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TOPICAL REVIEW

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Topical Review

Environmental energy harvesting based on triboelectric nanogenerators

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Abstract
With the fast development of the Internet of Things, the energy supply for electronics and sensors has become a critical challenge. The triboelectric nanogenerator (TENG), which can transfer mechanical energy from the surrounding environment into electricity, has been recognized as the most promising alternative technology to remedy the shortcomings of traditional battery technology. Environmental mechanical energy widely exists in activities in nature and these environmental energy sources can enable TENGs to achieve a clean and distributed energy network, which can finally benefit the innovation of various wireless devices. In this review, TENGs targeting different environmental energy sources have been systematically summarized and analyzed. Firstly, we give a brief introduction to the basic principle and working modes of the TENG. Then, TENGs targeting different energy sources, from blowing wind and raindrops to pounding waves, noise signalling, and so on, are summarized based on their design concept and output performance. In addition, combined with other energy technologies such as solar cells, electromagnetic generators, and piezoelectric nanogenerators, the application of hybrid nanogenerators is elaborated under different scenarios. Finally, the challenges, limitations, and future research trends of environmental energy collection are outlined.

Keywords: self-powered system, self-powered sensor, environmental energy, triboelectric nanogenerator

(Some figures may appear in colour only in the online journal)

1. Introduction

With the rapid development of the Internet of Things (IoT) in the digital era, the manner of communication has been changed by the application of various portable and wireless electronic devices and sensors [1, 2]. To maintain the operation of these information networks, a huge number of intelligent electronics and sensors are needed and the energy supply for all these devices has become a critical challenge. Since the main features of these electronics and sensors are portability and miniaturization, the conventional choice is to use rechargeable energy storage devices, including chemical batteries and capacitors, to power these devices. However, with the inherent shortcomings of these energy storage devices such as limited charge times and potential safety risks, they are not fully applicable and all-weather to electronics. Moreover, battery waste also creates serious pollution problems, which is becoming increasingly serious as time goes on. Hence, a powerful and sustainable energy-harvesting technique, which can transfer various forms of energy from the surrounding environment into electricity, could be an alternative to remedy the shortcomings of traditional battery technology [3–5]. Accordingly, a series of distinct mature technologies for energy conversion have been developed to convert environmental energy into electricity, and includes electromagnetic generators (EMGs), solar cells (SCs), thermoelectric generators, biofuel cells, and so on. For a long time, ubiquitous mechanical energy has been neglected due to its small energy density, low frequency, and perceived difficulty, but it shows particular features that are worth attention like its widespread existence and easy access. Since 2012, the concept of the triboelectric nanogenerator (TENG) proposed by Wang *et al* has been recognized as the most promising technology for harvesting mechanical energy over a wide frequency range [6–8]. In recent years, the study of the TENG has been extended to different fields and many unprecedented advantages of the TENG, including low cost, lightweight, easy fabrication, and high power density, have been fully developed by researchers [6].

Environmental mechanical energy widely exists in the natural activities of the ecological cycle, ranging from blowing wind and raindrops to pounding waves, noise signals, and so on. These environmental energy sources can enable TENG-based harvesters to achieve a clean and distributed energy network [9]. These rechargeable energy nodes based on the TENG technique can enable the innovation of a wireless sensory device, which appears to be a feasible option for future information networks with extended lifetimes [10–12]. Besides, the positions of distributed energy-harvesting nodes can be self-organized into groups or adapted to unpredictable environments including areas not easily accessible for traditional energy collectors [13, 14]. Hence, the TENG as a high-power environmental energy-harvesting device opens an avenue to solving the bottleneck of power supply for versatile sensing platforms or monitoring devices that need to work autonomously in remote areas, providing a fundamental technology for a smart information network and next-generation communication technology.

In this review, TENGs targeting different environmental energy sources have been systematically summarized and analyzed. The article firstly reviews the development of the TENG on the basis of its basic principle and working modes. In the next section of the review, an in-depth introduction is provided on a fundamental comprehension of the TENG and its theoretical origins, material selection, and modification methods. Subsequently, a detailed review of recent important progress in TENGs including the representative materials and inventive structural designs is presented. Furthermore, we discuss the hybrid nanogenerator (HNG), which combines the TENG with other energy generation techniques like SCs, EMGs, and piezoelectric nanogenerators. Finally, the challenges and future research trends in the collection of environmental energy are summarized at the end of the review.

2. Overview of TENGs

2.1. Environmental energy harvesting by TENGs

As one of the most widely recognized harvesting techniques, the TENG has achieved remarkable progress in environmental energy collection with many unique advantages. Taking wind energy harvesting as an example, wind farms have generally been constructed based on electromagnetism and a turbine structure, which can create environmental noise and cause potential harm to the local ecological environment. Besides, due to the features of the equipment such as a large volume and mass, and high installation cost, a wind farm has to operate under high wind speed conditions [15, 16]. On the contrary, the TENG can solve these problems by operating well under a lightweight and weak vibration, which allows it to be applied in densely populated cities. As for water wave energy, the traditional EMG is heavy and needs to be supported by a platform while the low frequency, large area, and randomness of water wave energy greatly restricts the efficiency of traditional hydropower generation. However, by using a network of arrays of integrated TENGs to harvest water wave energy on a large scale, it is possible to establish an efficient and low-cost energy-harvesting method that can fully utilize the low-frequency energy from water waves [17]. Then, as one of the most undervalued environmental energies in our environment, raindrop energy is usually overlooked because of its small size and utilization rate. Combined with TENGs, it is possible to effectively harvest raindrop energy for different construction and working sites such as rooftops, rain gear, vehicles, and even plants. Also, as a common type of energy in nature, sonic energy has been overlooked for a long time due to its low power density and the lack of an effective harvesting technology. TENGs can continuously and steadily harvest weak and irregular low-frequency vibrations generated by sonic energy in the environment and convert this energy into electricity, which offers the opportunity to meet the energy requirements of sensor systems in infrastructure monitoring, environmental monitoring, and other applications [18]. Finally, the TENG also has many advantages in the field of hybrid energy collection, such as the combination of SCs or electromagnetism [19]. From individual to integrated, in part or in entirely, typical examples and application scenarios for TENG-based energy collection in different environments are shown in figure 1, with the same color horizontal lines representing the same energy.

2.2. Basic principle and working modes of TENGs

The theoretical basis of the TENG is Maxwell's displacement current which is introduced by the Maxwell equation:

$$\boldsymbol{J}_{\mathrm{D}} = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}}{\partial t},$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{D}$ is the electric displacement field, $\boldsymbol{P}$ is polarization field density, and the ε_0 is the material's permittivity. The existence of displacement current not

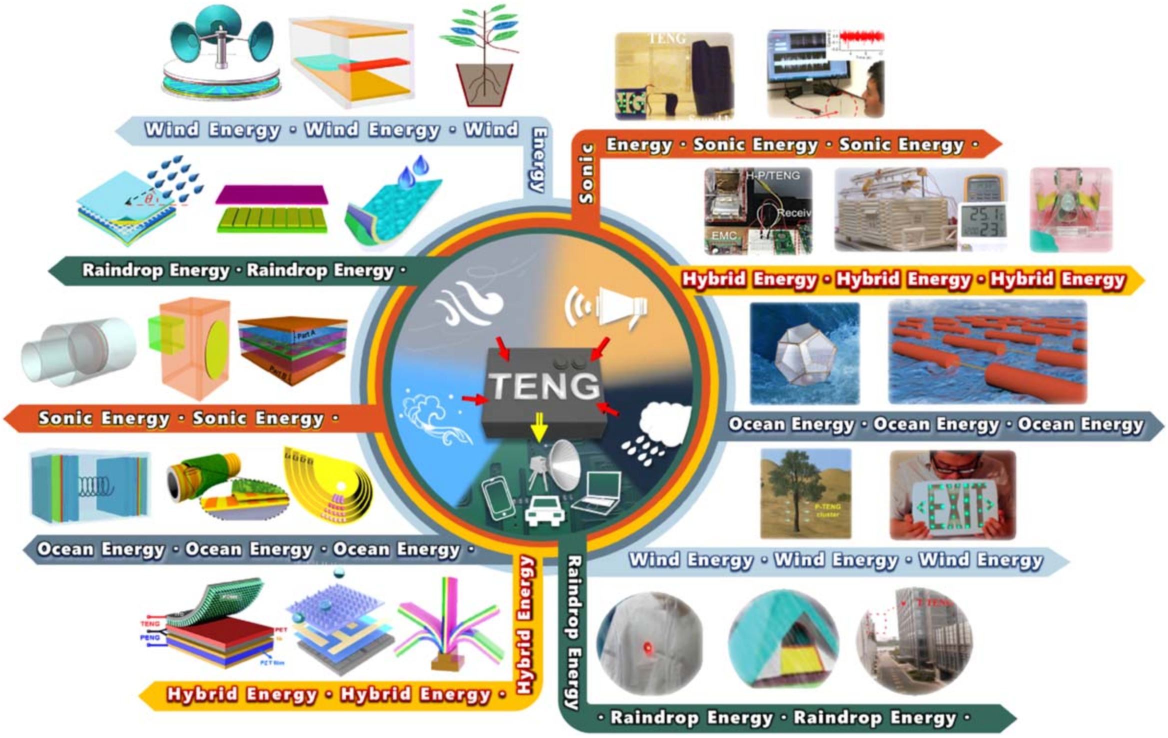

Figure 1. Classification of TENGs and applicable application scenarios from environmental energy types. (Reproduced from [16, 20–22, 23, 24, 25–27, 28, 29–31, 32, 33, 34–36, 37–41] with the permission of the American Chemical Society, Elsevier Ltd, Springer Nature, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, and the Royal Society of Chemistry).

only helps unify the electric and magnetic fields, but also illustrates that in the dielectric with surface electrostatic charges, such as piezoelectric materials and triboelectric materials, the displacement current includes the polarization density $\boldsymbol{P}_s$ that has been caused by surface electrostatic charges: $\boldsymbol{J}_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_s}{\partial t}$, the second term of the equation shows that the polarization field produced by surface electrostatic charges can cause currents, which is the fundamental foundation of TENGs [42, 43].

As a newly arisen technique in the energy collection field, the principle of the TENG has been inspired by triboelectrification existing in life. When two dielectric materials are physically in contact to generate a triboelectric charge, a potential difference is created by separating the two surfaces through mechanical movement, which can make electrons flow in the external circuit and thus balances the electrostatic system. Early on, four simple but reliable and feasible working modes were proposed, which are the vertical contact-separation mode [44, 45], the lateral-sliding mode [46–48], the single-electrode mode [49, 50], and the freestanding triboelectric-layer mode [51]. With the deepening development of research on TENGs, working modes are increasingly not limited to one of the four. According to the current energy shortage and the huge power gap, and the HNG with its adaptability and diversity has attracted widespread attention. Gradually, the boundaries between the four working modes are blurred, but the original mode can always be found in present designs.

2.3. Material selection and modification

Although triboelectrification exists in almost all materials, the selection of good materials is the first step to manufacture TENGs with excellent electrical properties, which highly rely on the difference of electronic affinity between two contact materials. The greater difference of electron affinity can lead to the higher the triboelectric charge density and the electrical contact performance of the TENG [52–54]. Moreover, in the actual selection of materials, TENG application scenarios with both physical and chemical characteristics should also be considered [55, 56]. For example, the corrosion resistance of a TENG and the influence of saltwater salinity and other factors should be considered in ocean energy collection [57, 58]. Besides, hydrophobicity, softness, electrification also are noteworthy factors that can help a TENG maintain a stable working condition in different situations. For example, silicone rubber can be used to make flexible wearable energy harvesters because of its plasticity and durability [59–61].

Based on the selection of materials, surface modification is an effective method to enhance the TENG's output performance. One of the methods to increase the triboelectric area of the material surface is to change the physical structure of the material surface microscopically, which can increase the amount of charge during triboelectrification [62]. Generally speaking, conventional methods of surface modification include, but not limited to sandpaper treatment [63], nanowire arrays [64] and so on. Besides, fluorinated surface modification [65], plasma-enhanced chemical vapor deposition films [66], spin coating and preparation of composite structures of micropores and nanoparticles can achieve the purpose of surface modification adapt to disparate materials [67, 68].

2.4. Structural design of TENGs

Generally, the structure and the composition of the TENG is a crucial factor directly influencing output, which can improve the electrostatic charge density. In the case of the contact-separation mode of a TENG for instance, Niu *et al* reported that the separation distance of two friction layers affects the output, and voltage and the speed of the motion determines the output current [69]. Furthermore, the thickness of the dielectric layer and the separation distance can also influence the performance, while an ultrathin dielectric layer and a fully separation motion can maintain a higher output. Finally, Niu and Wang established a theoretical model for the model and deduced TENG parameters, including a quantitative relationship for optimal resistance [70]. According to the theoretical model, the real-time output of a TENG can be mathematically characterized, and its relevant parameters including contact surface, effective dielectric thickness, and clearance distance can be systematically studied. In addition to designing the parameters of the friction layer, Cheng *et al* designed a mechanically triggered switch device based on a contact-separation mode. This TENG can reduce the time of charge/discharge and improve the instantaneous output signal [71]. Furthermore, a multi-layer structure is also an effective way to improve a TENG's output performance. The TENG with a multi-electrode structure designed by Cheng *et al* can increase the total charge transport volume exponentially, while working stably in a variety of modes [72].

Additionally, for the lateral-sliding TENG and the free-standing TENG, the instantaneous current can be improved by increasing the number of grating units on the triboelectric surface [73–75]. In the different resistance ranges, more energy can be produced by the grating electrode with a thinner pitch ($<108\ \Omega$). In 2014, Niu *et al* put forward the theoretical model of the freestanding TENG with an in-depth explanation of its working mechanism which relies on the electrode gap and area size [50]. Up to now, the freestanding triboelectric-layer mode has been developed with several unique structures and has been widely applied in environmental energy harvesting [76, 77]. Hence, an excellent structural design, appropriate material selection, and surface modification can enable an outstanding performance of the electrification of various TENGs.

3. TENGs for wind energy harvesting

3.1. General working principles of the WD-TENG

The WD-TENG plays a significant role in converting energy from the surrounding environment, which is a clean and sustainable way to harvest kinetic energy effectively from airflow and obtain electrical energy. COMSOL simulation is an advanced and effective method to research the principle of wind TENGs (see figure 2(a)) developed by Quan *et al* [78], who performed a COMSOL simulation comparison of the potential distribution between a bilateral stationary TENG and a unilateral stationary TENG. Wang *et al* reported a TENG based on elasto-aerodynamics [79] and contact electrification, as shown figure 2(b). The related working principle depends on the output performance of the periodic contact separation between the Kapton membrane and the polytetrafluoroethylene (PTFE) membrane. The frictional coupling between electrical and electrostatic induction then causes the electrons to flow alternately between electrodes.

The COMSOL simulation shown in figure 2(c) is a structural fluid flow interaction model for the qualitative prediction of the interaction behavior between airflow and the Kapton membrane [79], which can be used to solve the structural deformation of belts using elastic formulas and nonlinear geometric formulas to allow for large deformation. The relative rotation between the PTFE film and the aluminum film can occur under the driving of the wind, as shown in figure 2(d), and then the tubular sliding TENG can reach an open-circuit voltage (VOC) [80]. Meanwhile, through COMSOL finite-element simulation, the potential distribution and charge transfer between the aluminum membrane and the ground can be verified. With the rotation angles changing, the electric output of the TENG displays different fluctuations of the total transferred charge and the potential distribution.

3.2. Progress in wind energy collection

As one of the cleanest, most abundant, and widely used energy sources, wind energy has played a significant role in electricity supply [13, 81]. Traditional wind technology relies mostly on electromagnetic induction and turbine designs, but there are disadvantages which include a huge, expensive installation, complex equipment structures, and high start-up wind speed. Compared with traditional harvesting techniques which are limited in remote areas, the application of TENG has many advantages such as small size, low cost, lightweight, and low start-up speed. Meanwhile, the WD-TENG can also serve in various sensor applications, including wind-speed monitoring [82] and breath-out alcohol concentration [83]. So far, the WD-TENG can be briefly divided into two types: a flutter-driven structure [84, 85] and a rotational structure [20, 21]. Also, in recent years many new structures for wind energy harvesting have been introduced and these structures are discussed in the following.

