanical energy from human motions and ocean waves. Strategies including material patterns, material functionalization, hybridization of materials or devices, and power management circuit introductions are now being investigated to enhance the output performance of TENGs.\[51–61\] In addition, when serving as self-powered sensors, diverse TENG structures have been constructed owing to the versatile working modes. Applications such as healthcare and biomedicine, robotic control, human machine interfaces (HMIs), and automations have already been extensively demonstrated via TENGs.\[62–74\] Furthermore, technology convergence is happening on TENGs including wireless signal transmission techniques, nanophotonics, novel fabrication techniques, etc., bringing novel and unexpected applications for TENGs and the green earth.\[75–78\]

Machine learning (ML) integrated TENGs are also successfully demonstrated for individual recognition, gesture recognition, object recognition, etc., matching the current development of green earth with high intelligence.\[61,64,79–83\] Overall, in the built-up of IoT integrated green earth, TENG technology can effectively contribute to either sensing modules or power supply modules in every aspect of the green earth.

Regarding TENG-enabled wearable sensors and electronics for sustainable IoT integrated green earth in Figure 1, this review will provide an overview of the progress in these fields with respect to the flexible/wearable materials and devices, hybrid and self-sustained systems integration, corresponding practical applications, and convergence with advanced techniques enabling promising IoT integrated green earth. Figure 2 summarizes the main content of this review. Based on the four working mechanisms for TENGs (including contact and separation mode, lateral sliding mode, single electrode mode, and freestanding triboelectric layer mode) in Figure 2a, we have reviewed the development of TENGs regarding the advancements in materials and applications toward green earth. As summarized in Figure 2b, we will introduce novel and functional materials for improved wearability, including stretchability, transparency, ultrathin thickness, and self-healing capability of the devices. Materials with environmental-friendly such as biodegradability and biocompatibility are reviewed to be more compatible with green earth. Hybrid materials enabling the multifunctionality of wearable electronics will also be discussed. Beyond the materials development, we will then focus our discussions on the TENGs enabled diverse applications in the IoT integrated green earth. Figure 2c illustrates the roadmaps for TENGs in the miscellaneous fields. First, for biomedical applications, we will review from the conventional wearable e-skins enabled healthcare monitoring to the integrated biomedical systems, and the currently most challenging implantable electronics will also be discussed. Second, regarding the human machine interfaces and automation applications, with the emphasis on wearable electronics, some recent and significant examples of intelligent sensing, HMI, and even the smart automation will be discussed, which can play important roles in the control interfaces of green earth. Third, aiming for an energy-saving green earth, we will also review the TENGs as EHs. Nowadays, the most common strategies for performance enhancement include the hybrid mechanism, structural improvement as well as the circuit designs. Thus, novel devices and systems for energy harvesting systems will be reviewed in terms of indoor and outdoor applications. Fourth, we will discuss the development of TENGs from a single device to their enabled self-sustained IoT systems as well as the further artificial intelligence of things (AIoT) systems. Meanwhile, the convergence of TENG with advanced technologies, including photonics, microelectromechanical systems (MEMS) fabrication, plasmonic, large-scale fabrication will be discussed in detail, showing great potential for technology convergence and commercialization in green earth. Subsequently, TENGs enabled applications for diverse scenarios in green earth will be introduced including transportation, rain and wind, ocean, as well as outer space. Lastly, perspectives about the research trends for wearable sensors and electronics toward green earth are provided, innovating toward human-friendly, environment-friendly, self-sustainability, and higher intelligence.
2. Novel and Functional Materials for the Development of Wearable TENGs

In this section, we will briefly review novel and functional materials for TENG devices that help improve human body wearability, such as stretchability, skin-adhesiveness, self-healing capability, breathability, washability/waterproof capability, antibacterial capability, biocompatibility, etc.

2.1. Stretchable and Self-Healing Materials for TENGs

Triboelectric materials and electrode materials are two fundamental and crucial components to the construction of TENG devices. Elastomers like silicone rubber, PDMS, and Eco-fleX are extensively investigated as triboelectric layers due to their structure-design abilities resulting from the liquid state and stretchable capabilities after solidifying. For the stretchable
Figure 2. Summarized roadmaps of TENGs in the green earth development. a) The working mechanisms of TENGs. Reproduced with permission. Copyright 2020, Wiley. Reproduced with permission. Copyright 2021, Wiley. Reproduced with permission.
electrode materials, two common methods are employed, e.g., structure designs using materials with high Young's modulus (kirigami structure,[39,84] paper folding,[40] etc.) and synthesis and applications of materials with low Young's modulus (liquid metal,[85] saline, hydrogel,[86,87,88] iongel,[89] etc.). Recently, Wang et al. have proposed a stretchable and shape-adaptive TENG based on potassium iodide and glyceral (KI-Gly) liquid electrolyte (Figure 3a).[90] The low Young's modulus of this material endows the stretchability of ≈300% for the fabricated TENG device and the output performance can maintain under 250% tension stretching for 10,000 cycles. Due to the shape-adaptive capability and stretchability, this bulk device can be worn on different body parts, e.g., knee, elbow, and wrist, to harvest human motion energy through bending and releasing process. Meanwhile, a wearable touch panel has been fabricated by arraying TENG units as touch-sensing components and the touch panel is attached onto the arm as a self-powered interactive device for HMI. When the finger types the touch panel units attached onto the forearm, the letters “TENG” or “HENU” can be successfully displayed on the liquid crystal display (LCD) screen via a microcontroller unit (MCU). Moreover, a body motion counter based on the TENG can also be constructed for counting the number of human arm swings. In order to achieve better skin-attachability and wearability, Jiang et al. have developed a TENG device that is not only stretchable but also ultrathin and washable, serving as the skin-like highly sensitive self-powered haptic sensor (Figure 3b).[91] PDMS is used as the triboelectric material and silver nanowires are distributed evenly throughout the thermoplastic polyurethane (TPU) nanofiber network as the electrode. On the bottom side, the commercial VHB tape with outstanding mechanical and thermal properties is adapted, serving as the structural supporting and protection layer. The TENG achieves super stretchability of 300% while possesses great transparency, ultrathin thickness of 89 μm and light weight of 230 mg. Washability test is also conducted for this device, and it maintains stable performance after multiple washes. Owing to the mentioned properties that are compatible with wearability, including ultrathin thickness, stretchability and washability, a 3 × 3 self-powered haptic sensor array has been demonstrated by attaching it onto human hand. A skin-like game control interface is developed in this work by combining the skin-like sensor array with a signal processing circuit and a LabVIEW program-based computer. When the finger touches the sensor pixel, real-time results can be displayed in the designed program, which controls character movement in games.

Moreover, the ideal type of wearable sensors is the so-called epidermal sensors, where the sensors are extremely lightweight, soft, and has good attachability and compatibility with human skin. Recently, An et al. have developed an epidermal tattoo-like self-powered triboelectric sensor based on vertically aligned standing gold nanowires (v-AuNWs), as shown in Figure 3c.[92] The stretchable conductor is prepared by elastomer-bonded v-AuNWs with exceptionally high strain (500%) while maintaining high conductivity and triboelectric output performance. The skin-like triboelectric pressure-sensing tattoos can be fabricated on human skins following the steps of embedding v-AuNWs into ultrathin elastomers, micropatterning, peeling off, and transferring to human skin, aiming for HMI applications. The TENG device has good compatibility with human skin under different deformations, e.g., compressing, stretching, and twisting. Such self-powered tattoo sensors could be further integrated with a soft printed circuit board (PCB), functioning as HMI for wireless vehicle controllers. Furthermore, as shown in Figure 3d, Wong et al. have proposed a series of ultrathin, soft TENGs with well-designed aesthetic patterns by using the state-of-the-art processing techniques in epidermal electronics.[93] The electrode is prepared by sputtering Cu on the polyimide (PI) film, followed by photolithography and etching to obtain the designed electrode patterns. Transfer printing technology is also utilized here by transferring the PI–Cu–PI structure onto human skin from the glass substrate. Afterward, the PDMS film is transferred onto the human skin as the triboelectric and encapsulation layer of the device. Owing to the adhesives of liquid bandage and the tens-of-μm thickness, this TENG can be conformally attached to human skin as an epidermal sensor. It is illustrated that the TENG can be twisted, bent and stretched which shows great compatibility as the sensor on human skins. When attached on different body positions (e.g. arm, chest, back, tummy, and thigh), the TENG can be utilized as the body motions sensor to distinguish different motions from the obtained signals. Meanwhile, the authors also fabricate arrow-like TENG serving as the human–machine interface for remote car control.

Besides, during daily movement and exposure to complicated environment, some cracks or damages to the wearable
Figure 3. Novel and functional materials for the development of wearable TENGs. a) A stretchable, shape adaptable, and biocompatible TENG based on liquid electrolyte for wearable human–machine interaction. Reproduced with permission.\cite{90} Copyright 2020, Wiley. b) A stretchable, washable, and ultrathin TENG as skin-like sensitive self-powered haptic sensors. Reproduced with permission.\cite{91} Copyright 2021, Wiley. c) Nanowire tattoo enabled epidermal TENG for soft wearable human–machine interface. Reproduced with permission.\cite{92} Copyright 2020, Elsevier. d) An ultrathin and soft TENG with well-designed aesthetic patterns for activity monitoring and wearable HMI control. Reproduced with permission.\cite{93} Copyright 2021, Wiley. e) A self-healing and nondrying conductive organogel based environment-resistant TENG. Reproduced with permission.\cite{89} Copyright 2021, Elsevier. f) An abrasion and fracture self-healable TENG with ultrahigh stretchability and long-term durability. Reproduced with permission.\cite{97} Copyright 2021, Wiley. g) Bioinspired self-healing TENG as HMI touchpad with pressure-sensitive adhesiveness. Reproduced with permission.\cite{98} Copyright 2020, Wiley.
self-powered sensors are inevitable. Fortunately, the investigation of self-healing materials helps alleviate these troubles and prolongs the lifetime of the sensors. The self-healing ability is achieved mainly due to two mechanisms, e.g., the release of healing agent and the movement of dynamic bonds in the materials.[97,98] The former one has limited times of self-healing until the agents are totally released while the latter one can be sustained. As for the application of self-healing materials in TENG technology, both triboelectric materials and electrode materials are considered. Polymers containing double-sulphur bonds (e.g., vitrimer elastomers) and hydrogen bonds (e.g., hydrogels) are greatly adopted.[68,86,95,96] In Figure 3e, Huang et al. have proposed a self-healing, hydrophobic and icedophobic TENG with outstanding nondrying and nonfreezing properties.[89] The self-healing and nontoxic conductive organohydrogel is applied as the electrode while the self-healing and flexible 1U-PDMS elastomer crosslinked by imine bond and quadruple hydrogen bonding is applied as the triboelectric material. The organohydrogel can achieve great stretchability and bendability even after the self-healing process while the self-healed 1U-PDMS can also be bent and twisted. Such a device is employed as the energy harvesting device and its output performance can be perfectly maintained under different temperatures ranging from −30 to 80 °C. In addition to the fractures caused by extreme stretching or bending, abrasions also commonly exist owing to the frequently friction on the surfaces. Thus, in Figure 3f, Jiang et al. have proposed a self-healable TENG with ultrahigh stretchability and long-term durability that can heal abrasion and fractures simultaneously at room temperature.[90] The triboelectric material for this self-healing TENG is prepared by incorporating hydrogen bonds and dynamic metal–ligand coordination into PDMS chains. Besides the self-healing capability at room temperature, the fabricated elastomer also exhibits great stretchability of 10 000%. The electrode material for TENG is obtained by dispersing the nanosilver powered with the above elastomer. The self-healing TENG possesses ultrastretchability of 1800% and the high output performance can be maintained even at maximum stretching level. When the TENG is stretched until break until the whole TENG can recover its function in 20 min at room temperature. In addition, the rough surface caused by abrasion could also become smoother after healing for 30 min at room temperature. And the whole device can be recovered to its original state after 2 h. Besides the materials development, the self-healing TENGs are also developing toward wearable application. For example, in Figure 3g, Gao et al. have proposed a bioinspired self-healing HMI touchpad with pressure-sensitive adhesive on target substrates, e.g., human skin.[98] The prepared polyzwitterion-clay nanocomposite hydrogel is a soft, transparent (98.8%), and stretchable (1500% strain) ionic conductor. With the PDMS as the triboelectric material and proposed self-healing hydrogel as the electrode, the output performance of constructed TENG can be maintained after cutting and self-healing process. A surface-capacitive touch system is adopted to monitor the touching position, both point-to-point touch and continuous moving can be perceived. It is demonstrated that the pressure-sensitive pad can be utilized to play a piano game after cutting then joining. A 2D touchpad is labeled with 17 input positions and adhered on the computer screen to form an integrated hydrogel touch screen for writing letters. Also, a wearable touchpad is integrated with a computer system and used to play the Angry Birds game where different movements and touching positions on the pad are defined as different commands for the game control.

2.2. Biocompatible and Biodegradable Materials for TENGs

In the construction of green earth, researchers are paying more attention to environmental-friendly materials. Biodegradability and biocompatibility are two popular parameters in developing wearable and implantable electronics. Generally, biocompatible and biodegradable TENGs are constructed with natural materials or synthetic materials.[46] In Figure 4a, Jiang et al. have summarized biocompatible and biodegradable materials originating from nature, including cellulose, chitin, silk fibroins, rice paper, egg white, etc.[99] The biocompatibility of these materials is investigated using L929 cells. The result shows that the cells can grow and proliferate without obvious stagnation, indicating nontoxic and biocompatibility of these natural materials. Based on these materials, the authors have constructed various fully biodegradable TENGs, and the output performances are compared to get the triboelectric series of these five materials. Among them, the biodegradability of the silk fibroins based TENGs is studied in vivo and in vitro. It is illustrated that the TENG degrades slowly in 84 days in both scenarios. Moreover, the methods of improving the output performance and the stability of natural biocompatible materials are also developed. In Figure 4b, Kim et al. have developed a chitosan–diatom based TENG for biofriendly and skin-attachable wearable devices.[100] The diatom frustule and chitosan are known as two biocompatible ocean biomaterials. The authors have examined the intracutaneous reactivity of the chitosan–diatom mixtures, and it turns out that although all sites did not show any edema, the tested samples only showed very slight erythema on several sites at 24 h while the red sites disappeared beyond 48 h. This result indicates that the chitosan–diatom film can meet the requirement of the global standard of biosafety. The highly porous diatom frustule is used as the additives to greatly change electropositivity of chitosan films. When the chitosan–diatom film is used as the tribopositive layer and Al as the electrode layers, the fabricated TENG shows enhanced output performance compared with the pure chitosan one. In practical application, the chitosan–diatom film is applied in developing a watch as a power supply, and a skin-attachable motion sensor for healthcare monitoring. In Figure 4c, Xu et al. have developed a mesoscopic doped silk fibrin with enhanced mechanical properties and chemical stability to solve the intrinsic brittleness as well as the poor chemical stability of pure silk film.[100] Besides high transparency, biocompatibility and biodegradability, the doped silk films show superior chemical stability when exposed to 100 °C and 3–11 PH. The mechanical flexibility is improved to a stretchability of 250% and good stability is maintained within 1000 bending cycles. A TENG device is prepared by using this doped silk film as the positive layer, PTFE as the negative layer and Ag conducting films as the electrode layers. Depending on the different electrical outputs of the TENG under varying conditions.
contact areas, the TENG is applied to control the transparency of the electrochromic rearview mirror in the car when touched with different quantities of fingers. Thus, a self-powered mechnosensational communication system for a smart car is formed. Empirically, the natural biocompatible materials based TENGs are also demonstrated as wearable sensors for human physiological monitoring. In Figure 4d, Wang et al. have proposed a fully biodegradable and water-soluble TENG based on recycled papers and a water-soluble graphite electrode.[102] The cellulosic nanocrystal (CNC) in the papers is extracted and mixed with methylcellulose (MC) to form the positive triboelectric layer and the pure MC layer is served as the negative triboelectric layer. The CNC and MC films can both be dissolved in water after 30 min and degraded fully in the natural environment after 30 days. Based on this TENG, the authors have developed a bandage sensor for respiration monitoring when attached to the abdomen. An obvious voltage change in the range of 0.3–0.8 V would be generated in various respiratory states, namely, slight breathing, normal breathing, rapid breathing, and deep breathing. In addition to the natural biocompatible and biodegradable materials, synthetic biomaterials are also play key roles in the development of TENGs. In Figure 4e, a breathable, biodegradable, and antibacterial e-skin is proposed based on all-nanofiber TENG.[103] It is fabricated by sandwiching silver nanowire (Ag NW) between polylactic-co-glycolic acid (PLGA) and polyvinyl alcohol (PVA). With micro-to-nanohierarchical porous structure, the e-skin has a high specific surface area for contact electrification and numerous capillary channels for thermal-moisture transfer. Through adjusting the concentration of Ag NW and the selection of PVA and PLGA, the antibacterial and biodegradable capability of e-skins can be tuned, respectively. The e-skin can achieve real-time and self-powered monitoring of whole-body physiological signal and joint movement. This work provides a new strategy for multifunctional e-skins with excellent practicability.

