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Review

Advances in Triboelectric Nanogenerators for Sustainable and Renewable Energy: Working Mechanism, Tribo-Surface Structure, Energy Storage-Collection System, and Applications

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Abstract: Triboelectric nanogenerators (TENGs) are emerging as a form of sustainable and renewable technology for harvesting wasted mechanical energy in nature, such as motion, waves, wind, and vibrations. TENG devices generate electricity through the cyclic working principle of contact and separation of tribo-material couples. This technology is used in outstanding applications in energy generation, human care, medicinal, biomedical, and industrial applications. TENG devices can be applied in many practical applications, such as portable power, self-powered sensors, electronics, and electric consumption devices. With TENG energy technologies, significant energy issues can be reduced or even solved in the near future, such as reducing gas emissions, increasing environmental protection, and improving human health. The performance of TENGs can be enhanced by utilizing materials with a significant contrast in their triboelectrical characteristics or by implementing advanced structural designs. This review comprehensively examines the recent advancements in TENG technologies for harnessing mechanical waste energy sources, with a primary focus on their sustainability and renewable energy attributes. It also delves into topics such as optimizing tribo-surface structures to enhance output performance, implementing energy storage systems to ensure stable operation and prolonged usage, exploring energy collection systems for efficient management of harvested energy, and highlighting practical applications of TENG in various contexts. The results indicate that TENG technologies have the potential to be widely applied in sustainable energy generation, renewable energy, industry, and human care in the near future.

Keywords: triboelectric nanogenerator; renewable and sustainable; energy storage; energy collecting system; energy applications

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1. Introduction

The triboelectric nanogenerator (TENG)-based triboelectricity effect is now emerging as a principle for an outstanding sustainable and renewable energy source, through energy-harvesting technologies that harvest wasted mechanical energy and convert this energy into electricity for daily living [1,2]. This advanced technology converts wasted mechanical energy into electrical energy from many types of energy sources, such as human walking [3], wind [4], motions, vibrations, and waves [3,5–9]. It has been verified that TENGs have characteristics of low-cost fabrication [10], sustainable energy [11–14], green energy, and renewable energy sources [15–17].

Traditional energy is extracted from non-renewable sources by burning or methods related to burning, with a large number of disadvantages, such as gas emissions, discharge of toxic pollutants, global warming, and negative effects on human health. These impacts need to be rapidly reduced or eliminated to protect our health and environment. The total carbon dioxide emissions captured from the energy sector was about 36.6 gigatons (Gt) in 2021, following an increase of 1.9 Gt in 2020. The 2021 net zero roadmap for the global energy strategy targets a net zero scenario for emissions by 2050, corresponding to 90% usage of electrical energy from renewable energy [18]. The global total renewable energy capacity (TREC) statistics for 2023 show strong development of renewable energy throughout the world during the years from 2013 to 2022. The TREC was about 1566.49 gigawatt (GW) in 2013. In 2014, the TREC value was about 1699.06 GW. The TREC indicators were 1852.78 GW, 2018.26 GW, 2186.04 GW, 2359.39 GW, 2543.38 GW, 2813.16 GW, 3077.24 GW, and 3371.79 GW in the years of 2015, 2016, 2017, 2018, 2019, 2020, 2021, and 2022, respectively. The records indicate that the total renewable energy capacity increased by about 8.5% per annum from 2013 to 2022, on average, with the highest increase of 10.6% in 2020 [19].

Sustainable and renewable energies are a potential choice for sustainable development for the whole world. Sustainable and renewable energy resources and technologies are used to convert natural energy, including solar energy, bioenergy, geothermal energy, hydropower, ocean energy, wind power, triboelectric generation, and triboelectric nanogenerator energy, into usable energy. Many research groups have focused on the development of methods, technologies, techniques, and materials to harvest renewable energy sources into useful energy, improve the quality of renewable energy conversion, strengthen sustainable characteristics, enhance renewable energy systems, and apply renewable energy in daily life. This research includes developing a biomethane generation technique for a green energy strategy [20], building an optimization algorithm model of photovoltaic power prediction for renewable energy development [21], using a deep learning method to improve the stability of power generation from an oscillating water wave energy converter [22], constructing a model reference adaptive control to increase the output performance quality of a hybrid renewable energy system [23], combining a photovoltaic system and a power grid for compressor motor applications [24], integrating renewable energy resources and electrical vehicles in a power system [25], using an active power filter to connect renewable energy to the power grid to improve the grid network performance [26], using intelligent methods to track the maximum power of a wind energy harvesting system to improve a renewable energy system [27], developing a model of a hybrid storage system of photovoltaic and hydrogen energy for agricultural, residential, industrial, and transportation applications [28], and using neuro-fuzzy technology to manage smart grids with the penetration of photovoltaic power [29].

TENGs can work as sustainable and renewable generators to produce electricity for electricity-consuming devices. Applications include using a sustainable power TENG for vibration sensor application with the ability of self-powered action [30], acting as a self-powered environmental monitor with a multidirectional vibration mechanism [31], and acting as the sustainable power for electronic devices [32].

The tribo-material and tribo-surface structure are crucial in the construction of a triboelectric nanogenerator for harvesting wasted mechanical energy and enabling many effective applications. Tribo-material couples induce a triboelectrical effect during the working cycle of a TENG. Power generation can be achieved in the contact–separation mode and sliding mode between a tribo-surface couple. The output current density is strongly dependent on the triboelectrical materials via the electrical effect difference of the materials [33–37]. The polymer typically collaborates with a metal in the TENG to facilitate the collection or release of electrons, enabling the flow of electrical current through an external circuit. The triboelectric series, which is a quantified list of triboelectric materials, has been tested and developed for TENG applications. Subsequently, materials in the triboelectric series that have the ability to lose or gain electrons under the testing condition of the contact and separation cycle have been identified [38]. Based on the triboelectric series, TENG devices are built for harvesting energy in the shortest working time. It has been clearly proven that tribo-surface structures can enhance the output performance of the TENG by increasing the friction between the two triboelectric surface materials [39–42]. The key to increasing the output performance of the TENG is based on increasing the contact between the two materials. This is closely related to the contact area of the tribo-surface couples, which is strongly increased by introducing advanced surface morphology characteristics to the TENG [43,44]. Tribo-surface structures have received a large amount of attention from research groups aiming to enhance TENGs' output performance. These efforts include using a TENG with a multilayer harvester based on the biomimetic structure to enhance its performance [45], developing the surface structure of special micro-arrays to improve contact friction between two tribo-surfaces to increase the electrical output performance [46], using a novel surface structure and mechanism of microneedle patterns to enhance the TENG's output performance [47], using a honeycomb structure in a TENG to harvest vibration energy for an engine condition monitor with a self-powering capacity [48], and using a lawn structure in a TENG to harvest wind energy [49].

Energy storage (ES) has the important duties of storage and management of the harvested energy from the TENG. ES is an effective method to stabilize electric current in electronic devices and electricity-consuming equipment [50–52]. Renewable energy that is produced from renewable energy sources comes from nature. The natural resource's energy performance depends on natural behaviors such as seasons, weather, time of day, months, and hours. These phenomena directly affect the output power of renewable energy harvesters. Energy storage is extremely crucial to store redundant energy that is harvested from renewable energy sources. The stored energy will be used as needed [53–58].

Energy collecting systems (ECSs) are one of the effective ways to manage and control the harvested energy from TENGs. With ECSs, the harvested energy can be effectively applied for different purposes such as directly powering an electrical consumption device, storing energy for long-term use, and penetrating a power grid [59–63].

Practical application of the TENG involves bringing its harvesting capabilities to serve in daily life. The machines can actively function using TENG energy harvesters. The sensors can harvest and transmit signals, enabling their application in powering themselves or other devices through TENG technology. The diodes and electrical lights can be lit up by a TENG device. There are tremendous plurality of mechanical, biomechanical, electronic, and Internet-of-Things devices, as well as self-powered sensors, protection devices, and portable equipment, that can be effectively powered by TENG harvesters [64–72]. There are many applications of TENGs in the energy sector such as self-powered devices for electrochromic systems [73], TENGs for biomedical microsystems with sustainable power ability [74], human–machine interface systems [75], and human mechanical energy sensors for sport applications [76]. TENG applications are diverse, including biosystems, sensors, human healthcare aid, monitoring systems, industrial applications, self-powered systems, environment sensors, smart homes, manufacturing systems, therapeutics, and sustainable applications [77–82]. Many other applications of TENGs are critical for human daily living, such as smart transportation monitoring systems [83], R-TENGs for sensing, energy harvesting and actuator applications [84], TENGs for Internet-of-Things (IoT) devices with self-powered abilities [85], TENGs for self-powered sensors [86], and TENGs for flow sensors [87].

This paper reviews current TENG technologies with the sustainable energy generation principle to produce electricity from wasted mechanical energy sources, the surface structure applied to harvest energy and enhance output performance of TENGs, the energy storage system used to store energy for stable electrical consumption supported by TENGs, the energy collecting system used to manage and control the harvested energy from TENGs, and many practical sustainable and renewable energy applications as well as the hot issues of the benefits, challenges, and solutions to improving the powering and servicing of TENGs. TENGs' working mechanisms are mentioned in theory with four basic models of the TENG, including the single-electrode model, the free-standing triboelectric layer model, the in-plane sliding mode, and the vertical contacting–separating model. The surface structure introduces many structure patterns into TENGs to increase the output performance of devices, such as microneedle structures, nanowire structures, graphene morphology, micro pyramids, nanofibers, diamond-like carbon structures, textile patterns, hydrophobic sponge structures, carbon nanotubes, hybrid micro–nano structures, nanowire arrays, and wrinkle structures. Energy storage is the key technique to store large amounts of TENG energy for long-term use, maintain the stable working condition of the TENG and avoiding fluctuation in input triggers on the TENGs during the process of energy production. Energy collection systems play a vital role in ensuring the sustainability of energy powering systems. They utilize an effective structural diagram for harvesting wasted mechanical energy from TENGs, comprising fundamental components such as the harvesting unit, processing unit, energy storage block, and energy consumption system. Sustainable and renewable energy applications are crucial for TENGs with a wide range of applications including lighting applications, energy storage, smart houses, transportation, power grids, manufacturing, sensors, portable devices, access points, monitoring devices, electric consumption equipment, and human healthcare. In this paper, we address critical issues pertaining to the benefits, challenges, and solutions associated with TENG technology. We highlight the advantages of TENGs, including their sustainability, low cost, and flexibility and their ability to harvest energy from diverse sources. Additionally, we discuss the disadvantages, such as low output energy performance and susceptibility to dust, and propose solutions to overcome these limitations. These solutions encompass technologies for more efficient mechanical energy harvesting; surface modifications to enhance TENG output performance; methods, techniques, mechanisms, and materials to improve their energy output; and energy storage to maintain a balanced electric current generated by TENGs. The results show that TENG technologies can be widely applied in sustainable energy generation, renewable energy, industry, and human healthcare in the near future.

2. Materials and Methods

2.1. Working Mechanism of the TENGs

TENGs have four working mechanisms to produce electricity via the triboelectrification behavior between two materials during contact. The contact and separate operation of two tribo-materials causes movement of charged particles from one material to the other. Figure 1 shows the four working modes of TENGs: the single-electrode, free-standing triboelectric layer, in-plane sliding, and vertical contacting–separating modes. Figure 1a shows a single-electrode TENG and its working mechanism. Figure 1b shows a free-standing triboelectric layer TENG and its working mechanism. Figure 1c shows an in-plane sliding mode TENG and its working mechanism. Figure 1d shows a vertical contacting–separating mode TENG and its mechanical working mechanism. Single-electrode TENG (S-TENG) devices produce an electric flow via an external load connected to the ground and an electrode mounted on the TENG. An S-TENG consists of two triboelectric material layers with just only one electrode on the metal layer to harvest electricity. During the working process of the S-TENG, one triboelectric layer comes into contact cyclically with another layer; electric particles will be charged on the triboelectric material surfaces and an electric flow will be generated by the potential difference between the electrode and the ground [88]. An S-TENG is featured by the open-circuit voltage (V_{OC}), short-circuit charge (Q_{SC}), and the capacitance (C), which are governed by the following relationship (1) [89].

$$Q_{SC} = V_{OC} \times C \tag{1}$$

where

V_{OC} is the open-circuit voltage.

Q_{SC} is the short-circuit charge.

C is the capacitance.

Free-standing triboelectric layer (F-TENG) devices are composed of one free-standing layer of dielectric material and two metal pads with two electrodes attached to the metal layer to harvest electricity. An F-TENG generates electrical flow by contact between the dielectric layer from one metal layer and another metal layer; electrons will charge the triboelectric material layers and an electrical flow will move via an external load under the unbalance condition of the potential between the two electrodes [90]. An F-TENG has an open-circuit characteristic addressed by the following Equations (2) and (3) [91]:

$$V_{OC} = \frac{2\sigma x}{\varepsilon_0} \quad (2)$$

where
V_{OC} is the open-circuit voltage.
σ is the triboelectric charge density.
x is the separating distance.
ε_0 is the vacuum permittivity.

$$R\frac{dQ}{dt} = -\frac{1}{C}Q + V_{OC} \quad (3)$$

where
V_{OC} is the open-circuit voltage.
Q is the transferred charge.
R is the resistance.
C is the capacitance.

In-plane sliding TENG (I-TENG) devices generate an electric current via an in-plane sliding action to make contact between the two triboelectric material surfaces. An I-TENG consists of triboelectric material layers and two electrodes attached to direct the current moving through the output resistance during the sliding cycles of the tribo-surfaces in outward and inward sliding directions. During the in-plane sliding cycles in an I-TENG, the tribo-surfaces come into contact with each other; positive and negative electric particles will be charged on the triboelectric surfaces and the sliding action will cause an imbalance in the potential, leading to the I-TENG producing a current moving via the external load [92]. An I-TENG creates an electrical current with the open-circuit voltage (V_{OC}) calculated by the following Equation (1) and the short-circuit current formulated by the following Equations (4) and (5).

$$V_{OC} = \frac{\sigma x}{\varepsilon_0(l - x)}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) \quad (4)$$

where
V_{OC} is the open-circuit voltage.
σ is the triboelectric charge density.
l is the length of the dielectric layers.
x is the separation distance between the dielectric layers.
ε_0 is the vacuum permittivity.
ε_{r1} is dielectric layer 1's permittivity.
ε_{r2} is dielectric layer 2's permittivity.

$$I_{SC} = \sigma\omega\frac{dx}{dt} \quad (5)$$

where
I_{SC} is the short-circuit current.
ω is the width of the dielectric layers.
σ is the triboelectric charge density.
x is the separation distance between the dielectric layers.

Vertical contact–separation mode TENG (V-TENG) devices consist of a triboelectric material coupled to two attached electrodes to harvest mechanical energy into electricity. The V-TENG working mechanism is based on a contact and separation cycle between the two triboelectric surfaces. During the working process, electric particles will be induced on the triboelectric surfaces under complicated physical conditions of contact–separation with force and friction; the potential difference will occur via the contact–separation action, leading to an electrical flow via the external load [47]. A V-TENG produces an electrical flow with an open-circuit voltage (V_{OC}) expressed by the following Equation (6) and a short-circuit current governed by the following Equation (7) [93]:

$$V_{OC} = \frac{\sigma x(t)}{\varepsilon_0} \tag{6}$$

where
V_{OC} is the open-circuit voltage.
σ is the triboelectric charge density.
x is the distance between the two contact surfaces.
ε_0 is the vacuum permittivity.

$$I_{SC} = \frac{S\sigma d_0}{(d_0 + x(t))^2} \frac{dx}{dt} \tag{7}$$

where
I_{SC} is the short-circuit current.
S is the contact surface area.
d_0 is the effective thickness coefficient.

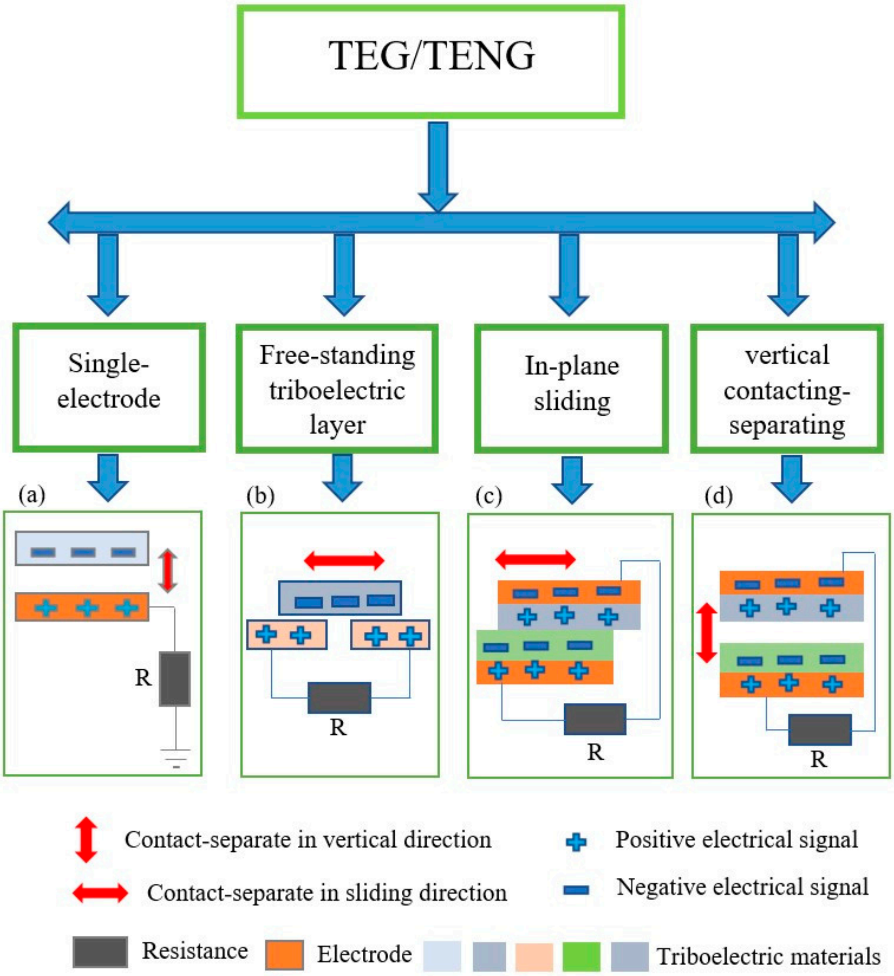

Figure 1. The four working modes of TENGs. (**a**) A single-electrode TENG and its working mechanism. (**b**) A free-standing triboelectric layer TENG and its working mechanism. (**c**) An in-plane sliding mode TENG and its working mechanism. (**d**) A vertical contacting–separating mode TENG and its mechanical working mechanism.

In summary, the working mechanism of TENGs is based on the contact and friction between two triboelectric materials, resulting in the generation of electric current. TENGs have a simple structure that relies on the pairing of triboelectric materials, such as metal and polymer materials. With these working mechanisms, TENGs are capable of effectively harnessing a wide range of wasted mechanical energy resources, from minor triggers to substantial impacts. For instance, TENGs operating in the contacting–separating mode have been developed to collect energy from sound waves, yielding a peak current of 0.45 mA and a charging rate of 61 μC/s within the frequency range of 50 Hz–425 Hz [94]. Moreover, TENGs employing the contacting–separating mechanism can serve as power sources, delivering a peak power density of approximately 7 W/m^2, a short-circuit current of 175 μA, and a short-circuit voltage of 400 V, harnessed from acoustic energy sources with a pressure level of 115 dB and a frequency of 170 Hz [95]. Furthermore, TENGs based on the contacting–separating mode can generate electric power with a peak power density of about 5.07 W/m^2, a short-circuit current density of about 16.9 mA/m^2, and a short-circuit voltage of about 1080 V, by utilizing the pressure characteristics of vehicle motion ranging from 1.25 to 6.25 kPa [96]. Additionally, TENGs designed with a single-electrode mode can convert eye motion into electricity, yielding approximately 750 mV, suitable for self-powered communication systems [97]. TENGs can also be constructed in a free-standing mode to convert ocean wave energy into electricity, with impressive electrical characteristics, including a maximum power density of 28.2 W/m^3 [98]. Lastly, TENGs based on the in-plane sliding mode have the capability to generate direct current with electrical characteristics of 270 μA/m^2 and 80 V [99].