The WD-TENG with a flutter-driven structure harvest wind energy, first reported by Yang *et al*, offers a new concept for many researchers to scavenge wind energy. As shown in figure 3(a), the TENG consists of two layers of aluminum foil and a fluorinated ethylene propylene (FEP) film, which are assembled in a cuboid acrylic tube [83]. Since one side of the FEP film is fixed on the tube, the free side of the FEP film vibrates up and down, causing periodic motion between the two aluminum foils when external wind is applied to the system. This vibration results in output voltage/current across the external load resistance. The VOC and short circuit

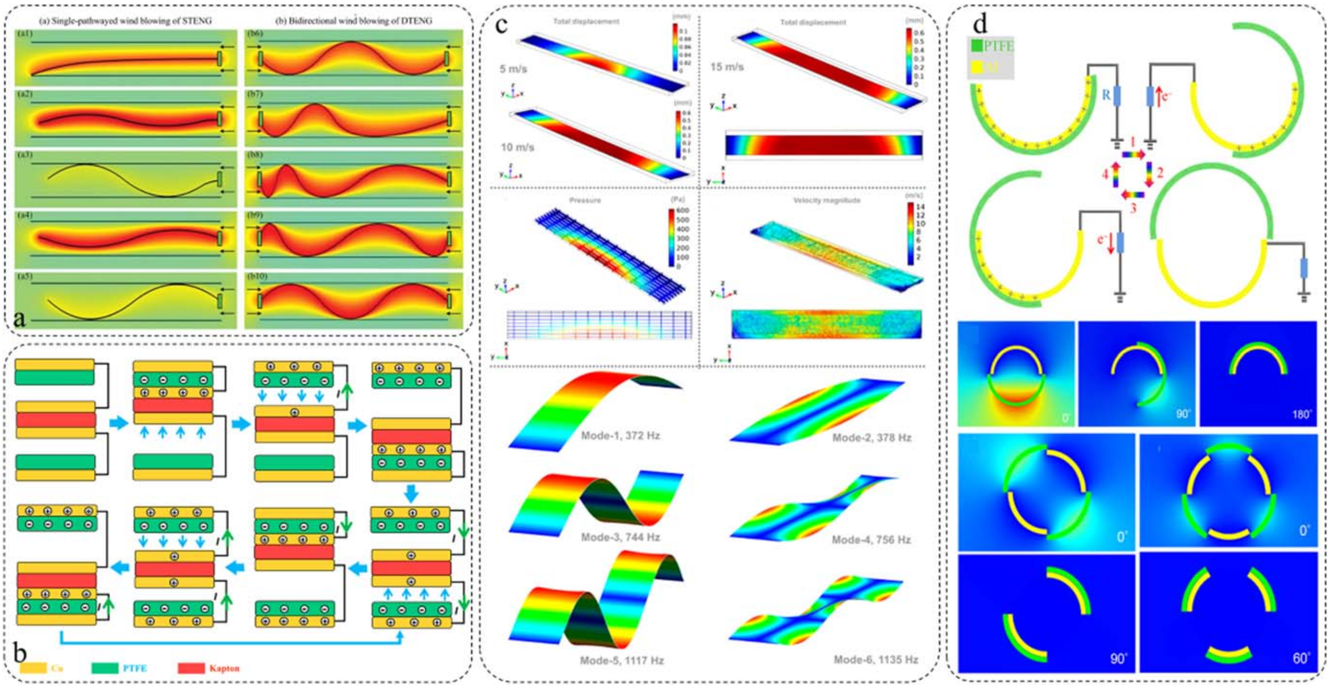

Figure 2. The working principle of the WD-TENG. (a) The COMSOL simulation of electric potential distributions and potential differences for the single and bilateral fixed TENGs under an open-circuit condition. (Reproduced with permission from [78]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (b) Schematic diagrams of the electricity generation process of contact-separation TENGs. (Reproduced with permission from [79]. Copyright 2015 American Chemical Society). (c) COMSOL simulation to qualitatively predict the interaction behavior between the airflow and the Kapton film. (Reproduced with permission from [79]. Copyright 2015 American Chemical Society). (d) COMSOL simulation and electricity generation process of a tubular wind TENG. (Reproduced with permission from [80]. Copyright 2014 Tsinghua University Press and Springer-Verlag, Berlin Heidelberg).

current (Isc) of this WD-TENG can reach 100 V and 1.6 μA, respectively and a output power of 0.16 mW with an external load resistance of 100 MΩ, which is enough to provide motivation for the exit sign. Figure 3(b) shows a pendulum-shaped TENG (P-TENG) [22] that uses a thin strip as the charge pump to replenish charges to the triboelectric layer and gain a remarkable energy-harvesting efficiency. Besides, there is an air gap between the triboelectric layer and the electrode of the P-TENG, which can achieve frequency doubling performance without friction resistance. Lin *et al* proposed a large-scale generation model to harvest wind energy in the desert [22]. Then, based on a TENG with a typical rotational structure, a self-powered air cleaning system, shown in figure 3(c), was designed to remove SO_2 and tiny particles in the air and use the grating electrode to enhance the electrostatic attraction [86]. TENG-driven air purification systems are evolving, such as the TENG developed by Gu *et al* that depends on multi-layer nanofibers to purify air and control bacteria [87, 88].

Different from the TENG with one fixed electrode, as shown in figure 3(a), the random vibration of the independent electrode can cause an unstable output signal, so Zhao *et al* proposed an upgraded double-side-fixed TENG with Ag nanoparticles and nylon film as electrodes and a vibrating film, respectively (see figure 3(d)) [89]. In addition, the PI/rGO foam was designed as a pressure-sensitive component combined with a TENG to be assembled as a self-powered pressure sensor, producing a VOC and Isc of 130 V and 7.5 μA, respectively [23]. Figure 3(e) shows another typical TENG with a rotating structure including the stator and rotor, as well as a photograph based on a single harvester assembly for a TENG farm which is shown in this research to harvest energy under both low and high wind speeds [23]. Moreover, since the TENG wind harvesters are better than conventional wind turbines at low wind speeds, this work demonstrates a viable green active energy-harvesting method.

3.3. Applications

The utilization of wind energy has always been a focus of research on energy harvesting, but the applications of the conventional electromagnetic wind generator based on turbines and the electromagnetic effect is limited by complex structures and high costs of preparation. WD-TENGs are mainly made of conventional polymer thin films, which are low cost, easy to manufacture and scale up, and can be used in a variety of applications. With the increasingly in-depth research, the structural diversity of the TENG is becoming more and more varied. Based on biodegradable plant leaves and leaf powders, Feng *et al* proposed a WD-TENG [90], as shown in figure 4(a), which can produce current and voltage up to 15 μA and 430 V at the operating frequency of 5 Hz. In addition, the TENG tree can be applied to early warning and indicator lights in mountainous areas or islands, and shows a broad prospect in practical applications. As can be seen in figure 4(b), a TENG with a vertically stacked structure can not only multiply the output power but can also harvest bi-

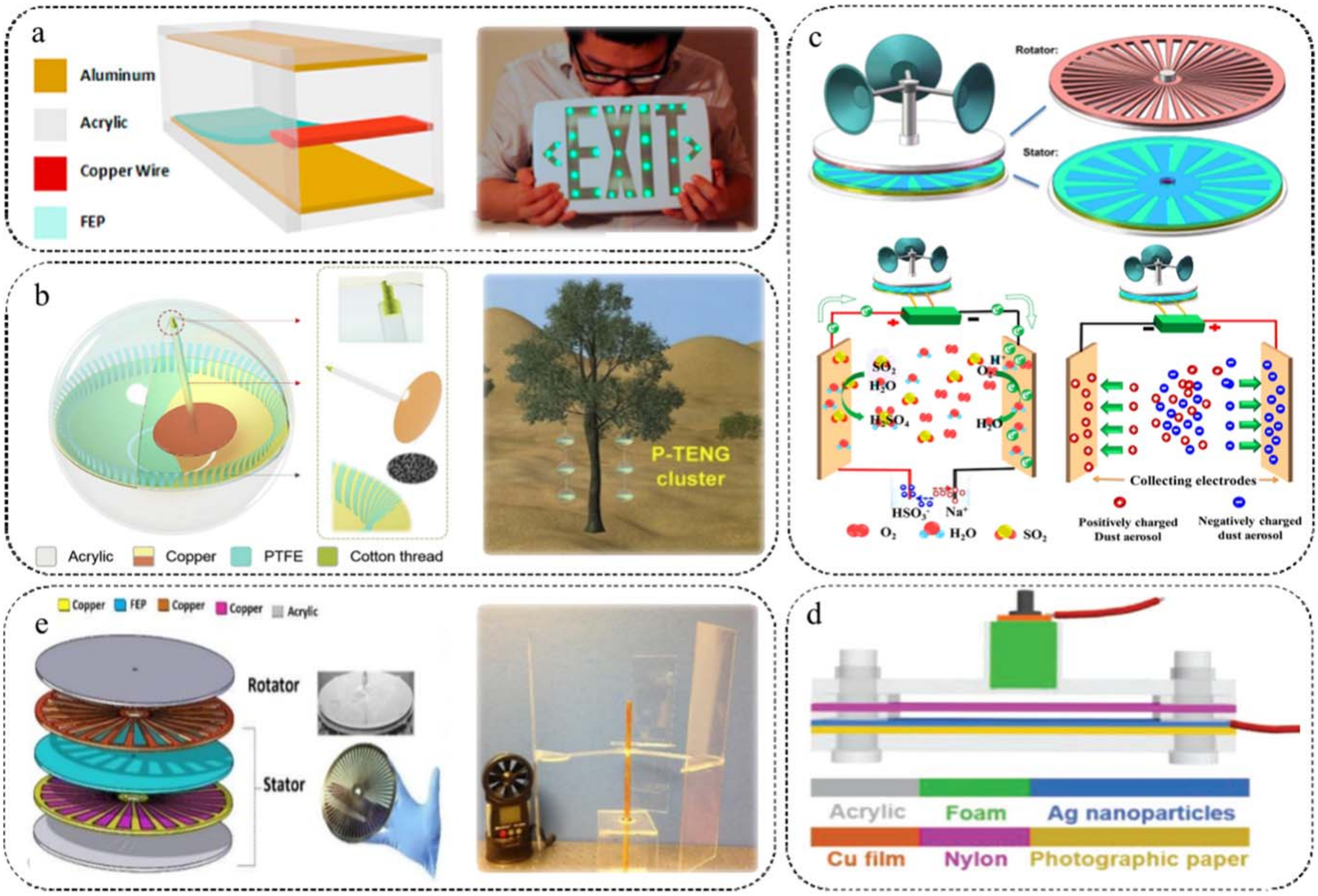

Figure 3. Various structures and their application of a WD-TENG. (a) The structure and application of the first reported WD-TENG. (Reproduced with permission from [20]. Copyright 2013 American Chemical Society). (b) Schematic of a P-TENG and P-TENG clusters applied in the desert. (Reproduced with permission from [21]. Copyright 2019 Elsevier). (c) Schematic of a TENG and illustrations of the principles of SO_2 (left) and dust (right) elimination based on electrostatics. (Reproduced with permission from [22]. Copyright 2015 Elsevier). (d) Schematic of the as-fabricated WD-TENG. (Reproduced with permission from [89]. Copyright 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (e) Schematic illustration of a TENG with a rotator and a stator, and a photograph of a TENG harvester. (Reproduced with permission from [23]. Copyright 2017 Elsevier Ltd).

directional wind [91]. Through the analysis of the dependence of load resistance, the maximum output power of 0.903 μW is reached with a load resistance of 10 MΩ. Further, an array of TENGs with kelp-like forms as shown in figure 4(c) can harvest most surrounding wind in different directions, which can be arranged into a wind farm and easily mounted on rooftops or railway tracks [91]. Additionally, figure 4(d) shows a TENG mounted on top of a vehicle for wind energy harvesting, which uses the Venturi design structure with a flag-like film [82]. This TENG can quickly charge super-capacitors between 7$\sim$15 m s^{-1} in less than 7 min during commuting, while the adjustment of the device can improve the output performance to accommodate a variety of environmental applications. A WD-TENG in a wind tunnel is shown in figure 4(e). Olsen *et al* investigated the relationship between motion frequency and voltage response, which is influenced by the movement of a FEP plastic ribbon [92]. This TENG device can generate power at wind speeds as low as 1.6 m s^{-1}, which is suitable for both anemometers and power generators.

In addition to single/two-sided polymer thin-film structures, the TENG has many emerging structural designs and material options that continue to promote the development of wind energy conversion. For example, figure 5(a) shows a traditional wind-cup TENG with a rotating structure, which is the first TENG combined with traditional techniques to produce a new operating mechanism for wind energy harvesting [94]. Under the effect of a breeze, the rotor blade with a PTFE membrane continuously sweeps through the stator with an aluminum film, which can reach a VOC of 250 V and an Isc of 0.25 mA. The materials used for a TENG are not only from synthetic materials but also from natural materials that remain to be developed. Figure 5(b) shows an ultra-low-friction HNG for wind energy, which has a high output performance and can well match the power supply requirements [95]. This is the original TENG with a rotating-contact structure. Based on this, many modified TENGs have been proposed, such as the TENG with bird feathers proposed by Cho *et al* [96]. This TENG is composed of a hyper-branched filament with water resistance and heat preservation, which generates high output

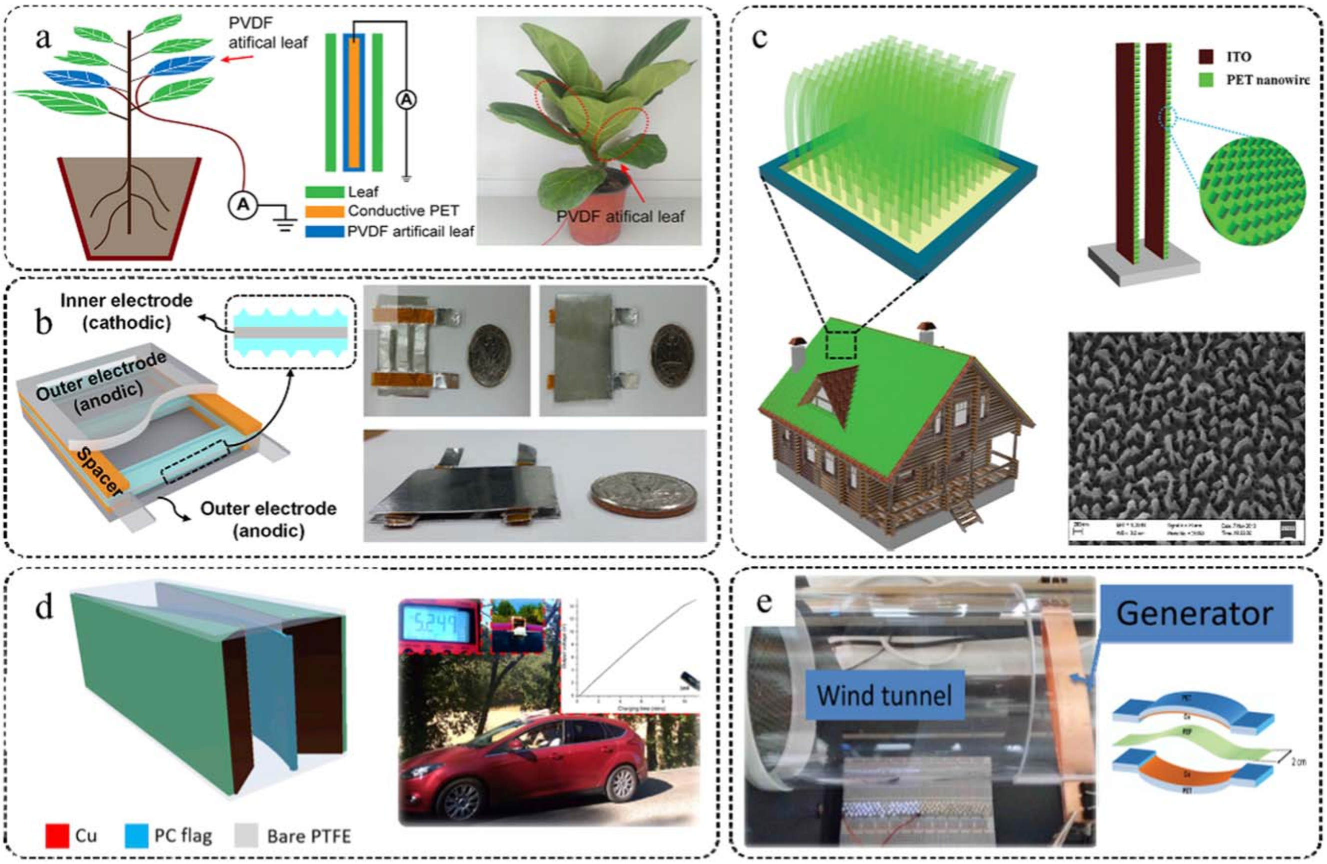

Figure 4. (a) Schematic of a TENG tree. (Reproduced with permission from [90]. Copyright 2018 Elsevier Ltd). (b) Schematic of a single-layer VS-TENG (a TENG with a vertically stacked structure) with protruded pyramid arrays at the surface. (Reproduced with permission from [91]. Copyright 2014 Elsevier Ltd). (c) Schematic of a lawn structured TENG with a surface modification installed on a rooftop. (Reproduced with permission from [93]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (d) Schematic of a large-scale TENG mounted on the roof of a car to harvest ambient wind with the inset showing the process of charging a super capacitor. (Reproduced with permission from [82]. Copyright 2019 Elsevier Ltd). (e) Photograph of a TENG mounted inside a wind tunnel. (Reproduced with permission from [92]. Copyright 2019 Springer Nature).

performance because of the hyper-branched structure, the interlocking effect of the barbs, and the model that increases the triboelectric contact area.