Thus, the required properties for improved wearableability of sensors and electronics include stretchability, transparency, ultrathin thickness, adhesiveness, self-healing capability, biocompatibility, biodegradability, etc. In Table 1, we have summarized materials used in the recent wearable TENGs with focus on these required properties.

2.3. Hybrid Materials Enabled Multifunctionality for Wearable Electronics

Complementary to the construction of the wearable self-powered device using single functional material, hybrid materials, and mechanisms are utilized in one device, leveraging their synergistic effect for performance enhancement and multifunctionality purposes.[112] In terms of performance enhancement, Yang et al. have developed a tribo-ferroelectric synergistic e-textile with high thermal-moisture stability (Figure 5a).[113] The e-textile consists of four functional fabric layers, including nanofiber nonwovens poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) and polyamide 6 (PA6) with opposite electron-affinity as two triboelectric layers, nickel–copper (Ni–Cu) fabric electrode for charge induction, and the moisture-wicking fabric for directional water transport and rapid evaporation. The P(VDF-TrFE) nanofibers also act as a ferroelectric polymer for constructing tribo-ferroelectric synergistic enhancement effect. And electrospinning was adopted to induce rich ferroelectric β-phase as well as the steering polarization of CF2 dipoles in P(VDF-TrFE) nanofiber. Owing to the tribo-ferroelectric synergistic effect introduced by ferroelectric polymer nanofibers, the peak power density is seven times as large as that of the reported breathable triboelectric textiles. Such a high-output device is fabricated into cloth to harvest energy from human motions and the stored energy can be used for LCD powering and self-powered gesture monitoring system. On the other hand, the multisensing capability can be achieved through the utilization of hybrid materials. In Figure 5b, Zhu et al. have proposed a hybrid electronic skin with multimodal sensing capabilities by combining triboelectric effect and piezoelectric effect.[114] The device includes not only the contact and noncontact sensing in contact–separation process but also sensing in continuous deformation process. The triboelectric layer with a porous structure is fabricated from a lotus leaf-mold patterned method. And the piezoelectric layer is prepared by the multiwalled carbon nanotubes (MWCNTs)-doped poly(vinylidene fluoride) (PVDF) nanofibrous membrane. Conductive fabrics are employed as the electrode materials for both sensing materials. With the vertical packing of all the materials respectively, the e-skin with hybrid modal-sensing capabilities can be obtained. Such a device can be combined with a mask to monitor respiration in real time, leveraging the two modes of external forces from contact/separation process and continuous contacting process. Four breathing patterns, i.e., no breathing, faint breathing, normal breathing, and deep breathing can be easily distinguished through the response signals. For tactile sensing, as the external force of the fingers increases, the output signal increases, indicating its potential applications in intelligent prosthetics, smart robots, and patients with skin damages. Combining triboelectric effect and thermoelectric effect, Chen et al. have developed a self-powered pressure–temperature dual-functional sensor as e-skin in Figure 5c.[115] The device is constructed with three layers: the pressure sensing layer relies on the triboelectric effect with patterned PDMS
Table 1. A summary of wearable triboelectric nanogenerators.

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Working mode</th>
<th>Triboelectric material</th>
<th>Electrode material</th>
<th>Stretchability</th>
<th>Transparency</th>
<th>Ultrathin thickness</th>
<th>Self-adhesiveness</th>
<th>Self-healing capability</th>
<th>Biocompatibility</th>
<th>Biodegradability</th>
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</thead>
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<tr>
<td>[104]</td>
<td>Single electrode mode</td>
<td>Silicone rubber</td>
<td>Ag NW</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>[105]</td>
<td>Single electrode mode</td>
<td>Rubber</td>
<td>Conductive liquid</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>NA</td>
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<tr>
<td>[106]</td>
<td>Single electrode mode</td>
<td>Silicone rubber</td>
<td>CNT–silicone rubber composite</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>[107]</td>
<td>Single electrode mode</td>
<td>PVDF-HFP</td>
<td>rGO</td>
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<td>NA</td>
<td>NA</td>
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<td>[108]</td>
<td>Single electrode mode</td>
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<td>Liquid PEDOT:PSS</td>
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<td>NA</td>
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<td>[109]</td>
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<td>Silicone rubber</td>
<td>Cotton with Ag</td>
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<tr>
<td>[110]</td>
<td>Single electrode mode</td>
<td>PDMS</td>
<td>CNT–Ag NW fiber</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>[88]</td>
<td>Single electrode mode</td>
<td>Silicone rubber</td>
<td>CNFs/MXene dispersion</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>[112]</td>
<td>Contact and separation mode</td>
<td>PDMS/PAMPS ionogel</td>
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<td>Yes</td>
<td>Yes</td>
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<td>[113]</td>
<td>Single electrode mode</td>
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<td>Gellan–PAM–PEDOT:PSS hydrogel</td>
<td>Yes</td>
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<td>[14]</td>
<td>Single electrode mode</td>
<td>PDMS</td>
<td>Ionogel</td>
<td>Yes</td>
<td>Yes</td>
<td>NA</td>
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<td>NA</td>
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</tr>
<tr>
<td>[93]</td>
<td>Single electrode mode</td>
<td>PDMS</td>
<td>Cu</td>
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Figure 5. Hybrid mechanisms enabled multifunctionality of wearable electronics. 
b) Triboelectric and piezoelectric synergistic electronic skin with multimodal sensing capabilities. Reproduced with permission.[132] Copyright 2020, Elsevier. 
c) A multimodal TENG skin sensor with direct temperature-pressure perception. Reproduced with permission.[133] Copyright 2022, Elsevier. 
d) Triboelectric–piezoelectric–pyroelectric hybridized
shield layer (Al), and a substrate (PDMS). The touch visualization and mapping at low-pressure threshold is dependent on both electrostatic induction and electroluminescence through triboelectricity in the contact and separation process. A programmable touch operation platform with four pixels is demonstrated for the control of the external audio module and display module. Luminescence at different touches, the corresponding characters displayed on the external LCD screen, and the real-time electrical signals are acquired in the four channels. Such device is suitable for applications in interactive wearable devices, artificial prosthetics, and intelligent robots.

3. Applications of Wearable Sensors and Electronics in Green Earth

Benefiting from the investigation of the flexible/wearable materials, plenty of wearable electronics are enabled to function in various aspects, including healthcare, biomedicine and implantation, wearable HMI, smart planting, as well as robotic control and automations.[137–141] In this section, we will detailly introduce some associated wearable electronics in these fields to show their great application prospect for the development of green earth.

3.1. Wearable Sensors and Electronics for Healthcare and Biomedical Applications

3.1.1. Wearable Sensors for Human Motion and Physiological Monitoring

Wearable sensors are thoroughly investigated nowadays as healthcare sensors for physical and chemical sensing. Epidermal devices like e-skin are designed for attaching to human skin closely, allowing for direct and accurate monitoring of body signals, including body temperature, body hydration, psychological states, etc. Regarding temperature sensing, Sang et al. have developed an ultrasensitive epidermal sensor arrays for continuous skin temperature monitoring with high precision in Figure 6a.[142] The ultrahigh sensitivity is realized via the gold(Au)-doped silicone nanomembrane (SiNM) as the active sensing layer, where the fermi-level of Si is adjusted by the Au resulting in the improvement of thermal sensitivity. Subsequently, the ultrathin layer of Au-doped SiNM is transferred to the polyimide and PDMS substrate and patterned into a 4 × 4 sensor array with a serpentine structure for larger resistance change under temperature changes. The interconnections in the arrays are fabricated by thermally evaporated Cu and patterned into mesh structure to minimize the applied strain. Finally, polyimide is coated for encapsulation with a following patterning. The obtained epidermal device can be delaminated from the PDMS and then attached on human skin conformally for temperature monitoring. The temperature coefficient of resistance of the epidermal sensor is about −37 270.72 ppm per °C, higher than the current metal-based temperature sensors and is even as high as the inorganic material based temperature sensors. In the continuous monitoring of body temperature during exercise, the proposed sensor shows obvious and ultrahigh precision of the body temperature change. This work lays a foundation for body temperature monitoring under different circumstances, promisingly valuable for disease management in healthcare. In Figure 6b, Zhang et al. have proposed a conductive polymer electrode with great self-adhesiveness and stretchability by solution processing of biocompatible blends of PEDOT:PSS, waterborne polyurethane (WPU) and α-sorbitol.[143] Benefiting from the great conductivity, skin-compliant stretchability and appreciable adhesion on both dry and wet skin conditions, thus it is utilized as epidermal sensor to monitor physiological signals of human body, including ECG, EMG, and EEG. This epidermal sensor is proven to have lower contact impedance with skin and relatively low noise level in static and dynamic conditions, ensuring the robust and long-term monitoring of physiological signals under complex daily movements. The authors have further successfully applied this sensor to identify the arrhythmia of a patient with atrial fibrillation and muscle activity in a clinical setting. Besides the physical signal monitoring in healthcare, epidermal sensors are also applied for body fluid monitoring in healthcare. In Figure 6c, Yao et al. have reported a wearable hydration sensor based on skin impedance measurement.[144] The epidermal sensor consists of a pair of Ag NWs interdigital electrodes (IDE) encapsulated with a PDMS matrix. Detailly, the Ag NWs are cast in an interdigitated pattern and then embedded just below the surface of PDMS to form two stretchable, interdigital electrodes. The two electrodes act as a capacitor that can be used to measure skin hydration. Since the skin impedance is a commonly used method to measure skin hydration, the developed sensor is attached on the skin with the Ag NWS facing the skin surface. The skin impedance can be modeled using a series of capacitors and resistors regarding the skin, electrode–sensor interface, and the electrodes themselves. When the lotion is applied on the skin, a significant drop in skin impedance is achieved, indicating the increase of skin hydration. And the impedance increases gradually in the following 20 min, corresponding to the hydration recovery of skin. Besides the simple impedance testing of skin to monitor the body hydration, Pu et al. have reported an epidermal bio-microfluidic device for reliable blood glucose monitoring, as shown in Figure 6d.[145] Different from the current solutions for blood glucose prediction that utilize sweat glucose, this work indicates the blood glucose based on the transdermal interstitial fluid (ISF) where the glucose concentration is more related to that in blood. The self-powered flexible antibacterial tactile sensor. Reproduced with permission.[134] Copyright 2019, Elsevier. e) Piezoelectric–thermoelectric–triboelectric hybridized self-powered sensors for multifunctional tactile sensing. Reproduced with permission.[133] Copyright 2020, American Association for the Advancement of Science. f) Triboelectric–optical model enabled self-powered user-interactive electronic skin for programmable touch operation platform. Reproduced with permission.[136] Copyright 2020, American Association for the Advancement of Science.
Owing to their intrinsic ultrahigh pressure sensitivity. In healthcare, which can be enabled by TENGs monitoring of muscles strength for multipoints simultaneously. This sensor can realize direct and quantitative measurements of the targeted muscles, the TENG is either compressed or stretched so that slight pressure. With contraction and relaxation of the targeted muscles, the TENG is composed of the self-healable ionic hydrogel as electrode layer, micropatterned graphene and PtNPs is introduced into the working electrode surface so as to improve the sensitivity of the glucose sensor. Notably, the fabrication of flexible epidermal electrodes, nanomaterial modification, and enzyme immobilization is realized by inkjet printing, enabling the low-cost and facile manufacturing. In vivo application, the epidermal device shows robust testing results of blood glucose, indicating its applications toward noninvasive continuous monitoring of blood glucose even for hypoglycemia. Moving forward, in addition to the conventional working mechanisms including resistive, impedance, or electrochemical sensors that require external power supply, self-powered sensors enabled by TENG are also developed as wearable epidermal devices for healthcare applications. In Figure 6e, Wang et al. have proposed a stretchable, self-healing, and skin-mounted active sensor for muscle function assessment. The stretchable TENG is composed of the self-healable ionic hydrogel as electrode layer, micropatterned silicone rubber and middle parylene-C as triboelectric layers, and dielectric elastomer (VHB) and top parylene as the substrate and encapsulating layers. The obtained TENG shows certain flexibility and stretchability, which are suitable to match the tissue modulus and deformations of human muscles. The self-healing capability of the electrode is characterized by cutting the hydrogel into two parts, while the two parts quickly recovered to the original state in less than 6 min, proving the great self-healing capability of the hydrogel. The authors have attached three TENG sensors on human arm for muscle function assessment relying on the high sensitivity of TENGs to slight pressure. With contraction and relaxation of the targeted muscles, the TENG is either compressed or stretched so that positive and negative triboelectric signals are generated, respectively. This sensor can realize direct and quantitative monitoring of muscles strength for multipoints simultaneously, showing great potential for real-time rehabilitation training. Furthermore, accurate monitoring of arterial pulse is also critical in healthcare, which can be enabled by TENGs owing to their intrinsic ultrahigh pressure sensitivity. In Figure 6f, Wang et al. have reported an epidermal TENG sensor for high-precision measurement of arterial pulse. The TENG sensor is based on contact and separation mode where the PTFE and Cu serve as two triboelectric layers and the conductive double sided adhesive (CDA) is treated as the electrode. The Cu powder layer with a natural graded microstructure is formed on the surface of the CDA using a coating process, which is cost-effective and has strong operability. Owing to the light-weight and adhesiveness, the epidermal TENG sensor can be conformally attached on the human skin for arterial pulse monitoring. It turns out that the output voltage acquired from this sensor show three specific characteristic peaks of arterial pulse, indicating its high sensitivity. The average heart can also be calculated from the obtained waveforms. Compared with the laser vibrometer, the TENG sensor also shows consistent results, proving the high accuracy of the proposed epidermal sensor. Meanwhile, the epidermal TENG sensor shows different waveforms when attached to different people. This epidermal, high-precision, reliable arterial pulse sensor based on TENG is providing new inspirations for wearable sensors in healthcare application.

3.1.2. Wearable Biomedical Systems

As mentioned earlier, the breakthrough in materials and sensing technologies bring more possibilities for wearable devices which are served as the crucial units for human–machine interactions. Besides the applications of enabling the physical sensation and motion captures, another key research direction of wearable devices is to develop the biomedical systems for obtaining various information ranging from physiological signals to chemical analysis of body fluid. Currently, a considerable amount of studies are focusing on the systematic integration of the multimodal sensors on a flexible or skin attachable platform. In Figure 7a, Chung et al. present a wireless, noninvasive monitoring system which can simultaneously monitoring heart rate, respiration rate, temperature, and blood oxygenation, as well as body motion and orientation, acoustic signatures of cardiac activity, vocal biomarkers, surrogate for systolic blood pressure, etc. To achieve these functions, the entire system contains several sensing devices, such as electrode pads, an accelerometer, a thermometer, a photodetector, an oximeter, and relevant signal processing circuits. All of the components are interconnected by S-shaped connectors using a flexible PCB technique. For long-term monitoring, the battery unit is designed as modular part through magnetic force attaching. The elastomer encapsulation also ensures the protection of the whole system and the biocompatibility with human skin. This kind of integrated wearable biomedical monitoring system shows a promising solution for postacute monitoring, patients with homecare, trauma situations, and low-resource environments. On the other hand, with the same technology platform, this type of integrated system can also be applied for compression therapy, which was reported by Park et al. (Figure 7b). This wireless monitoring system is able to track both temperature and 3D pressure, in order to conduct...
Figure 7. Wearable sensors and systems for biomedical applications. a) A skin-interfaced biosensors for physiological monitoring in neonatal and pediatric care. Reproduced with permission.\cite{148} Copyright 2020, Springer Nature. b) A wireless compression therapy system. Reproduced with permission.\cite{149} Copyright 2020, American Association for the Advancement of Science. c) A wearable sensor arrays for in situ perspiration analysis.
the necessary adjustment of therapeutic pressure from graduated compression stockings for lower extremity conditions.