Figure 2 depicts a detailed working mechanism diagram of a typical TENG operating in the vertical contacting–separating mode. This illustration serves to elucidate the electrical production mechanism employed by TENG devices. The electrical production can be addressed in the electrostatic charge procedure. In the initial position, triboelectric materials are in a balanced condition without any electron transfer in the dielectric materials, as shown in Figure 2a. When the two triboelectric material surfaces come into contact with each other, the tribo-negative material receives electrons donated by the tribo-positive material due to the physical phenomenon of the triboelectric effect, as shown in Figure 2b. The separating phase induces an electric current through an output load as shown in Figure 2c. The electrons will form the next potential balance condition as shown in Figure 2d. The imbalance condition occurs when pressing the TENG again and induces an electric current, moving via an external load as shown in Figure 2e. As a result, the repeated cycle of contact and separation of the two triboelectric materials produces an alternative current (AC) flow by an output load.

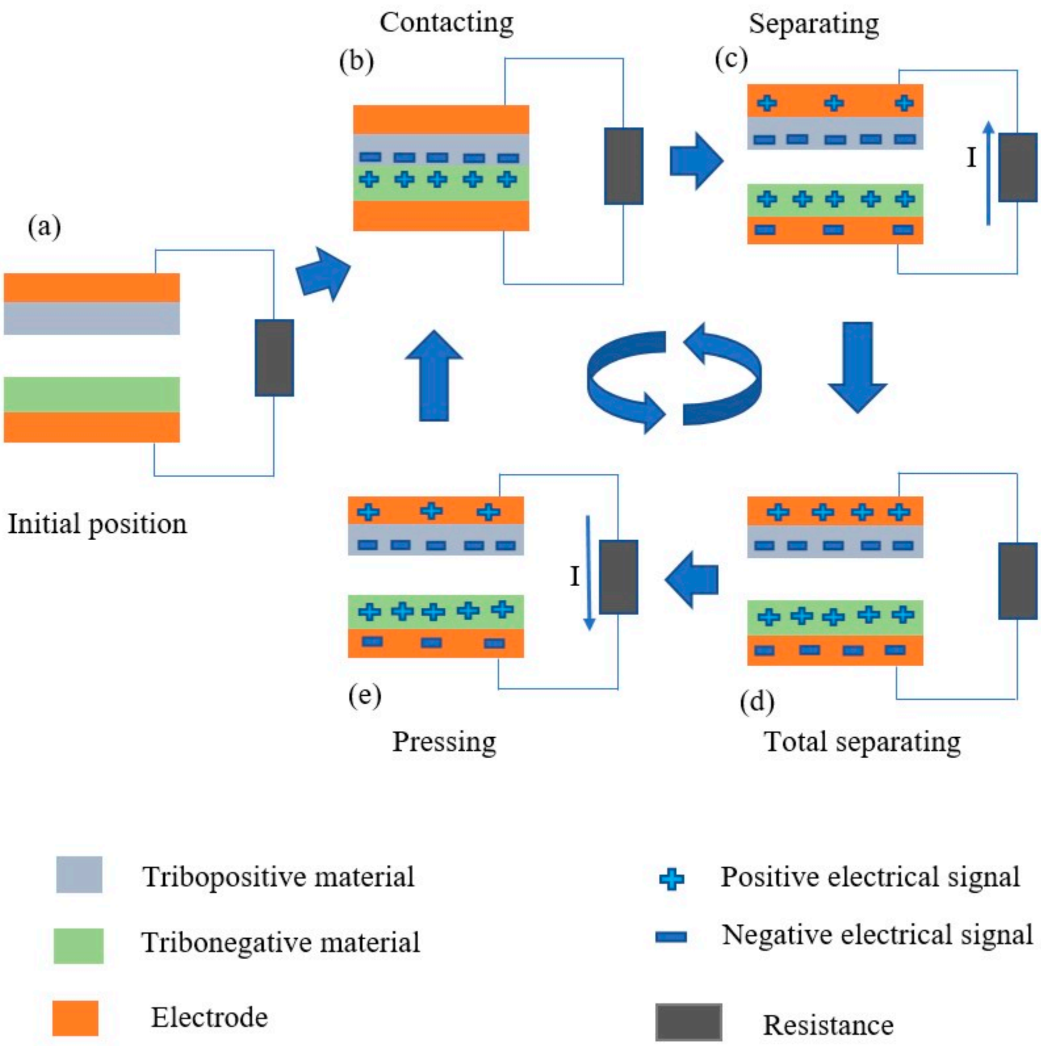

Figure 2. The detailed working mechanism diagram of a common TENG working in the vertical contacting–separating mode: (**a**) initial position condition without electricity induced in the dielectric materials; (**b**) the contacting stage in which the tribo-negative material receives electrons via donation from the tribo-positive material; (**c**) the separating stage that produces an electric current through an output load; (**d**) the total separating state that forms the next potential balanced condition; (**e**) the pressing state that induces an electric current, moving via an external load.

2.2. Triboelectric Materials

Triboelectric materials are very important in the production process of electricity during the working cycle of TENGs via the triboelectric effects of a tribo-material couple. Dielectric materials are available in nature from a diverse range of sources, including metals, polymers, organic materials, and inorganic materials. Advanced tribo-materials are easy to find, low cost, environmentally friendly, and have simple fabrication characteristics. They can sustainably work in nature to harvest mechanical energy converted into electrical energy from renewable sources. In particular, these materials can act enduringly under friction conditions and even in severe environments. Thus, advanced tribo-materials with triboelectric characteristics have been attracting many researchers to develop more and more TENG models to harvest huge amounts of energy from nature. Electricity generation via TENGs can be achieved by contact–separation or sliding modes between the two triboelectric surfaces. The electrical charge density depends on the physical properties of the triboelectric material couple during the working cycle of the TENG. Figure 3 shows the triboelectric series with the electron acceptor and donor characteristics of tribo-materials. The figure shows the strong electrification behavior of tribo-materials in the triboelectric series; tribo-materials will receive or donate electrons from or to each other [38]. The triboelectric series reveals that many materials in our living environment can be used in TENGs, for example, TENGs from PTFE film and aluminum to harvest ocean energy [100], triboelectric generator devices constructed of microneedle PDMS and aluminum to harvest mechanical energy into electricity [47], TENGs fabricated by ZnO nanorods and Si micro-pillar arrays to transform wasted energy into electricity [101], and TENGs from porous Na_2CO_3 material and polydimethylsiloxane film for moving sensors [102].

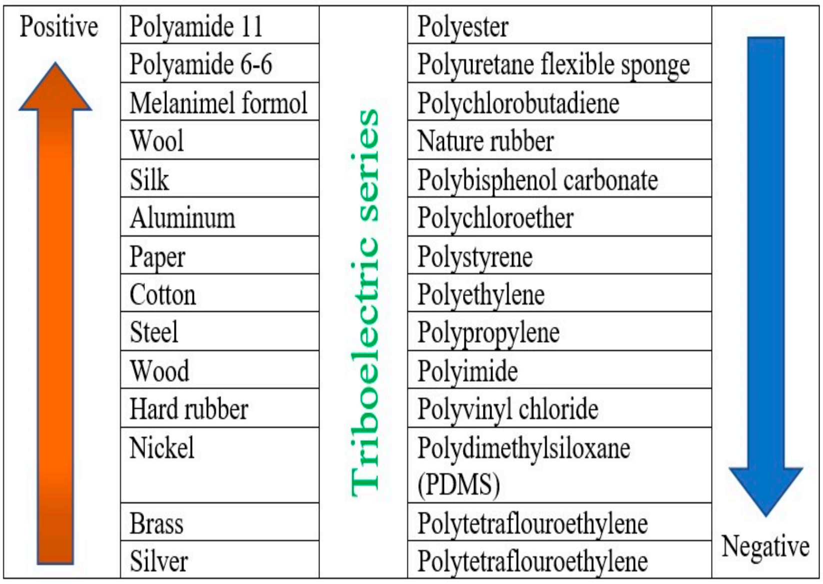

Figure 3. The triboelectric series with the positive and negative characteristics of the tribo-materials.

Besides the working mechanism, triboelectric material couples are very important in producing electrical power via their triboelectric effect by way of donor or acceptor electron particles. Metals are normally selected as the donor because of the improved electrostatic induction ability of metals such as copper and aluminum. Polymers are generally chosen to receive electrons in TENG harvesters because of the triboelectric effect of negative triboelectric materials like polymers, wood, fiber, paper, and composites [34,103]. When negative triboelectric materials are coupled with positive triboelectric materials, they form a triboelectric nanogenerator capable of harnessing substantial wasted mechanical energy and converting it into electricity for practical applications. These applications include TENGs made with aluminum and Kapton materials, which achieved an output performance of a short-circuit current of 2.8 μA and an open-circuit voltage of 40 V at a working frequency of 4 Hz [104]. Additionally, TENGs made with aluminum and polytetrafluoroethylene (PTFE) result in electric characteristics featuring a maximum open-circuit voltage of 130 V, a maximum short-circuit current of 6.6 μA, and a peak power output of 350 μW [105]. Furthermore, the development of a TENG utilizing copper particles and polytetrafluoroethylene generated an output power profile with a peak current density of about 41.4 mAm^{-3} [106]. Lastly, introducing a bimetallic hydroxide composed of nickel/copper and polytetrafluoroethylene induced electric power generation with a peak power density of about 1.3 mW/cm^2, a short-circuit current of 36.15 μA, and an open-circuit voltage of 328 V [107].

Researchers continue to seek new tribo-materials to expand the capability of harvesting wasted energy for practical applications. For instance, the combination of two triboelectric polymer films, nylon and polytetrafluoroethylene, was used to construct a TENG that exhibited impressive power characteristics, including a power density of about 5.3 Wm^{-2}, an open-circuit voltage of 1300 V, and a short-current density of about 4.1 mAm^{-2} [72]. Additionally, an msw-TENG was built using liquid metal as the positive tribo-material and silicon as the negative tribo-material, producing a power output of 15 μW, suitable for self-powered biomedical sensors [72]. Furthermore, a TENG was constructed using cellulose/nylon-PDMS/silver, resulting in an output performance featuring a power output of 352 μW, a peak open-circuit voltage of 170 V, and a short-circuit current of 0.8 μA, making it applicable for biomechanical monitoring and energy harvesting [108].

2.3. Tribo-Surface Structure

In addition to triboelectric materials, the tribo-surface structure stands out as one of the most critical factors for enhancing the output performance of TENGs. Researchers are consistently drawn to the triboelectric surface as they seek solutions to improve TENG performance. The morphology of the tribo-surface exhibits potent triboelectric characteristics through its structure, pattern, and surface densities, all of which contribute to enhancing the triboelectric effect when two tribo-materials come into contact during their working cycle. Microstructure or nanostructure patterns in particular demonstrate a significant contribution to increasing TENG output performance by effectively increasing the friction and contact area during the interaction of the tribo-surfaces.

Many research groups are focused on improving the performance of TENGs by employing novel or specialized structures. These include using a microneedle structure made of PDMS material to enhance electricity generation [47], utilizing nanocomposites of polyester/Ag nanowires/graphene for TENGs [109], incorporating a graphene sheet with PDMS material to enhance the power output of TENGs [110], designing an arch-shaped TENG with micro-pyramid PDMS material to convert mechanical energy into electricity [111], utilizing a nanofiber with an electrospun ion gel for TENGs to boost output power [112], employing a micropattern fluoropolymer TENG made of polyperfluorodecyl methacrylate (FDMA) to generate electrical characteristics such as a voltage of 68 μV and a current of 6.68 A [113], producing a TENG with a textile structure of PTFE to harvest energy from all sliding directions [114], creating a hydrophobic sponge structure for TENGs to produce sustainable energy with an output performance of 0.1 mA/cm^2 in current density [115], constructing a fabric-structured TENG to achieve a maximum output performance of 3.2 W/m^2 measured in power density [116], utilizing a textile structure for TENGs to achieve a maximum power density of 38.8 mW/m^2 [117], designing TENGs with micro/nanostructures to achieve an output performance of 25.1 V measured in open-circuit voltage [118], fabricating a polypropylene nanowire array structure for TENGs to produce an output performance of 19 mA/m^2 measured in short-circuit current density [119], introducing a wrinkle structure for TENGs to generate a maximum current output of about 182 μA [120], and using a polydimethylsiloxane film with carbon nanotubes on the surface for TENGs to harvest a power output of 60 mA m^{-2} by current density unit [121]. Table 1 showcases some outstanding results achieved through the application of tribo-materials and tribo-surface structures in TENGs. The table illustrates that these TENGs were constructed using a triboelectric material couple of a metal and a polymer to induce electrification, and they employ surface structures on the tribo-surface to enhance the output performance, achieving hundreds of volts in open-circuit voltage for various applications.

In summary, the tribo-surface structure plays a pivotal role in enhancing the output performance of TENGs. For instance, introducing a hierarchical fabric material with a fiber surface enhances the TENG's output performance, yielding an electrical characteristic of 3.2 Wm^{-2} [116]. Similarly, achieving a high output performance, such as a 19 mAm^{-2} short-circuit current and a 1900 V maximum open-circuit voltage, is possible by using a TENG with a nanowire array on a polypropylene (PP) tribo-surface [119]. Furthermore, a TENG with a PDMS micro-pyramid structure resulted in an enhanced output performance, characterized by a power density of about 802.3 mWm^{-2}, a short-circuit current of 9.5 μA, and an open-circuit voltage of 275 V [122]. Additionally, a TENG with a PDMS micro-patterned structure and a nanosheet of graphene oxide yielded good electrical features, including approximately 630 V, a power density of 3 Wm^{-2}, and a current density of about 2.1 mAm^{-2} [123]. However, there are several limitations associated with applying tribo-surface enhancements to TENGs, particularly concerning fabrication technology and materials. These challenges include the use of very expensive gold film with a crumpled structure for TENGs to achieve an output performance featuring a peak current of 10.13 μA, a peak voltage of 124.6 V, and a peak power density of about 0.22 $mWcm^{-2}$ [124]. Additionally, the costly lithography technique is employed to create micropyramid structures using a silicon mold master to improve the output performance of TENGs [125]. In response to these challenges, researchers in the field of TENG technology have sought solutions to overcome the disadvantages and enhance the output performance, expand applications, and facilitate energy harvesting for various routine purposes. These efforts include using a natural leaf to mold the PDMS pattern for TENGs, resulting in an output performance of about 45 mWm^{-2} [126], employing a cost-effective cellulose material for sustainable TENGs [127]; and exploring low-cost biodegradable materials for TENG applications [128].

Table 1. Output performance characteristics of some outstanding TENGs.

Tribo-Materials	Surface Structure	Output Performance				Ref.
		Open-Circuit Voltage (V_{OC})	Short-Circuit Current (I_{SC})	Current Density	Power Density	
PDMS/Al	Microneedle	102.8 V	43.1 μA	1.5 μA/cm^2		[47]
Polyester/Silver/graphene	Nanowire	-	-	-	7 nW/cm^2	[109]
Copper/PDMS/graphene	Graphene	-	-	-	4.8 W/m^2	[110]
Al/PDMS	Micro-pyramid	22 V	9 μA	1.13 μA/cm^2		[111]
Al/Kapton-Ion gel nanofiber/Al	Nanofiber	45 V	-	49 μA/cm^2		[112]
Al/PFDMA/AL/PET	diamond-like carbon	68 V	6.68 μA			[129]
PTFE/Nylon/Ag	Textile	62.9 V				[114]
Al/PDMS	Hydrophobic sponge structure			0.1 mA/cm^2		[115]
Polyvinylidene/Fabric	carbon nanotube	125 V			3.2 W/m^2	[116]
Nylon fabric/PVC	Textile structure	136 V	2.68 μA		38.8 mW/m^2	[117]
Au/polytetrafluoroethylene (PTFE)	Micro/nano structure	25.1 V	7.3 μA	-	-	[118]
Al/PP	nanowire array	1900V	-	19 mA/m^2	-	[119]
Aluminum/PDMS	Wrinkle structure	-	182 μA	-		[120]
Aluminum/PDMS	carbon nanotubes	-	-	60 mA/m^2	-	[121]

3. Energy Storage

Energy storage (ES) is one of the most important applications of a TENG, for storing redundant or unused energy harvested from the TENG sources for long-term usage. The ES stage is also an effective method to keep electric consumption devices working in sustainable conditions under a fluctuating current. The ES is shown as a good way to stabilize the output performance of the TENG [130]. ES involves effective techniques to power small devices that use electricity output from the TENG [131]. There are many research groups that are focused on energy storage technology and methods for TENGs, such as developing theories and techniques to manage energy storage from TENGs [132], constructing an energy storage system to store output energy of TENGs and make a sustainable power source for a temperature sensor [133], optimizing the charging system of the TENG to obtain efficient energy storage [134], developing a sustainable and renewable system for the TENG for energy storage [135], using a robust TENG with a nanoarray structure to store energy [136], and designing an energy storage system to store electrical energy from the TENG with a rigid–flexible design [137]. Figure 4 shows a proposed energy storage system to store the harvested energy from a TENG. Figure 4a shows the TENG sources used to convert wasted mechanical energy. Figure 4b shows the processing unit used to process electrical signals into the desired output. The processing unit (PU) can be a power management circuit made of a rectifier bridge, an LTC-3588 linear technology chip, or a combination of a rectifier bridge and the LTC-3588 to control the balancing value of the output voltage of the TENG as it stores electricity in an energy storage medium [137]. A PU can be also applied by using a capacitor, a rectifier bridge, and inductors to form a special power management circuit to enhance the energy storage efficiency of a TENG [138]. Another example of a PU is a passive power management circuit consisting of one diode, one inductor, and a capacitor to enhance the energy storage performance of the TENG [131]. Figure 4c shows an energy storage unit used to manage and store energy from a TENG. The energy storage unit can be a capacitor or a battery used to store electricity produced from the TENG [132]. An all-solid-state Na-ion battery can be used to store energy from the TENG with a stable power output capacity [52]. A Li-ion battery is also a good choice for a flexible charging unit [139]. Following this, the TENG devices harvest renewable energy from nature for storage applications. The processing medium is a power management circuit used to control the electrical current and to direct the output power of the TENG into the storage devices. An example of a processing medium is a rectifier bridge used to effectively change alternating current into direct current before powering into capacity or storage devices. The energy storage equipment is now diverse from capacity to battery. The energy storage unit can store energy for long-term use or directly manage the current from the TENG into an electronic device for safe working conditions, evading fluctuating current through the power consumption devices.

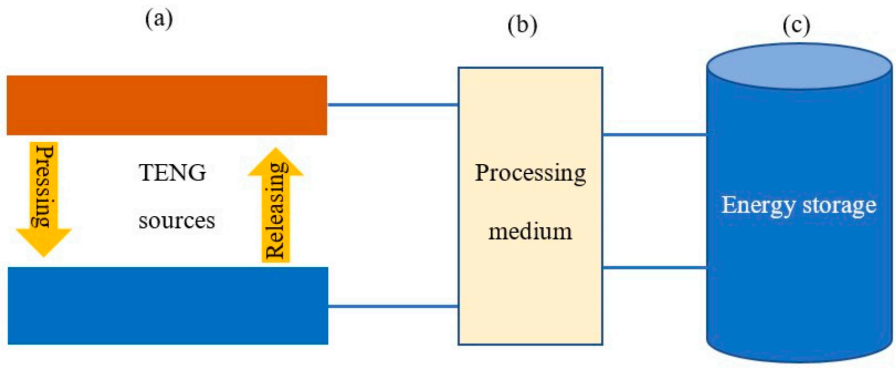

Figure 4. An energy storage system to store harvested energy from the TENG. (**a**) The TENG sources used to harvest wasted mechanical energy. (**b**) A processing unit is used to process the electrical signals into the desired output performance. (**c**) An energy storage unit is used to manage and store energy from the TENG.

TENGs have many advantages to perform the duty of energy storage such as portability, sustainable charging, self-charging of the energy storage system [60], flexible charging [140], and wearable self-charging features [141]. However, TENGs encounter certain limitations during the energy storage process, including issues such as self-discharge problems and leakage currents, which contribute to the loss of stored energy in the capacitor [142]. Recent technological advancements have been developed to address the drawbacks associated with self-discharge issues. These include the development of suppression techniques aimed at eliminating the problem of self-discharge when charging energy into storage media from the TENG [143,144].