According to the development of the IoT and sensor networks in contemporary society, self-service devices and various sensors including fiber grating sensors, capacitive sensors, and wireless integrated network sensors are also being developed rapidly. The TENG for wind energy collection is becoming an important energy source for sensors. A TENG-driven active wind-speed sensor (see figure 5(c)) was proposed by Xu *et al* [97]. In their research, an AF-TENG with different materials, film length, inlet speed, and humidity are systematically studied and reported. The real-time wind speed measured based on the output voltage frequency of the AF-TENG is in good agreement with the commercial anemometer, and the AF-TENG speed sensitivity is approximately 0.13 $(\mathrm{m\,s^{-1}})/\mathrm{Hz}$ or 7.7 $\mathrm{Hz}/(\mathrm{m\,s^{-1}})$. In the process of the contact separation between the triboelectric surfaces, the size and tightness of the contact area can affect the output of the TENG. Figure 5(d) shows an angle-shaped TENG (AS-TENG) composed of FEP and aluminum film, which has an angular structure conducive to the enhancement of contact electrification and electrostatic induction effects [98]. Besides, the AS-TENG reduces the start-up wind speed by constructing wedge shaped air channels, enabling wind harvesting to occur in simpler, more convenient scenarios.

The WD-TENG has a variety of structures, the most typical of which are the film vibration structure and rotational structure, such as the P-TENG and the TENG tree with a contact-separation mode. In terms of the selection of materials, various types of synthetic polymer films and naturally existing materials have gained a place in the preparation of TENGs. On the other hand, there are also several concerns that need to be addressed in the future study of the WD-TENG. The WD-TENG has advantages for collecting energy from light breezes, but the energy conversion efficiency is very important for further promoting WD-TENG applications. Moreover, in large-scale integration, the maintenance of a WD-TENG can increase the cost of production, and the integrated system in a series mode is more likely to cause a failure of the whole system due to damage of a single unit.

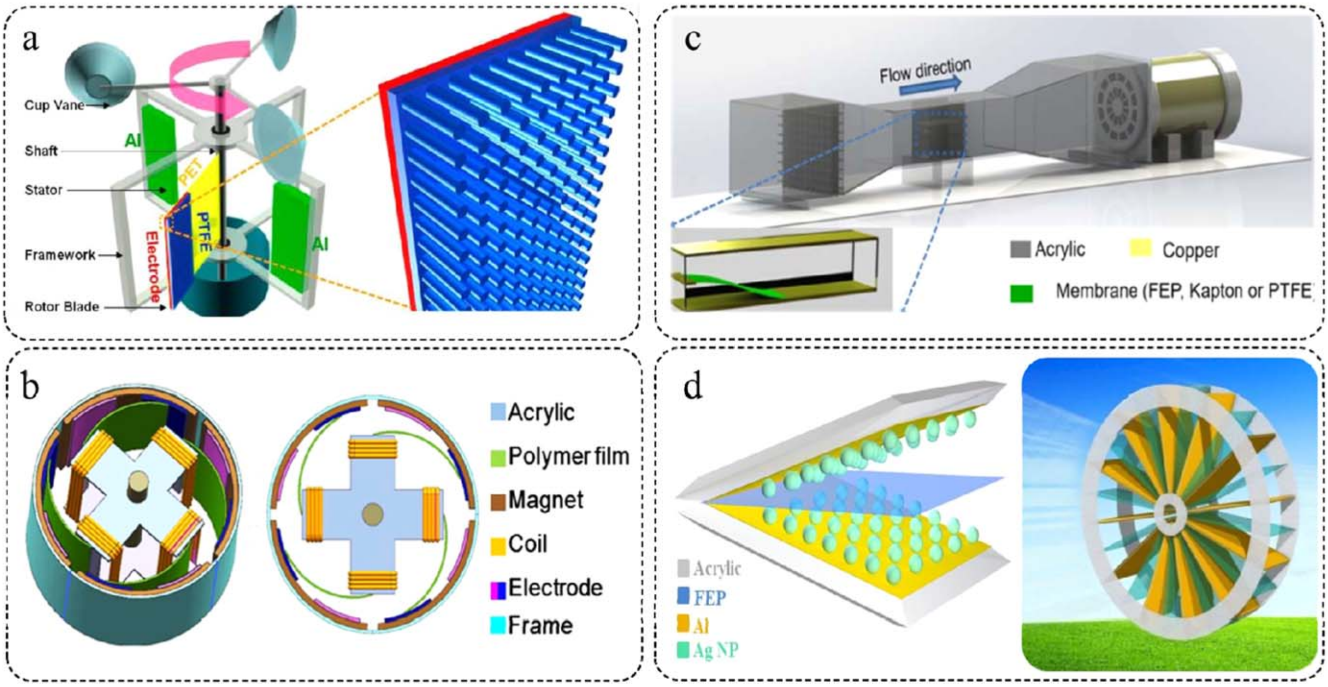

Figure 5. Different structures and surface modifications of TENGs. (a) Schematic of an R-TENG with an enlarged picture of the nanowire-like structures on the surface of the PTFE. (Reproduced with permission from [94]. Copyright 2013 American Chemical Society). (b) (Reproduced with permission from [95]. Copyright 2018 American Chemical Society). (c) Schematic of a wind tunnel and the wind-speed sensor design of an aeroelastic flutter-based triboelectric nanogenerator (AF-TENG). (Reproduced with permission from [97]. Copyright 2017 Elsevier Ltd). (d) Structure and schematic diagram of an AS-TENG. (Reproduced with permission from [98]. Copyright 2018 Elsevier Ltd).

4. TENGs for raindrop energy harvesting

4.1. Principle of raindrop energy collection based on the superhydrophobic surface

Raindrop energy has not been fully developed in the field of energy collection. However, based on the development of the TENG, the rain-related energy can make up for the deficiency of an SC on rainy days. Generally, studies of raindrop energy focus on two energies: the mechanical impact energy from the raindrop and the electrostatic energy generated from the contact electrification on the liquid/solid interface [99]. The raindrop energy harvesting device can be applied to many structures used in daily life, such as common buildings, as shown in figure 6(a), [24]. The transparent TENG, installed outside the building, runs in a single-electrode mode, which greatly facilitates the energy harvesting from continuously flowing droplets. In addition to high transparency and excellent machinability, the hydrophobic PTFE film enables TENG surfaces to have the features of self-cleaning, anti-sticking, de-icing, and anti-contamination. When the distance between the positively charged waterdrop and the PTFE film decreases, the potential difference between the FTO electrode and the ground is generated. As the droplets leave the film, a negative potential difference is formed between the FTO electrode and the ground. This process causes electron transfer to occur in the external circuit for continuous output.

Furthermore, Lin *et al* provided a detailed explanation of the raindrop power generation principle from the process of contact electrification with air/pipes and/or a PTFE thin film, as can be seen in figure 6(b) [100]. As the positively charged waterdrop approaches the PTFE film, there is a positive potential difference between the copper electrode and the ground, which causes the electron transfer to produce a positive instantaneous current. When a TENG works through the contact between the waterdrop and the PTFE film, ionization of PTFE surface groups make the PTFE negatively charged when the water drops onto the surface. At the same time, the water droplet has a certain volume, which forms a positive electric double layer and neutralizes the charges on the contact surface. When waterdrops leave the PTFE film surface, the potential difference between the copper electrode and the ground produces an instantaneous negative current. The triboelectric charge can be maintained continuously on the PTFE film with poor conductivity. Once the water droplets keep falling onto the PTFE film, the potential difference can be re-established and electrons move back to reach a new equilibrium. Thus, the continuously following water droplets lead to a continuous output.

In addition to buildings that can be found everywhere, plants can be grown in the natural landscape, which are often noted for their ability to store energy due to photosynthesis. However, few people have thought that plants could also be used in combination with an RD-TENG. Chen *et al* utilized triboelectrification on plant organs to construct an RD-TENG (see figure 6(c)) [101], and realized the generation of charges in the process of triboelectrification by exploiting the petal equipped microstructures and nanostructures on the

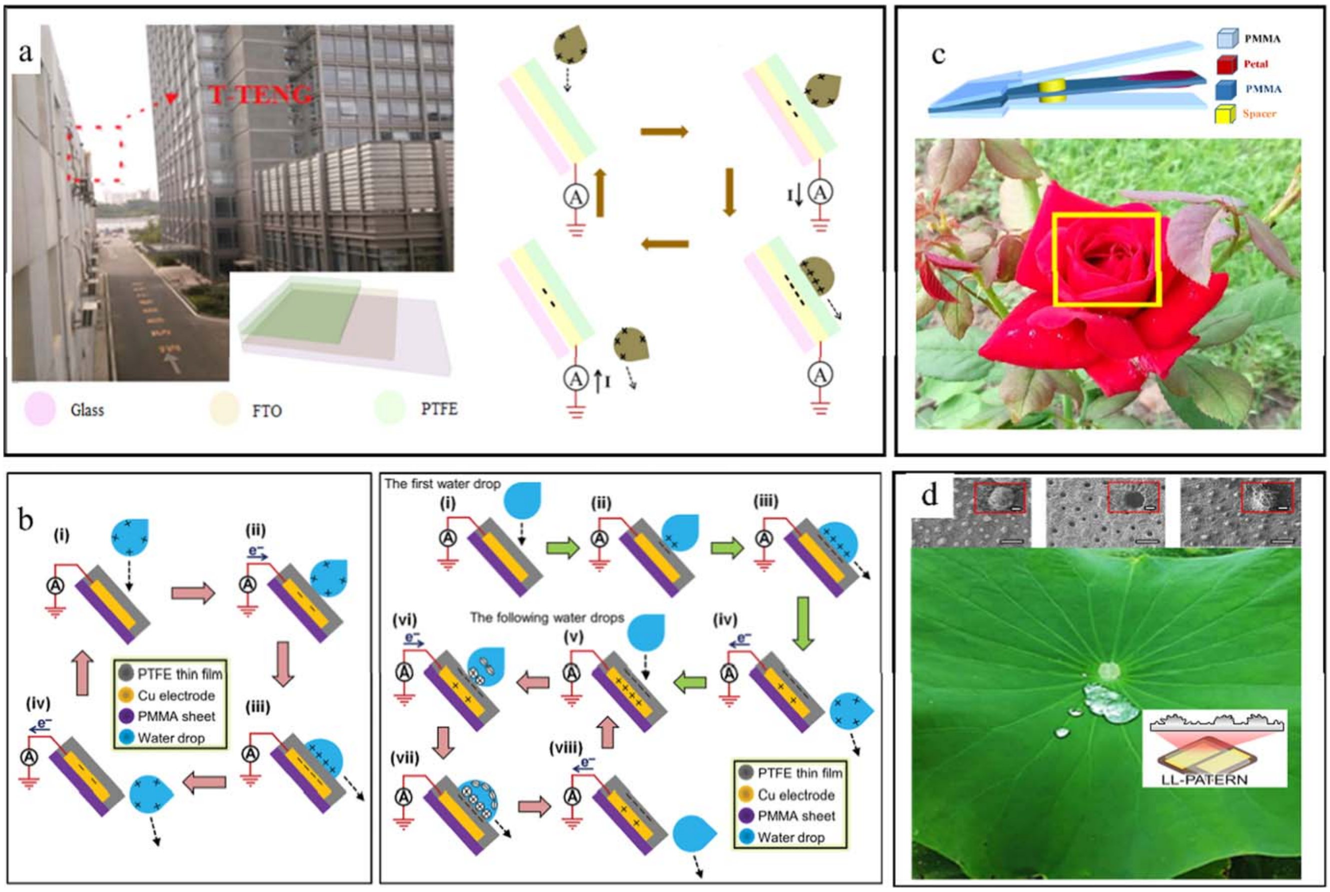

Figure 6. A liquid–solid contact electrification of the raindrop triboelectric nanogenerator (RD-TENG) which harvests raindrop energy in daily life. (a) Working mechanism and application of the tower-like triboelectric nanogenerator (T-TENG). (Reproduced with permission from [24]. Copyright 2015 Springer Nature). (b) Working mechanism of the RD-TENG based on the contact electrification process. (Reproduced with permission from [100]. Copyright 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (c) Electrification on the natural Chinese red rose. (Reproduced with permission from [101]. Copyright 2018 Elsevier Ltd). (d) Schematic of discrete liquid–solid contact electrification on the surface of a natural lotus leaf. (Reproduced with permission from [102]. Copyright 2017 Elsevier Ltd).

hydrophobic surface. In addition, the power output density of the TENG can reach 27.2 mW m^{-2} with a 50 MΩ load resistance. Also inspired by natural lotus leaves, water droplets can roll and fall naturally on the surface, which realizes a discrete liquid–solid contact electrification. Choi *et al* manufactured a natural lotus leaf-TENG (see figure 6(d)) [102], which is a simple and cost-effective way to modify a rough surface by thermal nanoimprinting and to improve the electrical output performance.

4.2. Applications and their related superhydrophobic surfaces

Raindrops produce energy during continuous rolling and sliding on a superhydrophobic surface and thus, studying the characteristics and modification of the superhydrophobic surface is important [103]. The superhydrophobic surface helps achieve the function of self-cleaning, waterproofing, and anti-fouling on rainy days [104–106]. In addition, the superhydrophobicity of the film facilitates the sliding motion of waterdrops, including a better electric performance of the RD-TENG. On this basis, the multi-unit transparent TENG with the structural design of 'top-down' and 'bottom-up' is shown in figure 7(a), and can be integrated well with buildings, vehicles, or silicon-based SCs [25]. In particular, each unit of the integrated equipment works independently, which can avoid damage to the equipment due to occasional failure. Based on a waterproof fabric (see figure 7(b)), a waterproof-fabric-based multifunctional triboelectric nanogenerator (WPF-MTENG) is demonstrated, which is flexible, adaptable, and can be applied to a self-powered sensor [26]. A combination of WPF-MTENG with different rain gear including raincoats and umbrellas is shown in the photograph in figure 7(b). Moreover, WPF-MTENG can be mounted on roofs and tents to harvest raindrop energy, enabling the application of a TENG for alternative energy collection and wearable devices. Figure 7(c) shows a self-cleaning/rechargeable power supply system consisting of a hydraulic TENG and embedded fiber supercapacitors [27]. Generally, the process of positively charged raindrops sliding over the TENG's gate electrode generate alternating current output, and supercapacitors are a good alternative to the rectifier to store the energy. After 100 s in the shower, which simulates a stream of falling raindrops, the VOC of the power raincoat reaches 4 V and the light-emitting diode (LED) lights up to more than 300 s.