As another important aspect, chemical sensors that aim at evaluating human sweat can also reveal much information without invasive approaches. As illustrated in Figure 7c, Gao et al. have developed a wrist consisting of a chemical sensor array for in situ perspiration analysis.[152] The proposed device can detect sweat metabolites and electrolytes simultaneously and selectively. The skin temperature is also monitored for calibration. The amperometric glucose and lactate sensors are adopted with glucose and lactate oxidases, and the enzymatic sensors can autonomously generate current signals by applying a mediator of Prussian blue dye to lower the reduction potential to $\approx$0 V. In Figure 7d, Baker et al. have developed a skin-interfaced microfluidic device via roll-to-roll manufacture for the analysis of regional sweat chloride concentration and sweating rate.[153] The main sensing part includes multilayered microfluidics, dye, and bioassay reservoirs, which can support the colorimetric reactions between sweat in the microchannel and deposited chemical reagents. This colorimetric sensing strategy is able to provide quantitative assessment through smartphone image processing for real-time sports monitoring. Noticeably, for these skin wearable systems, the repeated strain caused by daily movements may damage the devices. An integrated self-healable electronic skin system was then proposed by Son et al., as shown in Figure 7e.[154] A polymer matrix consists of a crosslinked network with strong (4,4'-methylenebis(phenyurea)) and weak (isophorone bisurea) dynamic bonding units incorporated into a PDMS backbone is utilized for self-healable and stretchable electrodes and sensors, such as ECG sensor, and capacitive based strain sensor. Additionally, the addition of Cu-doped ZnS makes the polymer become an electroluminescent skin with the capacitive behavior of the light emitting capacitor and reliable waterproof operation. As a result, a system level self-healable e-skin is demonstrated with sensing and display functions. In Figure 7f, an electrotherapy system consisting of a wireless network of modular devices was reported. It can controls cardiac rhythms, track cardiopulmonary status, and provide multihaptic feedback. In addition, the pacemaker also possesses bioresorbable capability.[153]

Power consumption as a major concern for wearable systems also draw great attentions.[155] Kim et al. have reported a real-time skin-interfaced monitoring system for detecting the sweat loss and electrolyte composition.[156] To achieve battery free function, an RF antenna and NFC microcontroller is encapsulated in the PDMS, so that the power support and the signal readout can be performed wirelessly via the mobile phone. In Figure 7g, Lin et al. have proposed a self-powered sensor system for gas detection wrist band by integrating the solar cell power supply and planar MnO$_2$-based supercapacitors as energy storage units.[156] The printable MnO$_2$/rGO/PEDOT:PSS hybrid ink active layer is then applied for gas sensing with the aid of sensing materials, such as SnO$_2$. Furthermore, biofuel cell is another power source, which is mentioned frequently. Yu et al. have presented a fully perspiration-powered electronic skin, which obtains the energy from human sweat through lactate biofuel cells (Figure 7h).[157] The biofuel cell integrates the cross-dimensional nanomaterial, including lactate oxidase immobilized bioanodes to catalyze the lactic acid to pyruvate, and Pt alloy nanoparticle-decorated cathodes for reducing the oxygen to water. Hence, the redox reaction can generate a peak power of $\approx$3.5 mW cm$^{-2}$. The resistive human motion sensor and the monitoring of the metabolic analytics can be realized. Recently, the research of nanogenerator also brings the possibility of achieving the self-powered system. In Figure 7i, Shi et al. have developed a MEMS-based piezoelectric ultrasonic EH. The array design with varied parameters can perform the broadband response to the various frequencies of the input ultrasonic waves.[158] On the other hand, piezoelectric materials, such as PVDF film, were also reported by Sun et al. to fabricate the nanogenerator for harvesting the mechanical energy from heart beat motions to supply the cardiac monitoring and body tracking applications, as illustrated in Figure 7j.[159] TENG as another emerging nanogenerator technology also can be a promising solution for low-cost and biocompatible power supply. Hinchet et al. have demonstrated a high-frequency vibrating TENG for harvesting the ultrasonic energy, as depicted in Figure 7k.[160] A large membrane of perfluoroalkoxy and the Au/Cu electrode are utilized as the triboelectric layers. Together with the circuit consisting of the rectifier, the transformer, and the battery, the integrated power supply system is successfully implemented for wearable applications. In Figure 7l, by leveraging the human body as a medium of power transmission, a body-integrated self-powered system for HMI and healthcare monitoring was demonstrated. The power from the electриfication of the human body by walking can be wirelessly delivered to the whole system on human body to charge various devices, such as pacemakers and wrist bands.[161] Moreover, there are also attempts to directly use the triboelectric output to activate the wearable functional units. A self-powered microneedle-based drug delivery system which
can be powered by the customized TENG has been demonstrated. Both the microneedle array and contact–separation based TENG are integrated on the elastomeric band.\[162]

Generally, these system level integrations of the commercial sensors, microprocessors, wireless modules, and batteries are indicating the feasibility of wearable biomedical systems. Moving forward, the recent advancements of nanogenerators and other power generation techniques can not only improve the sustainability of the whole systems, but also can enhance the performance or functionalities.

3.1.3. Implantable Electronics and Systems

In terms of biomedical applications, the implantable devices also play important roles in enabling the monitoring of the physiological symptoms of various organs and offering the treatment via specific mechanisms, such as pacemakers, therapy, drug delivery, etc.\[163–166\] Unlike those e-skin like systems, the issue of power supply becomes a severe problem for developing a long-term sustainable implantable device. As a solution, numerous nanogenerators were designed to overcome it (\[67,167,168–175\]).

Dagdeviren et al. have reported a flexible mechanical EH made by an array of PZT thin film, which was encapsulated by PI film (Figure 8a).\[177\] Together with a rectifier and a microbattery, this PENG can collect and store the energy from the natural contractile and relaxation of the heart, lung, and diaphragm, with a maximum power density of 1.2 µW cm⁻². For a real demonstration of powering the commercial implantable electronics, Li et al. have designed a PENG with an elastic skeleton and two piezoelectric composites made by single-crystalline Pb(Mg₁/₃Nb₂/₃)O₃–PbTiO₃ (PMN-PT), as shown in Figure 8b.\[178\] A switchable electric circuit is also designed by changing the connection of the two piezoelectric composites between series and parallel connections, in order to tune the output power based on the implantable electronics. As a result, the output current of 15 µA can support the full-function cardiac pacemaker in an adult Yorkshire swine by harvesting the heart motion energy. However, for these lead-based PENGs, the biocompatibility is a major concern for their implantable applications, even though the encapsulations are available. TENGs with much more material choices are becoming another solution.\[179–183\]

In Figure 8c, an implantable TENG consisting of PTFE and Al was reported by Zheng et al. To achieve the contact–separation motion, a Ti backbone is applied as a keel structure.\[182\] The surface microstructure is also introduced to improve the output performance, which can reach a power density of ≈10.7 µW cm⁻². With the aid of the foldable coil, the triboelectric output induced by heart beat can be collected and transmitted wirelessly for medical monitoring. On the other hand, the biodegradable and bioabsorbable materials become emerging trend for realizing the short-term functionality, while eliminating the risk of the secondary surgery for removal of implantable devices. As depicted in Figure 8d, Jiang et al. have presented natural material based TENGs made by various materials, such as cellulose, rice paper, chitin, egg white, etc.\[183\] Together with bioabsorbable electrodes, the major part of the proposed device can be absorbed in 84 days. As a power source, the output of this TENG is successfully utilized to coordinate and repair the abnormal cardiomyocytes. Similarly, in Figure 8e, a biodegradable TENG was also developed by using biodegradable polymers, such as poly(l-lactide-co-glycolide) (PLGA), and resorbable metals, such as Mg. The as-fabricated device can assist the nerve cells stimulation.\[184\] Applying the piezoelectric enhanced triboelectric mechanism, Tao et al. proposed a flexible implantable devices which can monitor and at the same time harvest the biomechanical energy from the heartbeat of rats, as shown in Figure 8f.\[185\] The implantable device with the size of 1.5 × 1.5 cm² is able to charge a 4.7 µF capacitor to 0.5 V within 5 min. Figure 8g shows a self-powered photodynamic therapy system designed by Liu et al. aiming at providing a promising solution for long-term self-sustained autonomous cancer therapy.\[186\] The biomechanical energy from body motion can be collected by the PENG and then used to stimulate pulsed light to suppress tumor cell growth. The output pulse of TENG can also be applied as a neurostimulator, as demonstrated in Figure 8h.\[187\] With the ability of providing self-powered pulses similar to commercial stimulator, the proposed implantable TENG has wide applications in mechano-neuromodulation for bladder function.

3.2. TENG-Based Wearable Sensors and Electronics for HMI, Robotic Automation, and Plants Monitoring

3.2.1. Wearable Sensors and Electronics Enabled HMI

As the robotic and virtual reality technologies are experiencing drastic development, the human machine interfaces are then urged for the effective and seamless linkage between human and the digital world. Starting from the conventional control terminals, such as joystick, keyboard, and touchpad, there are enormous efforts focus on the wearable devices to facilitate the intuitive human machine interactions and the immersive haptic feedback.\[188–195\]

Owing to the advancements of various materials, the conventional piezoresistive and capacitive sensors are able to be designed as flexible patches with the great wearability. Hua et al. have developed a stretchable sensory e-skin with the multimodal sensing capabilities, including temperature, strain, humidity, light, magnetic field, pressure, and proximity, as illustrated in Figure 9a.\[196\] The meandered connecting wires enable 800% expansion. With the aid of the properly designed hierarchical structure, this multifunctional e-skin shows a superior solution compared to normal human skin. Recently, TENG-based sensors show many advantages including customizable design, wide options of materials, and low cost.\[197–199\] In addition, the self-generated large triboelectric output voltage improves the long-term sustainability and reduces the complexity of signal processing circuits. Wang et al. have reported a TENG sensing matrix for real-time tactile mapping.\[200\] This device utilizes the PDMS as triboelectrification layer, and the cross-bar designed electrodes to form the sensor array. Hence, the finger sliding induces triboelectric output can be collected to identify the writing trajectory as a flexible touchpad. However, many of these TENG sensors can only perform the dynamic sensing response to the mechanical stimuli due to the basic
operation mechanism, which gives an output pulse that related to the transient contact force and contact time.\cite{65,201,202} In Figure 9b, Wang et al. have proposed a large area TENG sensor array with both static and dynamic pressing sensing capabilities.\cite{203} With the aid of the MOSFET integrated switch circuit, the whole device can be turned on under low pressure and support sustainable current for monitoring the static force, which is more suitable to be utilized as large-area force mapping.

On the other hand, the increasing amount of the electrodes applied on those flexible sensing arrays also brings the trouble
Figure 9. Wearable sensors and electronics enabled human–machine interfaces. a) A highly stretchable multifunctional sensing array with hierarchical patterned sensing units. Reproduced with permission.\textsuperscript{[196]} Copyright 2018, Springer Nature. b) Large area triboelectric sensor array with static and dynamic pressure detection and mapping. Reproduced with permission.\textsuperscript{[203]} Copyright 2021, Wiley. c) A triboelectric sensing array with minimal electrodes as 3D motion control interface. Reproduced with permission.\textsuperscript{[198]} Copyright 2018, American Chemical Society. d) A direct current-based triboelectric sensor for motion vector detection. Reproduced with permission.\textsuperscript{[206]} Copyright 2020, Wiley. e) A sensitive triboelectric electromechanical sensor
to the back-end signal readout and processing. As a solution, the special patterned electrodes, such as grid and ring-shaped patterns, are then developed by Shi et al.\textsuperscript{[204,205]} These sensors usually have fewer or even single output electrode. By sliding across the different patterns, a specific number of output voltage peaks are generated to represent the defined control functions. In Figure 9c, Chen et al. have presented a TENG sensing array with only two pairs of electrodes to detect the writing trajectory.\textsuperscript{[198]} Each pair of electrodes are located at two ends of the sensor array. Hence, the distance between the contact point and these two electrodes will determine the amplitudes of the coupled triboelectric outputs. By calculating the output ratio from two electrodes, the contact point can be defined. Additionally, this strategy also helps to reduce the effect of environmental variations on the absolute output amplitude. Instead of functioning as the flexible touchpads, the direct monitoring of human motions is also being studied frequently. Similar designs of electrode pairs have been reported to develop the motion vector sensor via direct current signals.\textsuperscript{[206]} By connecting the electrode pairs to the bottom electrode accordingly, the motion-induced triboelectric output can be generated on the electrode pairs which are in line or partially in line with the motion directions (Figure 9d).

Muscle or acoustic wave triggered mechanical motions can also be detected by membrane designed TENGs with high sensitivities. In Figure 9c, Zhou et al. have developed a bionic triboelectric electromechanical sensor for converting the real-time micromotion of masseter muscle into the control command.\textsuperscript{[207]} With the double air chamber structures connected by the pores, the muscle motion can be amplified by the vibration film with the capability of large deformation, and reach a sensitivity of 54.6 mV mm\textsuperscript{−1}. Hence, by attaching the device onto the masseter muscle, the different triggering habits during speaking can be analyzed for human–machine interactions.

Meanwhile, fusion of sensing information is usually an effective tool to expand the data dimension for enhanced recognition. As illustrated in Figure 9f, a noncontact HMI was fabricated by integrating a MEMS humidity sensor and a TENG motion sensor.\textsuperscript{[208]} With the information fusion, the proposed device can provide multimodal continuous and dynamic sensory information regarding the finger motions. As depicted in Figure 9g, inspired by the delta parallel controller used in remote control for medical and industrial scenarios, Hou et al. have presented a 3D TENG sensor as an HMI.\textsuperscript{[209,210]} Three gears with the triboelectrification layer attached on their teeth, and three pairs of the contact blades are applied as the quantitative rotation sensors. Based on the design of the delta parallel structure, translation motions along X, Y, and Z axes can be converted into rotation motions.

Moreover, the continuous discovery of the wearable HMIs eventually leads to the integrated system for realizing the multidimensional and multimodal detection, and haptic feedback for better user experiences.\textsuperscript{[211–216]} For instance, as shown in Figure 9h, a soft sleeve with the resistive strain sensors made by carbon fiber–polymer composites was reported by Araromi et al.\textsuperscript{[217]} The as-fabricated device is featured the versatile and compliant transduction mechanism via strain-mediated contact in anisotropically resistive structures, which gives a gauge factors greater than 85 000. This textile-based arm sleeve can recognize gestures by detecting the corresponding muscle deformation. Besides these soft sleeve or clothes based wearable HMIs, the exoskeletons, as another important platform, can also be explored to deploy the sensors for capturing body motions. By integrating the rotational TENG sensor on the exoskeleton system, an exoskeleton sensory system for monitoring the upper limb motions was reported. (Figure 9i).\textsuperscript{[218]} The proposed sensor consists of a grating PTFE pattern and a bistable switch as a universal solution for quantitative motion detection, such as bending, rotation, linear sliding, and twisting, etc., to reduce the complexity of signal processing. Besides, the strong correlation between exoskeleton and human body can assist the further kinematic analysis of physical activities through the rotation sensing data.

Noticeably, with the aid of the minimalistic design, TENG sensors can also be developed as the integrated sensory system containing the feedback functions. In Figure 9j, Zhu et al. have developed a sensory and haptic feedback glove, which is composed of the elastomeric dome shaped finger sensor and the palm sliding sensor, as well as PZT-based piezoelectric haptic stimulator.\textsuperscript{[219]} Thus, the motions of the entire hand can be completely tracked for virtual space interaction. Additionally, the ML technique is also implemented to achieve the further sensing data interpretation for enabling the object recognition functions via the grabbing of the glove. In the meantime, to further simplify the system design, a tactile and haptic ring with multimodal sensing and feedback was shown in Figure 9k.\textsuperscript{[220]} The compact ring design can offer continuous finger bending sensing, vibrational haptic feedback, as well as thermal feedback. In terms of haptic feedback monitored by the TENG-based sensor, a soft modular glove was presented with the capabilities of multimodal sensing and feedback functions, as illustrated in Figure 9l.\textsuperscript{[221]} By utilizing a basic structure of a nichrome ring and a elastomeric air chamber, the as-fabricated unit possesses triboelectric sensing of static and dynamic contact, vibration, strain, and pneumatic actuation. This unit also
performs pneumatic tactile haptic feedback and electroresistive thermal haptic feedback. With the aid of ML algorithm, the entire glove demonstrated the augmented feedback. Together with self-powered flexible sensors, these integrated systems will pave the way for realizing the sustainable and intelligent HMIs for highly effective interactions.