Energy storage can be evaluated via the capacitor charging ability of the TENG. Table 2 shows some successful examples of energy storage from the charging ability of the TENGs. The table shows that the MN-PDMS TENG has an excellent charging ability, with charging characteristics of a charging voltage of 2.1 V in the charging time of about 0.56 s [47]. The table shows other charging voltages of different TENGs that are higher than that of the MN-PDMS TENG, but they require longer charging times, for example, a charging voltage of 3 V during the charging time of 117 min (3 V-117 min couple) that is exhibited by a

TENG of PTFE/PDMS with a nanoparticle structure [140], a 1.5 V–1.36 h couple is exhibited by a TENG of PPy/PTFE with a micro/nanostructure [145], a 3 V–9 s couple is exhibited by a TENG of Al/FEP with a micro/nanostructure [146], a 3 V–320 s couple is exhibited by a TENG of Al/PTFE materials [147], a 2.2 V–1 min couple is exhibited by a TENG of Nylon/PTFE with a nanostructure [148], and a 2.5 V–35 s couple is exhibited by a TENG of Al/PTFE with a nanostructure [105].

Table 2. Some examples of energy storage from the charging ability of the TENGs.

Tribo-Materials	Surface Structure	Output Performance			Refs.
		Charging Time	Charging Voltage	Energy Storage Medium	
PDMS/Al	Microneedle	0.56 s	2.1 V	Capacitor	[47]
PTFE/PDMS	Nanoparticles	117 min	3 V	Micro-supercapacitor	[140]
PPy/PTFE	Micro/nanostructure	1.36 h	1.5 V	Supercapacitor	[145]
PET/PDMS	Wrinkle structure	3 h	900 mV	Capacitor	[149]
Al/FEP	Micro/nanostructure	9 s	3 V	Capacitor	[146]
Cu/PTFE	-	90 s	1.2 V	Capacitor	[150]
Al/PTFE	-	320 s	3 V	Capacitor	[147]
Nylon/PTFE	Nanostructure	1 min	2.2 V	Capacitor	[148]
Al/PTFE	-	38 s	1.09 V	Capacitor	[151]
Al/PTFE	Nanostructure	35 s	2.5 V	Capacitor	[105]
Al/PTFE	Nanostructure	20 s	0.39 V	Capacitor	[152]

4. TENG Energy Collecting System

Figure 5 shows a proposed TENG energy collecting system (TENG-ECS) with the core unit of the TENG used to produce electricity from all daily mechanical activities. The figure shows the energy flow moving from raw mechanical energy to electrical energy for its applications. The energy collecting system includes basic components arranged in a logical diagram to harvest wasted mechanical energy. Figure 5a shows the mechanical energy sources that are the input energy for the energy converter, with many types of activities such as walking, motion, vibrations, waves, and wind. Figure 5b shows a TENG harvester that changes mechanical energy into electrical energy, with four types of working modes including single-electrode, free-standing triboelectric layer, in-plane sliding, and vertical contacting-separating modes. Figure 5c shows the power management block with the duty of directing the electricity produced from the TENG into the desired electrical source for further applications, such as changing alternating current into direct current to charge the capacitor or for loads using direct current, inverting the alternating current into an alternating current for use in the power grid or for electrical applications using an alternating current, and boosting the output voltage of the TENG by using a voltage boosting circuit. Figure 5d shows the power grid block with the duty of connecting the electricity from the TENGs to the power grids for further applications or transporting the TENG electricity over long distances. Figure 5e shows the load block that enables TENG electricity use in devices such as portable electronics, sensors, diodes, and so on. Figure 5f shows the storage block with the duty of storing the electrical energy generated from the TENG for long-term use. The energy collecting system is a harvesting–processing–storage–consumption energy system that was constructed for TENG harvesting energy systems and other energy collecting systems such as solar, hydropower, geothermal energy, biomass, wind power, and marine energy systems. The system was derived from input energy resources like motion, wind, water waves, vibration, and oscillation. These energy sources are changed into electricity by a TENG device. Subsequently, the power management unit is used to control and manage the current electrical consumption demand of the designer. The targets of the harvested energy are very diverse, including loads that use the current from the TENG, storage units used to store energy for long-term use or prevent the electrical current from fluctuating in electronic devices, and powering a power grid to transfer electricity to remote areas.

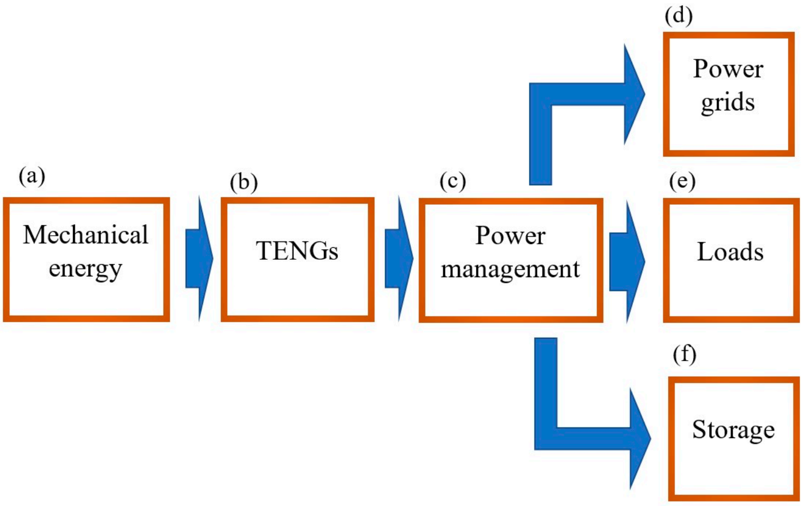

Figure 5. A TENG-based energy collecting system. (**a**) The mechanical energy sources that provide input energy for the energy converter come from many types of activities such as walking, motion, vibration, waves, and wind. (**b**) The TENG harvester changes energy from mechanical energy into electrical energy with four types of working modes, including single-electrode, free-standing triboelectric layer, in-plane sliding, and vertical contacting–separating modes. (**c**) The power management block has the duty of handling the current for electrical applications. (**d**) The power grid block has the duty of connecting the electricity from the TENGs to the power grids for further applications or supplying TENG electricity to distant areas. (**e**) The load block enabled the direct use of TENG electricity such as in portable electronics, sensors, diodes, and so on. (**f**) The storage block has the duty of storing electrical energy generated from the TENG for long-term use.

Sustainable and renewable energy conversion systems have garnered significant attention for their potential to incorporate TENGs, offering a host of outstanding characteristics that contribute to the sustainable and renewable development of our society. These encompass a wide array of applications, including the construction of a TENG-based self-powered system designed to harvest wind and water energy for electronic devices and wind speed sensors [153]. Additionally, there is a growing interest in building hybrid systems that combine photovoltaic and TENG technologies to efficiently capture both solar and mechanical energy and convert it into electrical energy [154]. Furthermore, there are efforts to fabricate active resonance TENG systems capable of collecting renewable wave energy to power the Internet of Things (IoT) in marine environments [155]. Moreover, there is ongoing work in constructing flexible corrugated TENG-based intelligent systems tailored for human-centric applications [156]. Initiatives to create TENG-based ocean energy conversion systems have gained traction, with the aim of harnessing the vast potential of ocean energy and transforming it into electricity [157]. The development of sustainable TENGs for self-powered wind sensor systems, enabling the detection of natural wind speed and direction, is also advancing [158]. Additionally, TENG-based self-powered electrochemical systems are being explored for various sustainable practical applications [159]. In parallel, efforts are underway to construct sustainable and renewable TENG-based self-powered multifunctional systems capable of efficiently converting mechanical energy into electrical energy [160].

A TENG energy collecting system offers several advantages compared to electrical energy systems, including a green electric power system [17], the ability to collect energy from diverse sources regardless the time of day, a low-capital cost, a self-power collecting mechanism, eco-friendliness [161], and applicability to self-powered biomedical systems [162]. However, TENG energy collecting systems do face certain limitations concerning electricity generation, energy storage, load driving, and integration into the power grid. These limitations include discontinuous triggers resulting from input mechanical signals and relatively low power performances [163].

There are many solutions to eliminate these limitations such as eliminating discontinuous triggers by building a hybrid energy collecting system formed by TENGs and electromagnetic and piezoelectric generators to collect many types of energy for electrical systems such as remote monitors, AI, and networks of sensors [164]. Limitations can be overcome by using large-scale power systems to boost power performance [165], constructing hybrid collecting energy systems for TENGs and solar cells to enhance the energy conversion efficiency even in rainy weather conditions [166], and developing systems of power management models to obtain stable and flexible TENG-ECSs [167].

An AC/DC inverter is one of the best solutions to boost the output performance of a TENG for applications needing high voltages, for example, an AC/DC converter was built to increase the open-circuit voltage of a TENG to 2.5 kV via a multiple voltage doubling circuit for micro plasma applications [168]; a power management circuit was constructed based on an AC/DC inverter to boost the output, increasing the output voltage up to twofold and the power output fourfold [169]; and an AC/DC voltage multiplier circuit was developed for TENGs to produce a DC high voltage for driving micro plasma sources [170]. Figure 6 shows the power management kit of a voltage-boosting circuit to produce an AC boosting voltage in three steps: with an AC/DC converter, a DC/DC boost converter, and a DC/AC inverter. The AC/DC converter changes the alternating current produced by the TENG into a direct current. The DC/DC boost converter changes the direct current produced by the AC/DC converter into a DC and increases it multiple times via several electrical components such as diodes, inductors, switches, and capacitors. The DC/AC inverter converts the direct current back to an alternating current which can later be supplied to a power grid or electrical equipment. The proposed model uses a full-wave rectifier with the feature of a smooth output waveform.

Figure 6. The power management model of a voltage-boosting circuit with three types of transformers: an AC/DC converter, a DC/DC boost converter, and a DC/AC inverter.

5. Applications

TENGs typically consist of two fundamental advanced triboelectric materials, namely a metal and a polymer, with special surface structures introduced on the polymer surface to enhance the TENGs' output performance. These surface structures encompass a variety of designs, including nanostructures [40], pyramid patterns [171], microrod morphologies [172], nanowires [173], textile structures [174], micro rhombic patterns [175], microneedle structures [47], nanowrinkle patterns [176], porous structures [83], and hybrid structures combining nanofibers and microspheres [177]. The applications of these powerful TENGs based on polymer materials and their structures span a wide range, including energy storage, transportation applications, manufacturing, portable devices, sensors, access points, monitoring devices, smart homes, power grids, lighting applications, electric consumption equipment, and human healthcare applications. TENGs can directly power electricity-consuming devices or connect to them indirectly through additional equipment. Figure 7 provides examples of TENG applications in lighting and charging. Figure 7a illustrates an electrical circuit connected to a TENG for charging, while Figure 7b demonstrates an electric circuit powered by a TENG for lighting applications. The MN-PDMS TENG, with an MN-TENG power output of 102.8 V open-circuit voltage and a short-circuit current of 43.1 μA, can charge a voltage of 2.1 V into a capacitor and illuminate 53 diode bulbs connected in series [47]. These practical examples showcase the successful application of TENGs and can serve as models for other triboelectric nanogenerator devices. Energy storage applications safeguard electricity-consuming equipment and store energy for future use. Transportation applications encompass traffic engineering, charge transportation behavior [178], self-powered sensors [179], and intelligent transportation systems [180]. Manufacturing applications promote green, renewable, and sustainable development in areas such as sustainable wastewater treatment [181], powering electrospinning systems to manufacture nanofibers [182], and monitoring the working conditions of robotics [183]. In the realm of portable devices, TENGs contribute to powering portable electronics [17], serving as portable power supplies [184] and enhancing portable mobile applications [185].

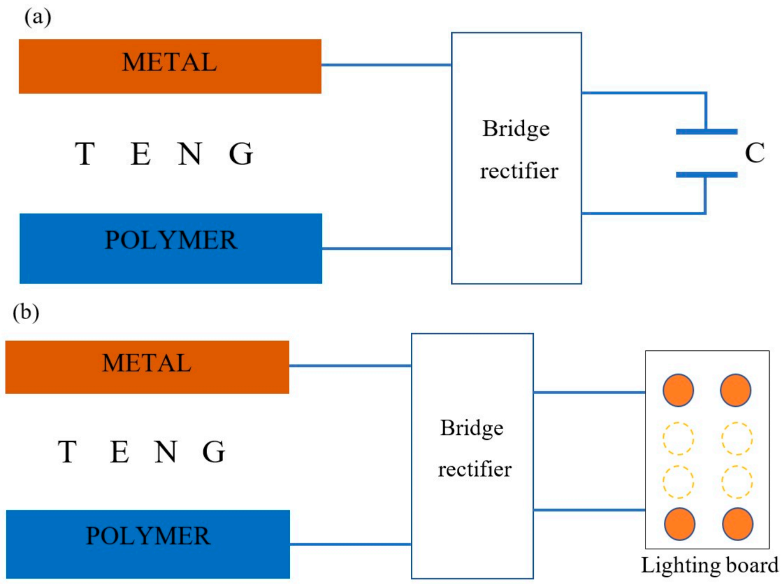

Figure 7. Some examples of TENGs in charging and lighting applications: (**a**) an electrical circuit connected to a TENG for charging applications; (**b**) an electric circuit driven by a TENG for lighting applications.

Sensors are ideal candidates for harnessing the power from TENGs due to their compact size and minimal energy requirements. Sensors exhibit excellent characteristics when powered by TENGs, leading to various practical applications such as TENGs for active sensors [186], TENGs for wave sensors in maritime engineering [187], TENGs for flexible sliding sensors in IoT applications [188], tactile sensor systems powered by TENGs to monitor pressure distribution [189], TENGs for flow sensors in automobile applications [190], self-powered sensors using TENGs for sports applications [191], and TENGs for self-powered speed sensors in traffic applications [192]. Access point applications leverage TENGs to provide power for the IoT infrastructure [193]. In industrial settings, device monitoring is a highly effective application of TENGs, including the use of pressure sensors powered by TENGs to monitor fluid status [194], employing TENGs as self-powered sensors for monitoring machinery conditions [195], and utilizing TENGs to monitor flue gas systems [196]. Furthermore, TENGs have the potential for numerous applications in our daily lives, including smart homes [197], power grids [198], lighting applications [199], electricity-consuming equipment [200], and human healthcare applications [201].

The applications of TENGs have been incredibly diverse since their inception, spanning from lighting to industrial use, from on-shore to off-shore settings, and from self-powered devices to power grid integration. TENGs have clearly demonstrated their suitability for sustainable and renewable energy applications [202,203]. Figure 8 illustrates the multitude of applications for TENGs, including biosystems, sensors, human healthcare, monitoring systems, industrial applications, self-powered systems, environmental sensors, smart homes, manufacturing systems, and therapeutic applications. TENGs find versatile application in our daily lives, such as serving as self-powered sensors for artificial intelligence applications like machine learning or IoT [204], contributing to the development of sustainable ocean monitoring systems [205], monitoring marine environments through self-powered TENG sensor systems [206], and supporting sensor applications in the chemical and biological fields [207]. TENGs play a role in various applications, from soft robotics with TENG sensors [208] to self-powered wind speed sensors [209], vibration sensors [210], and gas sensors [211], as well as applications in rescue and protection [212] and industrial monitoring systems [213]. They are also applied in therapeutic applications [214], smart fitness systems [215], the loom weaving industry [216], cooling water monitoring in industrial settings [217], medical electronic devices [218], precision medicine in cancer treatment [219], human healthcare monitoring [220], biosystems [221], smart home applications [222], and smart factories [223]. Additionally, TENGs contribute to smart grid applications [224].

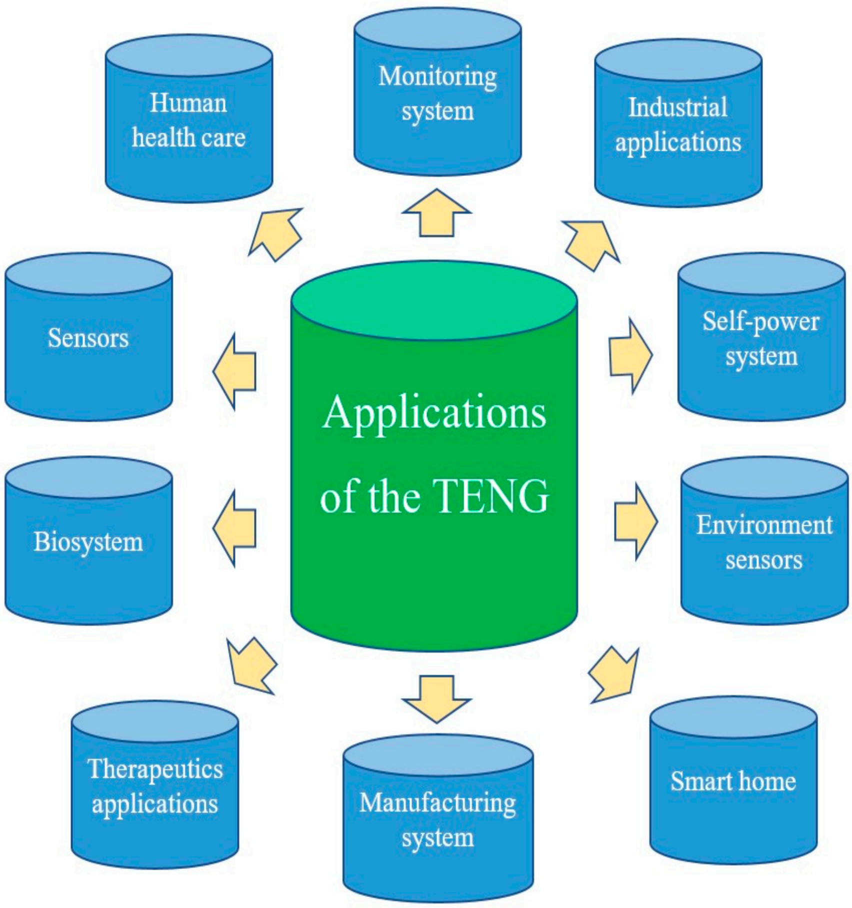

Figure 8. The numerous applications of TENGs, including biosystems, sensors, human healthcare, monitoring systems, industrial applications, self-powered systems, environment sensors, smart homes, manufacturing systems, and therapeutic applications.

TENG applications offer numerous outstanding advantages for sustainable energy development. Examples include the development of a disk-shaped TENG based on nylon and Kapton to generate sustainable output power for oil recycling work [14], the creation of a TENG as a sustainable power source for ocean monitoring systems [205], the introduction of a TENG made from fluorinated ethylene propylene and copper electrodes with the ability to sustainably harvest energy for chemical composition analyses [225], the utilization of a sustainable energy harvester from a disk TENG for self-powered mechanical sensor applications [226], and the use of a TENG with sustainable self-power for electrochemical synthesis applications [227]. Additionally, sustainable TENGs have been fabricated using cellulose materials [127], introduced into wearable electronics applications [228], developed with Cam drivers for practical and industrial applications [229], employed as sustainable power sources for biomedical microsystems [74], used for sustainable energy generation with solid–liquid contact mechanisms in practical sensor applications [230], and created with sustainable output currents using asymmetrical designs for electronic devices and energy storage applications [231].

Triboelectric nanogenerators also possess characteristics suitable for renewable energy conversion technology. Research groups have been actively involved in developing and applying TENGs for renewable energy applications, such as using a WT-TENG (a TENG-based water tube design) to harvest renewable energy [232], harnessing renewable mechanical energy for green hydrogen production with TENGs [233], converting renewable energy from the ocean through segmented TENG structures for self-powered marine applications [234], fabricating TENGs to convert renewable cellulosic energy into electrical energy for self-powered biodegradable applications [235], scavenging renewable mechanical energy for smart sensors using TENGs constructed from polymethyl methacrylate and polyvinylidene difluoride [236], developing robust TENGs to harvest renewable mechanical energy for self-powered speedometer applications [237], and utilizing renewable-energy-harvesting TENGs from ocean waves for self-powered pressure and load sensors [4].