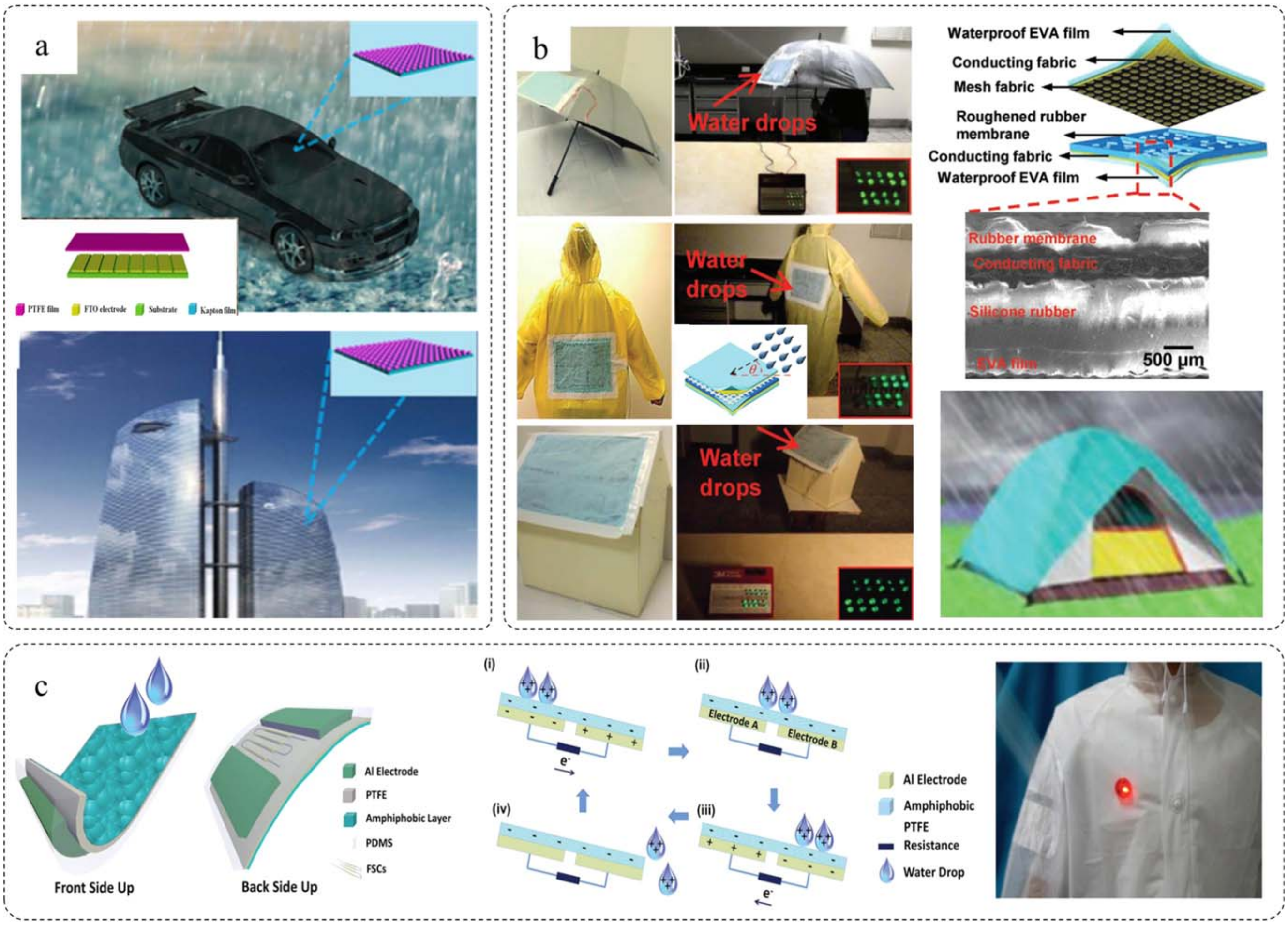

Figure 7. Various application scenarios of an RD-TENG. (a) The potential applications of the multi-unit transparent TENG for a vehicle and building. (Reproduced with permission from [25]. Copyright 2016 Elsevier Ltd). (b) (Reproduced from [26] with permission from WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (c) Schematic diagram of the self-cleaning property and application of the SPS (self-cleaning/charging power system). (Reproduced with permission from [27]. Copyright 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

Instead of a single plane, the droplet-driven TENG used to harvest energy from the bouncing water droplets between two superhydrophobic surfaces, which converts both the electrostatic potential and mechanical energies into electric energy, is shown in figure 8(a) [107]. With the bounding motion of the droplet between two superhydrophobic surfaces, the generation of an inductive charge can lead to a difference in the potential between the electrodes, so that electrons can be transferred to generate a current. To increase the impact force of the water bouncing on the surface, the best working parameters of the TENG are investigated , such as the tilt angle of the plane, contact angle, number, and volume of waterdrops. Coincidentally, the dual-mode water-TENG (w-TENG) with a superhydrophobic surface, as shown in figure 8(b), is fabricated by a superhydrophobic TiO_2 layer to increase the photocatalytic activity and antibacterial property [108]. Furthermore, the w-TENG can be used as a self-powered sensor to detect ethanol since the decrease in triboelectric charges on the water droplets induced by the ethanol can result in a decrease of the electrical output signal. Hence, this research has proved that TENGs as self-powered sensors can be applied to toxic ion pollution and gas sensing systems. Natural fabric/textile is appropriate for wearable devices due to the advantages of being environmentally friendly, wear-resistant, flexible, and breathable, and can serve as the basic triboelectric material for a wearable TENG. Prepared from microcrystalline cellulose, hydrophobic cellulose oleoyl ester nanoparticles (HCOENPs) are a low cost, eco-friendly coating material, which can be applied to the surface of materials to achieve superhydrophobicity. As shown in figure 8(c), the fabric-based w-TENG fabricated by HCOENP-coated polyethylene terephthalate (PET) has good waterproof, anti-fouling, and self-cleaning functions, and can maintain a good working performance in harsh environments [104]. In addition to stable and effective waterproof performance, the synthesized HCOENPs expand the possibility for their application in cotton, silk, flax, PET, nylon, and other common fabrics in wearable self-powered devices. Based on the superhydrophobic surface, a water-solid triboelectric nanogenerator (W-TENG) with a self-repairing function is shown in figure 8(d) [109]. This device can repair itself by heating and releasing fluorinated alkyl silane filled into the surface pores of the tape when damage to a W-TENG appears on the surface during long-term usage. The superhydrophobic

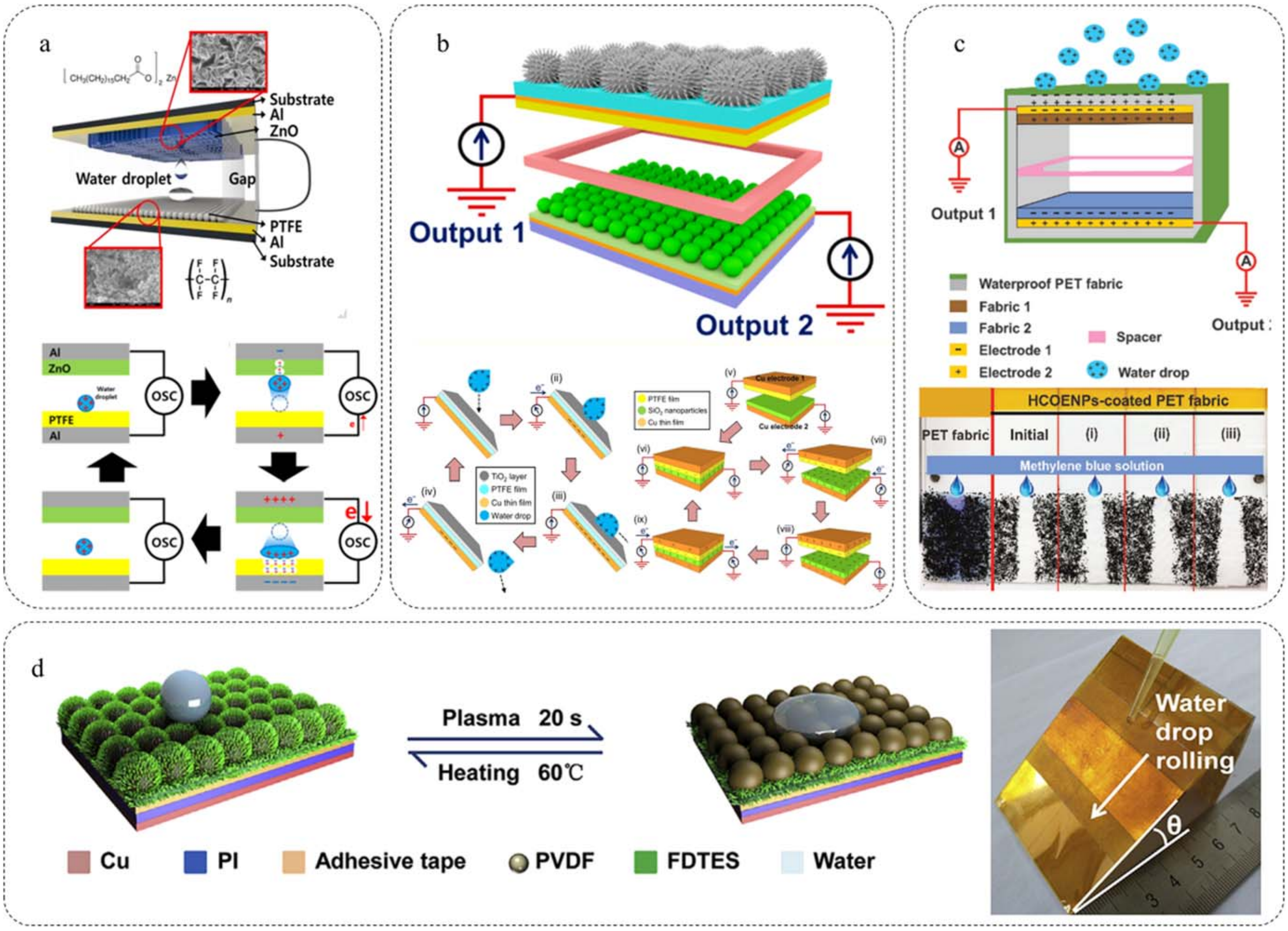

Figure 8. Schematic of a typical RD-TENG. (a) Schematic and working mechanism of a WD-TENG. (Reproduced with permission from [107]. Copyright 2019 Elsevier Ltd). (b) Schematic and working mechanism of a dual-mode TENG (DM-TENG). (Reproduced with permission from [108]. Copyright 2014 American Chemical Society). (c) Schematic of an all-fabric-based DM-TENG and self-cleaning presentation of the dust of a PET fabric. (Reproduced with permission from [104]. Copyright 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (d) Photograph of a W-TENG array and schematic of the damage and healing processes of the superhydrophobic surface by plasma-etching and heating treatments. (Reproduced with permission from [109]. Copyright 2019 Elsevier Ltd).

surface can also be restored by superhydrophobic adhesive tape adhering polyvinylidene fluoride (PVDF) nanospheres after being mechanically damaged. Self-healing is a great benefit to extend its working time and reduce maintenance costs when it collects energy in nature.

Moreover, there are some reports of interdigital electrodes (IDEs) and a grating structure to catch raindrop energy. Yun *et al* reported a cone-shaped IDE-based TENG, as shown in figure 9(a), that significantly increases the current output by changing the folding angle and the volume/speed of water droplets [110]. Besides, the design of a thin aluminum foil, PET film, and PTFE film equips the IDE-based TENG with collapsibility, flexibility, and rollability to be reliable and durable in flexible devices. Although the average current does not grow linearly with the increase of cone volume, this method is simple and operable. Since the modern Internet is a large part of human life, cryptographic keys are the first defense line to protect people's information. Thermal noise and quantum effects have been proved to be the source of real random numbers, but they are often used infrequently because of the expensive computational cost. Figure 9(b) shows a method to obtain real random numbers from raindrops by combining the triboelectric and electrostatic induction effects at the solid−liquid interface of a TENG with an irregular grating structure [111]. This method expresses excellent predictability and repeatability.

The pseudocapacitive effect between the graphene and waterdrops, as shown in figure 9(c), has been reported recently and this different combination of graphene/PTFE provides insight into droplet harvesting for new materials [112]. Due to the triboelectric potential, positive and negative charges accumulate on the bottom and top surfaces of graphene on PTFE. Besides, these top negative charges are pushed forward by the removable waterdrops. In addition to these listed methods, which use the electrification and electrostatic induction between a solid and liquid to harvest raindrop energy, Nie *et al* proposed a liquid–liquid TENG that works based on the interaction between two pure liquids (as shown in figure 9(d)) [113]. This TENG can harvest the mechanical energy of an object without changing the motion of the water droplets. Two kinds of working principles are designed based on this liquid membrane. One is to harvest the

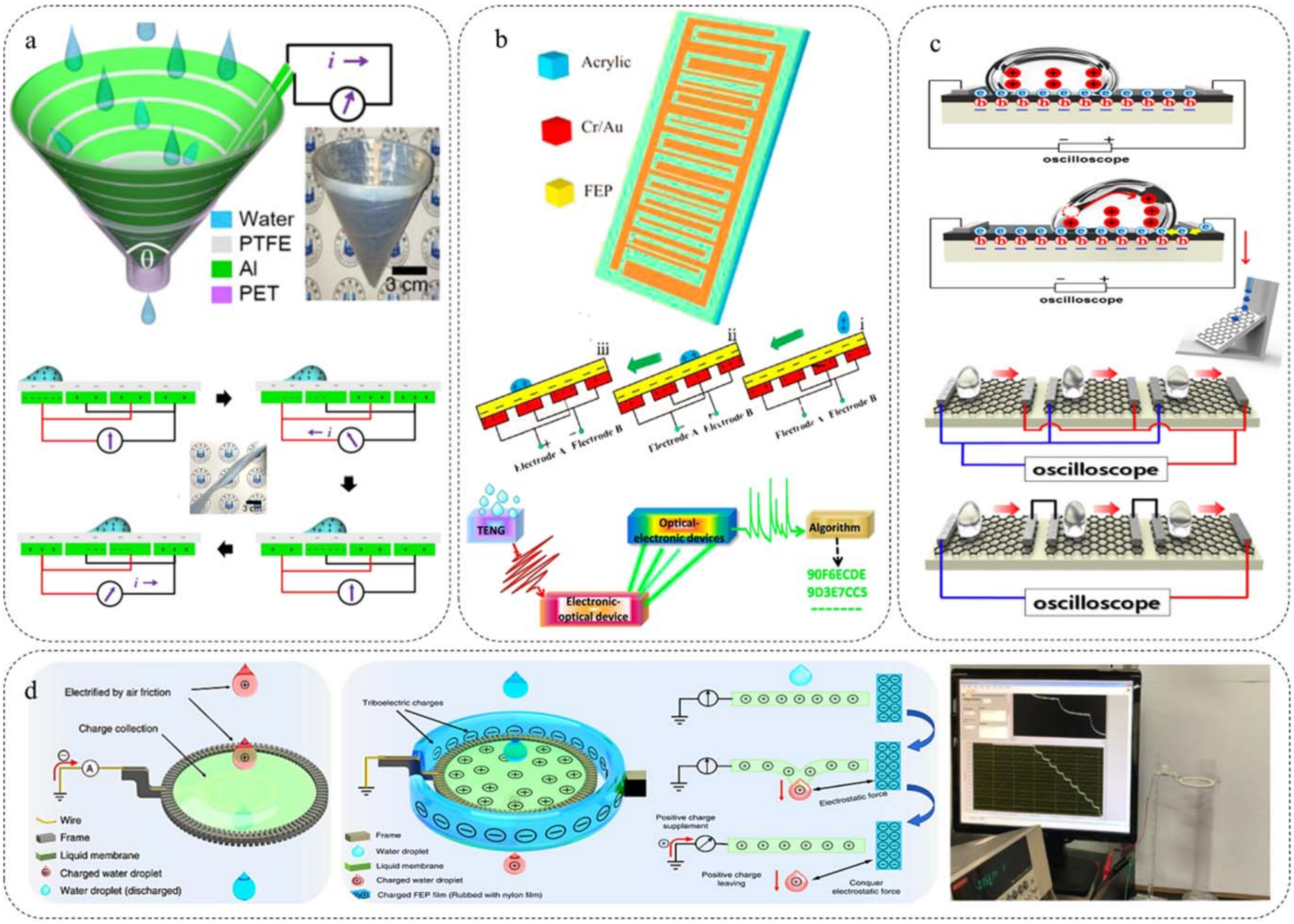

Figure 9. Special applications of a solid–liquid contact. (a) Schematic and working mechanism of a cone-shaped IDE-based TENG. (Reproduced with permission from [110]. Copyright 2017 Elsevier Ltd). Working mechanism of a TENG with an irregular grating structure and a description of the random number generator. (Reproduced with permission from [111]. Copyright 2016 American Chemical Society). (c) Schematic and electric power generation mechanism of a WPF-MTENG. (Reproduced with permission from [112]. Copyright 2016 American Chemical Society). (d) Process of the energy generation of water droplets passing through a charged liquid film. (Reproduced with permission from [113]. Copyright 2019 Springer Nature).

surface charge of falling droplets with a grounded liquid membrane. The second is to harvest the mechanical energy based on a pre-charged membrane. When the droplet passes through the pre-charged membrane, it takes charges away from the membrane. In this process, the electrostatic balance is constantly destroyed and restored, so there is displacement current output. This TENG can be used for many applications, such as electrostatic charge removal in microelectronic devices, surface charge detection, and so on, which provides a new way to harvest liquid droplet energy.