3.2.2. Wearable Sensors and Electronics Enabled Robotics Control and Automation

Aiming for green earth, robots with enhanced intelligence will gradually replace manpower to do more labor-intensive work for advanced automation in unmanned working space, ranging from service, industry, exploration, to healthcare and medical treatment.[222] Besides, functional sensors are also the key to realizing intelligence-enhanced robots by endowing them the ability to perceive and interact with the external world. Current mature sensing technologies for robots include conventional solutions based on the encoder, potentiometer and IMU, and flexible solutions based on resistive sensors,[223–226] optical fiber,[227–229] and capacitive sensors,[230,231] to implement tactile, strain as well as temperature perception. However, all these sensors need continuous driving voltage, which leads to high power consumption for huge amounts of sensor nodes under the AoT framework, and hinders their applications for sustainable remote-work robots. To address this issue, the self-powered sensing approach based on TENG has emerged recently, showing not only the potential to help soft robots perceive stimuli via self-generating electricity to realize the long-term sustainable sensory system but also good compatibility with the soft robots thanks to TENGs wide material choices.[7,138,31,232]

As shown in Figure 10a, to enable the tactile perception of a robot arm, Ji et al. reported a two-axis TENG as a flexible collision-sensing skin.[233] The 3D-modeling structure of the TENG makes it easy to be compressed even under a slight external force/pressure for high-sensitivity detection. The positive triboelectric cylinder in the device is composed of nitrile rubber and stainless steel, while the negative counterpart is made of copper wool mixed with silicone rubber. With the cross-inserted cylinder pairs, stimuli from the vertical and horizontal directions can be detected simultaneously to achieve two-axis sensing. By leveraging appropriate circuits for signal processing, a robot-arm stop system was successfully implemented for safety purposes in the smart factory. Besides the perception of external stimuli, the real-time motion measurement of the robots themselves is also essential, which can be used as feedback information to realize more precise control and status monitoring for high-efficient product lines. Wang et al. developed a TENG-based self-powered angle sensor for robotic arms as illustrated in Figure 10b.[234] By specially designing the electrode patterns of the rotary sliding TENGs, the rotating angle of the robotic joints can be measured at high resolution (2.03 nanoradian) and sensitivity (5.16 V/0.01°). Moreover, the bending direction can also be detected by overlapping electrodes of the upper and lower TENGs to induce a phase difference in signals. With the help of this sensor, a robotic manipulator was successfully demonstrated to reproduce traditional Chinese calligraphy, showing the capability of the sensor to precisely monitor the movement trajectory of the robot in real time.

Compared with the above-mentioned rigid robotic manipulators, soft robots[234–236] made of soft materials have been investigated frequently recently and show advantages of high flexibility and large nonlinear/multidegree deformations,[237–241] enabling conformal contact with external objects and applicable to various scenarios without the specific design for a certain product line to save costs. Though some works have shown the feasibility and effectiveness of the TENG-based flexible sensors for soft robot perception, they mainly focus on the utilization of one type of sensory information, i.e., tactile or curvature.[242–245]

For realizing more diversified perception and interactive functions to implement the anthropomorphic robots, multimodality sensory signals from different kinds of sensors are required to be fused into one intelligent sensory system. Chen et al. have reported a cable-driven smart finger-like actuator, enabled by two types of TENGs for simultaneously pressure and bending sensing as shown in Figure 10c.[246] The tribo-skin patch with micropyramid structures is able to detect proximity, contact, and pressure with high sensitivity, and the inner TENG placed in the back section of the actuator is sensitive to the finger deformation where the maximum sensing angle can be up to 150°. The sensory information collected by the two types of TENGs can be further fused to get a more precise motion perception of the gripper, including approaching, grabbing, and releasing, demonstrating the complementary effects between different sensors for better analytic results. With ML technology for further data fusion and analysis, automatic grabbed object recognition function can be realized for TENG-enabled intelligent soft manipulator as indicated in Figure 10d.[247] Combining the output signals collected from the TENG bending sensor and the TENG tactile sensor, valuable sensory information, including shape, size, contact position, and contact area, during the gripping process can be extracted and utilized to identify different objects with various shapes and sizes. The accuracy for recognizing 16 objects with the fused sensory system can reach up to 98.125%, which is higher than that achieved by the pure TENG bending sensor or pure TENG tactile sensor, showing the effectiveness of the multimodality sensor fusion in realizing more complex interactive/perception functions for soft robots.

Another strategy of sensor fusion is to hybridize TENG based self-powered sensors with other sensing mechanisms, e.g., resistive, piezoelectric, etc., to utilize the advantages of different sensors for a more advanced integrated system.[248] As shown in Figure 10e, Li et al. proposed a hybrid tactile sensor that integrates a TENG sensor with an electromagnetic inductance transducer for object recognition.[249] The TENG sensing unit can reflect the surface material properties of an object, while the inductance sensor can measure the electromagnetic induction of a target, which is related to the inherent characteristics of shape, conductivity, as well as water content. Moreover, the TENG sensor output is easily influenced by grasping force and speed, whereas the inductive signal is less affected. Such kind of complementary effect can help to maintain the sensing and recognition performance of the integrated system. By feeding the multimodal data into the ML analytic, a higher classification accuracy (98.75%) can be achieved for eight fruits compared to
that based on the TENG signals only (87.81%). Between, due to the penetration capability of electromagnetic induction, objects packaged in different ways can also be identified, and the accuracy can reach 95.93%. This study demonstrates the potential of multimodality sensor fusion in realizing more complex interactive/perception functions for intelligent robots.

Though TENG-based sensors contribute to zero-power sensory systems to enable long-term sustainable robots, the wireless transmission modules under the IoT network still mean high power consumption, especially considering the massive robots in smart factories and other unmanned working spaces. To this issue, EHs based on electromagnetic, piezoelectric, etc., can serve as the power supply and be integrated with the self-powered sensors to realize fully self-sustainable IoT-enabled robotic systems. In Figure 10f, Ra et al. proposed a self-sustainable conveyor roller system for product identification by hybridizing the TENG sensor and EMG. The TENG sensor is realized by modifying the surface of the roller, and can generate the signal containing the information of the material, size, and movement speed of the transported product. Between, the EMG unit is designed to harvest the rotational kinetic energy of the roller and directly supply the power to MCU and wireless module for data processing and transmission. With this hybridized sensory system, real-time monitoring of the product information was achieved without the external power supply, demonstrating the potential to realize zero-power IoT-based sensory systems for intelligent robots in net-zero smart factories.

3.2.3. Wearable Sensors and Electronics Enabled Smart Plants Monitoring

Plants and crops are treated as indispensable components in the green earth. For higher agricultural production and high-quality plants, a large quantity of devices can be equipped to plants and connected into the IoT framework to realize real-time monitoring of plants conditions and management of environment control systems. Focusing on a single plant, growth conditions and health status are of great significance, thus real-time, nondestructed monitoring technologies are emerging. Like human wearable sensors, plant wearable sensors such as strain sensors, humidity sensors, temperature sensors, light intensity sensors, etc., are considered to be lightweight, ultrathin, breathable, etc. As shown in Figure 11a, Nassar et al. have developed a compliant plant wearable device with the combination of a strain sensor, a temperature sensor and a humidity sensor. The wearable strain sensor is a resistive sensor, developed by depositing Au as the electrode on the PDMS substrate while the PDMS substrate is prestrained. The temperature and humidity sensor are all patterned with certain structures and then transferred onto PDMS, which only have a thickness of 50 μm. The strain sensor is fixed on the plant while the temperature sensor and humidity sensor are directly attached onto the leaf of the plant. The three plant sensors are integrated with a miniaturized programmable system-on-chip and a small rechargeable battery to realize a lightweight system using low-power Bluetooth technology, enabling the connection to the cloud and continuous monitoring of real-time conditions. In Figure 11b, a humidity sensor, a temperature sensor and an optical sensor are integrated together in one device, which is attached onto the leaf for microenvironment monitoring. It should be noted that only the humidity sensor is attached directly onto the leaf where the porous graphene electrode and the plastic foam spacer guarantee no influence to transpiration of the leaf. Hydration of the plant can be monitored in real-time and timely actions such as (watering, lighting, or temperature control) can be taken. Furthermore, in Figure 11c, Zhao et al. have proposed a multifunctional epidermal sensor that is directly transferred onto the plant leaves, containing a humidity sensor, a temperature sensor, a strain sensor, and a light sensor. Evaluation under a controlled environment indicates excellent precision of the sensor. The sensor has been demonstrated to measure plant physiology and environmental conditions continuously and simultaneously for 2 days, and there is little influence on the hosting plant after 45 days. A wireless sensing platform can transmit the sensing results to a distance longer than 100 m, demonstrating the capability to form sensor networks to facilitate large-scale plant research and precision agriculture. Besides, as shown in Figure 11d, an epidermal plant sensor is also demonstrated for gas sensing. Here, integrated array of field-effect transistors and sensors composed of carbon nano-tube (CNT) channels and graphitic electrodes and interconnects are formed directly from the in situ synthesis. This array structure is transferred and laminated directly on the surface of a plant leaf for sensing DMMP vapor. The layout of this all-carbon device follows most of the topography of the leaf without generating any significant cracks in the CNT and graphitic structures. Also, negligible delamination of the device from the leaf is observed after 1 month. The real-time gas sensing on the plant leaf can be achieved because the sensing signal appears immediately with the response time of 5 s and the intensity increases linearly with the concentration of the vapor.

It should be noted that for the plant wearable sensors discussed above, they are either the resistive sensors, the capacitive sensors or the transistor sensor. Power sources are required for the sensors’ operation. In order to create a green-energy and zero-energy-consumption environment for smart farming, a self-powered IoT system is required. In Figure 11e, Lan et al. have developed a plant wearable TENG as the power source for an on-plant self-powered sustainable agriculture system. The TENG consists of a CNT electrode coated on a layer of poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), showing micro- to-nanohierarchical porous structures and high electrostatic adhesion, great breathability, and hydrophobicity. By attaching the TENG onto the leaves, electricity can be generated either from the contact and separation between leaves and TENGs due to wind flowing or from rain dropping on the TENGs at rainy days. Based on this, a self-powered agriculture is constructed, where a plant sensor without a battery is fixed in the soil for monitoring various parameters (soil moisture, soil fertility, light intensity, and temperature) and the sensor is driven by the capacitor, which is previously charged by the TENG. The monitored parameters can be sent out to a mobile phone via Bluetooth so that the health status of plants can be obtained in real time. In terms of the TENGs devices, owing to their advantages of vast material choices, it is feasible that plant leaves can be utilized as the triboelectric layer and electrode material to construct the device. As shown in Figure 11f,
the authors have developed two TENGs. One is the leaf-based TENG where plant leaves are directly utilized as the triboelectric layer and the other one is the leaf power-based TENG where the leaves are grinded into powders for TENG fabrication. Based on the advancement of the plant wearable sensors/devices, environment and plant health monitoring are developing toward noninvasive monitoring, real-time monitoring, higher accuracy, self-sustainability, and recyclability, which

show great potential in building a smart farm in the green earth.

4. TENGs Integrated Hybrid Devices as EHs in Indoor and Outdoor Applications

Typically, the above-mentioned devices aiming at wearable applications mostly focus on one specific mechanism. Although those designs can ensure simplicity and low cost, and have specific advantages regarding the mechanism been used, they also show the imperfection at the same time. Therefore, the hybrid systems constructed by combining devices with various operation mechanisms become more desirable, in the advancement of leveraging the distinctive advantages from multiple mechanisms, energy sources, and sensing signals. In this section, we will introduce the hybrid devices and systems for indoor and outdoor applications as EHs, targeting on the zero power consumption requirement for green earth.

4.1. Hybrid Devices for Indoor Energy Harvesting

For the in-door hybridized EHs aiming for scavenging a single energy source, biomechanical energy usually becomes the first choice for its widest distribution and high energy density. Corresponding designs typically contain two main categories. One is the flexible design with the hybridization of TENG and PENG—washable, foldable, and stretchable, therefore with wearable comfort. The other is the nonflexible design introducing the EMG to enhance the output power. Hou et al. proposed a rotational pendulum-designed EH with the integration of EMG and TENG, as depicted in Figure 12a.[257] The device contains a pendulum rotor, TENG blades, EMG coils, and a cylindrical frame. The pendulum rotor consists of a magnet made of NdFeB and a copper ring curling around the magnet. Four sets of circular coils are placed at the bottom and the frame connected in series. The TENG blades contain a sandwiched structure with an inner copper electrode layer covered by two FEP films on each side. An external stimulus can drive the rotor magnet to rotate and produce the electromagnetic current, while it will also periodically contact the flexible blades and slide through the FEP layers to generate the triboelectric output. With the optimization based on the measurements of various device configurations, a maximum power density of 3.25 W m$^{-2}$ of TENG and 79.9 W m$^{-2}$ of EMG can be achieved under the driving frequency of 2 Hz. And a great output performance for harvesting irregular and ultralow-frequency biomechanical energy has also been realized. Besides the nonflexible design, a wearable device with the tribo-ferroelectric synergistic effect has been proposed by Guo et al., as illustrated in Figure 12b.[258] For the all-fiber device, silk and PVDF nanofibers were first electrospun on the two conductive fabrics as the top TENG and bottom PENG parts, respectively. The PVDF fabric layer can also act as the piezoelectric-enhanced layer for augmented electric output through the interaction principles to improve the polarization of TENG. Negative piezoelectric charges can be induced on the upper surface of PVDF fibers when compressed if the PVDF layer is negatively polarized, where positive piezoelectric charges are also induced in the upper electrode fabric. This process leads to the accordant working state of TENG and PENG since they have the same potential direction. Thanks to that, a higher electric output can be achieved. The device can reach an outstanding maximum output performance with open-circuit output voltage of 500 V, short-circuit current of 12 µA, and power density of 0.31 mW cm$^{-2}$ through the collaboration between TENG and PENG. Figure 12c shows a hybridized EH for harvesting biomechanical and biochemical energy developed by Li et al.[259] For the TENG part, Kapton film and Al foil act as the friction layers. To improve the output performance, the Kapton film was treated through inductively coupled plasma-reactive ion etching to form micropillars on the surface, and the Al foil was also polished through sandpaper to increase the surface roughness. Besides, an inner spacer was applied to create the gap between the two layers. The open-circuit voltage of 22 V and short-circuit current of 0.24 µA have been achieved for the TENG part. For the glucose fuel cell (GFC) part, the bacterial cellulose membrane was applied as the supporting matrix for the MWNTs, prepared as the cathode and anode films. The GFC consists of an anode, a Au electrode, a PET substrate, a cathode, and a fixture. After being immersed in a glucose solution, the oxidation of glucose molecules happens at the anode to generate gluconic acid. And electrons flow from the anode to the cathode through an external circuit and generate the current. Besides, the Pt-Pd catalyst was loaded several times to improve the output performance, reaching an output current of 10.5 µA. The integration of TENG and GFC can sufficiently harvests biomechanical and biochemical energy simultaneously, with an increased capacitor charging performance compared to a single unit. Whereas this work still utilizes a traditional capacitor as the energy storage unit, Lu et al. proposed a wearable e-textile microgrid system (Figure 12d).[260] A flexible triboelectric generator (TEG) and a biofuel cell (BFC) are applied to harvest the biomechanical energy from low-frequency human motion and biochemical energy from perspiration, respectively. The judicious integration of these two EHs with complementary relationships is able to achieve stable power output by compensating the limitations of each other under the circumstances like delayed perspiration or lack of motion. To store the energy generated from the above two EHs, a flexible supercapacitor is also applied to regulate the low-current, high voltage input from the TEG and the high-current, low-voltage input from the BFC. The energy harvested solely from human motion is able to power a wristwatch with an LCD or a sensor-electrochromic display system operating in pulsed motion for more than 30 min with a 10 min movement. All modules in the proposed system are textile-based and fabricated through screen printing, with durability, flexibility, and compatibility with clothes. Besides biomechanical and biochemical energy, thermal energy is also an important energy source generated by the human body. Seo et al. proposed a hybridized EH to scavenge thermal energy and biomechanical energy, as shown in Figure 12e.[261] With the applied bismuth telluride (Bi$_2$Te$_3$) material, when touching the EH, the body heat from human fingers can drive the electrons from n-type and holes from p-type to the cold side and generate the thermoelectric output. At the same time, with a PDMS layer attached to the surface, the triboelectric output can also be obtained due to the large difference in electron affinity between the PDMS.
layer and human skin. Under a low tapping frequency, the thermoelectric output dominates and makes up for the deficiency. A power density of $3.27 \, \mu\text{W cm}^{-3}$ has been obtained under the driving frequency of 2.5 Hz, and technologically relevant micro-watts of average power can be generated under the frequency ranging from 0.5 to 2.5 Hz. Although EHs already have great output performance scavenging a single energy source from the ambient environment, they may also suffer a decrease in the practical application scenarios for the instability of the corresponding energy source. For example, the indoor light intensity may vary among different time periods, the actual vibration in the environment is random and exists in a wide frequency range. 