6. Benefits, Challenges, and Solutions

TENGs are generally preferred in numerous energy harvesting devices for a wide range of applications in our daily lives. They possess outstanding characteristics such as low costs, flexibility, and the ability to harness energy from diverse wasted energy sources [202,203]. However, TENGs also come with some disadvantages, including low output performances and susceptibility to dust. Despite these limitations, TENGs have garnered significant attention from research groups seeking to overcome these challenges and improve their output performance for various energy harvesting applications [204]. The benefits of TENGs are extensive and include their sustainable energy harvesting capabilities from converting abundant wasted mechanical energy resources into electrical energy [205] and their low capital cost [238], durability [239], suitability for self-powered devices [240], robust structure [241], compact size for human healthcare applications [242], sustainability for biomedical microsystems [74], flexibility [243], sensitivity in biochemical sensor diagnostics [244], portability [245], lightweight design [246], eco-friendliness [247], green energy conversion abilities [248], multifunctionality for self-powered sensors [249], smart features [250], high material availability for fabrication, simple structure, and compatibility with a variety of trigger sources in nature [202,203]. Numerous research efforts have focused on utilizing TENGs for self-powered sensing applications. Examples include the development of a triboelectric nanogenerator for self-powered chemical sensors [251], the construction of a ring-shaped vibration TENG for vibration sensors [252], the creation of a sliding-mode TENG for self-powered security applications [253], the fabrication of a 3DWE-TENG for self-powered stretchable sensors, the construction of an SWF-TENG for self-powered stretchable sensing [254], the development of self-powered humidity sensors with structured surfaces (nanowire, nanoporous, nanotube, and monolayer) [255], the use of a garment-integrated TENG for pressure sensors [256], the construction of hybrid TENGs for self-powered sensors [257], self-powered humidity, and temperature sensors [258], the utilization of a flexible TENG based on MXene/GO composites for self-powered health monitoring [259], the construction of a C-TENG for self-powered strain sensors [260], and the production of a hybrid TENG and a piezoelectric nanogenerator for self-powered wearable sensors [261]. Numerous surveys have highlighted the advantages of TENGs, such as their potential as a blue energy source [262], their role as a renewable energy resource [263], their green energy source suitability with sustainable diagnostics for human healthcare applications [244], their clean energy source attributes with small sizes [150], their ability to offer flexibility and smart applications through materials like MXene-TENG [264], their use as a self-powered device for biomechanical energy harvesting and behavior sensing [265], their suitability for portable and flexible wearable sensing and human healthcare applications [266], their ability to provide flexible and self-charging power systems [267], their capacity for stability and selectivity in self-powered and advanced chemical sensor systems [268], their capability to enhance the energy conversion efficiency for powering LEDs and various TENG applications [269], their proficiency as an effective power resource for flexible pressure sensing and portable electronic equipment [270], their competence in harvesting energy from low-frequency acoustic waves for capacitor charging [146], their ability to sensitively detect physiological signals [146], their characteristics of sustainable and efficient energy conversion with a light weight and low capital cost [146], their ability to collect biomechanical energy for human motion and wearable applications [146], their capability to charge and store energy in capacitors or batteries [271], their outstanding features including stability, portability, high energy harvesting efficiency, and compatibility with a variety of materials [272], their specificity with a simple structure, stable electric generation, and easy fabrication [245], their capacity to harvest wasted mechanical energy from various sources such as wind, raindrops, sound, waves, and hybrid energy [273], their eco-friendly nature [274], their high-quality renewable energy source status [275], their stretchability, reliability, and safety in energy provision [276], their durability in harsh environments [277], their biodegradability and sustainability in medical treatment applications [278], and their bio-friendly characteristics and transparency features [279].

Challenges associated with triboelectric nanogenerators (TENGs) encompass several aspects, including the attachment of dust and environmental particles to the surface of triboelectric materials, discontinuous output signals resulting from intermittent input triggers, the difficulty of enhancing the output performance of the TENGs [280], issues related to low energy generation [263], technology immaturity and unreliable serviceability [221], limitations in durability [281], secure and efficient power management problems [282], the need to find practical applications [283], the difficulty of enhancement of the structure of TENG to improve energy harvesting performance [80], challenges related to miniaturization, stability, efficiency, and encapsulation [284], restrictions to low-power generation [285], biosafety concerns when applying TENGs in biosensors [286], and environmental pollution issues [287]. Many experimental studies have revealed the specific limitations of TENGs, such as the impact of environmental factors like relative humidity and air pressure on reducing TENG charge generation. For instance, it has been observed that TENG charge power increases by approximately 20% as the humidity decreases from 90% to 10% [288]. Solutions to these challenges encompass a wide array of technologies, structures, methods, techniques, mechanisms, and materials aimed at mitigating the limitations of TENGs. These solutions include the use of well-designed structural devices to mitigate the attachment of environmental dust and particles, the implementation of energy storage systems to ensure a smoother output performance [289], the utilization of nanocomposite materials to address the low output performance [290], the application of polymer materials to withstand environmental hazards such as sunlight, waves, and wind [157], the construction of hybrid energy harvesting device models and material optimization to enhance TENG energy harvesting [291], the incorporation of smart textile materials to improve the energy harvesting efficiency [292], the use of cellulose materials to enhance output performance and environmental friendliness [127], the design of advanced structures to boost TENG output performance [293], the incorporation of hybrid TENG and piezoelectric elements to increase the electrical output performance [294–296], the introduction of friction layers, biocompatible materials, and electrode layers to address biosafety concerns [286], and the use of degradable eco-friendly materials to address environmental issues [287]. Additional solutions are under development to overcome TENG deficiencies, with a focus on designing and packaging TENGs to mitigate the effects of relative humidity and air pressure on the output performance. Some efforts are also directed towards adapting low-power TENGs for applications with a low energy consumption, such as in sensing and Internet of Things devices, to bridge the gap in TENG output performance [297]. Moreover, solid–liquid tribo-interfaces are being explored to mitigate surface wear issues experienced by TENGs during operation [298]. One promising solution involves the use of recyclable polymers for TENG production. A production project roadmap using recycled polymer materials from PET bottles in Singapore and India, for instance, has the potential to produce small-scale TENG devices for the populations of both countries [299].

7. Conclusions

Triboelectric nanogenerators (TENGs) hold immense potential for sustainable and renewable energy-harvesting devices, offering several advantages including reductions in gas emissions, environmental protection, and improvements to human health. This innovative technology is capable of harnessing wasted mechanical energy from various sources such as motion, waves, wind, and vibrations, converting it into electrical energy. TENG devices operate based on the cyclic principle of contact and separation between tribo-material pairs. They find applications in a wide range of practical scenarios, including portable power sources, self-powered sensors, electricity-consuming equipment, manufacturing systems, and industrial processes. TENGs are capable of producing electrical power with hundreds of volts and hundreds of microamps, and have the ability to illuminate numerous LEDs. Moreover, TENGs can be adapted to generate power in the range of kilovolts for practical applications. This paper provides an overview of current TENG technologies, highlighting their sustainable and renewable energy generation principles, which enable the production of electricity from otherwise wasted mechanical energy sources. The mechanisms and energy conversion principles of TENGs are explained for how to enhance the output performance of the TENGs. Four working mechanisms of TENGs are theoretically described, including the single-electrode model, the free-standing triboelectric layer model, the in-plane sliding model, and the vertical contacting–separating model. Various surface structures, such as nanowires, microneedles, graphene morphology, nanofibers, micropyramids, diamond-like carbon structures, textile patterns, carbon nanotubes, hydrophobic sponge structures, hybrid micro–nano structures, wrinkle structures, and nanowire arrays, are employed to enhance the output performance of TENGs. Energy storage systems are essential for stabilizing the operation of electricity-consuming equipment and enabling long-term energy storage, remote energy supply, and power supply to portable devices. Energy harvesting systems are employed to manage and control the harvested energy from TENGs for use in electrical equipment, power grids, and energy storage applications. Sustainable and renewable energy development represents a crucial application of TENGs, offering benefits such as environmental conservation, improved human health, reduced greenhouse gas emissions, and support for sustainable development across various sectors worldwide. Current TENG technologies leverage their renewable and sustainable energy generation principles to extract power from wasted mechanical energy resources, enhance output powers through surface structuring, employ energy storage systems to stabilize electrical output, and implement energy harvesting systems for efficient energy utilization. Voltage-boosting circuits are employed to increase the TENG output performance when a high-voltage power is required. Energy storage plays a pivotal role in storing TENG-generated energy for future use, ensuring stable power output and mitigating fluctuations during electricity generation. Energy harvesting systems are crucial for maintaining the sustainability of energy systems, with effective structures for collecting wasted energy, including harvesting blocks, processing units, energy storage components, and consumption systems. The applications of renewable and sustainable energy are vast, encompassing energy storage, lighting, transportation, smart homes, sensors, power grids, manufacturing, access points, portable devices, human healthcare, monitoring devices, and electrical consumption equipment. Notably, this paper addresses the advantages, challenges, and solutions associated with TENG technology, highlighting their benefits of sustainability, flexibility, cost-effectiveness, and the ability to tap into diverse energy sources. It also acknowledges the drawbacks regarding their low resistance to dust and low output performance and outlines solutions to overcome these limitations. These solutions include the development of technologies to harness more wasted energy, the application of surface structures to enhance the output performance, the improvement of methods, mechanisms, techniques, and materials to improve the output performance, and the utilization of energy storage methods to ensure a stable power output. The results presented herein offer hope that TENG technologies will see widespread application in sustainable energy generation, renewable energy production, industry, and human well-being in the near future.

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Abbreviations

Symbol and Acronym	Definition
Gt	Gigaton
TREC	Total renewable energy capacity
GW	Gigawatt
TENG	Triboelectric nanogenerator
ES	Energy storage
ECS	Energy collecting system
IoT	Internet of Things
S-TENG	Single-electrode TENG
F-TENG	Free-standing triboelectric layer
I-TENG	In-plane sliding TENG
V-TENG	Vertical contact–separation mode TENG
V_{OC}	Open-circuit voltage
σ	Triboelectric charge density
d	Distance between the two contact surfaces
ε_0	Vacuum permittivity
ZnO	Zinc oxide
Si	Silicon
Na_2CO_3	Sodium carbonate
PDMS	Polydimethylsioxane
Ag	Silver
mA cm^{-2}	Milliampere per square centimeter
W/m^2	Watt per square meter

mW/m^2	Milliwatt per square meter
V	Voltage
μA	Microampere
I_{SC}	Short-circuit current
nA	Nanoampere
AC	Alternating current
DC	Direct current
MN	Microneedle
PTFE	Polytetrafluoroethylene
FDMA	Poly-perfluorodecyl methacrylate
LIG	Laser-induced graphene
s	Second
h	Hour
min	Minute
PET	Polyethylene terephthalate
FEP	Fluorinated ethylene propylene
AI	Artificial intelligence

References

1. Shao, J.; Jiang, T.; Wang, Z. Theoretical foundations of triboelectric nanogenerators (TENGs). *Sci. China Technol. Sci.* **2020**, *63*, 1087–1109. [CrossRef]
2. Lin, L.; Chung, C.-K. PDMS Microfabrication and Design for Microfluidics and Sustainable Energy Application: Review. *Micromachines* **2021**, *12*, 1350. [CrossRef] [PubMed]
3. Yang, W.; Chen, J.; Zhu, G.; Yang, J.; Bai, P.; Su, Y.; Jing, Q.; Cao, X.; Wang, Z.L. Harvesting energy from the natural vibration of human walking. *ACS Nano* **2013**, *7*, 11317–11324. [CrossRef] [PubMed]
4. Wang, Y.; Yu, X.; Yin, M.; Wang, J.; Gao, Q.; Yu, Y.; Cheng, T.; Wang, Z.L. Gravity triboelectric nanogenerator for the steady harvesting of natural wind energy. *Nano Energy* **2021**, *82*, 105740. [CrossRef]
5. Proto, A.; Penhaker, M.; Conforto, S.; Schmid, M. Nanogenerators for Human Body Energy Harvesting. *Trends Biotechnol.* **2017**, *35*, 610–624. [CrossRef] [PubMed]
6. Rodrigues, C.R.S.; Alves, C.A.S.; Puga, J.; Pereira, A.M.; Ventura, J.O. Triboelectric driven turbine to generate electricity from the motion of water. *Nano Energy* **2016**, *30*, 379–386. [CrossRef]
7. Wen, X.; Yang, W.; Jing, Q.; Wang, Z.L. Harvesting broadband kinetic impact energy from mechanical triggering/vibration and water waves. *ACS Nano* **2014**, *8*, 7405–7412. [CrossRef]
8. Xie, Y.; Wang, S.; Lin, L.; Jing, Q.; Lin, Z.H.; Niu, S.; Wu, Z.; Wang, Z.L. Rotary triboelectric nanogenerator based on a hybridized mechanism for harvesting wind energy. *ACS Nano* **2013**, *7*, 7119–7125. [CrossRef]
9. Yeh, M.H.; Lin, L.; Yang, P.K.; Wang, Z.L. Motion-driven electrochromic reactions for self-powered smart window system. *ACS Nano* **2015**, *9*, 4757–4765. [CrossRef]
10. Ke, K.-H.; Lin, L.; Chung, C.-K. Low-cost micro-graphite doped polydimethylsiloxane composite film for enhancement of mechanical-to-electrical energy conversion with aluminum and its application. *J. Taiwan Inst. Chem. Eng.* **2022**, *135*, 104388. [CrossRef]
11. Chen, B.; Wang, Z.L. Toward a New Era of Sustainable Energy: Advanced Triboelectric Nanogenerator for Harvesting High Entropy Energy. *Small* **2022**, *18*, 2107034. [CrossRef] [PubMed]
12. Barkas, D.A.; Psomopoulos, C.S.; Papageorgas, P.; Kalkanis, K.; Piromalis, D.; Mouratidis, A. Sustainable Energy Harvesting through Triboelectric Nano–Generators: A Review of current status and applications. *Energy Procedia* **2019**, *157*, 999–1010. [CrossRef]
13. Li, S.; Wang, J.; Peng, W.; Lin, L.; Zi, Y.; Wang, S.; Zhang, G.; Wang, Z.L. Sustainable Energy Source for Wearable Electronics Based on Multilayer Elastomeric Triboelectric Nanogenerators. *Adv. Energy Mater.* **2017**, *7*, 1602832. [CrossRef]
14. Lei, R.; Shi, Y.; Ding, Y.; Nie, J.; Li, S.; Wang, F.; Zhai, H.; Chen, X.; Wang, Z.L. Sustainable high-voltage source based on triboelectric nanogenerator with a charge accumulation strategy. *Energy Environ. Sci.* **2020**, *13*, 2178–2190. [CrossRef]
15. Liang, Q.; Zhang, Q.; Yan, X.; Liao, X.; Han, L.; Yi, F.; Ma, M.; Zhang, Y. Recyclable and Green Triboelectric Nanogenerator. *Adv. Mater.* **2017**, *29*, 1604961. [CrossRef] [PubMed]
16. Abu Nahian, S.; Cheedarala, R.K.; Ahn, K.K. A Study of sustainable green current generated by the Fluid-based Triboelectric Nanogenerator (FluTENG) with a comparison of contact and sliding mode. *Nano Energy* **2017**, *38*, 458–466. [CrossRef]
17. Zhang, Q.; Zhang, Z.; Liang, Q.; Gao, F.; Yi, F.; Ma, M.; Liao, Q.; Kang, Z.; Zhang, Y. Green hybrid power system based on triboelectric nanogenerator for wearable/portable electronics. *Nano Energy* **2019**, *55*, 151–163. [CrossRef]
18. IEA. *World Energy Outlook 2022*; License: CC BY 40 (report), CC BY NC SA 40 (Annex A); IEA.: Paris, France, 2022; Available online: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf (accessed on 19 October 2022).

19. IRENA. *Renewable Capacity Statistics 2023*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2023; Available online: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Mar/IRENA_RE_Capacity_Statistics_2023.pdf?rev=d2949151ee6a4625b65c82881403c2a7 (accessed on 19 March 2023).
20. Wu, J.; Atchike, D.W.; Ahmad, M. Crucial Adoption Factors of Renewable Energy Technology: Seeking Green Future by Promoting Biomethane. *Processes* **2023**, *11*, 2005. [CrossRef]
21. Liu, L.; Li, Y. Research on a Photovoltaic Power Prediction Model Based on an IAO-LSTM Optimization Algorithm. *Processes* **2023**, *11*, 1957. [CrossRef]
22. Roh, C. Enhancing Power Generation Stability in Oscillating-Water-Column Wave Energy Converters through Deep-Learning-Based Time Delay Compensation. *Processes* **2023**, *11*, 1787. [CrossRef]
23. Travieso-Torres, J.C.; Ricaldi-Morales, A.; Véliz-Tejo, A.; Leiva-Silva, F. Robust Cascade MRAC for a Hybrid Grid-Connected Renewable Energy System. *Processes* **2023**, *11*, 1774. [CrossRef]
24. Martinez-Barbosa, A.; Guerrero-Ramirez, G.; Calleja-Gjumlich, J.; Guerrero-Ramirez, E.; Adam-Medina, M.; Aguilar-Castillo, C.; Aguayo-Alquicira, J. Modeling and Control of an Air Conditioner Powered by PV Energy and the Grid Using a DC Microgrid. *Processes* **2023**, *11*, 1547. [CrossRef]
25. Manousakis, N.M.; Karagiannopoulos, P.S.; Tsekouras, G.J.; Kanellos, F.D. Integration of Renewable Energy and Electric Vehicles in Power Systems: A Review. *Processes* **2023**, *11*, 1544. [CrossRef]
26. Dash, D.K.; Sadhu, P.K. A Review on the Use of Active Power Filter for Grid-Connected Renewable Energy Conversion Systems. *Processes* **2023**, *11*, 1467. [CrossRef]
27. Umar, D.A.; Alkawsi, G.; Jailani, N.L.; Alomari, M.A.; Baashar, Y.; Alkahtani, A.A.; Capretz, L.F.; Tiong, S.K. Evaluating the Efficacy of Intelligent Methods for Maximum Power Point Tracking in Wind Energy Harvesting Systems. *Processes* **2023**, *11*, 1420. [CrossRef]
28. Mohammed, A. An Optimization-Based Model for A Hybrid Photovoltaic-Hydrogen Storage System for Agricultural Operations in Saudi Arabia. *Processes* **2023**, *11*, 1371. [CrossRef]
29. Dragomir, O.E.; Dragomir, F.; Păun, M.; Duca, O.; Gurgu, I.V.; Drăgoi, I.-C. Application of Neuro-Fuzzy Techniques for Energy Scheduling in Smart Grids Integrating Photovoltaic Panels. *Processes* **2023**, *11*, 1021. [CrossRef]
30. Chen, J.; Zhu, G.; Yang, W.; Jing, Q.; Bai, P.; Yang, Y.; Hou, T.-C.; Wang, Z.L. Harmonic-Resonator-Based Triboelectric Nanogenerator as a Sustainable Power Source and a Self-Powered Active Vibration Sensor. *Adv. Mater.* **2013**, *25*, 6094–6099. [CrossRef]
31. Park, M.; Cho, S.; Yun, Y.; La, M.; Park, S.J.; Choi, D. A highly sensitive magnetic configuration-based triboelectric nanogenerator for multidirectional vibration energy harvesting and self-powered environmental monitoring. *Int. J. Energy Res.* **2021**, *45*, 18262–18274. [CrossRef]
32. Yoon, H.-J.; Ryu, H.; Kim, S.-W. Sustainable powering triboelectric nanogenerators: Approaches and the path towards efficient use. *Nano Energy* **2018**, *51*, 270–285. [CrossRef]
33. Khandelwal, G.; Maria Joseph Raj, N.P.; Kim, S.-J. Materials Beyond Conventional Triboelectric Series for Fabrication and Applications of Triboelectric Nanogenerators. *Adv. Energy Mater.* **2021**, *11*, 2101170. [CrossRef]
34. Zhang, R.; Olin, H. Material choices for triboelectric nanogenerators: A critical review. *EcoMat* **2020**, *2*, e12062. [CrossRef]
35. Chen, A.; Zhang, C.; Zhu, G.; Wang, Z.L. Polymer Materials for High-Performance Triboelectric Nanogenerators. *Adv. Sci.* **2020**, *7*, 2000186. [CrossRef] [PubMed]
36. Zhao, Z.; Zhou, L.; Li, S.; Liu, D.; Li, Y.; Gao, Y.; Liu, Y.; Dai, Y.; Wang, J.; Wang, Z.L. Selection rules of triboelectric materials for direct-current triboelectric nanogenerator. *Nat. Commun.* **2021**, *12*, 4686. [CrossRef] [PubMed]
37. Si, J.; Duan, R.; Zhang, M.; Liu, X. Recent Progress Regarding Materials and Structures of Triboelectric Nanogenerators for AR and VR. *Nanomaterials* **2022**, *12*, 1385. [CrossRef] [PubMed]
38. Zou, H.; Zhang, Y.; Guo, L.; Wang, P.; He, X.; Dai, G.; Zheng, H.; Chen, C.; Wang, A.C.; Xu, C.; et al. Quantifying the triboelectric series. *Nat. Commun.* **2019**, *10*, 1427. [CrossRef]
39. Tcho, I.-W.; Kim, W.-G.; Jeon, S.-B.; Park, S.-J.; Lee, B.J.; Bae, H.-K.; Kim, D.; Choi, Y.-K. Surface structural analysis of a friction layer for a triboelectric nanogenerator. *Nano Energy* **2017**, *42*, 34–42. [CrossRef]
40. Zou, Y.; Xu, J.; Chen, K.; Chen, J. Advances in Nanostructures for High-Performance Triboelectric Nanogenerators. *Adv. Mater. Technol.* **2021**, *6*, 2000916. [CrossRef]
41. Kim, D.; Jeon, S.-B.; Kim, J.Y.; Seol, M.-L.; Kim, S.O.; Choi, Y.-K. High-performance nanopattern triboelectric generator by block copolymer lithography. *Nano Energy* **2015**, *12*, 331–338. [CrossRef]
42. Park, J.; Cho, H.; Lee, Y.-S. Enhancing the Triboelectric Nanogenerator Output by Micro Plasma Generation in a Micro-Cracked Surface Structure. *Appl. Sci.* **2021**, *11*, 4262. [CrossRef]
43. Chung, C.K.; Ke, K.H. High contact surface area enhanced Al/PDMS triboelectric nanogenerator using novel overlapped microneedle arrays and its application to lighting and self-powered devices. *Appl. Surf. Sci.* **2020**, *508*, 145310. [CrossRef]
44. Ke, K.-H.; Chung, C.-K. High-Performance Al/PDMS TENG with Novel Complex Morphology of Two-Height Microneedles Array for High-Sensitivity Force-Sensor and Self-Powered Application. *Small* **2020**, *16*, 2001209. [CrossRef]
45. Zheng, Y.; Liu, T.; Wu, J.; Xu, T.; Wang, X.; Han, X.; Cui, H.; Xu, X.; Pan, C.; Li, X. Energy Conversion Analysis of Multilayered Triboelectric Nanogenerators for Synergistic Rain and Solar Energy Harvesting. *Adv. Mater.* **2022**, *34*, 2202238. [CrossRef]