5. TENGs for sonic energy harvesting

5.1. Sound field analysis

As one of the most common sources of energy in the surrounding environment, sound energy is ubiquitous but rarely developed and collected systematically like other energy sources are, which can be attributed to the low power density of the acoustic wave and the lack of effective harvesting technology. Meanwhile, the natural frequency of piezoelectric devices is difficult to match a sonic frequency, and a large amount of energy is lost in the process of energy conversion. The sound-driven TENG (SD-TENG) is a very appropriate, cost-effective approach to convert noise energy into available electricity [114–116]. The working principle of the SD-TENG based on sound energy harvesting can generally be explained from two aspects of sonic vibration, namely, the triboelectric effect and the electrostatic induction effect [117–119]. In addition, different from the mechanical vibration of traditional sonic energy devices, which is derived from the compression and expansion of air in the cavity of the device, the advanced SD-TENG relies on the transmission of sound waves to cause a periodic pressure difference between the two sides of the film, resulting in the mechanical vibration of the film. Moreover, like most ambient vibrations, sonic vibrations have a specific frequency with a certain bandwidth and time-dependent fluctuation. As a result, different from the conventional TENG in the contact-separation mode, the sound pressure that can be captured by the SD-TENG is quite small with a sound pressure of only 2 Pa at 100 dB. Therefore, the

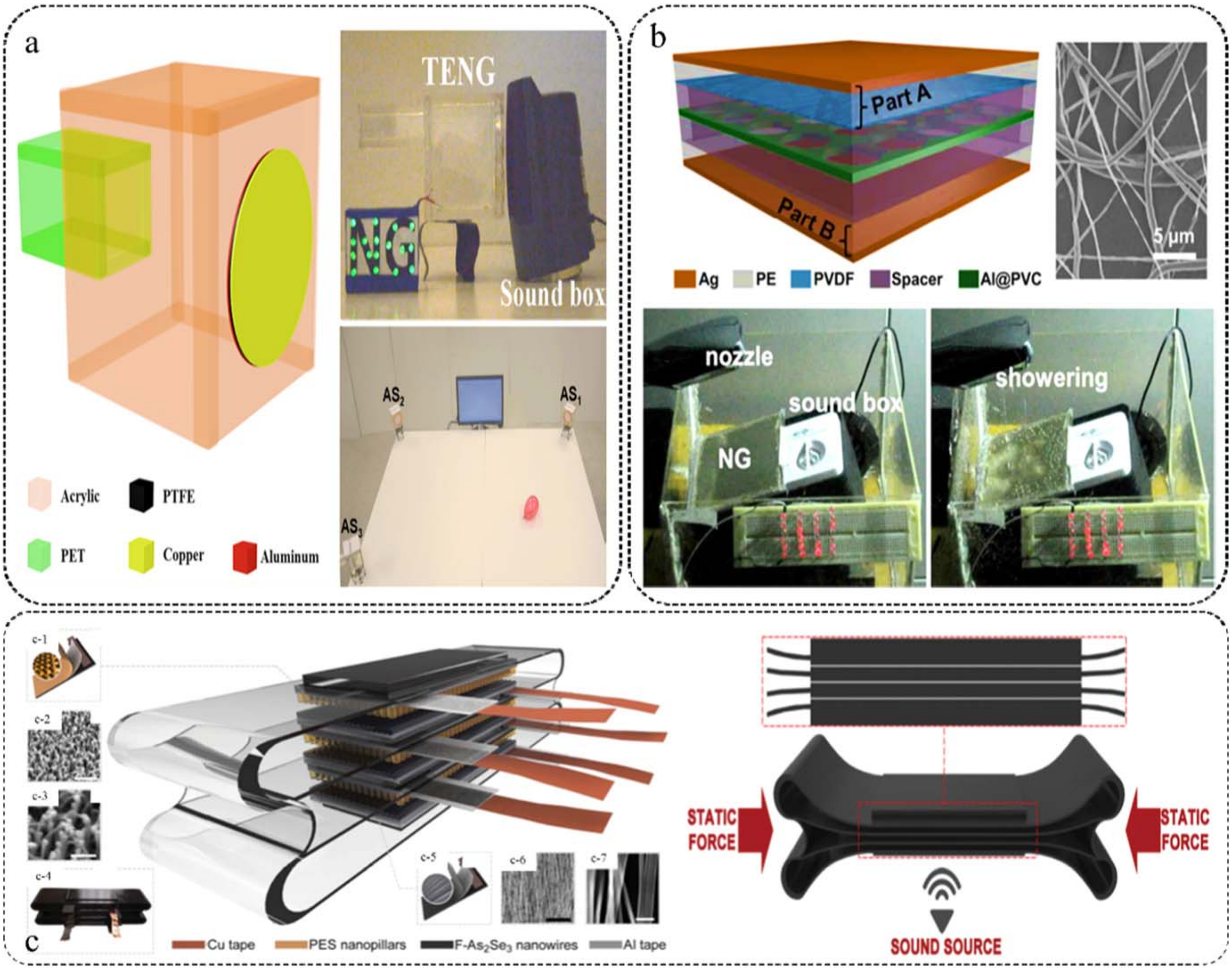

Figure 10. Basic structure of the SD-TENG. (a) Schematic and sound localization of organic film nanogenerators. (Reproduced with permission from [28]. Copyright 2014 American Chemical Society). (b) Structure of an SD-TENG and a scanning electron microscope image of the PVDF nanofibers. (Reproduced from [29] with permission from the Royal Society of Chemistry). (c) Schematic of chalcogenide-based 3D-printed multilayered TENG. (Reproduced with permission from [115]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

sound energy-harvesting device must have certain conditions, including a wide and appropriate vibration frequency range and be very sensitive to a small vibration.

5.2. TENGs for noise energy harvesting

As can be seen in figure 10(a), the first sound energy harvester based on an organic thin-film TENG utilizes a Helmholtz cavity to make it highly sensitive and operates properly at resonant frequencies, which reaches Isc and VOC of 15.1 μA and 60.5 V, respectively [28]. The concept proposed in this work enables self-powered sensing applications for sound energy harvesting, such as noise reduction, sound source positioning, wireless technology applications, and other aspects [120, 121]. Since TENG designs are usually open-ended, the output performance of TENGs can be affected by regular factors in the environment including dust, humidity, and temperature. Gu *et al* designed a highly robust SD-TENG (see figure 10(b)), which is able to work stably while isolating the triboelectric surface from the environment [29]. Even in harsh environments like dusty, moist, and rainy conditions, it can be driven steadily by sound and can light up 24 red commercial LEDs without energy storage. Further, it has been demonstrated that multilayered structures can generally provide a higher output performance than that of a single unit. Kanik *et al* reported a multilayered TENG with a core–shell nanostructure (polyethersulfones in core and As_2Se_3 in shell) (see figure 10(c)), which can be stimulated by sonic waves [115]. The response of a TENG to different frequencies of sound is designed to work more suitably at a lower frequency with a maximum VOC and Isc of 107.3 V and 0.49 μA, respectively, at 10 Hz. Moreover, a paper-based SD-TENG (see figure 11(a)) has drawn a lot of attention due to its advantages of being rollable, ultrathin, and lightweight with high processability [30]. The use of microporous arrays and the biodegradability of paper in this TENG can enhance the acoustic response. Different from the SD-TENG shown in figure 10(a), the vibration principle of a conventional TENG

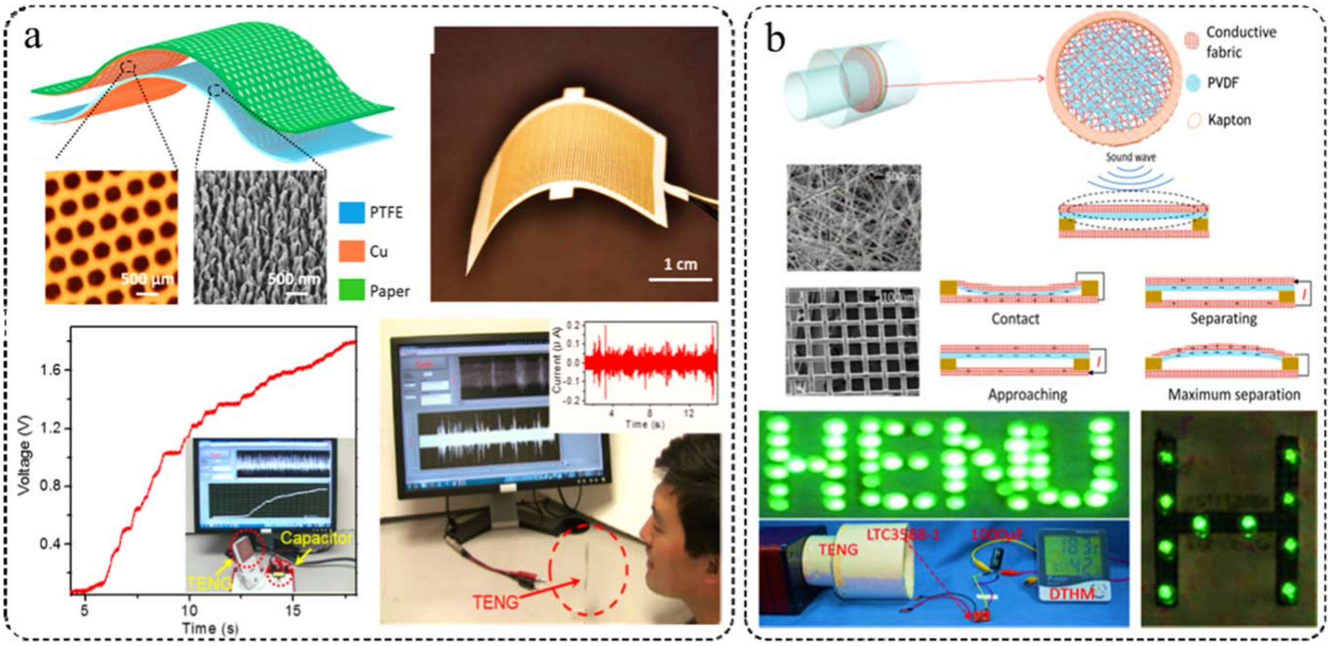

Figure 11. Thin-film TENGs used to collect sound energy. (a) Schematic and photograph of an as-fabricated paper-based TENG. (Reproduced with permission from [30]. Copyright 2015 American Chemical Society). (b) Structural design and working principle of the SD-TENG. (Reproduced with permission from [31]. Copyright 2019 Elsevier Ltd).

is not dependent on the compression and expansion of air but rather is dependent on the mechanical vibration of the membrane stack structure. A TENG can reach the maximum power density of 121 mW m^{-2} with a sound pressure of 117 dB. The energy loss varies depending on the waveform. For example, a plane wave usually loses less energy than an undefined or spherical wave. Therefore, the adoption of a tubular structure in the TENG design is beneficial to improve its output performance. Based on this theory, a TENG with a sandwiched structure [31] has been designed by Chen *et al* (see figure 11(b)), which can be used for self-powered active sensors, speed inspection, and sound recording. In addition, the micropores in the conductive fabric can effectively improve the efficiency of sound conduction in the PVDF triboelectric film, and the output voltage and instantaneous power density can be generated to 400 V and 7 W m^{-2} driven by sound. Therefore, the TENG can be used for both collecting energy from shear and longitudinal waves generated by sound waves.

The TENG's output performance is not only related to the type of sound wave, but also to the suitable materials and structures that can promote the propagation of sound waves and reduce the loss of sound energy during propagation. Figure 12(a) shows a TENG based on a porous mesh substrate that can allow continuous airflow and facilitates the propagation and collection of sound waves [122]. Besides, this TENG can be driven by sound waves in a wide range of 50–425 Hz, with a maximum output current density of 45 mA m^{-2} and a peak power density of 202 mW m^{-2}. At the same time, Cui *et al* conducted the extended life test [122]. The output signal still showed no sign of attenuation despite a continuous 7 day cycle of 100 million times. The integrated sonic enhanced TENG with a three-dimensional structure is shown in figure 12(b), which can obtain a peak power of 232.7 mA m^{-2} and 5414.9 mW m^{-2} when driven by sound [123]. Simultaneously, the TENG exhibits a new potential as a direct power supply for Fe $(OH)_3$ sol electrophoresis, which is also a combination of a TENG and electrochemical industry. Based on one-dimensional phononic crystals (PnC), figure 12(c) shows a sonic enhanced TENG, which is used to replace the intermediate scatter of PnC to achieve sound wave enhancement [124]. This is a promising method in which each of the steel scatters in the PnC can be substituted by the triboelectric harvester and is fully compatible with the structural characteristics of a TENG .

In summary, the collection of sonic energy is still limited by many factors, such as sources of instability and an overly broad range of frequencies. However, the utilization, and development of sound energy is a promising and significant field, and a better combination with a TENG remains to be explored and studied.