Figure 12. Hybridized devices and systems for indoor energy harvesting applications. a) A rotational pendulum-based EMG and TENG hybridized device aiming for mechanical energy harvesting for human motions. Reproduced with permission.\cite{257} Copyright 2019, Elsevier. b) An all-fiber hybridized piezoelectric-enhanced TENG for wearable energy harvesting. Reproduced with permission.\cite{258} Copyright 2018, Elsevier. c) A hybridized biofuel cell and TENG for bioenergy harvesting. Reproduced with permission.\cite{259} Copyright 2020, Springer. d) A wearable multimodular e-textile bioenergy microgrid system with TENG, BFC, and SC. Reproduced with permission.\cite{260} Copyright 2021, Springer Nature. e) A hybridized TEG and TENG for harvesting human activities. Reproduced with permission.\cite{261} Copyright 2019, American Chemical Societies. f) A hybridized TENG and PVC cell indoor EH for powering indoor electronics. Reproduced with permission.\cite{262} Copyright 2020, Elsevier.
range, and the thermal source can also fluctuate in a day.\textsuperscript{262–265} Therefore, to boost the output power and simultaneously stabilize the overall output in various environmental situations, hybridized EHs employing multiple mechanisms for diverse energy sources have been designed. Light is also an important energy source for indoor devices. Figure 12f shows an in-door hybridized EH with the integration of nonfullerene organic photovoltaic (OPV) cells and TENG. The high output voltage of TENG and high output current of OPV cells can compensate for each other to ensure a continuous and reliable output, while an improved charging performance of a 10 \( \mu \)F capacitor is also achieved.\textsuperscript{266}

### 4.2. Hybrid Devices for Outdoor Energy Harvesting

Meanwhile, for the sustainable development of the green earth, how to effectively scavenge the clean and renewable energy in the outdoor environment, e.g., solar energy, mechanical energy, and thermal energy, has drawn great concerns in recent decades to reduce the environmental issues brought by the massive consumption of fossil fuels. Considering that most of the earth’s surface is covered by the sea, abundant energy is stored in the ocean in the form of tide energy, wave energy, etc., which is easy to be accessed. The conventional way to harvest ocean-based mechanical energy is to use EMGs. However, the working frequency of EMGs is commonly higher than 50 Hz, and not applicable to ultralow-frequency (<10 Hz) ocean waves, thus leading to an energy conversion efficiency in low-frequency application. By concerning this issue, TENGs that are suitable for low-frequency mechanical energy harvesting have been investigated frequently as a promising solution for wave energy scavenging.\textsuperscript{267–272} Besides, many works have proven that TENGs can be hybridized with EMGs toward a more efficient converter\textsuperscript{273,274}, where the limitations of EMGs, i.e., poor performance under low working frequency, can be compensated by the TENGs, and TENGs’ low output current can also be enhanced via EMGs. As shown in Figure 13a, Feng et al. reported a swing-structure-based soft-contact cylindrical triboelectric–electromagnetic hybrid nanogenerator.\textsuperscript{275} The flexible rabbit hairbrush design can effectively reduce the operation resistance compared with the conventional rotation-mode TENGs when serving as the positive triboelectric material and rubbing with the negative FEP layer. By hybridizing EMGs for further output power improvement, a peak power density of 10.16 W m\(^{-3}\) and an average power density of 0.23 W m\(^{-3}\) can be achieved with the water wave agitation of 0.1 Hz. The self-powered temperature mapping and wireless transmitting function can also be successfully realized by connecting the hybridized harvester to a thermometer array and a wireless transmitter, showing its potential for future self-sustainable ocean environment monitoring and blue energy harvesting. In addition to integrating the outputs for higher outputs, another hybridizing strategy is to utilize different components to implement different functions, i.e., sensing and energy harvesting, toward a functional and self-sustainable hybridized system. A self-powered and self-functional tracking system consisting of a TENG-based inertial module and an EMG-powered GPS module has been developed by Gao et al. as illustrated in Figure 13b.\textsuperscript{276} The TENG and the EMG module are hybridized with a novel rotating gyro design, whose rotation and revolution motion under low-frequency and irregularly vibrating waves give rise to the triboelectric and electromagnetic outputs respectively. The electrode of the TENG is divided into eight parts for attitude monitoring with higher resolution, and a power management circuit capable of AC–DC conversion, DC voltage regulation, power storage, and release control is utilized to stabilize the GPS power supply provided by the EMG. When integrating the self-powered system into an autonomous underwater vehicle, real-time attitude, and position monitoring can be achieved in the actual working environment, i.e., Huanghai Sea, proving the effectiveness of the blue energy enabled hybridized EH for self-sustainable sensing under outdoor scenarios.

In addition to blue energy, hybrid devices are also utilized to enhance the energy harvesting efficiency of wind energy. Due to the ability to efficiently scavenge low-frequency mechanical energy, TENG-based wind EHs have been explored a lot recently.\textsuperscript{277–279} and can be further hybridized with EMGs or PENGs toward higher harvesting efficiency for realizing self-sustainable IoT systems. Rahaman et al. have developed a wind-driven hybridized nanogenerator consisting of a TENG, a PENG, and an EMG as shown in Figure 13c.\textsuperscript{280} The hybridized harvester converts the natural wind energy into rotation motion, under which the integrated three harvesting units can generate the electricity simultaneously. With the wind speed of 6 m s\(^{-1}\), the maximum output power of the TENG and EMG can reach 1.67 and 1.38 mW, respectively. At the same time, the magnetomagnetic-based EMG can contribute an optimal output power of 268.6 mW with an external load of 180 \( \Omega \). By utilizing a customized power management circuit, a wireless sensor unit can be directly driven by the harvester to wirelessly transmit the environmental data to a smartphone, showing the potential to implement self-powered environment monitoring sensor nodes in the subway system. Though high output can be achieved by these rotational-structural TENG-based harvesters under the relatively high-speed wind (>5 m s\(^{-1}\)), the average wind speed near the earth’s surface is \( \sim 3.28 \) m s\(^{-1}\), which may limit their applications in practical usage. Besides, the friction existing in the rotational structure may also increase the driving threshold of the device, as well as cause the loss of the friction layers. Based on these considerations, Zhang et al. have proposed shadow enhanced self-charging for wave and solar energy harvesting. Reproduced with permission.\textsuperscript{299} Copyright 2021, Springer Nature. g) A triboelectric–electromagnetic hybridized generator for portable/wearable electronics and self-powered IoT applications. Reproduced with permission.\textsuperscript{296} Copyright 2020, Wiley. h) A triboelectric–piezoelectric hybridized power module for self-sustained autonomous wireless sensing. Reproduced with permission.\textsuperscript{294} Copyright 2021, Elsevier. i) A triboelectric–thermoelectric hybridized generator for vehicles’ wasted heat energy harvesting. Reproduced with permission.\textsuperscript{297} Copyright 2021, Elsevier.
an ultradurable windmill-like hybrid nanogenerator as shown in Figure 13d.[283] The TENGs and EMGs are settled on cross-shaped frames, which can convert the wind energy into rotational motions of the fan, and further into the contact–separation activity of the generator. Moreover, in addition to serving as the essential components of the hybridized nanogenerator, the spring steel plate and the magnets can also serve as the accelerator to enhance the rotation of the device, where the spring can store the elastic energy and convert it into kinetic energy to boost the contact–separation of the TENG, and the weight of magnets can help to overcome the electrostatic adsorption between friction layers. With this novel design, the hybridized nanogenerator is successfully demonstrated to effectively scavenge the wind energy with a speed down to 1.8 m s⁻¹, expanding the applicable scenarios of TENG-based wind EHs.

Apart from the mechanical energies (i.e., wind energy, ocean wave energy), solar energy is also quite abundant in nature, and many works have utilized solar cells (SCs) to capture solar energy with high efficiency.[282–284] However, the scavenging effect of solar energy is easily influenced by weather conditions, especially when the sunlight is insufficient on cloudy or rainy days. Considering that TENGs have been proven as efficient tools to harvest the mechanical energies brought by the wind or raindrops,[285–288] SCs can be hybridized with TENGs toward adaptive environmental energy harvesting under varying weathers with the complementary functions between different mechanisms. As illustrated in Figure 13e, a hybrid all-in-one EH combining four spherical TENGs for wind and rain fluid energy scavenging and four integrated SCs for solar energy harvesting, has been developed by Xu et al.[289] In each TENG spherical shell, the electrodes of different layers on the same hemisphere side are connected to form two output electrodes. When the shells are driven by the wind or raindrop fluids to rotate, the FEP balls sealed in the shell will slide between the two electrodes, thus generating the triboelectric output based on triboelectrification and electrification, and high average output power of 5.63 mW is obtained. By integrating the outputs from SCs, self-powered applications including forest fire prevention, soil moisture control, and pipeline monitoring are successfully demonstrated, showing the potential in realizing a self-sustainable IoT sensor network that is applicable to all-weather condition. In addition to the influence of the weather, the shadows cast from moving units in such hybridized devices may also affect the performance of the SCs. To solve this issue, Zhang et al. reported a shadow-triбо-effect nanogenerator as shown in Figure 13f.[290] A Au/n-Si system is utilized to harvest the light energy based on the shadow effect, and a transparent PDMS layer is deposited on top as the negative friction layer that contacts with Al balls to transform the mechanical energy into triboelectricity. When the Au/n-Si system is partially illuminated, a large amount of photogenerated electrons and holes are generated in the depletion layer in the illuminated area. These accumulated electrons will overcome the Schottky barrier and jump into the metal, resulting in the surface potential difference and a directional electron flow from the bright region to the dark zone, thus generating the shadow-effect induced output. Hybridizing the outputs from the tribo-effect and shadow-effect, a high peak power density of 718 µW cm⁻² can be achieved under the water and the light stimuli, which are much higher than that obtained by the pure TENG (0.28 µW cm⁻²), showing the new avenues of the next-generation hybridized system for solar/mechanical energy harvesting.

Besides those energies existing in nature, the energy generated during human outdoor activities also has the potential to be transformed into useful electric energy. On the one hand, collecting biomechanical energy from human movement can be a good solution to provide sustainable power for portable or wearable electronics.[291,292] On the other hand, the vibration energy produced by human-driven vehicles can be utilized to realize self-powered IoT monitoring systems without the electricity from the automobile battery.[293–295] Maharjan et al. have proposed a universal self-chargeable power module by hybridizing two types of TENGs and an EMG as shown in Figure 13g.[296] Under the external vibration, the movable unit consisting of a magnet and Al layers will move downward and upward, resulting in the magnetic flux across the coils change and the sliding friction between the Al strip and the PTFE inner wall, thus generating the electromagnetic and triboelectric outputs respectively. Another contact–separation mode TENG is settled at the bottom of the entire module, and triggered by the collision when the magnet moves downward. By integrating a power management circuit and a Type-c outlet for more convenient connectivity, the hybridized module is successfully demonstrated to charge a smartphone/earbud/smart band by scavenging the human locomotion energy, e.g., walking, running, climbing, etc. Moreover, the vibration energy of the vehicles can also be collected by the harvester to construct a complete self-powered wireless monitoring system capable of detecting the temperature, humidity, and pressure of the in-car environment. Moving the application scenarios from automobiles to trains, Wang et al. have reported a self-sustained acceleration sensor based on the hybridized mechanism of triboelectric and piezoelectric as shown in Figure 13h.[297] A PZT is hinged–hinged mounted on the polymethyl methacrylate package with T-shaped masses bonded, and two contact–separation mode TENGs are settled at the top and the bottom serving as stoppers. Under external excitation, the piezoelectric nanogenerator can generate a root mean square power of 6.5 mW in 1.0 g acceleration under 25 Hz as the power source, while the TENG can be utilized as a self-powered accelerometer with good linearity and sensitivity. After integrating a power management circuit, two capacitors, an MCU, and an RF transceiver for energy storage, signal processing, and data transmission, the self-sustainable wireless sensor nodes for real-time train status monitoring can be successfully achieved, showing its great prospect in developing the remote IoT system in harsh environment. In addition to vibration energy, the heat generated during engine operation is another major wasted energy that can be used in vehicles. Lee et al. have utilized the shape memory effect and the superelastic effect of shape memory alloys to transform the heat into mechanical energy, i.e., rotational motion, that can be harvested by the disk-TENG (Figure 13i).[297] A TEG-based on the Seebeck effect is also hybridized into the system toward higher energy harvesting efficiency. Combining the outputs from these two mechanisms, the hybridized generator can be applied to commercial automobiles for real-time temperature monitoring inside the engine room, providing a promising solution for realizing self-energizing equipment in the actual application scenario.
5. Convergence of TENGs with Other Advanced Technologies

Technology convergence has opened new trends, pathways, and opportunities for the built-up of IoT integrated green earth where two or more independent technologies are integrated together and form exciting new outcomes. In this section, we will review the convergence of advanced technologies with TENG technologies to bring in newly enabled functionalities and possibilities to the TENG development.