46. Trinh, V.L.; Chung, C.K. Harvesting mechanical energy, storage, and lighting using a novel PDMS based triboelectric generator with inclined wall arrays and micro-topping structure. *Appl. Energy* **2018**, *213*, 353–365. [CrossRef]
47. Trinh, V.L.; Chung, C.K. A Facile Method and Novel Mechanism Using Microneedle-Structured PDMS for Triboelectric Generator Applications. *Small* **2017**, *13*, 11. [CrossRef]
48. Xiao, X.; Zhang, X.; Wang, S.; Ouyang, H.; Chen, P.; Song, L.; Yuan, H.; Ji, Y.; Wang, P.; Li, Z.; et al. Honeycomb Structure Inspired Triboelectric Nanogenerator for Highly Effective Vibration Energy Harvesting and Self-Powered Engine Condition Monitoring. *Adv. Energy Mater.* **2019**, *9*, 1902460. [CrossRef]
49. Zhang, L.; Zhang, B.; Chen, J.; Jin, L.; Deng, W.; Tang, J.; Zhang, H.; Pan, H.; Zhu, M.; Yang, W.; et al. Lawn Structured Triboelectric Nanogenerators for Scavenging Sweeping Wind Energy on Rooftops. *Adv Mater* **2015**, *28*, 1650–1656. [CrossRef]
50. Yao, Y.; Jiang, T.; Zhang, L.; Chen, X.; Gao, Z.; Wang, Z.L. Charging System Optimization of Triboelectric Nanogenerator for Water Wave Energy Harvesting and Storage. *ACS Appl. Mater. Interfaces* **2016**, *8*, 21398–21406. [CrossRef]
51. Xia, K.; Tian, Y.; Fu, J.; Zhu, Z.; Lu, J.; Zhao, Z.; Tang, H.; Ye, Z.; Xu, Z. Transparent and stretchable high-output triboelectric nanogenerator for high-efficiency self-charging energy storage systems. *Nano Energy* **2021**, *87*, 106210. [CrossRef]
52. Hou, H.; Xu, Q.; Pang, Y.; Li, L.; Wang, J.; Zhang, C.; Sun, C. Efficient Storing Energy Harvested by Triboelectric Nanogenerators Using a Safe and Durable All-Solid-State Sodium-Ion Battery. *Adv. Sci.* **2017**, *4*, 1700072. [CrossRef]
53. Beaudin, M.; Zareipour, H.; Schellenberglabe, A.; Rosehart, W. Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy Sustain. Dev.* **2010**, *14*, 302–314. [CrossRef]
54. Díaz-González, F.; Sumper, A.; Gomis-Bellmunt, O.; Villafáfila-Robles, R. A review of energy storage technologies for wind power applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2154–2171. [CrossRef]
55. Pourebrahim, R.; Tohidi, S.; Khounjahan, H. Chapter 3-Overview of energy storage systems for wind power integration. In *Energy Storage in Energy Markets*; Mohammadi-Ivatloo, B., Mohammadpour Shotorbani, A., Anvari-Moghaddam, A., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 41–64.
56. Azzuni, A.; Breyer, C. Energy security and energy storage technologies. *Energy Procedia* **2018**, *155*, 237–258. [CrossRef]
57. Kebede, A.A.; Kalogiannis, T.; Van Mierlo, J.; Berecibar, M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112213. [CrossRef]
58. Aneke, M.; Wang, M. Energy storage technologies and real life applications—A state of the art review. *Appl. Energy* **2016**, *179*, 350–377. [CrossRef]
59. Hu, T.; Wang, H.; Harmon, W.; Bamgboje, D.; Wang, Z.L. Current Progress on Power Management Systems for Triboelectric Nanogenerators. *IEEE Trans. Power Electron.* **2022**, *37*, 9850–9864. [CrossRef]
60. Luo, J.; Wang, Z.L. Recent advances in triboelectric nanogenerator based self-charging power systems. *Energy Storage Mater.* **2019**, *23*, 617–628. [CrossRef]
61. Jin, X.; Yuan, Z.; Shi, Y.; Sun, Y.; Li, R.; Chen, J.; Wang, L.; Wu, Z.; Wang, Z.L. Triboelectric Nanogenerator Based on a Rotational Magnetic Ball for Harvesting Transmission Line Magnetic Energy. *Adv. Funct. Mater.* **2022**, *32*, 2108827. [CrossRef]
62. Wu, H.; Wang, J.; Wu, Z.; Kang, S.; Wei, X.; Wang, H.; Luo, H.; Yang, L.; Liao, R.; Wang, Z.L. Multi-Parameter Optimized Triboelectric Nanogenerator Based Self-Powered Sensor Network for Broadband Aeolian Vibration Online-Monitoring of Transmission Lines. *Adv. Energy Mater.* **2022**, *12*, 2103654. [CrossRef]
63. Tang, X.; Hou, W.; Zheng, Q.; Fang, L.; Zhu, R.; Zheng, L. Self-powered wind sensor based on triboelectric nanogenerator for detecting breeze vibration on electric transmission lines. *Nano Energy* **2022**, *99*, 107412. [CrossRef]
64. Prada, T.; Harnchana, V.; Lakhonchai, A.; Chingsungnoen, A.; Poolcharuansin, P.; Chanlek, N.; Klamchuen, A.; Thongbai, P.; Amornkitbamrung, V. Enhancement of output power density in a modified polytetrafluoroethylene surface using a sequential O_2/Ar plasma etching for triboelectric nanogenerator applications. *Nano Res.* **2022**, *15*, 272–279. [CrossRef]
65. Hatta, F.F.; Mohammad Haniff, M.A.S.; Mohamed, M.A. A review on applications of graphene in triboelectric nanogenerators. *Int. J. Energy Res.* **2022**, *46*, 544–576. [CrossRef]
66. Bhatta, T.; Sharma, S.; Shrestha, K.; Shin, Y.; Seonu, S.; Lee, S.; Kim, D.; Sharifuzzaman, M.; Rana, S.M.S.; Park, J.Y. Siloxene/PVDF Composite Nanofibrous Membrane for High-Performance Triboelectric Nanogenerator and Self-Powered Static and Dynamic Pressure Sensing Applications. *Adv. Funct. Mater.* **2022**, *32*, 2202145. [CrossRef]
67. Sun, W.; Luo, N.; Liu, Y.; Li, H.; Wang, D. A New Self-Healing Triboelectric Nanogenerator Based on Polyurethane Coating and Its Application for Self-Powered Cathodic Protection. *ACS Appl. Mater. Interfaces* **2022**, *14*, 10498–10507. [CrossRef] [PubMed]
68. He, W.; Li, S.; Bai, P.; Zhang, D.; Feng, L.; Wang, L.; Fu, X.; Cui, H.; Ji, X.; Ma, R. Multifunctional triboelectric nanogenerator based on flexible and self-healing sandwich structural film. *Nano Energy* **2022**, *96*, 107109. [CrossRef]
69. Rahman, M.T.; Rana, S.M.S.; Salauddin, M.; Zahed, M.A.; Lee, S.; Yoon, E.-S.; Park, J.Y. Silicone-incorporated nanoporous cobalt oxide and MXene nanocomposite-coated stretchable fabric for wearable triboelectric nanogenerator and self-powered sensing applications. *Nano Energy* **2022**, *100*, 107454. [CrossRef]
70. Hajra, S.; Sahu, M.; Sahu, R.; Padhan, A.M.; Alagarsamy, P.; Kim, H.-G.; Lee, H.; Oh, S.; Yamauchi, Y.; Kim, H.J. Significant effect of synthesis methodologies of metal-organic frameworks upon the additively manufactured dual-mode triboelectric nanogenerator towards self-powered applications. *Nano Energy* **2022**, *98*, 107253. [CrossRef]
71. More, Y.D.; Saurabh, S.; Mollick, S.; Singh, S.K.; Dutta, S.; Fajal, S.; Prathamshetti, A.; Shirolkar, M.M.; Panchal, S.; Wable, M.; et al. Highly Stable and End-group Tuneable Metal–Organic Framework/Polymer Composite for Superior Triboelectric Nanogenerator Application. *Adv. Mater. Interfaces* **2022**, *9*, 2201713. [CrossRef]

72. Wu, Y.; Li, Y.; Zou, Y.; Rao, W.; Gai, Y.; Xue, J.; Wu, L.; Qu, X.; Liu, Y.; Xu, G.; et al. A multi-mode triboelectric nanogenerator for energy harvesting and biomedical monitoring. *Nano Energy* **2022**, *92*, 106715. [CrossRef]
73. Yang, X.; Zhu, G.; Wang, S.; Zhang, R.; Lin, L.; Wu, W.; Wang, Z.L. A self-powered electrochromic device driven by a nanogenerator. *Energy Environ. Sci.* **2012**, *5*, 9462–9466. [CrossRef]
74. Zhang, X.S.; Han, M.D.; Wang, R.X.; Zhu, F.Y.; Li, Z.H.; Wang, W.; Zhang, H.X. Frequency-multiplication high-output triboelectric nanogenerator for sustainably powering biomedical microsystems. *Nano Lett* **2013**, *13*, 1168–1172. [CrossRef] [PubMed]
75. Chung, C.-K.; Huang, Y.-J.; Wang, T.-K.; Lo, Y.-L. Fiber-Based Triboelectric Nanogenerator for Mechanical Energy Harvesting and Its Application to a Human–Machine Interface. *Sensors* **2022**, *22*, 9632. [PubMed]
76. Li, C.; Zhu, Y.; Sun, F.; Jia, C.; Zhao, T.; Mao, Y.; Yang, H. Research Progress on Triboelectric Nanogenerator for Sports Applications. *Energies* **2022**, *15*, 5807. [CrossRef]
77. Lin, Z.; Chen, J.; Li, X.; Zhou, Z.; Meng, K.; Wei, W.; Yang, J.; Wang, Z.L. Triboelectric Nanogenerator Enabled Body Sensor Network for Self-Powered Human Heart-Rate Monitoring. *ACS Nano* **2017**, *11*, 8830–8837. [CrossRef] [PubMed]
78. Wang, Z.L.; Chen, J.; Lin, L. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy Environ. Sci.* **2015**, *8*, 2250–2282. [CrossRef]
79. Zhou, L.; Liu, D.; Wang, J.; Wang, Z.L. Triboelectric nanogenerators: Fundamental physics and potential applications. *Friction* **2020**, *8*, 481–506. [CrossRef]
80. Rahimi Sardo, F.; Rayegani, A.; Matin Nazar, A.; Balaghiinaloo, M.; Saberian, M.; Mohsan, S.A.; Alsharif, M.H.; Cho, H.-S. Recent Progress of Triboelectric Nanogenerators for Biomedical Sensors: From Design to Application. *Biosensors* **2022**, *12*, 697. [CrossRef]
81. Khandelwal, G.; Maria Joseph Raj, N.P.; Kim, S.-J. Triboelectric nanogenerator for healthcare and biomedical applications. *Nano Today* **2020**, *33*, 100882. [CrossRef]
82. Li, X.; Cao, Y.; Yu, X.; Xu, Y.; Yang, Y.; Liu, S.; Cheng, T.; Wang, Z.L. Breeze-driven triboelectric nanogenerator for wind energy harvesting and application in smart agriculture. *Appl. Energy* **2022**, *306*, 117977. [CrossRef]
83. Zhang, J.; Su, E.; Li, C.; Xu, S.; Tang, W.; Cao, L.N.Y.; Li, D.; Wang, Z.L. Enhancing Artifact Protection in Smart Transportation Monitoring Systems via a Porous Structural Triboelectric Nanogenerator. *Electronics* **2023**, *12*, 3031. [CrossRef]
84. Segkos, A.; Tsamis, C. Rotating Triboelectric Nanogenerators for Energy Harvesting and Their Applications. *Nanoenergy Adv.* **2023**, *3*, 170–219. [CrossRef]
85. Shang, Y.; Li, C.; Yu, G.; Yang, Y.; Zhao, W.; Tang, W. High Storable Power Density of Triboelectric Nanogenerator within Centimeter Size. *Materials* **2023**, *16*, 4669. [CrossRef] [PubMed]
86. Nguyen, Q.T.; Vu, D.L.; Le, C.D.; Ahn, K.K. Recent Progress in Self-Powered Sensors Based on Liquid–Solid Triboelectric Nanogenerators. *Sensors* **2023**, *23*, 5888. [CrossRef]
87. Nguyen, T.H.; Ahn, K.K. The Effect of a Magnetic Field on Solid–Liquid Contact Electrification for Streaming Flow Energy Harvesting. *Energies* **2023**, *16*, 4779. [CrossRef]
88. Guo, H.J.; Li, T.; Cao, X.T.; Xiong, J.; Jie, Y.; Willander, M.; Cao, X.; Wang, N.; Wang, Z.L. Self-Sterilized Flexible Single-Electrode Triboelectric Nanogenerator for Energy Harvesting and Dynamic Force Sensing. *Acs Nano* **2017**, *11*, 856–864. [CrossRef] [PubMed]
89. Niu, S.; Liu, Y.; Wang, S.; Lin, L.; Zhou, Y.S.; Hu, Y.; Wang, Z.L. Theoretical Investigation and Structural Optimization of Single-Electrode Triboelectric Nanogenerators. *Adv. Funct. Mater.* **2014**, *24*, 3332–3340. [CrossRef]
90. Wang, S.; Xie, Y.; Niu, S.; Lin, L.; Wang, Z.L. Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and non-contact modes. *Adv. Mater.* **2014**, *26*, 2818–2824. [CrossRef]
91. Niu, S.; Liu, Y.; Chen, X.; Wang, S.; Zhou, Y.S.; Lin, L.; Xie, Y.; Wang, Z.L. Theory of freestanding triboelectric-layer-based nanogenerators. *Nano Energy* **2015**, *12*, 760–774. [CrossRef]
92. Wang, S.; Lin, L.; Xie, Y.; Jing, Q.; Niu, S.; Wang, Z.L. Sliding-Triboelectric Nanogenerators Based on In-Plane Charge-Separation Mechanism. *Nano Lett.* **2013**, *13*, 2226–2233. [CrossRef]
93. Niu, S.M.; Wang, S.H.; Lin, L.; Liu, Y.; Zhou, Y.S.; Hu, Y.F.; Wang, Z.L. Theoretical study of contact-mode triboelectric nanogenerators as an effective power source. *Energy Environ. Sci.* **2013**, *6*, 3576–3583. [CrossRef]
94. Cui, N.; Gu, L.; Liu, J.; Bai, S.; Qiu, J.; Fu, J.; Kou, X.; Liu, H.; Qin, Y.; Wang, Z.L. High performance sound driven triboelectric nanogenerator for harvesting noise energy. *Nano Energy* **2015**, *15*, 321–328. [CrossRef]
95. Chen, F.; Wu, Y.; Ding, Z.; Xia, X.; Li, S.; Zheng, H.; Diao, C.; Yue, G.; Zi, Y. A novel triboelectric nanogenerator based on electrospun polyvinylidene fluoride nanofibers for effective acoustic energy harvesting and self-powered multifunctional sensing. *Nano Energy* **2019**, *56*, 241–251. [CrossRef]
96. Zheng, Z.; Yu, D.; Wang, B.; Guo, Y. Ultrahigh sensitive, eco-friendly, transparent triboelectric nanogenerator for monitoring human motion and vehicle movement. *Chem. Eng. J.* **2022**, *446*, 137393. [CrossRef]
97. Pu, X.J.; Guo, H.Y.; Chen, J.; Wang, X.; Xi, Y.; Hu, C.G.; Wang, Z.L. Eye motion triggered self-powered mechnosensational communication system using triboelectric nanogenerator. *Sci. Adv.* **2017**, *3*, 7. [CrossRef]
98. Rui, P.; Zhang, W.; Zhong, Y.; Wei, X.; Guo, Y.; Shi, S.; Liao, Y.; Cheng, J.; Wang, P. High-performance cylindrical pendulum shaped triboelectric nanogenerators driven by water wave energy for full-automatic and self-powered wireless hydrological monitoring system. *Nano Energy* **2020**, *74*, 104937. [CrossRef]
99. Song, W.-Z.; Qiu, H.-J.; Zhang, J.; Yu, M.; Ramakrishna, S.; Wang, Z.L.; Long, Y.-Z. Sliding mode direct current triboelectric nanogenerators. *Nano Energy* **2021**, *90*, 106531. [CrossRef]