Sound energy is a broad concept, including sound, ultrasonic, and infrasound. Infrasound generally exists in the occurrence of natural disasters such as volcanoes and earthquakes. Meanwhile, the infrasound may have a strong resonance with a human body within a certain range, which is potentially harmful to the human body. Ultrasound is a kind of sound wave with a frequency higher than 20 000 Hz, which can exist in the ocean and many other environments [125, 126]. Although there are many problems to be solved in underwater ultrasonic energy collection, including low output power and low energy efficiency conversion, the emergence of this technique offers a new idea for ultrasonic energy collection. Xi *et al* designed a TENG to harvest acoustic energy in water (see figures 13(a)–(c)), which can achieve instantaneous output current by the contact-separation mode

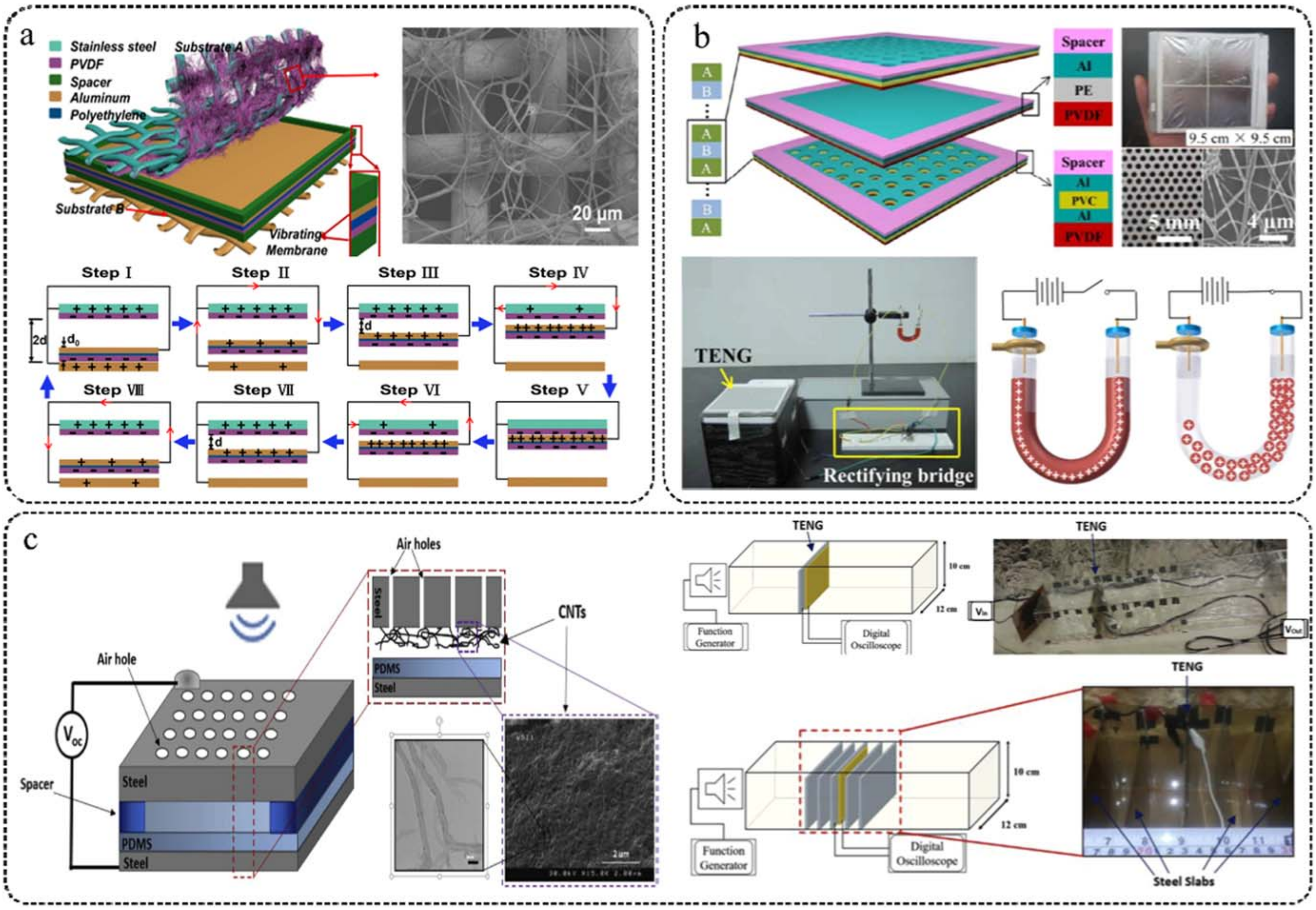

Figure 12. Different structural designs of a SD-TENG. (a) Schematic and working principle of a fabricated SD-TENG. (Reproduced with permission from [122]. Copyright 2015 Elsevier Ltd). (b) Schematic of a TENG and the application of an Fe $(OH)_3$ sol electrophoresis experiment. (Reproduced from [123] with permission from the Royal Society of Chemistry). (c) Schematic of a fabricated sonic TENG and the test configuration when the TENG is embedded in the designed PnC. (Reproduced with permission from [124]. Copyright 2018 Elsevier B.V).

with spherical particles as a medium under ultrasonic stimulation [127]. Under the input ultrasonic at the parameters of 80 kHz and 1.38 W cm^{-2}, the TENG with PTFE pellets and two copper electrode plates reaches an output voltage and current of 170 V and 0.12 A, which can be used as a power supply or integrated with supercapacitors to fabricate a power supply system. Furthermore, based on the fully encapsulated boxed structure of the TENG , the device can tolerate pressure from both shallow water and deep water.

6. TENGs for ocean energy harvesting

6.1. Development of ocean energy

Ocean energy is the most abundant environmental energy, and both waves and tides have a large amount of mechanical energy that needs further development and utilization [100, 128, 129]. In an actual ocean, the use of ocean energy is challenging due to the variety of ions in the water that may cause corrosion and damage to the electronic equipment, and the water surface is unpredictable as a result of severe weather and fierce wind [130]. Different from the traditional generators, which are bulky, expensive, and complex to manufacture, the TENG, which has the advantages of high conversion efficiency, low cost, and lightweight, has been increasingly applied to generate ocean energy power [131]. The TENG's principles of ocean energy harvesting can be roughly divided into two cases: direct contact between the tribo-surface and water and an encapsulated device relying on solid–solid contact [132, 133]. The direct contact between the tribo-surface and water is similar to the case of raindrop energy harvesting, while the device relying on solid–solid contact is affected by the surface roughness and the contact/triboelectric area.

Currently, research on TENG-based ocean energy harvesting covers many aspects, including the structural design, system optimization, atmospheric regulation, external excitation, and so on. Encapsulated TENG designs have better corrosion resistance and structural designs, including air gap structures to reduce dielectric shielding against water, nanoparticles for lubrication, multi-layer integrated structures, and an improved space utilization rate. Besides, the large-scale integration of a TENG network also relies on its design for increased flexibility and autonomy, which can possibly form self-powered wireless sensor networks [134, 135]. On the

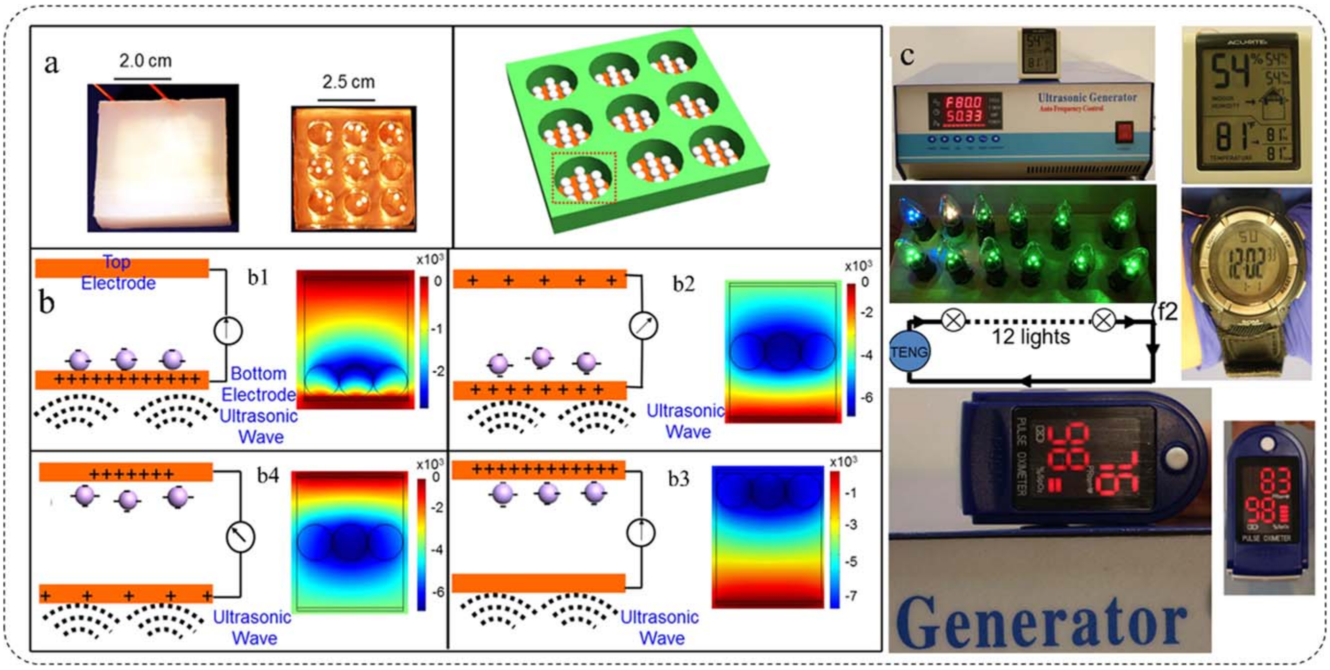

Figure 13. Design, working principle, and application of the acoustic energy TENG. (Reproduced with permission from [125]. Copyright 2017 Elsevier Ltd). (a) Photograph showing the packaged TENG and inter-structure of the TENG. (b) Working principle of the device and finite-element simulation. (c) Photographs of the digital temperature-humidity weather monitor and the electrical watch continuously driven by the TENG .

other hand, potential applications of ocean energy include, but are not limited to, long-term environmental monitoring, navigation at sea, decomposition of hydrogen fuel water, and purification of polluted water [136–138]. Furthermore, TENG networks floating on the ocean shore can be constructed to integrate with wind turbines or solar panels to form a multi-type energy power plant [139, 140].

6.2. Collection of wave energy by TENGs

6.2.1. TENGs based on solid–liquid contact electrification. A schematic of the first water-based TENG, as shown in figure 14(a), generates electrical energy and depends on the contact electrification and electrostatic induction between the water and the polydimethylsiloxane (PDMS) film with a pyramid array pattern [141]. These microstructures on the PDMS can act as a stable gap between two contact materials without strain while they can also increase the contact area for a higher output. The peak voltage and short circuit current density of this w-TENG are 52 V and 2.45 mA m^{-2}, showing the possibility of utilizing liquid motion to extract water energy from the environment.

Simultaneously, based on solid–liquid contact electrification, an NI-TENG is described in figure 14(b), which consists of multiple thin-film layers with vertically distributed nanowires covering the surface of PTFE [142]. As one of the electrodes is submerged in water, an imbalance of potential between the two electrodes generates a current in the external circuit. Additionally, the existence of different water wave tapes has little effect on the output current, and increasing the number of columns can improve the tolerance of the NI-TENG to the environment. Different from the previous two figures, the buoy-like TENG [143], as shown in figure 14(c), mainly harvests mechanical energy by the solid–liquid contact between the liquid inside the closed unit and the membrane material. At the same time, the device has the ability to produce several continuing damping output signals by one trigger pulse, which produces output signals even after the external trigger stops. This is appropriate for harvesting ocean energy, especially low-frequency and random water wave motion. Another solid–liquid TENG based on an advanced grillage design is shown in figure 14(d), where alternating currents between the electrodes are caused by the continual contact between the device and the water [144]. With six bars of integrated electrodes, the TENG is fixed in the tank for testing and it is able to generate a current signal output with shaking water waves and flushing shower water. Hence, the connection of planar sheets into a network is an appropriate method for massive energy harvesting, achieving an average output power of 0.12 mW at a relative speed of 0.5 m s^{-1}.

6.2.2. TENGs based on fully encapsulated structures. Although water wave energy is rarely affected by seasons or climate, the solid–liquid contacting TENG is vulnerable due to the long exposure to an open environment (the effect of humidity on output performance, dust, and material erosion on the life of the TENG) [145, 146]. Therefore, a TENG that can be used for a long time in a harsh environment should be completely encapsulated, as shown in figure 15(a). A whirling-folded TENG (WF-TENG) has been fabricated by new modeling technology and printed circuit board technology [147]. An air gap structure is designed between

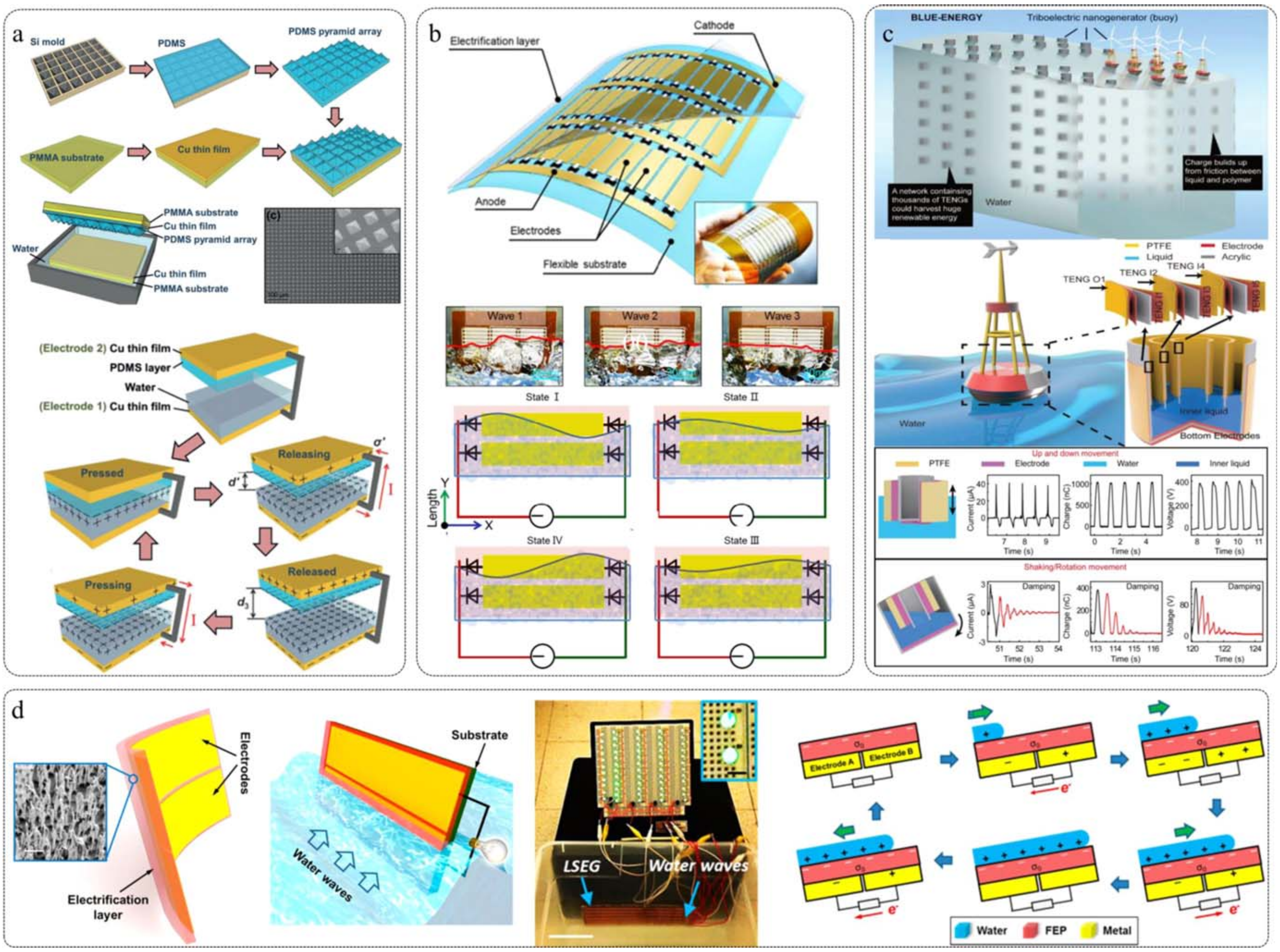

Figure 14. Typical TENGs based on a solid–liquid contact. (a) Fabrication process of patterned PDMS pyramid array and the related device. (Reproduced with permission from [141]. Copyright 2013 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (b) Schematic of the output current characteristics of a network-capable integrated triboelectric nanogenerator (NI-TENG) activated by different types of water waves. (Reproduced with permission from [142]. Copyright 2018 American Chemical Society). (c) Schematic of the output signals the network of the buoy TENG. (Reproduced with permission from [143]. Copyright 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (d) Schematic of the electricity-generating process of a LSEG (liquid–solid electrification-enabled generator). (Reproduced with permission from [144]. Copyright 2014 American Chemical Society).

the WF-TENG and the bottom of the spherical shell, which can maximize space utilization and minimize electrostatic shielding. With a wave frequency of 1.4 Hz and wave height of 10 cm, the single spherical WF-TENG reaches a peak power of 6.5 mW, and it can be integrated into a self-charging TENG network for large-scale ocean energy collection as well. Based on sliding electrification, a case-encapsulated triboelectric nanogenerator (cTENG) is shown in figure 15(b), which converts mechanical energy into electrical energy during reciprocating movement in the ocean [32]. With grating patterns on the electrode, the cTENG relies on the sliding surface to allow two cylindrical structures to move relatively on the same axis, while PTFE nanoparticles exist between the contact surfaces to achieve a higher degree of energy conversion. When cTENG slides at 1 m s^{-1} for a distance of 3.8 cm, the output charge is 12.7 μC and the average output power is 12.2 mW. As shown in figure 15(c), the completely encapsulated TENG proposed, the instantaneous output power of the 6 cm spherical TENG with a multi-electrode arrangement is 10 mW, which is sufficient to charge a series of supercapacitors within a few hours [148]. The TENG is an effective approach to achieve large-scale ocean energy harvesting, as the natural frequency of a conventional TENG design is in accordance with the vibration frequency of water waves (>10 Hz), and the rolling structure is lightweight enough to harvest energy from low-frequency wave motion. In addition to the structural design, breakthroughs in the material used have proven to be an important direction in the research of TENGs as well. A TENG with a silicone rubber/carbon black composite electrode [33], as shown in figure 15(d), is able to make contact with dielectric membranes. This coupled flexible electrode and spring structure provide a new strategy for TENG device research through adjusting the triboelectric material, structure, and triboelectric surface area.