5.1. Convergence of TENGs with Self-Sustained IoT Systems

With the development of EHs regarding the designs, mechanisms, and materials, their output performance and feasibility to be applied in various environments have improved simultaneously. Moving forward, the ultimate goal of the EHs is the establishment of self-sustainable systems or systems with a prolonged battery lifetime by sufficiently utilizing the waste energy from the ambient environment, e.g., biomechanical energy associated with human body motions. We have witnessed the flourishing of multifarious self-sustainable systems targeting diversified applications, which integrate the developed EHs with other functional components, such as power management circuits, energy storage units, sensing units, etc.\[298-105\] Guo et al. proposed an artificial intelligence-based walking stick integrated with a self-sustainable wireless IoT sensing system (Figure 14a).\[106\] This walking stick is designed as a comprehensive real-time monitoring platform to provide physical and cognitive healthcare for aged people and people with disabilities. Two modularly designed units, one hybridized unit and one rotational unit, are the critical components for achieving such functions. The hybridized unit contains a top press TENG (P-TENG) with five separate electrodes, a rotational TENG (R-TENG), and a rotational EMG. Basically, the P-TENG and R-TENG can realize contact point sensing and contact speed sensing, respectively. Further equipped with artificial intelligence for data analysis, advanced functions such as disability evaluation, motion distinction, user identification, and gait abnormality detection can be achieved. The rotational unit only contains the EMG, which focuses on the power supply for a wireless sensing system. Thanks to the pawl-ratchet system, the unit is able to transfer the slow linear motion of a walking stick to a high-speed rotation of the inner ratchet. Besides, the ratchet can keep rotating by inertia and generate continuous output, sparing the device from being limited by the stimuli frequencies. The maximum peak power of the rotational unit is 55.1 mW under a load resistance of 100 Ohm. Besides, the average output power is 27.5 mW under 1 Hz driving frequency and remains 6.3 mW when decreased to less than 0.1 Hz. The outstanding output performance makes it a reliable power supply for a self-sustainable IoT system. The entire system contains two rotational units, one power management circuit (LTC-3588), a GPS location sensor, environmental humidity and temperature sensors, and a wireless module. With the power management circuit, the voltage generated by two rotational units is first rectified and amplified to charge a 4000 µF small capacitor. Once fully charged, the energy stored in the small capacitor is released to charge a 2-F supercapacitor, acting as the primary energy storage unit for the system. It takes around 18 min to stabilize the 2-F supercapacitor to 3.6 V. After fully charged, the 2-F supercapacitor can power the whole system for 6 s with every 90 s of charging. By introducing the self-sustainable IoT system, the omnimonitoring of users can be realized. In other words, the caregiving walking stick can monitor the user’s current motion status and location and sends out an alarm if accidents are detected. As shown in the figure, the system can tell the user [Tom] is entering a park through the main entrance based on the output of hybridized unit and data from the IoT sensing system. When the user trips over a branch on the ground at the sports center, the walking stick can immediately detect this abnormality and trigger the alarm to call for instant help. Similarly, another self-sustainable system was realized by Jiang et al. (Figure 14b).\[107\] A wearable noncontact freerotating hybridized nanogenerator (WRG) is proposed as the main power supply for the self-sustainable system. The WRG contains free-rotation TENG parts and EMG parts. Through a mechanical transmission structure, the WRG can convert the vertical motion of humans to the rotation of the rotor, namely, transferring the gravitational energy into rotational kinetic energy. The maximum output power of 13.8 mW and 40.3 µW can be achieved for the TENG and EMG parts. Merging the output power from both parts, the WRG can charge a commercial lithium-ion battery with a capacity of 3.4 mAh from 1.9 to 3.3 V in only 2 min. With the WRG as the power supply, a self-sustainable GPS system for monitoring the location and route of moving individuals has been realized. Put the WRG into a shoe, and the mechanical energy generated by the running and walking of users for ≈8 s can withstand the GPS module for 4 s. In addition to the mechanical energy generated by the vertical displacement of humans, which is mainly from gravity, body motions like bending of the elbow, swinging of the shoulder, opening and clenching of the fist, etc., are also very promising mechanical energy sources. Among them, lower-limb motions typically produce the largest power compared to other parts.\[108\] Gao et al. proposed a self-sustainable wearable system harnessing the mechanical energy from lower-limb motions (Figure 14c).\[109\] The motion-capturing and energy harvesting hybridized lower-limb (MC-EH-HL) system contains a sliding block-rail-based piezoelectric bimorph array generator (S-PEG) and a ratchet-based TENG (R-TENG). The R-TENG in this system acts as a sensor for detecting bidirectional joint rotation, composed of two ratchet paws and a ratchet wheel. To enable bidirectional rotation, the two ratchet paws and the ratchet wheel are connected with coaxial bearings. A hollow part with a cylindrical shape and a spring are fixed on the pawl to form vertical motions with the ratchet wheel. And contact–separate TENG can be achieved with PET and PTFE materials on each side. The S-PEG as the main power supply is designed with a sliding block-rail structure. Twenty pieces of PZT bimorphs are parallelly inserted into a 3D-printed base structure with one free end sitting in a frame. Two half-cylinders linked with a rod can slide back and forth to bend and release PZT plates to make them self-oscillate. Maximum power of 2.4 mW is achieved under a driving frequency of 0.75 Hz, and a 350 mAh battery can be charged from 1.0 to 3.7 V within 2 h. The energy stored can sustain an Arduino
NANO for 180 s under sleep mode and wirelessly transmit 12 sets of 4-channel data. The proposed system can estimate physical parameters like raised foot height, step length, and kicking of lower-limb motions. Furthermore, multiple application scenarios, including rehabilitation monitoring, sports monitoring, and HMI for VR games, have been successfully demonstrated with the proposed system. Besides wearable devices, the wireless sensing nodes placed in the city also take a large amount in the IoT era. In addition to the huge volume, harsh environment and serious contamination make it arduous if all of them are powered with traditional batteries.[310–312] Therefore, the self-sustainability for such systems is as well vital to be achieved. Zhang et al. proposed a self-sustainable sensor network for monitoring the equipment's operations in the industry (Figure 14d).[313] The device contains two TENG parts, one for broadband width vibration energy harvesting (P-TENG) and the
other for frequency monitoring (S-TENG). The P-TENG can generate voltage output from 200 to 380 V under the vibration frequency from 6 to 20 Hz. With a designed power management module, the power generated can efficiently charge the energy storage capacitor from 0 to 3.3 V. The S-TENG is connected with a signal processing unit with a comparator and a counter to obtain the vibration frequency. The entire system starts to work when the storage capacitor reaches the opening voltage of a microprocessor, and the vibration information will be transmitted wirelessly. The information can be transmitted every 2.5 min when the system is working under 14 Hz, proved an effective solution for self-sustained autonomous vibration monitoring.

5.2. Convergence of TENGs with Novel Wireless, Nanophotonic, Plasmonic, and MEMS Technologies

Signal transmission and analysis technologies are of great importance to the development of TENG sensors and electronics to enable faster and more efficient communication in the IoT system. The convergence of TENG with wireless technology has brought high impact to the data communication of TENGs. Wen et al. have proposed a battery-free short-range self-powered wireless sensor network by using TENG-based direct sensory transmission (Figure 15a). With the help of a mechanical switch or diode-switch, the output and frequency of TENG signals can be enhanced by instantaneous discharging in short period, initiating the potential for direct signal transmission without additional wireless modules or external power suppliers. Resonant frequency can be identified instead of the magnitude of the output signal, providing a more stable testing result regardless of the humidity. This enables a highly sensitive and wireless force sensing application. Also, through varying combinations of TENG, capacitance and the switch states, a wireless 2D toy car control and 3D VR drone control are realized with distinguishable resonant frequencies generation. Another wireless technology integrated TENG work is demonstrated in Figure 15b by combining the TENG with surface acoustic wave resonator (SAWR). The electrical signal generated by the TENG is applied to modulate the response signal of the SAWR via a tuning network. A designed reader interrogates the SAWR and receives its response via the radio frequency link, then demodulation is performed on the SAWRs response to obtain the sensing signal. A wireless pressure sensor is demonstrated without any battery and can exhibit the wireless transmission over a distance of 2 m. The authors have demonstrated the small pressure sensing capability using three steel balls of different weight falling from the same height. It shows distinguishable voltages for the three balls. Also, by taking advantage of the frequency modulation mechanism, the authors have demonstrated a wireless matrix keyboard with four resonators of different center frequencies. The identity of each unit can be individually retrieved without any crosstalk by analyzing the spectrum of the response signal. In addition, TENG is also applied to offer the voltage for the modulation of nanophotonic devices and the modulated optical signal can be regarded as the readout. As shown in Figure 15c, the TENG is integrated with the aluminum nitride (AlN) Mach-Zehnder interferometer modulator where the capacitive nature of the AlN modulator enables the TENG to work in the open-circuit condition, and inversely the electrical voltage generated from TENG enables the modulation of interference peak shifts for AlN modulator via electro-optic Pockels effect for readout. The enabled open-circuit condition of this system can realize continuous sensing in terms of the entire pressing and releasing process of the TENG. Otherwise, the pulse-like signals will be generated in short-circuit condition without the AlN modulator, resulting in unstable and lossy information. Leveraging the integration of TENG and nanophotonic readout, various linear sensitivities independent of force speeds are achieved in different interaction force ranges. Toward practical applications, the authors have developed a smart glove to realize continuous and real-time robotics control. The bending degree of the robotic hand is related with the applied force on the TENG terminal. With the TENG on the thumb connecting to the photonic device, the entire pressing process can be displayed in the robotic hand with different bending states correspondingly. Furthermore, depending on the convergence of nanophotonic and triboelectric technology, Dong et al. have also demonstrated a highly secure biometrics-protected optical communication system together with ML integration in Figure 15d. Comprehensively, a TENG sensor is designed with a central ellipse for generating biometric information and surrounding protruded digitate electrodes for control information recording. Then, the two kinds of information generated by TENG are loaded into the optical time domain directly based on the triboelectric effect and Pockels effect, without the need of any external power supply. It is proven that this loading has no interruption to the original digital information propagating in optical fibers, the multiplexing of information enables the sealing of digital information with biometric information to enhance the complexity of the transmitted information. ML is used to analyze the transmitted information, providing ≈95% accuracy for identification of 15 users. Secure communication between users and the cloud is established after user identification for document exchange and smart home control. This work provides a self-powered, low-cost, easy-to-access, highly secure architecture for cloud communication. In addition to the convergence of TENG with signal readout technologies to enable wireless transmission, stable output, and highly secure communication, TENG is also integrated with advanced devices that require electricity. In Figure 15e, the authors have demonstrated a multibit tribotronic nonvolatile memory where a vertically stacked graphene/hexagonal boron nitride/molybdenum disulfide van der Waals heterostructure is integrated with a contact and separation mode TENG. Unlike traditional nonvolatile memory, the integrated device can be controlled by mechanical signal instead of using traditional power sources. The programming/erasing states can be modulated by the triboelectric potential, which is determined by changing the distance between the two triboelectrification layers. Under the synergistic effect of the floating gate, the electrons in the MoS2 channel can tunnel to the graphene and be stored in or released from the floating gate through the generated positive and negative electrostatic potential as an external gate voltage alternative, thereby enabling the programming/erasing states. This device exhibits a large memory window of 60 V, a high on/off ratio of
Figure 15. Convergence of TENGs with novel wireless, nanophotonics and MEMS technologies. a) Convergence of TENG with unique power management system for battery-free and short rage self-powered wireless sensor network. Reproduced with permission. Copyright 2020, Elsevier.
b) Convergence of TENG with a surface acoustic wave resonator for passive wireless TENG sensor. Reproduced with permission. Copyright 2020,
105 via manipulating mechanical power distance from −0.2 to +0.2 mm, a long retention time up to 6000 s, a stable switching behavior for over 100 cycles, and a multilevel data storage capability of 14 stages by different external stimuli. This work proves a versatile and multifunctional platform for the application in multilevel data storage. With the help of power management systems, boosted electrical energy (∼kV) can be achieved by TENG and further leveraged to obtain plasma discharge for high-voltage related applications.[319,320] In the work by Zhu et al. (Figure 15f), they have proposed a strategy to detect the concentration of volatile organic compound (VOC) based on the TENG plasma-enhanced infrared (IR) spectroscopy absorption and ML algorithm.[320] Although IR technology provides an effective solution to detect chemical structures of VOC molecules, it is limited by the weak light matter interaction resulting in large optical paths. Here, IR technology is integrated with TENG technology to achieve fast response, accurate quantization, and good selectivity. The ultrahigh voltage is achieved from the multiswitched manipulation of a TENG with repeated sliding and then applied in a particular type of tip–plate electrode configuration to introduce the plasma discharge. Therefore, the VOC species and their concentrations are well-quantified from the wavelength and intensity of spectra signals with the enhancement from plasma in the IR detection. Also, owing to the assistance of ML analysis, real-time dynamic monitoring with fast response and high accuracy can be achieved based on massive spectral data for multiple absorption peaks. In addition to the advanced applications with TENG convergence technologies, the fabrication of TENG devices is moving toward minimization and mass production. In Figure 15g, Chen et al. have developed a micro triboelectric ultrasonic device by integrating a TENG with MEMS technology.[78] It sets the world record for the smallest TENG with a 50 µm-sized diaphragm and enables the working frequency of megahertz. The suspended silicon membrane and the silicon oxide layer serve as the triboelectric layers while the top gold layer and the highly doped silicon layer underneath serve as the two electrodes. This microdevice works in contact and separation mode, and with 63 kPa@1 MHz ultrasound input, it can generate the voltage signal of 16.8 and 12.7 mV through oil and sound-attenuation medium, respectively. It has also achieved the signal-to-noise ratio of 20.54 dB and exhibited the potential for signal communication by modulating the incident ultrasound. This work provides possible solutions for energy harvesting in implantable applications.

5.3. Convergence of TENGs with Large-Scale Fabrication Techniques

Facing the rapid advancement of TENG technology, the commercialization issue is also gradually taken into consideration by researchers. Large-scale fabrication technologies are deployed in the fabrication of TENG devices to enable low-cost and mass production for commercial applications. In Figure 16a, Lee et al. have proposed a mechanically robust TENG based on a newly developed surface-textured glass fabric reinforced silicon oxide hybrid film (SGH film).[321] The large-scale SGH film is fabricated through a roll-to-plate and UV curing process. To enable the SGH film with hierarchical patterns for performance enhancement, the microdome patterns are inversely engraved on a glass substrate by HF-based etching and surface smoothing process as the mold. The developed film could have a size of 370 × 470 mm², and the size is also adjustable from millimeter to tens of centimeter owing to the scalable roll-to-plate process. Owing to the hierarchical patterns on the film, the prepared TENG show increasing output compared with the flat one. Thus, the proposed large-scale fabrication technology help provide low-cost, scalable device size and stable TENGs for commercial applications. In Figure 16b, Zhou et al. have proposed a textile-based TENG via a facile and universal fabrication process.[322] The basic fiber in the textile is fabricated by pumping liquid metal into uniform ultrafine polymer hollow fiber, where the polymer serves as the triboelectric material and the liquid metal serves as the electrode material. The large-scale textile based TENG is made of the liquid metal/polymer core shell fibers via a simple weaving machine. In addition to energy harvesting, the TENG has been successfully applied to multifinger sensing and smart home control systems as well. Moreover, Figure 16c shows large-scale smart carpert for self-powered full detection.[123] The large-scale carpet is fabricated via the commercially available weaving method, where the TENG arrays are embedded in the common textile. The basic TENG fiber is also of core–shell structure with common cloth fiber as the triboelectric material and conductive fiber as the electrode material, respectively. The TENG array embedded smart carpet shows high sensitivity to pressure, fast response, washability as well as compatibility for home decoration. The authors have applied the smart mat at home for real-time falling detection with the help of data acquisition and data processing devices. Compared with normal walking, the falling motion would result in touching multiple units in the TENG array and the signals will be triggered and analyzed to estimate whether the user falls. If so, the alarm will be turned on for timely help. Similarly, in Figure 16d, Lin et al. have proposed a large-scale and washable smart bedsheet based on TENG arrays for self-powered sleeping monitoring.[324] Here the TENG units are composed of conductive fiber and PET. Conductive fibers are laminated onto the top and the bottom fabrics, in between are the wavy-structured PET films. The TENG-based textile shows an excellent pressure sensitivity, fast response time of less than 80 s, and high comfortability. Given these advantages, a bedsheet with multiple TENG pixels is developed to...
monitor sleeping positions and sleeping behaviors in real time. The sleeping positions, body postures as well as the pressure distributions are monitored the whole night to generate the sleeping quality report. A self-powered warning system in case of a sleeper falling down from the bed is also demonstrated. Beyond healthcare monitoring using textile based large-scale TENGs, Dhakar et al. have demonstrated a thin-film, large-scale TENG for sitting posture detection based on large-scale roll-to-roll UV embossing in Figure 16e.[325] Patterned PET film and copper film are utilized as the two triboelectric layers, where the patterned PET is enabled by the roll-to-roll UV embossing. Blank PET is fixed on the unwinding module as the substrate for UV curable resin deposition in the coating module. Then the microstructure on the PET is patterned by UV embossing module, followed by separating the embossed PET from the embossing roller and rewinding for collection in the rewinding module. The obtained micropatterned PET film is rather flexible and scalable, it is cut into 40 cm × 40 cm for the fabrication of the TENG. Cu film is laminated on the LCP film and assembled on top of the patterned PET film with some sponges in between. Based on such fabrication technique, a large-scale TENG pressure sensor array is demonstrated with pressure detection sensitivity of 1.33 V kPa⁻¹. It is fixed on the back of a chair to monitor the sitting positions of users. Triboelectric output can be generated as the user touches the pixels, so that the touching positions can be mapped to obtain the sitting posture of the user. This work can be utilized for posture monitoring as well as sitting posture corrections. Overall, large-scale fabrication technologies are effectively developed for the commercialization of all kinds of TENGs, including roll-to-plate UV curing, roll-to-roll UV embossing technology, large-scale weaving technology, screen printing, etc. Meanwhile, the applications of these TENGs are covering EHs, self-powered wearable sensors for healthcare, HMI, etc.