100. Feng, L.; Liu, G.; Guo, H.; Tang, Q.; Pu, X.; Chen, J.; Wang, X.; Xi, Y.; Hu, C. Hybridized nanogenerator based on honeycomb-like three electrodes for efficient ocean wave energy harvesting. *Nano Energy* **2018**, *47*, 217–223. [CrossRef]
101. Baek, S.H.; Park, I.K. Flexible piezoelectric nanogenerators based on a transferred ZnO nanorod/Si micro-pillar array. *Nanotechnology* **2017**, *28*, 7. [CrossRef]
102. Cui, C.; Wang, X.; Yi, Z.; Yang, B.; Wang, X.; Chen, X.; Liu, J.; Yang, C. Flexible Single-Electrode Triboelectric Nanogenerator and Body Moving Sensor Based on Porous Na2CO3/Polydimethylsiloxane Film. *ACS Appl. Mater. Interfaces* **2018**, *10*, 3652–3659. [CrossRef]
103. Luo, J.; Gao, W.; Wang, Z.L. The Triboelectric Nanogenerator as an Innovative Technology toward Intelligent Sports. *Adv. Mater.* **2021**, *33*, 2004178. [CrossRef]
104. Cheedarala, R.K.; Song, J.I. Sand-polished Kapton film and aluminum as source of electron transfer triboelectric nanogenerator through vertical contact separation mode. *Int. J. Smart Nano Mater.* **2020**, *11*, 38–46. [CrossRef]
105. Phan, H.; Hoa, P.N.; Tam, H.A.; Thang, P.D.; Duc, N.H. Multi-directional triboelectric nanogenerator based on industrial Q-switched pulsed laser etched Aluminum film. *Extrem. Mech. Lett.* **2020**, *40*, 100886. [CrossRef]
106. Ouyang, R.; Huang, Y.; Ye, H.; Zhang, Z.; Xue, H. Copper particles-PTFE tube based triboelectric nanogenerator for wave energy harvesting. *Nano Energy* **2022**, *102*, 107749. [CrossRef]
107. Xia, K.; Wu, D.; Fu, J.; Hoque, N.A.; Ye, Y.; Xu, Z. A high-output triboelectric nanogenerator based on nickel–copper bimetallic hydroxide nanowrinkles for self-powered wearable electronics. *J. Mater. Chem. A* **2020**, *8*, 25995–26003. [CrossRef]
108. Hu, S.; Han, J.; Shi, Z.; Chen, K.; Xu, N.; Wang, Y.; Zheng, R.; Tao, Y.; Sun, Q.; Wang, Z.L.; et al. Biodegradable, Super-Strong, and Conductive Cellulose Macrofibers for Fabric-Based Triboelectric Nanogenerator. *Nano-Micro Lett.* **2022**, *14*, 115. [CrossRef] [PubMed]
109. Wu, C.X.; Kim, T.W.; Li, F.S.; Guo, T.L. Wearable Electricity Generators Fabricated Utilizing Transparent Electronic Textiles Based on Polyester/Ag Nanowires/Graphene Core-Shell Nanocomposites. *ACS Nano* **2016**, *10*, 6449–6457. [CrossRef] [PubMed]
110. Xia, X.N.; Chen, J.; Liu, G.L.; Javed, M.S.; Wang, X.; Hu, C.G. Aligning graphene sheets in PDMS for improving output performance of triboelectric nanogenerator. *Carbon* **2017**, *111*, 569–576. [CrossRef]
111. Xue, C.Y.; Li, J.Y.; Zhang, Q.; Zhang, Z.B.; Hai, Z.Y.; Gao, L.B.; Feng, R.T.; Tang, J.; Liu, J.; Zhang, W.D.; et al. A Novel Arch-Shape Nanogenerator Based on Piezoelectric and Triboelectric Mechanism for Mechanical Energy Harvesting. *Nanomaterials* **2015**, *5*, 36–46. [CrossRef]
112. Ye, B.U.; Kim, B.J.; Ryu, J.; Lee, J.Y.; Baik, J.M.; Hong, K. Electrospun ion gel nanofibers for flexible triboelectric nanogenerator: Electrochemical effect on output power. *Nanoscale* **2015**, *7*, 16189–16194. [CrossRef]
113. Ha, J.; Chung, J.; Kim, S.; Kim, J.H.; Shin, S.; Park, J.Y.; Lee, S.; Kim, J.-B. Transfer-printable micropatterned fluoropolymer-based triboelectric nanogenerator. *Nano Energy* **2017**, *36*, 126–133. [CrossRef]
114. Paosangthong, W.; Wagih, M.; Torah, R.; Beeby, S. Textile-based triboelectric nanogenerator with alternating positive and negative freestanding woven structure for harvesting sliding energy in all directions. *Nano Energy* **2022**, *92*, 106739. [CrossRef]
115. Lee, K.Y.; Chun, J.; Lee, J.-H.; Kim, K.N.; Kang, N.-R.; Kim, J.-Y.; Kim, M.H.; Shin, K.-S.; Gupta, M.K.; Baik, J.M.; et al. Hydrophobic Sponge Structure-Based Triboelectric Nanogenerator. *Adv. Mater.* **2014**, *26*, 5037–5042. [CrossRef] [PubMed]
116. Feng, P.-Y.; Xia, Z.; Sun, B.; Jing, X.; Li, H.; Tao, X.; Mi, H.-Y.; Liu, Y. Enhancing the Performance of Fabric-Based Triboelectric Nanogenerators by Structural and Chemical Modification. *ACS Appl. Mater. Interfaces* **2021**, *13*, 16916–16927. [CrossRef] [PubMed]
117. Paosangthong, W.; Wagih, M.; Torah, R.; Beeby, S. Textile-based triboelectric nanogenerator with alternating positive and negative freestanding grating structure. *Nano Energy* **2019**, *66*, 104148. [CrossRef]
118. Chen, H.; Wang, J.; Ning, A. Optimization of a Rolling Triboelectric Nanogenerator Based on the Nano–Micro Structure for Ocean Environmental Monitoring. *ACS Omega* **2021**, *6*, 21059–21065. [CrossRef]
119. Feng, Y.; Zheng, Y.; Ma, S.; Wang, D.; Zhou, F.; Liu, W. High output polypropylene nanowire array triboelectric nanogenerator through surface structural control and chemical modification. *Nano Energy* **2016**, *19*, 48–57. [CrossRef]
120. Cheng, X.; Meng, B.; Chen, X.; Han, M.; Chen, H.; Su, Z.; Shi, M.; Zhang, H. Single-Step Fluorocarbon Plasma Treatment-Induced Wrinkle Structure for High-Performance Triboelectric Nanogenerator. *Small* **2016**, *12*, 229–236. [CrossRef]
121. Wang, H.; Shi, M.; Zhu, K.; Su, Z.; Cheng, X.; Song, Y.; Chen, X.; Liao, Z.; Zhang, M.; Zhang, H. High performance triboelectric nanogenerators with aligned carbon nanotubes. *Nanoscale* **2016**, *8*, 18489–18494. [CrossRef]
122. Li, Z.B.; Li, H.Y.; Fan, Y.J.; Liu, L.; Chen, Y.H.; Zhang, C.; Zhu, G. Small-Sized, Lightweight, and Flexible Triboelectric Nanogenerator Enhanced by PTFE/PDMS Nanocomposite Electret. *ACS Appl. Mater. Interfaces* **2019**, *11*, 20370–20377. [CrossRef]
123. Moradi, F.; Karimzadeh, F.; Kharaziha, M. Rational micro/nano-structuring for high-performance triboelectric nanogenerator. *J. Alloy. Compd.* **2023**, *960*, 170693. [CrossRef]
124. Chen, H.; Bai, L.; Li, T.; Zhao, C.; Zhang, J.; Zhang, N.; Song, G.; Gan, Q.; Xu, Y. Wearable and robust triboelectric nanogenerator based on crumpled gold films. *Nano Energy* **2018**, *46*, 73–80. [CrossRef]
125. Dudem, B.; Kim, D.H.; Mule, A.R.; Yu, J.S. Enhanced Performance of Microarchitectured PTFE-Based Triboelectric Nanogenerator via Simple Thermal Imprinting Lithography for Self-Powered Electronics. *ACS Appl. Mater. Interfaces* **2018**, *10*, 24181–24192. [CrossRef] [PubMed]
126. Jie, Y.; Jia, X.; Zou, J.; Chen, Y.; Wang, N.; Wang, Z.L.; Cao, X. Natural Leaf Made Triboelectric Nanogenerator for Harvesting Environmental Mechanical Energy. *Adv. Energy Mater.* **2018**, *8*, 1703133. [CrossRef]

127. Zhou, J.; Wang, H.; Du, C.; Zhang, D.; Lin, H.; Chen, Y.; Xiong, J. Cellulose for Sustainable Triboelectric Nanogenerators. *Adv. Energy Sustain. Res.* **2022**, *3*, 2100161. [CrossRef]
128. Mi, Y.; Lu, Y.; Shi, Y.; Zhao, Z.; Wang, X.; Meng, J.; Cao, X.; Wang, N. Biodegradable Polymers in Triboelectric Nanogenerators. *Polymers* **2022**, *15*, 222. [CrossRef] [PubMed]
129. Zhang, L.; Cai, H.; Xu, L.; Ji, L.; Wang, D.; Zheng, Y.; Feng, Y.; Sui, X.; Guo, Y.; Guo, W.; et al. Macro-superlubric triboelectric nanogenerator based on tribovoltaic effect. *Matter* **2022**, *5*, 1532–1546. [CrossRef]
130. Zi, Y.; Wang, J.; Wang, S.; Li, S.; Wen, Z.; Guo, H.; Wang, Z.L. Effective energy storage from a triboelectric nanogenerator. *Nat. Commun.* **2016**, *7*, 10987. [CrossRef]
131. Qin, H.; Cheng, G.; Zi, Y.; Gu, G.; Zhang, B.; Shang, W.; Yang, F.; Yang, J.; Du, Z.; Wang, Z.L. High Energy Storage Efficiency Triboelectric Nanogenerators with Unidirectional Switches and Passive Power Management Circuits. *Adv. Funct. Mater.* **2018**, *28*, 1805216. [CrossRef]
132. Cheng, X.; Tang, W.; Song, Y.; Chen, H.; Zhang, H.; Wang, Z.L. Power management and effective energy storage of pulsed output from triboelectric nanogenerator. *Nano Energy* **2019**, *61*, 517–532. [CrossRef]
133. Feng, X.; Zhang, Y.; Kang, L.; Wang, L.; Duan, C.; Yin, K.; Pang, J.; Wang, K. Integrated energy storage system based on triboelectric nanogenerator in electronic devices. *Front. Chem. Sci. Eng.* **2021**, *15*, 238–250. [CrossRef]
134. Niu, S.; Liu, Y.; Zhou, Y.S.; Wang, S.; Lin, L.; Wang, Z.L. Optimization of Triboelectric Nanogenerator Charging Systems for Efficient Energy Harvesting and Storage. *IEEE Trans. Electron. Devices* **2015**, *62*, 641–647. [CrossRef]
135. Graham, S.A.; Chandrarathna, S.C.; Patnam, H.; Manchi, P.; Lee, J.-W.; Yu, J.S. Harsh environment–tolerant and robust triboelectric nanogenerators for mechanical-energy harvesting, sensing, and energy storage in a smart home. *Nano Energy* **2021**, *80*, 105547. [CrossRef]
136. Du, J.; Duan, J.; Yang, X.; Wang, Y.; Duan, Y.; Tang, Q. Charge boosting and storage by tailoring rhombus all-inorganic perovskite nanoarrays for robust triboelectric nanogenerators. *Nano Energy* **2020**, *74*, 104845. [CrossRef]
137. Xia, K.; Tang, H.; Fu, J.; Tian, Y.; Xu, Z.; Lu, J.; Zhu, Z. A high strength triboelectric nanogenerator based on rigid-flexible coupling design for energy storage system. *Nano Energy* **2020**, *67*, 104259. [CrossRef]
138. Wang, X.; Yang, Y. Effective energy storage from a hybridized electromagnetic-triboelectric nanogenerator. *Nano Energy* **2017**, *32*, 36–41. [CrossRef]
139. Wang, S.; Lin, Z.-H.; Niu, S.; Lin, L.; Xie, Y.; Pradel, K.C.; Wang, Z.L. Motion Charged Battery as Sustainable Flexible-Power-Unit. *ACS Nano* **2013**, *7*, 11263–11271. [CrossRef]
140. Luo, J.; Fan, F.R.; Jiang, T.; Wang, Z.; Tang, W.; Zhang, C.; Liu, M.; Cao, G.; Wang, Z.L. Integration of micro-supercapacitors with triboelectric nanogenerators for a flexible self-charging power unit. *Nano Res.* **2015**, *8*, 3934–3943. [CrossRef]
141. He, W.; Fu, X.; Zhang, D.; Zhang, Q.; Zhuo, K.; Yuan, Z.; Ma, R. Recent progress of flexible/wearable self-charging power units based on triboelectric nanogenerators. *Nano Energy* **2021**, *84*, 105880. [CrossRef]
142. Xiong, G.; Meng, C.; Reifenberger, R.G.; Irazoqui, P.P.; Fisher, T.S. A Review of Graphene-Based Electrochemical Microsupercapacitors. *Electroanalysis* **2014**, *26*, 30–51. [CrossRef]
143. Xia, M.; Nie, J.; Zhang, Z.; Lu, X.; Wang, Z.L. Suppressing self-discharge of supercapacitors via electrorheological effect of liquid crystals. *Nano Energy* **2018**, *47*, 43–50. [CrossRef]
144. Liu, K.; Yu, C.; Guo, W.; Ni, L.; Yu, J.; Xie, Y.; Wang, Z.; Ren, Y.; Qiu, J. Recent research advances of self-discharge in supercapacitors: Mechanisms and suppressing strategies. *J. Energy Chem.* **2021**, *58*, 94–109. [CrossRef]
145. Wang, J.; Wen, Z.; Zi, Y.; Zhou, P.; Lin, J.; Guo, H.; Xu, Y.; Wang, Z.L. All-Plastic-Materials Based Self-Charging Power System Composed of Triboelectric Nanogenerators and Supercapacitors. *Adv. Funct. Mater.* **2016**, *26*, 1070–1076. [CrossRef]
146. Xiao, X.; Liu, L.; Xi, Z.; Yu, H.; Li, W.; Wang, Q.; Zhao, C.; Huang, Y.; Xu, M. Research on an Optimized Quarter-Wavelength Resonator-Based Triboelectric Nanogenerator for Efficient Low-Frequency Acoustic Energy Harvesting. *Nanomaterials* **2023**, *13*, 1676. [CrossRef] [PubMed]
147. Yan, J.; Tang, Z.; Mei, N.; Zhang, D.; Zhong, Y.; Sheng, Y. Triboelectric Nanogenerators for Efficient Low-Frequency Ocean Wave Energy Harvesting with Swinging Boat Configuration. *Micromachines* **2023**, *14*, 748. [CrossRef] [PubMed]
148. Wang, Y.; Pham, A.T.; Tohl, D.; Tang, Y. Simulation Guided Hand-Driven Portable Triboelectric Nanogenerator: Design, Optimisation, and Evaluation. *Micromachines* **2021**, *12*, 955. [CrossRef]
149. Song, Y.; Cheng, X.; Chen, H.; Huang, J.; Chen, X.; Han, M.; Su, Z.; Meng, B.; Song, Z.; Zhang, H. Integrated self-charging power unit with flexible supercapacitor and triboelectric nanogenerator. *J. Mater. Chem. A* **2016**, *4*, 14298–14306. [CrossRef]
150. Zheng, J.; Cao, Z.; Han, C.; Wei, X.; Wang, L.; Wu, Z. A Hybrid Triboelectric-Electromagnetic Nanogenerator Based on Arm Swing Energy Harvesting. *Nanoenergy Adv.* **2023**, *3*, 126–137. [CrossRef]
151. Xia, Y.; Tian, Y.; Zhang, L.; Ma, Z.; Dai, H.; Meng, B.; Peng, Z. An Optimized Flutter-Driven Triboelectric Nanogenerator with a Low Cut-In Wind Speed. *Micromachines* **2021**, *12*, 366. [CrossRef]
152. Lee, K.; Lee, J.-w.; Kim, K.; Yoo, D.; Kim, D.S.; Hwang, W.; Song, I.; Sim, J.-Y. A Spherical Hybrid Triboelectric Nanogenerator for Enhanced Water Wave Energy Harvesting. *Micromachines* **2018**, *9*, 598. [CrossRef]
153. Xia, R.; Zhang, R.; Jie, Y.; Zhao, W.; Cao, X.; Wang, Z. Natural cotton-based triboelectric nanogenerator as a self-powered system for efficient use of water and wind energy. *Nano Energy* **2022**, *92*, 106685. [CrossRef]
154. Wu, Y.; Qu, J.; Chu, P.K.; Shin, D.-M.; Luo, Y.; Feng, S.-P. Hybrid photovoltaic-triboelectric nanogenerators for simultaneously harvesting solar and mechanical energies. *Nano Energy* **2021**, *89*, 106376. [CrossRef]

155. Zhang, C.; He, L.; Zhou, L.; Yang, O.; Yuan, W.; Wei, X.; Liu, Y.; Lu, L.; Wang, J.; Wang, Z.L. Active resonance triboelectric nanogenerator for harvesting omnidirectional water-wave energy. *Joule* **2021**, *5*, 1613–1623. [CrossRef]
156. So, M.Y.; Xu, B.; Li, Z.; Lai, C.L.; Jiang, C. Flexible corrugated triboelectric nanogenerators for efficient biomechanical energy harvesting and human motion monitoring. *Nano Energy* **2023**, *106*, 108033. [CrossRef]
157. Song, C.; Zhu, X.; Wang, M.; Yang, P.; Chen, L.; Hong, L.; Cui, W. Recent advances in ocean energy harvesting based on triboelectric nanogenerators. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102767. [CrossRef]
158. Yang, Y.; Zhu, G.; Zhang, H.; Chen, J.; Zhong, X.; Lin, Z.-H.; Su, Y.; Bai, P.; Wen, X.; Wang, Z.L. Triboelectric Nanogenerator for Harvesting Wind Energy and as Self-Powered Wind Vector Sensor System. *ACS Nano* **2013**, *7*, 9461–9468. [CrossRef]
159. Yeh, M.-H.; Guo, H.; Lin, L.; Wen, Z.; Li, Z.; Hu, C.; Wang, Z.L. Rolling Friction Enhanced Free-Standing Triboelectric Nanogenerators and their Applications in Self-Powered Electrochemical Recovery Systems. *Adv. Funct. Mater.* **2016**, *26*, 1054–1062. [CrossRef]
160. Heo, D.; Song, M.; Chung, S.-H.; Cha, K.; Kim, Y.; Chung, J.; Hwang, P.T.J.; Lee, J.; Jung, H.; Jin, Y.; et al. Inhalation-Driven Vertical Flutter Triboelectric Nanogenerator with Amplified Output as a Gas-Mask-Integrated Self-Powered Multifunctional System. *Adv. Energy Mater.* **2022**, *12*, 2201001. [CrossRef]
161. Sriphan, S.; Vittayakorn, N. Hybrid piezoelectric-triboelectric nanogenerators for flexible electronics: Recent advances and perspectives. *J. Sci. Adv. Mater. Devices* **2022**, *7*, 100461. [CrossRef]
162. Xia, X.; Liu, Q.; Zhu, Y.; Zi, Y. Recent advances of triboelectric nanogenerator based applications in biomedical systems. *EcoMat* **2020**, *2*, e12049. [CrossRef]
163. Liu, D.; Gao, Y.; Zhou, L.; Wang, J.; Wang, Z.L. Recent advances in high-performance triboelectric nanogenerators. *Nano Res.* **2023**, *16*, 11698–11717. [CrossRef]
164. Chen, X.; Ren, Z.; Han, M.; Wan, J.; Zhang, H. Hybrid energy cells based on triboelectric nanogenerator: From principle to system. *Nano Energy* **2020**, *75*, 104980. [CrossRef]
165. Ahmed, A.; Hassan, I.; El-Kady, M.F.; Radhi, A.; Jeong, C.K.; Selvaganapathy, P.R.; Zu, J.; Ren, S.; Wang, Q.; Kaner, R.B. Integrated Triboelectric Nanogenerators in the Era of the Internet of Things. *Adv. Sci.* **2019**, *6*, 1802230. [CrossRef] [PubMed]
166. Zhao, L.; Duan, J.; Liu, L.; Wang, J.; Duan, Y.; Vaillant-Roca, L.; Yang, X.; Tang, Q. Boosting power conversion efficiency by hybrid triboelectric nanogenerator/silicon tandem solar cell toward rain energy harvesting. *Nano Energy* **2021**, *82*, 105773. [CrossRef]
167. Yan, W.; Liu, Y.; Chen, P.; Cao, L.N.Y.; An, J.; Jiang, T.; Tang, W.; Chen, B.; Wang, Z.L. Flexible Film-Discharge-Switch Assisted Universal Power Management System for the Four Operation Modes of Triboelectric Nanogenerators. *Adv. Energy Mater.* **2022**, *12*, 2103677. [CrossRef]
168. Choi, S.; Cho, S.; Yun, Y.; Jang, S.; Choi, J.H.; Ra, Y.; La, M.; Park, S.J.; Choi, D. Development of a High-Performance Handheld Triboelectric Nanogenerator with a Lightweight Power Transmission Unit. *Adv. Mater. Technol.* **2020**, *5*, 2000003. [CrossRef]
169. Xu, S.; Zhang, L.; Ding, W.; Guo, H.; Wang, X.; Wang, Z.L. Self-doubled-rectification of triboelectric nanogenerator. *Nano Energy* **2019**, *66*, 104165. [CrossRef]
170. Cheng, J.; Ding, W.; Zi, Y.; Lu, Y.; Ji, L.; Liu, F.; Wu, C.; Wang, Z.L. Triboelectric microplasma powered by mechanical stimuli. *Nat. Commun.* **2018**, *9*, 3733. [CrossRef]
171. Zhang, S.; Rana, S.M.S.; Bhatta, T.; Pradhan, G.B.; Sharma, S.; Song, H.; Jeong, S.; Park, J.Y. 3D printed smart glove with pyramidal MXene/Ecoflex composite-based toroidal triboelectric nanogenerators for wearable human-machine interaction applications. *Nano Energy* **2023**, *106*, 108110. [CrossRef]
172. Zhang, L.; Su, C.; Cheng, L.; Cui, N.; Gu, L.; Qin, Y.; Yang, R.; Zhou, F. Enhancing the Performance of Textile Triboelectric Nanogenerators with Oblique Microrod Arrays for Wearable Energy Harvesting. *ACS Appl. Mater. Interfaces* **2019**, *11*, 26824–26829. [CrossRef]
173. Huang, L.-B.; Xu, W.; Tian, W.; Han, J.-C.; Zhao, C.-H.; Wu, H.-L.; Hao, J. Ultrasonic-assisted ultrafast fabrication of polymer nanowires for high performance triboelectric nanogenerators. *Nano Energy* **2020**, *71*, 104593. [CrossRef]
174. Wang, W.; Yu, A.; Liu, X.; Liu, Y.; Zhang, Y.; Zhu, Y.; Lei, Y.; Jia, M.; Zhai, J.; Wang, Z.L. Large-scale fabrication of robust textile triboelectric nanogenerators. *Nano Energy* **2020**, *71*, 104605. [CrossRef]
175. Zhang, P.; Deng, L.; Zhang, H.; He, J.; Fan, X.; Ma, Y. Enhanced Performance of Triboelectric Nanogenerator with Micro-Rhombic Patterned PDMS for Self-Powered Wearable Sensing. *Adv. Mater. Interfaces* **2022**, *9*, 2201265. [CrossRef]
176. Liu, L.; Yang, X.; Zhao, L.; Xu, W.; Wang, J.; Yang, Q.; Tang, Q. Nanowrinkle-patterned flexible woven triboelectric nanogenerator toward self-powered wearable electronics. *Nano Energy* **2020**, *73*, 104797. [CrossRef]
177. Sun, D.; Cao, R.; Wu, H.; Li, X.; Yu, H.; Guo, L. Harsh Environmental-Tolerant and High-Performance Triboelectric Nanogenerator Based on Nanofiber/Microsphere Hybrid Membranes. *Materials* **2023**, *16*, 562. [CrossRef] [PubMed]
178. He, W.; Shan, C.; Fu, S.; Wu, H.; Wang, J.; Mu, Q.; Li, G.; Hu, C. Large Harvested Energy by Self-Excited Liquid Suspension Triboelectric Nanogenerator with Optimized Charge Transportation Behavior. *Adv. Mater.* **2023**, *35*, 2209657. [CrossRef] [PubMed]
179. Matin Nazar, A.; Narazaki, Y.; Rayegani, A.; Rahimi Sardo, F. Recent progress of triboelectric nanogenerators as self-powered sensors in transportation engineering. *Measurement* **2022**, *203*, 112010. [CrossRef]
180. Cao, J.; Lin, Y.; Fu, X.; Wang, Z.; Liu, G.; Zhang, Z.; Qin, Y.; Zhou, H.; Dong, S.; Cheng, G.; et al. Self-powered overspeed wake-up alarm system based on triboelectric nanogenerators for intelligent transportation. *Nano Energy* **2023**, *107*, 108150. [CrossRef]
181. Chen, S.; Wang, N.; Ma, L.; Li, T.; Willander, M.; Jie, Y.; Cao, X.; Wang, Z.L. Triboelectric Nanogenerator for Sustainable Wastewater Treatment via a Self-Powered Electrochemical Process. *Adv. Energy Mater.* **2016**, *6*, 1501778. [CrossRef]