Figure 15 shows the general encapsulated designs of TENGs, most of which are spherical, cuboid, and common three-dimensional cubes. Therefore, some TENG-based

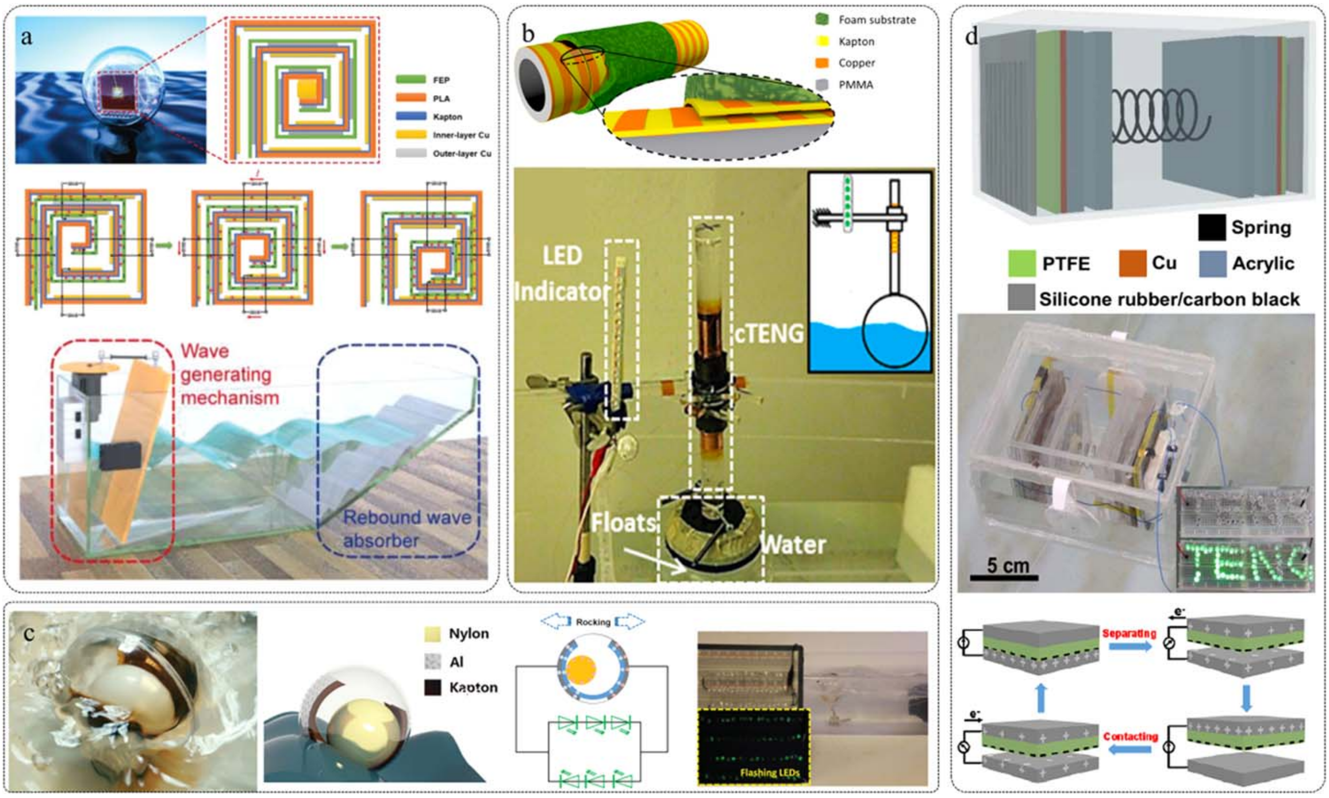

Figure 15. TENGs based on a fully encapsulated structure. (a) Schematic of a TENG floating on the water and the water tank used to generate water waves. (Reproduced with permission from [147]. Copyright 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (b) Schematic of a cTENG and its application. (Reproduced with permission from [32]. Copyright 2014 American Chemical Society). (c) Device structure, basic operations, and working principles of the RF-TENG with a rolling nylon ball enclosed. (Reproduced with permission from [148]. Copyright 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (d) Schematic illustration of silicone-based and spring-assisted TENG devices and the working principle of the TENG. (Reproduced with permission from [33]. Copyright 2018 American Chemical Society).

mechanical structural designs are shown in figure 16. Different from the vulgaris structure, the butterfly-inspired triboelectric nanogenerator (B-TENG) designed by Lei (see figure 16(a)), the circular arc design can produce two vibratory motions, which can better satisfy the direction of water wave propagation [149]. Moreover, the B-TENG has higher efficiency under various conditions of oscillation, which can directly drive 70+ LEDs and commercial thermometers with electric double-layer supercapacitors. Furthermore, a stacked pendulum-structured TENG based on the pendulum principle is shown in figure 16(b), which achieves regional contact by maintaining a compact disk-track structure for the rolling motion, thus improving the efficiency of the triboelectrification and output power in slow moving water waves [150]. Since the friction force rises according to the design of the contact area, the output performance can reach a peak power density of 14.71 W m^{-3} and an average power density of 1.05 W m^{-3} in waters with a frequency below 0.5 Hz.

For a long time, people have been inspired by structural designs found in nature, most of which are bionic structure. For example, the kelp-inspired bio-inspired triboelectric nanogenerator (BI-TENG), shown in figure 16(c), has excellent flexibility and bionic characteristics and can imitate kelp's swinging posture in the ocean to harvest the energy of low-frequency oscillation [151]. Even at the frequency of 1 Hz, the BI-TENG can also work stably and gains the maximum VOC and Isc (260 V and 10 μA, respectively). Correspondingly, based on the biological inspiration of jellyfish behavior, a practical bionic-jellyfish TENG is shown in figure 16(d), which has a good shape adaptability, air tightness, and a unique elastic resilience structure [152]. This resilience allows the detection of water levels and fluctuation by the slight deformations of a pressure-induced air–water interface, and even has the potential to develop a wireless self-powered undulation sensor warning system.

6.3. Harvesting of wave energy by networks of TENGs

Reliance on a single energy harvester plays a negligible role in obtaining a large amount of ocean energy, so the TENG network was developed to offset the energy consumption of the world through harvesting large-scale ocean energy, both on the surface or in the water. Figure 17(a) shows that a TENG with a sandwiched structure largely enhances the charge density of the contact electrification by creating PTFE nanowire arrays on the exposed surface [17]. In addition, a TENG can be connected on a large scale to form a network and used as a supporting substrate for integration with other energy harvesters. The fully encapsulated duck-shaped TENG

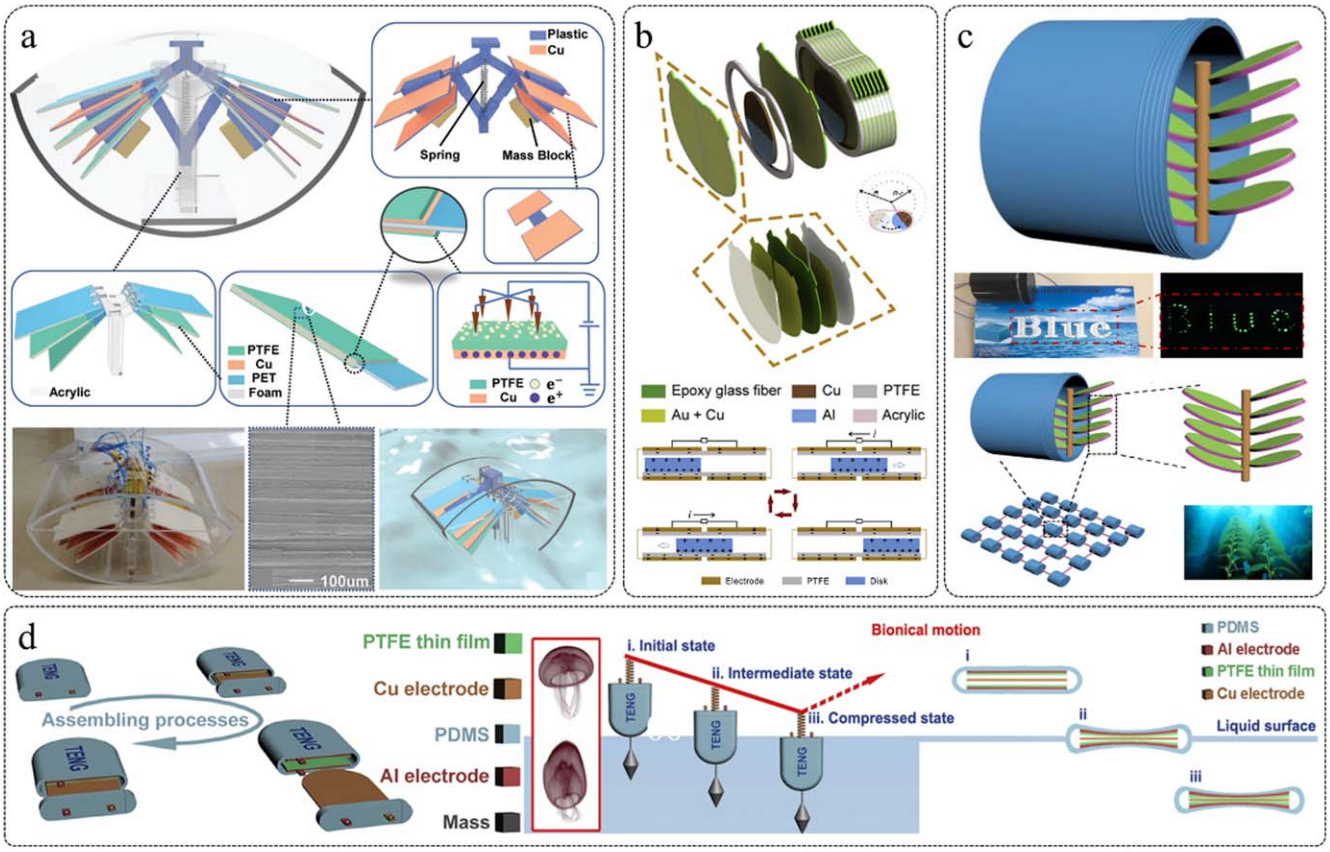

Figure 16. TENGs with typical structural designs. (a) Schematic of a B-TENG device. (Reproduced with permission from [149]. Copyright 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (b) Structure and working principle of the PS-TENG device. (Reproduced with permission from [150]. Copyright 2019 Elsevier Ltd). (c) Schematic of a TENG unit, the kelp-inspired TENG design, and the networks. Images of a kelp plant. (Reproduced with permission from [151]. Copyright 2018 Elsevier Ltd). (d) Schematic of a B-TENG and its application as a self-powered fluctuation sensor. (Reproduced with permission from [152]. Copyright 2017 Elsevier Ltd).

combines a freestanding rolling mode with a pitch motion, as illustrated in figure 17(b) [34]. The gravity center of the duck-shaped structure enables the TENG to reverse to a pre-determined time in the working position in the continuously moving ocean. When used as the multilayered duck, it can reduce maintenance costs and maintain a relatively stable system. The sea snake-based TENG with charged PTFE balls, as shown in figure 17(c), can decrease the electrostatic induction and figure out the effect of dielectric shielding through the air gap structure even in a high salinity water environment [35]. With the springs integrated into different segments, the TENG can be designed to bend flexibly and move quickly to produce a higher voltage and power density.

The dodecahedron device shown in figure 17(d) is integrated with 12 sets of wavy-structured robust TENGs with sandwich structures. If the units are integrated into a network, the average output power can reach 0.64 MW in an ocean with an area of 1 km^2 and a depth of 5 m [36]. As can be seen in figure 17(e), a spherical-shaped water-based triboelectric nanogenerator (SW-TENG) with a double layer on its internal and external surface is presented, which can obtain the wave energy in different directions by its highly symmetrical feature [153]. Unlike the typical hard ball design, the internal SW-TENG water mass design is well suited for water wave energy collection because of its 3D symmetrical structure, which allows energy to be collected more efficiently from any direction. At the same time, the SW-TENG can form a network on the surface of the ocean as power sources for sensors to build wave energy farms. A coupled design for a unit based on the ball-shell structured TENG is shown in figure 17(f) [154]. The rationally connected units can multiply the output and allows the TENG to have flexible connections between individual units. After the silicone rubber ball in the TENG is removed by ultraviolet light, the difference of the electron affinity to the ball and the dielectric layer seems to change, which enhances the triboelectrification effect. The TENG network can achieve a better output performance by using a modified connecting method at a large scale.

Liu *et al* reported an oblate spheroidal TENG is assembled from two TENG parts, as shown in figure 17(g), the upper parts with spring steel plates and lower parts with polymer films [155]. Besides, there is a rolling ball working in all-weather ocean conditions including calm and rough surfaces. Compared with the traditional spherical shell, this oblate spheroidal shell structure guarantees the high sensitivity of the lower part and the single upper part of the TENG can achieve a VOC of 281 V and an Isc of 76 μA. In figure 17(h), assembly joints made from magnets further