5.4. Convergence of TENGs with ML to Enable AIoT Systems

With the development of AIoT technology, advanced data analytics based on AI algorithms is applied to various sensor data.[326–329] AI technology can improve the accuracy of information and recover incomplete information by learning the characteristics of complete information. ML technology can also optimize the performance of sensor network and monitor the dynamic environment.[330–333] By selecting the proper learning models for specific sensing applications, more comprehensive information can be extracted to better control the self-sustained system.[334,335] On the one hand, many new types of sensors can be used as data source for the requirements of AI. On the other hand, the new AI algorithms are developed for the requirements of various self-powered sensors, particularly TENG-based self-powered sensors. For instance, Wu et al. have proposed a soft robotic manipulator integrated with an L-TENG sensor for bending angle detecting, a T-TENG sensor for contact position and area sensing and a PVDF sensor for temperature sensing, which can mimic the complex and multifunctional biological perception system of human skin to realize automatic object recognition function (Figure 17b).[345] Integrating three sensors on one pneumatic finger can acquire temperature distribution information of the grasped object, which enriches the perception function of the robotic finger and gives users a more comprehensive understanding of the product. With the help of the 1D-CNN algorithm for automatic feature extraction, the classification accuracy for six spherical and three oval objects can reach up to 96.1%, showing the identification performance of the proposed system for objects with similar shapes and sizes. This integrated system is also applicable to other shapes of objects, e.g., cubic, cylindrical, etc. And a high identification accuracy of 97.321% is achieved for 28 different shapes of goods.

As shown in Figure 17c, Shi et al. have proposed a smart floor monitoring system through the integration of self-powered triboelectric floor mats and DL-based data analytics.[346] The floor mats are fabricated with unique “identity” electrode patterns using a low-cost and highly scalable screen-printing technique, enabling a parallel connection to reduce the system complexity and the deep-learning computational cost. The stepping position, activity status, and identity information can be determined according to the instant sensory data analytics. The position sensing information from each step is adopted to control the lights in corresponding positions, while the full walking signal is analyzed by the CNN model to predict whether the person is...
a valid user of the room so as to autocontrol the door access. Comparing with camera and smart tag-based individual recognition, the smart floor monitoring system based on the dynamic gait-induced output signals provides a video-privacy-protected, highly convenient, and highly secure recognition approach. For a 10-person CNN model with 1000 data samples, the average prediction accuracy can reach up to 96.00% based on their specific walking gaits, offering a high accuracy in the practical real-time scenarios. Therefore, with the aid of DL-based data analytics, the developed smart floor monitoring system with the excellent capability of position sensing, activity monitoring, and identity recognition exhibits promising potential in the applications of automation, healthcare, security, and AiO IoT toward green earth. In addition, Shi et al. have proposed a more reliable smart floor monitoring system by integrating a robust floor mat array with advanced DL-assisted data analytics.[347] As shown in Figure 17e, this floor mat sensing separate two different function area, including two coding electrodes for position sensing and trajectory tracking, one sheet electrode for identity recognition. The output ratio of two coding electrodes with respect to the reference electrode will eliminate the disturbance of varying humidity and operating conditions. Two coding electrodes can configure a total of 16 floor mats with unique coding schemes through external wiring, which permits convenient batch manufacturing by the low-cost and large-scale screen printing over the previously developed floor sensors. Such smart floor sensing system can be applied for diversified smart home-based monitoring and interacting. In order to improve the accuracy of identity recognition in smart home system, Yang et al. proposed a robust TENG-based information mat (InfoMat) via an unique IDE design mat and a two-sensory entry mat, as shown in Figure 17e.[348] The IDE design can not only realize the large-scale arbitrary position sensing, and walking trajectory monitoring, but also realize the multiseres monitoring. The entry mat is integrated by one IDE design mat and one bottom weight sensing mat. On the one hand, the entry mat can be used to detect the contact area when user walks through the entry mat. On the other hand, the entry mat can measure the weight of user. Combining such multimodality sensory information for DL analysis, the accuracy can be improved to 99%.

The integration of AI and wearable sensors is popular in the application of hand gesture recognition because wearable sensors are typically conformal to human skin, allowing for an intimate contact with the user for high-quality data acquisition. Conventionally, sensing and recognition methods of hand gesture recognition often use algorithms that depend on visual images or videos. Compared with the wearable sensor technology, due to the high resolution of data, the camera sensor would get high accuracy and the AI algorithm of camera sensor is also abundant to adapt different applications. However, the efficiency of these methods is limited by the quality of the images, which are affected by environmental interference such as blocked objects and varying light conditions. Multimodal fusion has been shown to improve the recognition accuracy and precision of hand gesture recognition. As shown in Figure 17f, Wang et al. have presented a novel ML method that makes visual data combined with data from other sensors to achieve high-accuracy gesture recognition in various illumination environment.[349] The authors have fabricated an adhesive stretchable strain sensor using SWCNT for somatosensory data collection. After visual data processing through CNN, they used a sparse neural network for the integration and recognition of the fusion of visual and somatosensory data. Even if low-quality images are used, 100% high recognition accuracy can be successfully achieved through the complementation of somatosensory data. This method can be further used for robot manipulation with 98.3% accuracy in illuminated environment and 96.7% accuracy in dark environment. Overall, although several points of improvement can be made, this paper shows a significant approach that can overcome the illumination issue of visual-based hand gesture recognition.

State-of-the-art in the field of multisensor fusion has demonstrated the feasibility of a complex system in achieving higher accuracy using data from multiple sensors. For the case of gesture recognition, vision-based sensors are known to be sensitive to background lighting and color, whereas movement-based sensors can be complementary as it is more immune to this problem. Combining these two types of sensors can therefore increase the overall accuracy of the gesture recognition. As shown in Figure 17g, Liu et al. developed a wearable motion capture device by incorporating two orthogonally-placed microflow sensors as triaxis velocity sensors with triaxis inertial sensors integrated by a triaxis accelerometer and a triaxis gyroscope.[350] The wearable motion capture device can be used to implement accurate and robust 3D motion measurement for human limbs with the simplest setup. The proposed data fusion algorithm can determine attitude angles by incorporating the motion velocity detected by the flow sensor with inertial quantities detected by the inertial sensors. Therefore, the developed wearable device is competent to accurately measure 3D velocity, acceleration, and attitude angles of limbs in dynamic motion, which can be applied to know the intralimb coordination relationship between shank and thigh in human walking and running to find the natural coordination model for human lower limb. The proposed neural network model characterizes the intralimb coordination for human lower limb to determine the thigh motion from the shank motion in human walking and running. Thereby, people only need to wear single device on shank, while capable detect motions of both shank and thigh in real time. This configuration greatly simplifies the motion capture system and reduces the cost and alignment complexity of wearable devices.

6. TENGs Enabled Applications in Different Fields of Green Earth

Besides the investigations of TENGs regarding wearable self-powered sensors, EHs, and technology convergence, the practical applications of TENGs are also blooming from every aspect on the green earth. In this section, we will review the TENGs enabled applications in the fields of transportation, rain, and wind, ocean, as well as outer space to fulfill the sustainability of TENGs enabled green earth.

6.1. TENGs in Transportation

Besides the diversified application scenarios mentioned earlier, TENGs also stand out to be attractive candidates for intelligent
transportation systems. They can be integrated into vehicles or roads to provide real-time monitoring of humans, vehicles, and roads, which can promote the accomplishment of the cooperative vehicle infrastructure system. For instance, TENGs have been reported to be integrated with nonmotorized vehicles (e.g., bicycles) as the auxiliary power source of low-power electronics or self-powered sensors. Figure 18a presents a triboelectric bicycle tire (TBT) that utilizes the mechanical motion of a rolling tire for waste energy scavenging and pressure sensing. To avoid instability due to repeated friction, vibration, and other external factors, a reliable TBT has been proposed and developed, which consists of a rubber-based tire thread, inner tube, and a PTFE-Al layer inserted between them. The fully packaged TENG can generate electrical output without occupying extra space and induce minimal degradation of the mechanical properties of the tire, which can still generate an output voltage of 34 V after 120 000 cycles. The output peak amplitude and waveform vary with the tire pressure, demonstrating the feasibility of the TBT as a tire pressure sensor. In addition, the freestanding-mode TBT system that uses patterning to create a lot of peaks could construct a self-powered bicycle safety light by continually powering nine LEDs. Apart from being embedded into the tires, TENGs can also be integrated with brakes to collect kinetic energy from the braking systems. As shown in Figure 18b, a dual-mode rotary TENG (DMR-TENG) was designed and installed on the bicycle disc brake to collect mechanical energy in both riding mode and braking mode. The DMR-TENG consists of a stator and a rotator, which is the original steel plate working as a brake disc of the bicycle to maintain a good braking performance. As illustrated by the positional relationship of the DMR-TENG in riding mode and braking mode, the tension of the brake cable contributes to most of the friction torque by the contact of the brake pad and disk. This kind of intermittent contact can largely prolong the device’s lifespan and replenish its surface charge. The DMR-TENG can successfully illuminate 156 LEDs that are shining enough to be used as a warning signal on dark nights, and power a commercial speedometer for velocity detection and displaying in real-time.

Driver’s behaviors and fatigue states would directly affect the handling stability and safety of especially motorized vehicles, which account for a large portion of traffic accidents. To track the driver’s behavior comprehensively, Figure 18c presents a sector-shaped TENG (s-TENG) to monitor the opening and closing of the accelerator and brake pedals, and a symmetrical double tunable TENG (DT-TENG) for steering wheel angle detection. Generally, the voltage slope of the s-TENG is closely associated with the pedaling actions, with abrupt and normal pedaling easily differentiated by the voltage slope amplitude. Besides, the dual-electrode design on the upper and bottom disk of the DT-TENG enables steering angle tracking through the open-circuit voltage of the two electrodes. All the collected information can classify the driver’s behaviors into four characteristics: high-speed tuning, intense braking, rapid acceleration, frequent lane changes, and curve movement. On top of it, the driver’s actions can be further sorted into aggressive driving and safe driving with algorithm analysis, which can be returned to the driver to correct bad habits and hence improve driving safety. To make use of the substantial kinetic energy associated with the rotating tires of the vehicles, Figure 18d shows a specifically designed textile-based tire cord TENG (TC-TENG), consisting of PDMS-coated Ag textile integrated on the tire tread in contact with the road and the woven nylon textile on tire cord in contact with the tire tread. This configuration contributes to dual friction between the road and tire thread, as well as between the tire thread and cord, which can promote the maximum output performance for the rolling tires. At optimum load, the TENG produces a voltage of 225 V and a current of 42 µA, along with an output power of 0.5 mW. To demonstrate its applicability as an auxiliary power source for small electronics, the TC-TENG was integrated with a 1.8 scale car and successfully charged up a commercial capacitor that further powered a wireless speed sensor.

Aside from monitoring the vehicles directly through the embedded sensors, TENGs can be assembled onto roads for traffic surveillance as well. Figure 18e presents a self-powered wireless traffic volume sensing system composed of a rotating-disk-based hybridized triboelectric and electromagnetic nanogenerator, a wireless transmitter, and a counter. As a motor vehicle passes through the tunnel, a flowing wind will be produced to activate the hybridized nanogenerator, which can light up a globe light at a wind speed generated by an 8 m s\(^{-1}\) moving car. Besides, the wireless transmitter can trigger the counter each time a vehicle passes by, with the rotator running times displayed on the screen. As a result, this self-powered active traffic volume sensing system can provide great convenience to traffic administrations for real-time traffic flow adjustments and traffic congestion reduction. Another configuration design of the TENG for road traffic monitoring and management is provided in Figure 18f, where a self-powered triboelectric sensor (CN-TST) made of electrospun composite nanofibers is developed and distributed on the road surfaces. The instantaneous speed can be calculated by the duration of the \(Q_s\) signal, with the acceleration deduced from the detected speeds at two consecutive TENGs on the lane (e.g., CN-TST1 and CN-TST2). In addition, overlapping on the roads can be identified through the triggering signals of CN-ST5–CN-ST8. The whole traffic management system has been integrated with Alibaba IoT Platform, with Raspberry Pi being used as a device communication interface, enabling advanced capabilities of recognizing plate numbers and recording traffic rule-breaking vehicles.

Targeting the high-speed rail, an elastic rotation triboelectric nanogenerator (ER-TENG) is designed to capture the wind energy produced during high-speed train movements and to power relevant sensors, as shown in Figure 18g. Compared with conventional rotary sliding triboelectric nanogenerators, the ER-TENG is characterized by less friction force and higher output for harvesting wasted wind energy, with a driving torque only half that of a conventional rotating TENG due to the elastic contact mode design. The ER-TENG is also subjected to 250 000 cycles of high-rotation-speed testing (200 rpm) and still maintains 80% of its output performance after the test due to the reduced wear. Under the driving force of the simulated wind, a double-layer ER-TENG has been demonstrated as a feasible power source for commercial traffic lights and a hygrothermograph, showing its great prospect in intelligent high-speed train systems.
Figure 18. Applications of TENGs in transportation systems. a) A reliable triboelectric bicycle tire (TBT) for self-powered pressure sensing and bicycle safety lights powering. Reproduced with permission.[369] Copyright 2022, Elsevier. b) A dual-mode rotary TENG (DMR-TENG) assembled into the bicycle brake for kinetic energy harvesting in both riding mode and braking mode. Reproduced with permission.[370] Copyright 2021, Wiley. c) Drive...
6.2. TENGs in Rain and Wind