182. Li, C.; Yin, Y.; Wang, B.; Zhou, T.; Wang, J.; Luo, J.; Tang, W.; Cao, R.; Yuan, Z.; Li, N.; et al. Self-Powered Electrospinning System Driven by a Triboelectric Nanogenerator. *ACS Nano* **2017**, *11*, 10439–10445. [CrossRef]
183. Ji, S.; Shin, J.; Yoon, J.; Lim, K.-H.; Sim, G.-D.; Lee, Y.-S.; Kim, D.H.; Cho, H.; Park, J. Three-dimensional skin-type triboelectric nanogenerator for detection of two-axis robotic-arm collision. *Nano Energy* **2022**, *97*, 107225. [CrossRef]
184. Li, G.; Liu, G.; He, W.; Long, L.; Li, B.; Wang, Z.; Tang, Q.; Liu, W.; Hu, C. Miura folding based charge-excitation triboelectric nanogenerator for portable power supply. *Nano Res.* **2021**, *14*, 4204–4210. [CrossRef]
185. Mao, Y.; Zhu, Y.; Zhao, T.; Jia, C.; Wang, X.; Wang, Q. Portable Mobile Gait Monitor System Based on Triboelectric Nanogenerator for Monitoring Gait and Powering Electronics. *Energies* **2021**, *14*, 4996. [CrossRef]
186. Wang, S.; Lin, L.; Wang, Z.L. Triboelectric nanogenerators as self-powered active sensors. *Nano Energy* **2015**, *11*, 436–462. [CrossRef]
187. Xu, M.; Wang, S.; Zhang, S.L.; Ding, W.; Kien, P.T.; Wang, C.; Li, Z.; Pan, X.; Wang, Z.L. A highly-sensitive wave sensor based on liquid-solid interfacing triboelectric nanogenerator for smart marine equipment. *Nano Energy* **2019**, *57*, 574–580. [CrossRef]
188. Qiu, C.; Wu, F.; Shi, Q.; Lee, C.; Yuce, M.R. Sensors and Control Interface Methods Based on Triboelectric Nanogenerator in IoT Applications. *IEEE Access* **2019**, *7*, 92745–92757. [CrossRef]
189. Chang, K.-B.; Parashar, P.; Shen, L.-C.; Chen, A.-R.; Huang, Y.-T.; Pal, A.; Lim, K.-C.; Wei, P.-H.; Kao, F.-C.; Hu, J.-J.; et al. A triboelectric nanogenerator-based tactile sensor array system for monitoring pressure distribution inside prosthetic limb. *Nano Energy* **2023**, *111*, 108397. [CrossRef]
190. Zhu, D.; Guo, X.; Li, H.; Yuan, Z.; Zhang, X.; Cheng, T. Self-powered flow sensing for automobile based on triboelectric nanogenerator with magnetic field modulation mechanism. *Nano Energy* **2023**, *108*, 108233. [CrossRef]
191. Sun, F.; Zhu, Y.; Jia, C.; Zhao, T.; Chu, L.; Mao, Y. Advances in self-powered sports monitoring sensors based on triboelectric nanogenerators. *J. Energy Chem.* **2023**, *79*, 477–488. [CrossRef]
192. Gu, L.; Wang, Y.; Wang, X.; Li, S.; Wang, W.; Li, C.; Lin, C.; Li, Z.; Xu, J.; Cui, N.; et al. Waste Take-out Boxes Reused in High-Performance Triboelectric Nanogenerator for Energy Harvesting and Self-Powered Sensor. *ACS Appl. Electron. Mater.* **2023**, *5*, 2145–2155. [CrossRef]
193. Yang, Y.; Guo, X.; Zhu, M.; Sun, Z.; Zhang, Z.; He, T.; Lee, C. Triboelectric Nanogenerator Enabled Wearable Sensors and Electronics for Sustainable Internet of Things Integrated Green Earth. *Adv. Energy Mater.* **2023**, *13*, 2203040. [CrossRef]
194. Zhan, T.; Zou, H.; Zhang, H.; He, P.; Liu, Z.; Chen, J.; He, M.; Zhang, Y.; Wang, Z.L. Smart liquid-piston based triboelectric nanogenerator sensor for real-time monitoring of fluid status. *Nano Energy* **2023**, *111*, 108419. [CrossRef]
195. Luo, F.; Chen, B.; Ran, X.; Ouyang, W.; Shang, L. PEO-PDMS-based triboelectric nanogenerators as self-powered sensors for driver status monitoring. *Chem. Eng. J.* **2023**, *451*, 138961. [CrossRef]
196. Zhang, Z.; Gu, G.; Zhang, W.; Gu, G.; Shang, W.; Liu, Y.; Cheng, G.; Du, Z. Double loops power management circuit of pulsed triboelectric nanogenerator with enhanced efficiency at low operating voltage and its application in self-powered flue gas monitoring system. *Nano Energy* **2023**, *110*, 108360. [CrossRef]
197. Pandey, P.; Jung, D.-H.; Choi, G.-J.; Seo, M.-K.; Lee, S.; Kim, J.M.; Park, I.-K.; Sohn, J.I. Nafion-mediated barium titanate-polymer composite nanofibers-based triboelectric nanogenerator for self-powered smart street and home control system. *Nano Energy* **2023**, *107*, 108134. [CrossRef]
198. Hu, S.; Yuan, Z.; Li, R.; Cao, Z.; Zhou, H.; Wu, Z.; Wang, Z.L. Vibration-Driven Triboelectric Nanogenerator for Vibration Attenuation and Condition Monitoring for Transmission Lines. *Nano Lett.* **2022**, *22*, 5584–5591. [CrossRef]
199. Zhong, J.; Zhong, Q.; Fan, F.; Zhang, Y.; Wang, S.; Hu, B.; Wang, Z.L.; Zhou, J. Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs. *Nano Energy* **2013**, *2*, 491–497. [CrossRef]
200. Zhang, C.; Dai, K.; Liu, D.; Yi, F.; Wang, X.; Zhu, L.; You, Z. Ultralow Quiescent Power-Consumption Wake-Up Technology Based on the Bionic Triboelectric Nanogenerator. *Adv. Sci.* **2020**, *7*, 2000254. [CrossRef]
201. Yum, H.-Y.; Han, S.A.; Konstantinov, K.; Kim, S.-W.; Kim, J.H. Smart Triboelectric Nanogenerators toward Human-Oriented Technologies: Health Monitoring, Wound Healing, Drug Delivery. *Adv. Mater. Technol.* **2023**, *8*, 2201500. [CrossRef]
202. Chen, Y.; Zhang, Y.; Zhan, T.; Lin, Z.; Zhang, S.L.; Zou, H.; Zhang, G.; Zou, C.; Wang, Z.L. An Elastic Triboelectric Nanogenerator for Harvesting Random Mechanical Energy with Multiple Working Modes. *Adv. Mater. Technol.* **2019**, *4*, 1900075. [CrossRef]
203. Yar, A.; Kınas, Z.; Karabiber, A.; Ozen, A.; Okbaz, A.; Ozel, F. Enhanced performance of triboelectric nanogenerator based on polyamide-silver antimony sulfide nanofibers for energy harvesting. *Renew. Energy* **2021**, *179*, 1781–1792. [CrossRef]
204. Zhou, Y.; Shen, M.; Cui, X.; Shao, Y.; Li, L.; Zhang, Y. Triboelectric nanogenerator based self-powered sensor for artificial intelligence. *Nano Energy* **2021**, *84*, 105887. [CrossRef]
205. Ahn, J.; Kim, J.-S.; Jeong, Y.; Hwang, S.; Yoo, H.; Jeong, Y.; Gu, J.; Mahato, M.; Ko, J.; Jeon, S.; et al. All-Recyclable Triboelectric Nanogenerator for Sustainable Ocean Monitoring Systems. *Adv. Energy Mater.* **2022**, *12*, 2201341. [CrossRef]
206. Wang, D.; Zhang, D.; Tang, M.; Zhang, H.; Sun, T.; Yang, C.; Mao, R.; Li, K.; Wang, J. Ethylene chlorotrifluoroethylene/hydrogel-based liquid-solid triboelectric nanogenerator driven self-powered MXene-based sensor system for marine environmental monitoring. *Nano Energy* **2022**, *100*, 107509. [CrossRef]
207. Zhou, Q.; Pan, J.; Deng, S.; Xia, F.; Kim, T. Triboelectric Nanogenerator-Based Sensor Systems for Chemical or Biological Detection. *Adv. Mater.* **2021**, *33*, 2008276. [CrossRef]
208. Jin, T.; Sun, Z.; Li, L.; Zhang, Q.; Zhu, M.; Zhang, Z.; Yuan, G.; Chen, T.; Tian, Y.; Hou, X.; et al. Triboelectric nanogenerator sensors for soft robotics aiming at digital twin applications. *Nat. Commun.* **2020**, *11*, 5381. [CrossRef]

209. Zou, H.-X.; Zhao, L.-C.; Wang, Q.; Gao, Q.-H.; Yan, G.; Wei, K.-X.; Zhang, W.-M. A self-regulation strategy for triboelectric nanogenerator and self-powered wind-speed sensor. *Nano Energy* **2022**, *95*, 106990. [CrossRef]
210. Fang, L.; Zheng, Q.; Hou, W.; Zheng, L.; Li, H. A self-powered vibration sensor based on the coupling of triboelectric nanogenerator and electromagnetic generator. *Nano Energy* **2022**, *97*, 107164. [CrossRef]
211. Cai, C.; Mo, J.; Lu, Y.; Zhang, N.; Wu, Z.; Wang, S.; Nie, S. Integration of a porous wood-based triboelectric nanogenerator and gas sensor for real-time wireless food-quality assessment. *Nano Energy* **2021**, *83*, 105833. [CrossRef]
212. Niu, L.; Peng, X.; Chen, L.; Liu, Q.; Wang, T.; Dong, K.; Pan, H.; Cong, H.; Liu, G.; Jiang, G.; et al. Industrial production of bionic scales knitting fabric-based triboelectric nanogenerator for outdoor rescue and human protection. *Nano Energy* **2022**, *97*, 107168. [CrossRef]
213. Zhang, J.; Sun, Y.; Yang, J.; Jiang, T.; Tang, W.; Chen, B.; Wang, Z.L. Irregular Wind Energy Harvesting by a Turbine Vent Triboelectric Nanogenerator and Its Application in a Self-Powered On-Site Industrial Monitoring System. *ACS Appl. Mater. Interfaces* **2021**, *13*, 55136–55144. [CrossRef]
214. Xiao, X.; Chen, G.; Libanori, A.; Chen, J. Wearable Triboelectric Nanogenerators for Therapeutics. *Trends Chem.* **2021**, *3*, 279–290. [CrossRef]
215. Wu, R.; Liu, S.; Lin, Z.; Zhu, S.; Ma, L.; Wang, Z.L. Industrial Fabrication of 3D Braided Stretchable Hierarchical Interlocked Fancy-Yarn Triboelectric Nanogenerator for Self-Powered Smart Fitness System. *Adv. Energy Mater.* **2022**, *12*, 2201288. [CrossRef]
216. Feng, Z.; Yang, S.; Jia, S.; Zhang, Y.; Jiang, S.; Yu, L.; Li, R.; Song, G.; Wang, A.; Martin, T.; et al. Scalable, washable and lightweight triboelectric-energy-generating fibers by the thermal drawing process for industrial loom weaving. *Nano Energy* **2020**, *74*, 104805. [CrossRef]
217. Xuan, Z.; Wang, Z.L.; Wang, N.; Cao, X. Thermal-Driven Soft-Contact Triboelectric Nanogenerator for Energy Harvesting and Industrial Cooling Water Monitoring. *Small* **2023**, *19*, 2206269. [CrossRef]
218. Jiang, M.; Lu, Y.; Zhu, Z.; Jia, W. Advances in Smart Sensing and Medical Electronics by Self-Powered Sensors Based on Triboelectric Nanogenerators. *Micromachines* **2021**, *12*, 698. [CrossRef]
219. Chen, M.; Zhou, Y.; Lang, J.; Li, L.; Zhang, Y. Triboelectric nanogenerator and artificial intelligence to promote precision medicine for cancer. *Nano Energy* **2022**, *92*, 106783. [CrossRef]
220. Li, R.; Wei, X.; Xu, J.; Chen, J.; Li, B.; Wu, Z.; Wang, Z.L. Smart Wearable Sensors Based on Triboelectric Nanogenerator for Personal Healthcare Monitoring. *Micromachines* **2021**, *12*, 352. [CrossRef]
221. Shen, J.; Li, B.; Yang, Y.; Yang, Z.; Liu, X.; Lim, K.-C.; Chen, J.; Ji, L.; Lin, Z.-H.; Cheng, J. Application, challenge and perspective of triboelectric nanogenerator as micro-nano energy and self-powered biosystem. *Biosens. Bioelectron.* **2022**, *216*, 114595. [CrossRef]
222. Gao, L.; Hu, D.; Qi, M.; Gong, J.; Zhou, H.; Chen, X.; Chen, J.; Cai, J.; Wu, L.; Hu, N.; et al. A double-helix-structured triboelectric nanogenerator enhanced with positive charge traps for self-powered temperature sensing and smart-home control systems. *Nanoscale* **2018**, *10*, 19781–19790. [CrossRef]
223. Wang, X.; Zhu, C.; Wu, M.; Zhang, J.; Chen, P.; Chen, H.; Jia, C.; Liang, X.; Xu, M. A novel flow sensing and controlling system based on the flapping film triboelectric nanogenerator toward smart factories. *Sens. Actuators A Phys.* **2022**, *344*, 113727. [CrossRef]
224. Tong, X.; Tan, Y.; Zhang, P.; Cao, Y.; Wang, Y.; Li, X.; Ren, L.; Cheng, T. Harvesting the aeolian vibration energy of transmission lines using an omnidirectional broadband triboelectric nanogenerator in smart grids. *Sustain. Energy Fuels* **2022**, *6*, 4197–4208. [CrossRef]
225. Wang, J.; Wu, Z.; Pan, L.; Gao, R.; Zhang, B.; Yang, L.; Guo, H.; Liao, R.; Wang, Z.L. Direct-Current Rotary-Tubular Triboelectric Nanogenerators Based on Liquid-Dielectrics Contact for Sustainable Energy Harvesting and Chemical Composition Analysis. *ACS Nano* **2019**, *13*, 2587–2598. [CrossRef] [PubMed]
226. Lin, L.; Wang, S.; Niu, S.; Liu, C.; Xie, Y.; Wang, Z.L. Noncontact Free-Rotating Disk Triboelectric Nanogenerator as a Sustainable Energy Harvester and Self-Powered Mechanical Sensor. *ACS Appl. Mater. Interfaces* **2014**, *6*, 3031–3038. [CrossRef]
227. Wang, J.; Wen, Z.; Zi, Y.; Lin, L.; Wu, C.; Guo, H.; Xi, Y.; Xu, Y.; Wang, Z.L. Self-Powered Electrochemical Synthesis of Polypyrrole from the Pulsed Output of a Triboelectric Nanogenerator as a Sustainable Energy System. *Adv. Funct. Mater.* **2016**, *26*, 3542–3548. [CrossRef]
228. Chen, S.; Huang, T.; Zuo, H.; Qian, S.; Guo, Y.; Sun, L.; Lei, D.; Wu, Q.; Zhu, B.; He, C.; et al. A Single Integrated 3D-Printing Process Customizes Elastic and Sustainable Triboelectric Nanogenerators for Wearable Electronics. *Adv. Funct. Mater.* **2018**, *28*, 1805108. [CrossRef]
229. Lee, Y.; Kim, W.; Bhatia, D.; Hwang, H.J.; Lee, S.; Choi, D. Cam-based sustainable triboelectric nanogenerators with a resolution-free 3D-printed system. *Nano Energy* **2017**, *38*, 326–334. [CrossRef]
230. Cho, H.; Chung, J.; Shin, G.; Sim, J.-Y.; Kim, D.S.; Lee, S.; Hwang, W. Toward sustainable output generation of liquid–solid contact triboelectric nanogenerators: The role of hierarchical structures. *Nano Energy* **2019**, *56*, 56–64. [CrossRef]
231. Ryu, H.; Lee, J.H.; Khan, U.; Kwak, S.S.; Hinchet, R.; Kim, S.-W. Sustainable direct current powering a triboelectric nanogenerator via a novel asymmetrical design. *Energy Environ. Sci.* **2018**, *11*, 2057–2063. [CrossRef]
232. Wu, H.; Wang, Z.; Zi, Y. Multi-Mode Water-Tube-Based Triboelectric Nanogenerator Designed for Low-Frequency Energy Harvesting with Ultrahigh Volumetric Charge Density. *Adv. Energy Mater.* **2021**, *11*, 2100038. [CrossRef]
233. Ghosh, K.; Iffelsberger, C.; Konečný, M.; Vyskočil, J.; Michalička, J.; Pumera, M. Nanoarchitectonics of Triboelectric Nanogenerator for Conversion of Abundant Mechanical Energy to Green Hydrogen. *Adv. Energy Mater.* **2023**, *13*, 2203476. [CrossRef]