Raining and wind blowing are two common natural phenomena that containing huge mechanical energy, so TENG devices are promisingly designed as EHs and self-powered sensors by making use of these natural energy sources. Benefiting from the four different kinds of working mechanisms, versatile TENG structures are proposed for raindrop or wind energy conversion with high efficiency. In Figure 19a, Yun et al. have proposed an IDE-based TENG to harvest raindrop energy. The IDE Al is encapsulated with PTFE and PET film, forming a freestanding-mode TENG. When the raindrop with positive charges slides on the PTFE surface, electrical potential would be generated between the two IDE fingers, resulting in the current flowing between them. Compared with the TENG with only one or two electrodes, the TENG with interdigital electrode shows the highest output performance. Since the whole structure is flexible and twistable, the authors have proposed a cone-shape TENG to harvest raindrops more effectively. Besides the improved energy harvesting efficiency, it is also illustrated that the output current is highly related to the number and speed of raindrops, as well as the folding angle of the cone. In Figure 19b, Liu et al. have integrated three kinds TENGs with the umbrella for enhanced raindrop energy harvesting. A freestanding TENG with IDE (I-TENG) is attached to the upper surface of the a saccular contact–separation mode TENG (SCS-TENG), forming the surface of the umbrella. Meanwhile, an array of strip-shaped I-TENGs is standing on the umbrella surface. The output voltage of the three TENGs shows significant improvement compared with only one TENG or two TENGs. The umbrella with integrated TENGs can be used as a self-powered raining alarm system when connecting with the capacitor and the microcontroller. The capacitor would be charged when raindrops fall on the integrated TENG, and the microcontroller would analyze the voltage signal of the capacitor. Once the voltage reaches the threshold value, the alarm system would start to alarm. Inspired from conventional TENG working mechanisms, Xu et al. have proposed a novel working mechanism to harvesting droplet energy with boosted instantaneous power density. Different from the single-electrode TENG, an electrode is placed on the surface of the triboelectric layer and connected with the below electrode. Once the spreading of water droplet touches the upper electrode, the originally disconnected components would be bridged into a closed-loop electrical system. Therefore, the conventional interface would be transformed into a bulk effect so that the instantaneous power density could be enhanced by several orders of magnitude. Based on this novel mechanism for TENG, Zhang et al. have proposed a TENG-based large-scale and flexible greenhouse film for raindrop energy harvesting in Figure 19c. The greenhouse film is prepared by using the superhydrophobic untreated greenhouse film as triboelectric layer, the PEDOT:PSS coated on the untreated film as the lower electrode and the Cu foil attached on the untreated surface as upper electrode. This device exhibits high and stable output so that it can serve as reliable power source for green house monitoring, including the temperature, humidity, gas concentration, soil PH, etc. The developed self-sustainable system is beneficial to the realization of intelligent control of smart farming in green earth. Speaking of the applications of TENGs in wind energy conversion, Wang et al. have proposed a flag shaped TENG with excellent wind direction adaptability for wind energy harvesting and speed monitoring in Figure 19d. The flag-type TENG consists of two carbon-coated PET membranes and one strip of PTFE membranes with their edges sealed up. Therefore, the whole device is isolated from the ambient environment, enabling the humidity resistance of the TENG. The output voltages under varying humidity are well maintained. It is found in this work that a pair of flag-shaped TENGs with certain gas distance shows enhanced output performance compared with the only one TENG under wind blowing. The TENG can also be treated as self-powered wind speed sensor and the measuring results matches well with the commercial wind speed sensor. The high accuracy of wind speed testing results from different directions ensures a promising application of the sensor in green earth. Furthermore, Ahmed et al. have proposed a TENG farm for large-scale energy harvesting from natural wind (Figure 19e). Depending on the freestanding working mode, electricity can be generated via relative rotation between the two disks with patterns of microsized circular sectors, which is caused by the wind flowing in either high or low flowing speed. Meanwhile, the magnitude of output electric signals increases with the flowing speed of the wind so that the TENG device can be regarded as self-powered wind speed sensor for smart farm application. In addition to wind energy, raindrop energy and solar energy from the natural environment can also be harvested and converted to electricity for further applications. In Figure 19f, Roh et al. have developed an ultrathin unified energy harvesting module that is capable of working in various weather conditions, including rainy, windy, and sunny days. This module contains an SC for solar energy harvesting, one transparent TENG on the top for raindrop energy harvesting and the other TENG for wind energy harvesting. It can also be utilized as a self-powered weather sensor to detect raindrop, sunlight as well as wind speed according to the varying electrical outputs. Thus, based on these self-powered sensors, a weather monitoring platform is demonstrated for use in a smart farm with the help of a data acquisition system and a LabVIEW software to enable real-time environmental monitoring of the smart farm. Furthermore, the behavior through the sector-shaped TENGs (s-TENG) for accelerator and brake pedal movement sensing, and the double tunable structure (DT-TENG) for steering angle tracking. Reproduced with permission. A dual friction mode textile-based tire cord TENG (TC-TENG) for kinetic energy harvesting of rolling tires. Reproduced with permission. A rotating-disk-based hybridized nanogenerator for a self-sustainable wireless traffic volume sensing system. Reproduced with permission. An elastic rotation triboelectric nanogenerator (ER-TENG) to scavenge wind energy produced during high-speed train movements. Reproduced with permission.
Figure 19. Applications of TENGs in rain and wind. a) Interdigital electrodes based TENGs for effective energy harvesting from raindrop. Reproduced with permission. Copyright 2017, Elsevier. b) Umbrella-structured hybrid TENGs for raindrop energy harvesting. Reproduced with permission. Copyright 2019, Wiley. c) Novel TENGs with boosted output for raindrops energy harvesting and self-powered intelligent greenhouse. Reproduced...
EHs and sensors for rain and wind are also developing toward system integration and higher intelligence for multimodal data fusion and AIoT in smart farming applications.\(^\text{[194]}\)

### 6.3. TENGs in Ocean

The ocean, which covers more than 70% of the planet’s surface, is a tremendously valuable clean energy source and has advantages with less dependence on day–night rhythm, weather change, and seasonality.\(^{[195–198]}\) Whereas the low frequency of ocean waves also makes it challenging to scavenge mechanical energy efficiently. Therefore, plenty of EHs with designs like nonresonant structures or elaborated gearbox-like structures have been proposed.\(^{[199–200]}\) Zhang et al. presented a device with high energy collection efficiency through applying a vessel platform to integrate bifilar-pendulum coupled hybrid nanogenerator (BCHNG) modules (Figure 20a).\(^{[200]}\) The module is composed of two PENGs, one EMG, and two multilayer-structured TENGs (M-TENGs). Considering the low frequency of ocean waves and the gravitational energy simultaneously, thanks to the seesaw motion of the vessel and the swing motion of the bifilar pendulum. In the power transfer chain, the vessel is first used as the interface to intercept the power of ocean waves. The bifilar pendulum then acts as the PTO to scavenge the intercepted power generated by the vessel. Based on that, BCHNG modules consisting of three kinds of EHs can efficiently transfer the captured power of PTO to electricity. In the actual wave water operation status, the maximum output power of M-TENG, PENG, and EMG has reached 3.1, 2.9, and 0.6 mW, respectively, under loading resistances of 20 \(\Omega\), 2 \(K\Omega\), and 1 \(K\Omega\). Besides, benefiting from the elaborated design of the device to maximize the space utilization rate, a power density of 358.5 \(W\ m^{-2}\) has been achieved, which is one or two orders higher than previous works. And the proposed device protected by the vessel platform can achieve good stability in natural marine environments, getting rid of complex encapsulation. Wang et al. proposed a flag-like TENG that can work under extremely low-conditions to scavenge underwater ocean energy (Figure 20b).\(^{[201]}\) The flag-type EH operates similarly to a flag’s flapping in the wind, that the flapping can also be induced by the instability of the coupled fluid system underwater. The proposed underwater flag-like TENG (UF-TENG) system consists of a cylindrical structure. The vortex stress induced by the cylinder can enhance the vibration of the UF-TENG and further improve the electrical output under low flow velocities significantly. Besides, to maximally increase the output performance, other factors that influence the dynamics of the UF-TENG, like the aspect ratio and the bending stiffness, have been comprehensively investigated in this work. The optimized UF-TENG can work in a water flow velocity as low as 0.013 m s\(^{-1}\), and a peak output power of 52.3 \(\mu W\) has been successfully achieved. More importantly, the UF-TENG is also proven with high durability, which can operate steadily for over 3000 \(s\) at a high flow velocity of 0.175 m s\(^{-1}\), and the device output voltage is consistent for over 300 \(s\) in three days. Recently, Bhatta et al. proposed a hybridized device that can not only harvest the wave water motions with low frequency and unpredictable arbitrary features but also can serve as a self-powered sensor for monitoring multiple wave parameters (Figure 20c).\(^{[202]}\) The designed hybrid self-powered arbitrary wave motion sensing system is inspired by the elliptical trajectory of the shallow water waves. Such a shape can provide a flat curvature for a spherical magnet, which can also assist the free rolling of a magnet ball. The frame of the proposed system is fabricated by 3D printing, with PLA as the material. The primary energy scavenging function is achieved by the EMG, which contains a spherical magnet and planar spiral coils along all six faces to cover six degrees of freedom energy harvesting. The self-powered water wave parameters sensing function is realized by four TENGs attached along the four sides. To make the TENG and EMG work synergistically, a custom fabricated ferromagnetic composite film of iron–silicon chromium (FeSiCr) and PDMS are used as the TENG materials. Then the magnet used for EMG can also assist in the self-actuation of the TENG through magnetic attraction and lead to periodic contact and separation process between TENG layers. In regard to the energy harvesting characteristics, the proposed device can deliver a maximum output power of 106 and 44.8 mW when moving along the major axes and the minor axes, respectively. When placed in real waves, a peak power output of 40 mW can be achieved under a water wave frequency of 3 Hz. And it can work under an ultralow driven frequency of 0.2 Hz. As a self-powered motion sensor, the designed TENG can reach a frequency sensitivity of 34.61 \(V\ Hz^{-1}\) and an acceleration sensitivity of 39.97 \(V\ m^{-1}\). Besides, both the energy harvesting and the sensing parts show good durability, which can work stably for over 12 000 cycles of continued operation. Finally, a self-sustainable wireless system has been validated. The harvested electricity of the EMG can be used to power a circuit with a signal processing unit and a wireless transmission unit, which can acquire the sensing data of the TENG and send it to a smartphone wirelessly. To fully utilize the clean energy of ocean waves, Zhai et al. proposed a gear-driven unidirectional acceleration TENG (GU-A-TENG), which can further transmit the scavenged mechanical energy into clean hydrogen energy (Figure 20d).\(^{[202]}\) The proposed device has an elaborated gear set to amplify and rectify the disordered and low-frequency
ocean flow to unidirectional and high-frequency rotation. It can then generate a DC output with low voltage but high current, which can be fully utilized by a photoelectrochemical cell to produce hydrogen under sunlight. Furthermore, the system is designed with the ability to switch between two working modes automatically. When there is no sunlight, the energy scavenged by the GUA-TENG is used for charging a battery with a power management circuit. Under sunlight illumination, the energy scavenged is used to produce hydrogen. A peak output voltage and current of 7.1 V and 1.5 mA can be reached at the rotational speed of 120 rpm, which can charge the battery to 2.75 V within 200 s with an energy conversion efficiency of 3.69%. And a maximum hydrogen production rate of 4.65 µL min⁻¹ can be achieved at the rotation speed of 120 rpm with a conversion efficiency of 1.06%. To fully scavenge the mechanical energy of multidirectional ocean waves, Gao et al. proposed a gyroscope-structured TENG (GS-TENG), as shown in Figure 20e. The GS-TENG contains two cages with mutually perpendicular central axes as the inner and outer generation units to increase the power generation area. Such a design can allow two generation units to rotate freely and independently when excited by water waves. Under varied excitation directions and an acceleration of...
6 m s⁻², the open-circuit voltage can reach 730 and 160 V for the inner and outer generation units, respectively. Peak power of 0.6 mW with a power density of 0.28 W m⁻³ has been achieved. And the feasibility of connecting multiple GS-TENGs to realize large-scale ocean energy scavenging has been proved. Besides, the GS-TENG also shows great stability and durability, which can maintain its output performance throughout a one month real water experiment.

6.4. TENGs in Outer Space

Outer space exploration mission usually relies on the integration of the most advanced technologies from various fields. Especially for sensing and power generation solutions, as a cost intensive project with limited space, the self-powered sensor and appropriate nanogenerator can greatly improve the intelligence, the sustainability, and the reliability of the whole system. Due to the extreme environment of outer space, such as radiation, high and low temperature, as well as vacuum, many construction tasks are completed by robots or robotic arms, in order to avoid the potential risks. Unlike the conventional MEMS sensors, TENG sensors with good flexibility and customizability possess unique advantages in monitoring the detailed working activities of robots, such as climbing, gripping, and assembling. Hou et al. reported a scalable robotic cluster system for realizing the component-level in-orbit assembly ultralarge-scale space truss structures, as shown in Figure 21a.⁴⁰⁶ The robotic system consists of a mobile system and an operating system. The mobile system applies triboelectric robot leg sensors for detecting the slippage. The operating system uses triboelectric robot manipulator sensors which can detect the gripping. There are also triboelectric space truss sensors in charge of sensing the completed assembling of each truss. On the other hand, TENG-based discharge can also be as haptic feedback interface. As shown in Figure 21b, Shi et al. presented a TENG array with ball electrodes to make a feedback system which can enhance the perception of astronaut to the external environment.⁴⁰⁷ When the slider is sliding across the TENG array, the electrical output can be generated via the triboelectric effect. With the direct contact of the ball electrodes to human skin, the TENG electrostatic discharge can be delivered as electrical virtual tactile stimulation while wearing the protective space suits. PENG as another energy harvesting approach is also studied for outer space mission. In Figure 21c, Ye et al. presented a flexible piezoelectric energy generator comprised of composite materials which are tolerant to neutron radiation.⁴⁰⁸ And hence, this device can be a reliable power source by converting mechanical and biomechanical movements into electricity.

To further optimize the performance of nanogenerators in outer space environment, several research studies were carried out for evaluating the output under various conditions. As depicted in Figure 21d, to investigate the optimal way of harvesting mechanical energy from strong dust storms and surface vibrations on Mars, a Mars analogue weather chamber was fabricated by Seol et al., for analyzing the individual and combinatory impacts of various environmental factors on TENG.⁴⁰⁹ Du et al. proposed a self-healable TENG made by modified Ti₃C₂Tx MXene (m-MXene)-based nanocomposite elastomers.⁴¹⁰ The good electromagnetic absorption from m-MXene network and sheets offers outstanding EMI shielding performance to develop a self-powered wearable electronics for aerospace application.

Moreover, to reduce the risk of the unmanned Mars mission, numbers of sensors are required during different stages. In Figure 21e, a self-perceiving and repairing parachute system was presented for the Entry–Descent–Landing process of Mars exploration mission.⁴¹¹ The TENG-based sensory array on the surface of the parachute, and the shape memory alloy based self-repairing system can greatly reduce the possibility of the severe damage of the parachute under the impact of the dust storm.

On the other hand, there are several research studies focus on the application of TENG in high altitude scenarios. In Figure 21f, a TENG flag made by woven fabrics was demonstrated to harvesting the high altitude wind energy by using the meteorological balloon, in order to power the scientific devices.⁴¹² For the aircraft, a hierarchical honeycomb-structured TENG was designed to be integrated into the wings on the unmanned aerial vehicle for converting the flapping energy of ailerons into electricity (Figure 21g).⁴¹³

7. Conclusion and Perspectives

Aiming for the IoT integrated green earth, our review starts from discussing the novel functional materials which enables the wearable TENG sensors and harvesters to have stretchability, skin-adhesion, self-healing capability, biocompatibility, etc., so as to achieve improved wearable or even epidermal purpose in green earth. Triboelectric materials, together with piezoelectric, thermoelectric, pyroelectric, ferroelectric, and optical luminance materials are integrated to realize multifunctionality and output performance boost in the wearable electronics. Regarding the applications of wearable electronics, we have covered the devices for healthcare and biomeedicine application, as well as communication platforms including HMI, robotics control, and plants signal detections. Meanwhile, as another key trend for the development of green earth, energy consumption issue has raised great concern, where the energy consumption should be minimized. Thus, self-sustainable systems and self-powered sensors can be the two feasible strategies. As for the self-sustainable systems, we focus our discussions the hybridization of EHs (such as TENG, EMG, PENG, TEG, SC, etc.) for indoor and outdoor applications which helps compensate the limitations of pure TENG-based EHs, bringing in more stable working conditions and enhanced output performance.

Moving forward, technology convergence has become a new pathway to equip the IoT sensory systems with novel and exciting outcomes for the built-up of green earth. Here, we have introduced several advanced technologies converging with triboelectric technologies, enabling boosting of self-sustained IoT system, wireless sensing data transmission, real-time, and continuous communication interfaces, minimizing fabrication cost and increasing device scale. Also, with the convergence of AI technology, the abundant data from the sensory network can be comprehensively analyzed by ML/DL, more
accurate and complete information of the whole IoT system can be obtained to help construct the green earth. We also indicate that TENG technology is blooming in every aspect on the green earth, including transportation, nature environment (rain and wind), ocean, and even outer space. Overall, the great potential of TENGs enabled wearable sensors and electronics can be seen clearly in the development of IoT integrated green earth.

Witnessing the current achievements in IoT integrated green earth, plenty of efforts have been put on the wearable materials investigation, self-sustained system development, advanced technology convergence. The further advancement
will be continued toward the construction of sustainable IoT systems with improved portability and wearability, multifunctionalities, zero energy demand, higher intelligence. First of all, the improved portability and wearability of the systems depend greatly on the investigation of advanced materials. Thus, for the epidermal sensors, the stretchability, breathability, skin-compatibility as well as biocompatibility can be considered and combined. On the other hand, textile-based sensors can be another strategy so that washability, lightweight, cold feeling in summer and warm feeling in winter are all demanding properties. On top of this, more functionalities are expected to be integrated into one system to achieve higher utilization of the system. Owing to the versatile working mechanisms of sensors and the achievements of technologies from every field, multifunctionality can be a promising trend for the self-sustained systems. In this regard, it is also hopeful to address the energy consumption issue which is an inevitable bottleneck in the development of green earth. For further application, the sensitivity and stability of the self-powered sensors should be improved and the energy harvesting efficiency of the EHs should be modified either from material choices, structure constructions or multiple working modes hybridization. Finally, benefited from current AI technology, abundant data from the IoT sensor network can be automatically and comprehensively analyzed to extract critical information for further action like event recognition. Expecting the further exploiting of AI technology, ML algorithms, self-sustained systems with higher intelligence are envisioned to construct the AIoT integrated green earth. To wrap up this review, the self-sustainable IoT systems will be continuously advanced in every aspect of the green earth, including human body, smart farming, smart home, smart transportation, etc.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

electronics, green earth, internet of things, triboelectric nanogenerators, wearable sensors

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