234. Pang, H.; Feng, Y.; An, J.; Chen, P.; Han, J.; Jiang, T.; Wang, Z.L. Segmented Swing-Structured Fur-Based Triboelectric Nanogenerator for Harvesting Blue Energy toward Marine Environmental Applications. *Adv. Funct. Mater.* **2021**, *31*, 2106398. [CrossRef]
235. Roy, S.; Ko, H.-U.; Maji, P.K.; Van Hai, L.; Kim, J. Large amplification of triboelectric property by allicin to develop high performance cellulosic triboelectric nanogenerator. *Chem. Eng. J.* **2020**, *385*, 123723. [CrossRef]
236. Varghese, H.; Chandran, A. A facile mechanical energy harvester based on spring assisted triboelectric nanogenerators. *Sustain. Energy Fuels* **2021**, *5*, 5287–5294. [CrossRef]
237. Chen, J.; Yang, J.; Guo, H.; Li, Z.; Zheng, L.; Su, Y.; Wen, Z.; Fan, X.; Wang, Z.L. Automatic Mode Transition Enabled Robust Triboelectric Nanogenerators. *ACS Nano* **2015**, *9*, 12334–12343. [CrossRef]
238. Zhu, X.; Zhang, M.; Wang, X.; Jia, C.; Zhang, Y. A Portable and Low-Cost Triboelectric Nanogenerator for Wheelchair Table Tennis Monitoring. *Electronics* **2022**, *11*, 4189. [CrossRef]
239. Lu, Z.; Xie, Z.; Zhu, Y.; Jia, C.; Zhang, Y.; Yang, J.; Zhou, J.; Sun, F.; Mao, Y. A Stable and Durable Triboelectric Nanogenerator for Speed Skating Land Training Monitoring. *Electronics* **2022**, *11*, 3717. [CrossRef]
240. Barsiwal, S.; Babu, A.; Khanapuram, U.K.; Potu, S.; Madathil, N.; Rajaboina, R.K.; Mishra, S.; Divi, H.; Kodali, P.; Nagapuri, R.; et al. ZIF-67-Metal–Organic-Framework-Based Triboelectric Nanogenerator for Self-Powered Devices. *Nanoenergy Adv.* **2022**, *2*, 291–302. [CrossRef]
241. Jiang, T.; Pang, H.; An, J.; Lu, P.; Feng, Y.; Liang, X.; Zhong, W.; Wang, Z.L. Robust Swing-Structured Triboelectric Nanogenerator for Efficient Blue Energy Harvesting. *Adv. Energy Mater.* **2020**, *10*, 2000064. [CrossRef]
242. Wang, H.; Cheng, J.; Wang, Z.; Ji, L.; Wang, Z.L. Triboelectric nanogenerators for human-health care. *Sci. Bull.* **2021**, *66*, 490–511. [CrossRef]
243. Shin, J.; Ji, S.; Cho, H.; Park, J. Highly Flexible Triboelectric Nanogenerator Using Porous Carbon Nanotube Composites. *Polymers* **2023**, *15*, 1135. [CrossRef]
244. Zhao, Z.; Mi, Y.; Lu, Y.; Zhu, Q.; Cao, X.; Wang, N. From Biochemical Sensor to Wearable Device: The Key Role of the Conductive Polymer in the Triboelectric Nanogenerator. *Biosensors* **2023**, *13*, 604. [CrossRef] [PubMed]
245. Elvira-Hernández, E.A.; Nava-Galindo, O.I.; Martínez-Lara, E.K.; Delgado-Alvarado, E.; López-Huerta, F.; De León, A.; Gallardo-Vega, C.; Herrera-May, A.L. A Portable Triboelectric Nanogenerator Based on Dehydrated Nopal Powder for Powering Electronic Devices. *Sensors* **2023**, *23*, 4195. [CrossRef] [PubMed]
246. Zhang, J.; Xu, Q.; Gan, Y.; Sun, F.; Sun, Z. A Lightweight Sensitive Triboelectric Nanogenerator Sensor for Monitoring Loop Drive Technology in Table Tennis Training. *Electronics* **2022**, *11*, 3212. [CrossRef]
247. Kim, D.E.; Park, J.; Kim, Y.T. Flexible Sandwich-Structured Foldable Triboelectric Nanogenerator Based on Paper Substrate for Eco-Friendly Electronic Devices. *Energies* **2022**, *15*, 6236. [CrossRef]
248. Zhou, J.; Lu, C.; Lan, D.; Zhang, Y.; Lin, Y.; Wan, L.; Wei, W.; Liang, Y.; Guo, D.; Liu, Y.; et al. Enhancing the Output Performance of a Triboelectric Nanogenerator Based on Modified Polyimide and Sandwich-Structured Nanocomposite Film. *Nanomaterials* **2023**, *13*, 1056. [CrossRef]
249. Du, T.; Ge, B.; Mtui, A.E.; Zhao, C.; Dong, F.; Zou, Y.; Wang, H.; Sun, P.; Xu, M. A Robust Silicone Rubber Strip-Based Triboelectric Nanogenerator for Vibration Energy Harvesting and Multi-Functional Self-Powered Sensing. *Nanomaterials* **2022**, *12*, 1248. [CrossRef]
250. Dong, K.; Peng, X.; Cheng, R.; Wang, Z.L. Smart Textile Triboelectric Nanogenerators: Prospective Strategies for Improving Electricity Output Performance. *Nanoenergy Adv.* **2022**, *2*, 133–164. [CrossRef]
251. Zhu, Q.; Cao, X.; Wang, N. Triboelectric Nanogenerators in Sustainable Chemical Sensors. *Chemosensors* **2022**, *10*, 484. [CrossRef]
252. Wang, H.; Huang, H.; Wu, C.; Liu, J. A Ring-Shaped Curved Deformable Self-Powered Vibration Sensor Applied in Drilling Conditions. *Energies* **2022**, *15*, 8268. [CrossRef]
253. Munirathinam, P.; Chandrasekhar, A. Self-Powered Triboelectric Nanogenerator for Security Applications. *Micromachines* **2023**, *14*, 592. [CrossRef]
254. Chen, L.; Wang, T.; Shen, Y.; Wang, F.; Chen, C. Stretchable Woven Fabric-Based Triboelectric Nanogenerator for Energy Harvesting and Self-Powered Sensing. *Nanomaterials* **2023**, *13*, 863. [CrossRef] [PubMed]
255. Ku, C.-A.; Chung, C.-K. Advances in Humidity Nanosensors and Their Application: Review. *Sensors* **2023**, *23*, 2328. [CrossRef]
256. Wang, S.-C.; Zhang, B.; Kang, L.; Liang, C.; Chen, D.; Liu, G.; Guo, X. Flexible and Robust Triboelectric Nanogenerators with Chemically Prepared Metal Electrodes and a Plastic Contact Interface Based on Low-Cost Pressure-Sensitive Adhesive. *Sensors* **2023**, *23*, 2021. [CrossRef] [PubMed]
257. Li, Y.; Yu, J.; Wei, Y.; Wang, Y.; Feng, Z.; Cheng, L.; Huo, Z.; Lei, Y.; Sun, Q. Recent Progress in Self-Powered Wireless Sensors and Systems Based on TENG. *Sensors* **2023**, *23*, 1329. [CrossRef] [PubMed]
258. Li, G.; Cui, J.; Liu, T.; Zheng, Y.; Hao, C.; Hao, X.; Xue, C. Triboelectric-Electromagnetic Hybrid Wind-Energy Harvester with a Low Startup Wind Speed in Urban Self-Powered Sensing. *Micromachines* **2023**, *14*, 298. [CrossRef]
259. Yang, W.; Cai, X.; Guo, S.; Wen, L.; Sun, Z.; Shang, R.; Shi, X.; Wang, J.; Chen, H.; Li, Z. A High Performance Triboelectric Nanogenerator Based on MXene/Graphene Oxide Electrode for Glucose Detection. *Materials* **2023**, *16*, 841. [CrossRef]
260. Wang, X.; Li, X.; Wang, B.; Chen, J.; Zhang, L.; Zhang, K.; He, M.; Xue, Y.; Yang, G. Preparation of Salt-Induced Ultra-Stretchable Nanocellulose Composite Hydrogel for Self-Powered Sensors. *Nanomaterials* **2023**, *13*, 157. [CrossRef]

261. Rayegani, A.; Saberian, M.; Delshad, Z.; Liang, J.; Sadiq, M.; Nazar, A.M.; Mohsan, S.A.; Khan, M.A. Recent Advances in Self-Powered Wearable Sensors Based on Piezoelectric and Triboelectric Nanogenerators. *Biosensors* **2023**, *13*, 37. [CrossRef]
262. Cheng, T.; Gao, Q.; Wang, Z.L. The Current Development and Future Outlook of Triboelectric Nanogenerators: A Survey of Literature. *Adv. Mater. Technol.* **2019**, *4*, 1800588. [CrossRef]
263. Walden, R.; Kumar, C.; Mulvihill, D.M.; Pillai, S.C. Opportunities and Challenges in Triboelectric Nanogenerator (TENG) based Sustainable Energy Generation Technologies: A Mini-Review. *Chem. Eng. J. Adv.* **2022**, *9*, 100237. [CrossRef]
264. Pabba, D.P.; Satthiyaraju, M.; Ramasdoss, A.; Sakthivel, P.; Chidhambaram, N.; Dhanabalan, S.; Abarzúa, C.V.; Morel, M.J.; Udayabhaskar, R.; Mangalaraja, R.V.; et al. MXene-Based Nanocomposites for Piezoelectric and Triboelectric Energy Harvesting Applications. *Micromachines* **2023**, *14*, 1273. [CrossRef] [PubMed]
265. Jian, G.; Yang, N.; Zhu, S.; Meng, Q.; Ouyang, C. A Mousepad Triboelectric-Piezoelectric Hybrid Nanogenerator (TPHNG) for Self-Powered Computer User Behavior Monitoring Sensors and Biomechanical Energy Harvesting. *Polymers* **2023**, *15*, 2462. [CrossRef] [PubMed]
266. Amrutha, B.; Prasad, G.; Sathiyanathan, P.; Reza, M.S.; Kim, H.; Pathak, M.; Prabu, A.A. Fabrication of CuO-NP-Doped PVDF Composites Based Electrospun Triboelectric Nanogenerators for Wearable and Biomedical Applications. *Polymers* **2023**, *15*, 2442. [CrossRef]
267. Lu, Y.; Wu, T.; Ma, Z.; Mi, Y.; Zhao, Z.; Liu, F.; Cao, X.; Wang, N. Integration of Flexible Supercapacitors with Triboelectric Nanogenerators: A Review. *Batteries* **2023**, *9*, 281. [CrossRef]
268. Zhao, Z.; Zhu, Q.; Lu, Y.; Mi, Y.; Cao, X.; Wang, N. Chemical Sensor Based on Piezoelectric/Triboelectric Nanogenerators: A Review of the Modular Design Strategy. *Chemosensors* **2023**, *11*, 304. [CrossRef]
269. Li, W.; Leng, B.; Hu, S.; Cheng, X. Improving the Output Efficiency of Triboelectric Nanogenerator by a Power Regulation Circuit. *Sensors* **2023**, *23*, 4912. [CrossRef] [PubMed]
270. Gunasekhar, R.; Sathiyanathan, P.; Reza, M.S.; Prasad, G.; Prabu, A.A.; Kim, H. Polyvinylidene Fluoride/Aromatic Hyperbranched Polyester of Third-Generation-Based Electrospun Nanofiber as a Self-Powered Triboelectric Nanogenerator for Wearable Energy Harvesting and Health Monitoring Applications. *Polymers* **2023**, *15*, 2375. [CrossRef] [PubMed]
271. Sasmal, A.; Senthilnathan, J.; Arockiarajan, A.; Yoshimura, M. Two-Dimensional Metal-Organic Framework Incorporated Highly Polar PVDF for Dielectric Energy Storage and Mechanical Energy Harvesting. *Nanomaterials* **2023**, *13*, 1098. [CrossRef] [PubMed]
272. Zhou, Y.; Zhang, J.-H.; Li, S.; Qiu, H.; Shi, Y.; Pan, L. Triboelectric Nanogenerators Based on 2D Materials: From Materials and Devices to Applications. *Micromachines* **2023**, *14*, 1043. [CrossRef]
273. Tian, J.; Chen, X.; Wang, Z.L. Environmental energy harvesting based on triboelectric nanogenerators. *Nanotechnology* **2020**, *31*, 242001. [CrossRef]
274. Jiao, P. Emerging artificial intelligence in piezoelectric and triboelectric nanogenerators. *Nano Energy* **2021**, *88*, 106227. [CrossRef]
275. Qin, Y.; Zhang, W.; Liu, Y.; Zhao, J.; Yuan, J.; Chi, M.; Meng, X.; Du, G.; Cai, C.; Wang, S.; et al. Cellulosic gel-based triboelectric nanogenerators for energy harvesting and emerging applications. *Nano Energy* **2023**, *106*, 108079. [CrossRef]
276. Dharmasena, R.D.I.G.; Silva, S.R.P. Towards optimized triboelectric nanogenerators. *Nano Energy* **2019**, *62*, 530–549. [CrossRef]
277. Khan, U.; Kim, S.-W. Triboelectric Nanogenerators for Blue Energy Harvesting. *ACS Nano* **2016**, *10*, 6429–6432. [CrossRef]
278. Zhao, Z.; Lu, Y.; Mi, Y.; Meng, J.; Wang, X.; Cao, X.; Wang, N. Adaptive Triboelectric Nanogenerators for Long-Term Self-Treatment: A Review. *Biosensors* **2022**, *12*, 1127. [CrossRef] [PubMed]
279. Zhu, G.; Peng, B.; Chen, J.; Jing, Q.; Lin Wang, Z. Triboelectric nanogenerators as a new energy technology: From fundamentals, devices, to applications. *Nano Energy* **2015**, *14*, 126–138. [CrossRef]
280. Mahmud, M.A.P.; Zolfagharian, A.; Gharaie, S.; Kaynak, A.; Farjana, S.H.; Ellis, A.V.; Chen, J.; Kouzani, A.Z. 3D-Printed Triboelectric Nanogenerators: State of the Art, Applications, and Challenges. *Adv. Energy Sustain. Res.* **2021**, *2*, 2000045. [CrossRef]
281. Paosangthong, W.; Torah, R.; Beeby, S. Recent progress on textile-based triboelectric nanogenerators. *Nano Energy* **2019**, *55*, 401–423. [CrossRef]
282. Begum, S.R.; Chandrasekhar, A. Opportunities and Challenges in Power Management Systems for Triboelectric Nanogenerators. *ACS Appl. Electron. Mater.* **2023**, *5*, 1347–1375. [CrossRef]
283. Li, J.; Long, Y.; Yang, F.; Wang, X. Respiration-driven triboelectric nanogenerators for biomedical applications. *EcoMat* **2020**, *2*, e12045. [CrossRef]
284. Parandeh, S.; Etemadi, N.; Kharaziha, M.; Chen, G.; Nashalian, A.; Xiao, X.; Chen, J. Advances in Triboelectric Nanogenerators for Self-Powered Regenerative Medicine. *Adv. Funct. Mater.* **2021**, *31*, 2105169. [CrossRef]
285. Alagumalai, A.; Mahian, O.; Vimal, K.E.K.; Yang, L.; Xiao, X.; Saeidi, S.; Zhang, P.; Saboori, T.; Wongwises, S.; Wang, Z.L.; et al. A contextual framework development toward triboelectric nanogenerator commercialization. *Nano Energy* **2022**, *101*, 107572. [CrossRef]
286. Liu, Z.; Li, H.; Shi, B.; Fan, Y.; Wang, Z.L.; Li, Z. Wearable and Implantable Triboelectric Nanogenerators. *Adv. Funct. Mater.* **2019**, *29*, 1808820. [CrossRef]
287. Chao, S.; Ouyang, H.; Jiang, D.; Fan, Y.; Li, Z. Triboelectric nanogenerator based on degradable materials. *EcoMat* **2021**, *3*, e12072. [CrossRef]
288. Nguyen, V.; Yang, R. Effect of humidity and pressure on the triboelectric nanogenerator. *Nano Energy* **2013**, *2*, 604–608. [CrossRef]

289. Trinh, V.L.; Chung, C.K. Renewable energy for SDG-7 and sustainable electrical production, integration, industrial application, and globalization: Review. *Clean. Eng. Technol.* **2023**, *15*, 100657. [CrossRef]
290. Seung, W.; Yoon, H.-J.; Kim, T.Y.; Ryu, H.; Kim, J.; Lee, J.-H.; Lee, J.H.; Kim, S.; Park, Y.K.; Park, Y.J.; et al. Boosting Power-Generating Performance of Triboelectric Nanogenerators via Artificial Control of Ferroelectric Polarization and Dielectric Properties. *Adv. Energy Mater.* **2017**, *7*, 1600988. [CrossRef]
291. Chen, B.; Yang, Y.; Wang, Z.L. Scavenging Wind Energy by Triboelectric Nanogenerators. *Adv. Energy Mater.* **2018**, *8*, 1702649. [CrossRef]
292. Dong, K.; Hu, Y.; Yang, J.; Kim, S.-W.; Hu, W.; Wang, Z.L. Smart textile triboelectric nanogenerators: Current status and perspectives. *MRS Bull.* **2021**, *46*, 512–521. [CrossRef]
293. Liu, W.; Wang, Z.; Hu, C. Advanced designs for output improvement of triboelectric nanogenerator system. *Mater. Today* **2021**, *45*, 93–119. [CrossRef]
294. Guo, Y.; Zhang, X.-S.; Wang, Y.; Gong, W.; Zhang, Q.; Wang, H.; Brugger, J. All-fiber hybrid piezoelectric-enhanced triboelectric nanogenerator for wearable gesture monitoring. *Nano Energy* **2018**, *48*, 152–160. [CrossRef]
295. Zhang, W.; Chen, X.; Zhao, J.; Wang, X.; Li, X.; Liu, T.; Luo, B.; Qin, Y.; Zhang, S.; Chi, M.; et al. Cellulose template-based triboelectric nanogenerators for self-powered sensing at high humidity. *Nano Energy* **2023**, *108*, 108196. [CrossRef]
296. Chang, A.; Uy, C.; Xiao, X.; Xiao, X.; Chen, J. Self-powered environmental monitoring via a triboelectric nanogenerator. *Nano Energy* **2022**, *98*, 107282. [CrossRef]
297. Li, M.; Lu, H.-W.; Wang, S.-W.; Li, R.-P.; Chen, J.-Y.; Chuang, W.-S.; Yang, F.-S.; Lin, Y.-F.; Chen, C.-Y.; Lai, Y.-C. Filling the gap between topological insulator nanomaterials and triboelectric nanogenerators. *Nat. Commun.* **2022**, *13*, 938. [CrossRef]
298. Xia, X.; Zhou, Z.; Shang, Y.; Yang, Y.; Zi, Y. Metallic glass-based triboelectric nanogenerators. *Nat. Commun.* **2023**, *14*, 1023. [CrossRef]
299. Lai, W.L.; Sharma, S.; Roy, S.; Maji, P.K.; Sharma, B.; Ramakrishna, S.; Goh, K.L. Roadmap to sustainable plastic waste management: A focused study on recycling PET for triboelectric nanogenerator production in Singapore and India. *Environ. Sci. Pollut. Res.* **2022**, *29*, 51234–51268. [CrossRef]