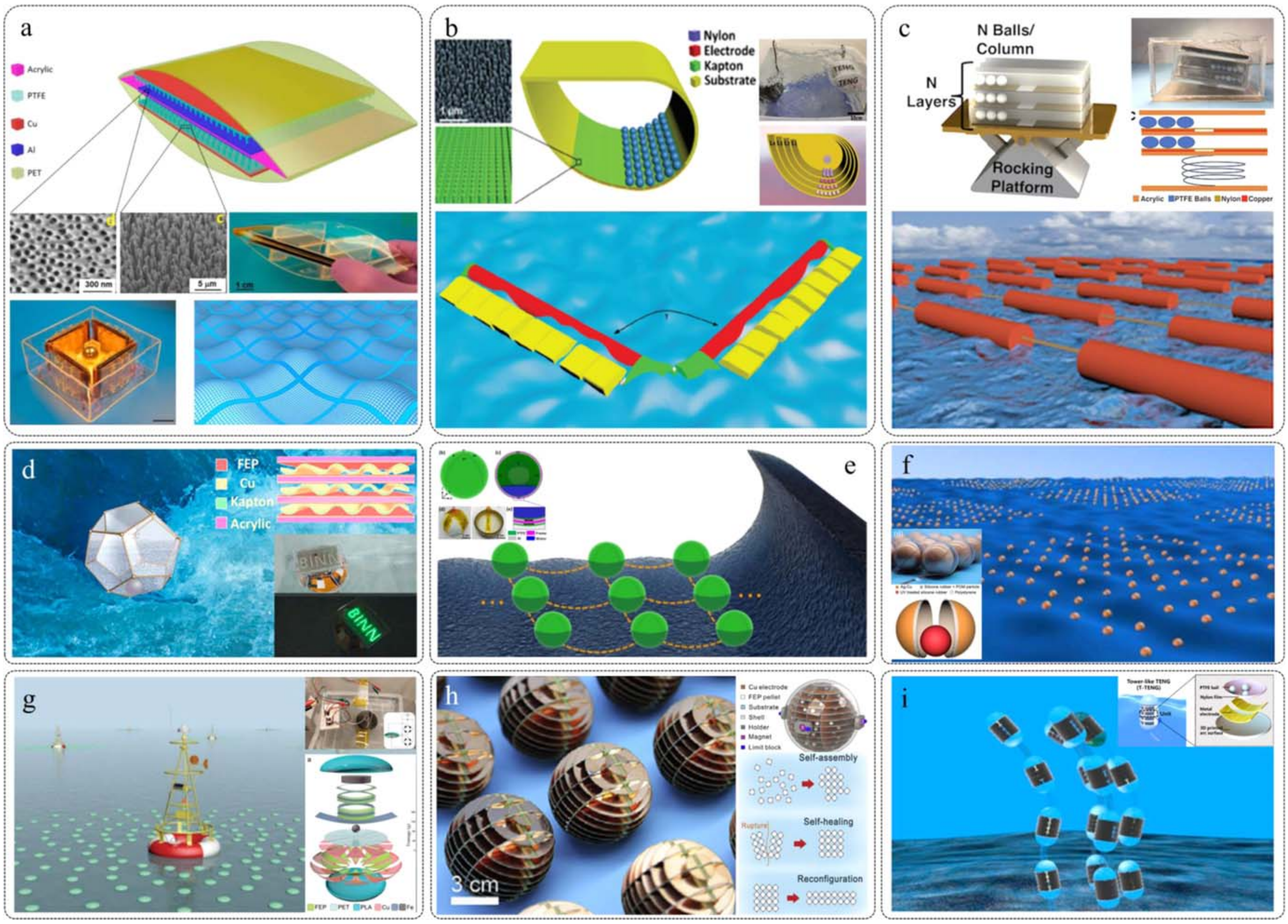

Figure 17. Networks of TENGs. (a) Schematic and photograph of a TENG with a SEM image of its nanopores on an aluminum electrode. (Reproduced with permission from [17]. Copyright 2015 American Chemical Society). (b) Schematic of a freestanding duck-shaped TENG based on rolling contact. (Reproduced with permission from [34]. Copyright 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (c) Array of Pelamis snake TENGs on an ocean energy farm. (Reproduced with permission from [35]. Copyright 2018 Elsevier Ltd). (d) Schematic and photograph of an SW-TENG. (Reproduced with permission from [36]. Copyright 2016 Elsevier Ltd). (e) Schematic of an SW-TENG and conceptual drawing of the SW-TENG array on a water surface. (Reproduced with permission from [153]. Copyright 2017 Elsevier Ltd). (f) Schematic of a TENG unit and an illustration of a potential future large-scale TENG network. (Reproduced with permission from [154]. Copyright 2018 American Chemical Society). (g) Schematic of the oblate spheroidal TENG and its network. (Reproduced with permission from [155]. Copyright 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (h) Schematic illustration of the self-assembly, self-healing, and reconfiguration of a TENG network. (Reproduced with permission from [156]. Copyright 2019 Elsevier Ltd). (i) Schematic of a T-TENG and its network-like arrays. (Reproduced with permission from [157]. Copyright 2019 American Chemical Society).

optimize the connection mode of the TENG network based on figure 17(f), which allows each TENG independent unit to be self-assembled, self-repaired, and flexibly configured. Hence, this adaptive mechanism can work well in bad weather [156]. A TENG for ocean energy collection is inevitably affected by humidity and dielectric shielding. Xu *et al* designed a T-TENG, as shown in figure 17(i), which can harvest wave energy in any direction by rolling charged balls over the arc surface with a nylon film [157]. The T-TENG does not need to adjust the phase of individual units independently because of the PTFE balls in the identical module after connecting are able to move in the same phase, and the power density of a single T-TENG is up to $1.03\ \mathrm{W\ m^{-3}}$. These TENGs with diversified structures for water wave energy collection open up a promising approach for the better utilization of ocean energy and ocean related sensor techniques.

7. TENGs for hybrid energy

A TENG has also been developed for collecting multiple types of energy from surrounding environments, which is also an important research direction in the study of the TENG [158–160]. There are two broad categories of TENGs for hybrid energy. The first one is to use the same triboelectrification effect to collect multiple types of mechanical energy. The other one is to combine a TENG with other energy-harvesting devices to harvest hybrid energy based on more than one physical principle [161]. For example, heat can be captured by thermoelectric devices and pyroelectric nanogenerators, which are sensitive to temperature changes in the environment. Meanwhile, thermoelectric devices can be integrated with a TENG to harvest the generated heat during the tribo-motions. In addition, EMGs are usually combined

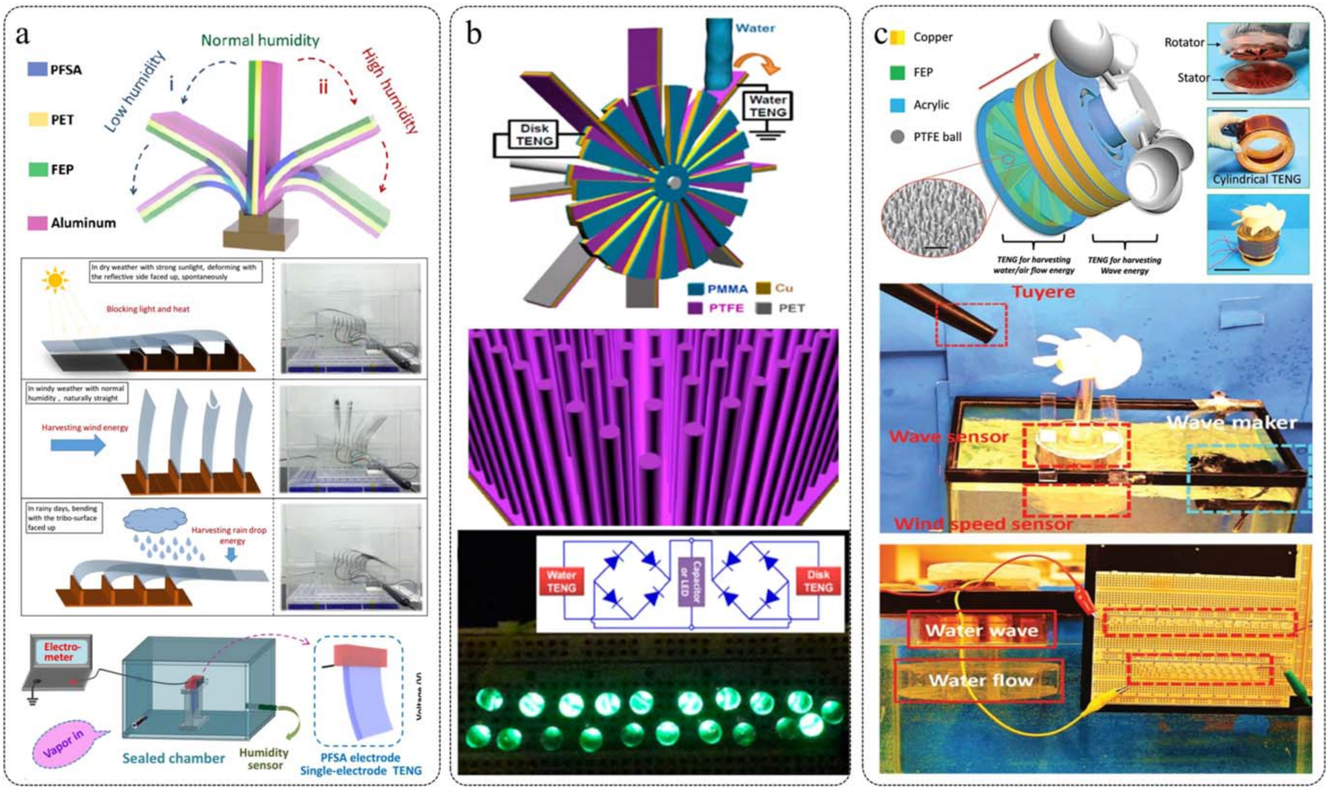

Figure 18. Multiple energy collection unit based on multi-mode TENGs. (a) Schematic configuration of a TENG and photographs of a TENG array applied in in dry, windy, and rainy weather with three functions. (Reproduced with permission from [166]. Copyright 2019 American Chemical Society). (b) Structural diagram of a hybridized TENG and photographs of 20 commercial LED bulbs driven by a hybridized TENG at a water flow rate of 54 ml s^{-1}. (Reproduced with permission from [167]. Copyright 2014 American Chemical Society). (c) Structural design and application of a multifunctional TENG. (Reproduced with permission from [168]. Copyright 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

with a TENG, in order to achieve better energy conversion efficiency for harvesting mechanical energy [162, 163]. However, the coupled system based on an EMG and a TENG is still collecting mechanical energy in the environment. Hence, we did not prepare a separate chapter to introduce this part.

7.1. Multifunctional TENGs

Multifunctional TENGs present a promising method for energy collection and other applications, as well as for the development of more intelligent IoTs. In order to adapt to different types of environmental energy, the TENG needs to modify its structure and it is difficult to harvest different types of mechanical energy (vibration, wind, raindrop, and so on) with a fixed TENG structure [164, 165]. Hence, a deformable TENG is developed to serve this demand. The vapor-driven actuation material based on provolone acid ionomer can help TENG arrays automatically adjust their bending angles. The TENG array generates energy from wind and raindrops under different weather conditions and different levels of humidity as shown in figure 18(a) [166]. The steam absorption process of a PSFA film may result in the accumulation of a surface charge on the film, and the two-mode TENG can be a steam sensor to identify variations in the concentration of various chemical vapors and monitor humidity changes. As can be seen from figure 18(b), the multifunctional TENG with a water wheel structure consists of the w-TENG and the disk-TENG, which can be used to collect energy from both streams and wind flow [167]. PTFE nanorods cover the surface of PTFE films, which equips a TENG with superhydrophobicity. When a TENG is driven by water at a flow rate of 54 ml s^{-1} or wind at 1.7$\sim$15.1 m s^{-1}, it can reach a VOC of 72 and 102 V, respectively. The other multifunctional TENG consists of a rotation TENG (r-TENG) and a cylindrical TENG (see figure 18(c)), which can harvest different types of energy like water waves, water flowing, and wind simultaneously [168]. TENGs with freestanding models are designed to generate VOCs of 490 and 100 V with Iscs of 24 and 2.7 μA, respectively. In addition, as shown in the figure, the output current signal of the r-TENG can change almost linearly with the wind speed, which makes it possible to be a self-powered wind-speed sensor.

7.2. TENGs and SCs

Recently, carbon-free energy is often mentioned as a method to use to mitigate climate change, and many technologies have been designed to capture carbon-free energy [168, 169]. Among them, SCs are considered a promising candidate because of their high energy conversion efficiency. However, SCs depend heavily on weather conditions [170]. If exposed

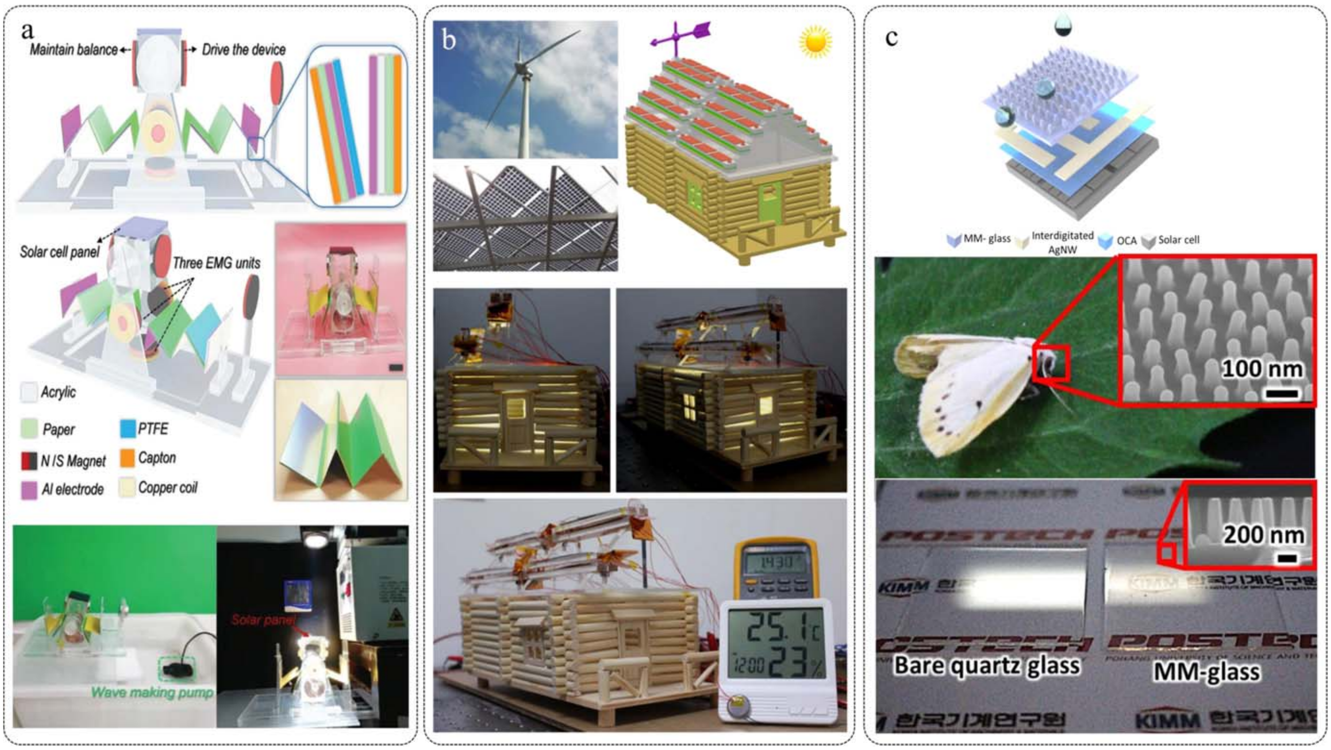

Figure 19. A hybrid nanogenerator combined with SCs and a TENG. (a) Structural design of the hybridized generator consisting of one solar panel, and two zigzag multilayered TENGs with four basic units and three EMG units. (Reproduced with permission from [39]. Copyright 2018 American Chemical Society). (b) Schematic of integrated hybridized nanogenerators on the roof of a house model. (Reproduced with permission from [16]. Copyright 2008 American Chemical Society). (c) Schematic of an MM-TENG with a mirror transmittance of 91% of visible light. (Reproduced with permission from [158]. Copyright 2008 American Chemical Society).

to rain or darkness for a long time, SCs may lose their normal functioning. Hence, various solutions have been proposed to overcome this obstacle, one of which is to combine SCs with complementary energy harvesters such as a TENG [171]. Unlike the commonly encapsulated TENG which is difficult to degrade, as shown in figure 19(a), a nonencapsulated pendulum-like paper-based HNG has the ability to integrate a solar panel and two paper-based TENGs with three EMGs [39]. The paper-based design can effectively improve the volume utilization rate of the equipment and avoid the complex work of equipment maintenance and disassembly. Figure 19(b) shows that the HNG that can be applied on the roof of an urban building to harvest solar/wind energy and provide effective lighting for the building or power for some indoor sensors without being affected by sunlight [16]. This integrated HNG can scavenge energy to drive temperature and humidity sensors. On the surface of SCs, a transparent material is fabricated to insulate the panel from contaminants, which provides less energy loss for HNGs. As can be seen in figure 19(c), a moth's eye mimicking TENG (MM-TENG) with a mirror transmittance of 91% of visible light is combined with an SC and a water-based TENG [158]. The periodic structure of the tapered nanopillar periodic structure in the moth's eye has anti-reflection properties, which give this TENG excellent light transmittance. This transmittance can mitigate the degradation of the optical performance caused by the water-based TENG. Therefore, the MM-TENG has a higher solar transmittance than the protective glass panels of conventional solar panels, and its self-cleaning properties also increase the life of solar panels.

When a TENG is combined with SCs, mutual influence is inevitable. While the presence of a TENG may affect the light absorption of SCs, SCs may also reduce the diversity of the TENG's structural design. But in the end the HNG achieves an output performance greater than that of a single unit. With the development of HNGs, the defects caused by the combination of the two are being continually improved. For example, Liu *et al* used a bifunctional nanometer folding material as the reflection layer between the TENG's friction layer and the SC, which enhanced the light transmittance [172].

7.3. Triboelectric-piezoelectric/pyroelectric nanogenerators

In the natural environment, due to the temperature changes caused by weather and time, the existence of thermal energy with uncertainty and randomness can be collected by thermoelectric devices. Piezoelectric and triboelectric effects can be utilized to harvest irregular mechanical energy from the natural environment, and the thermoelectric effect is applied to harvest thermal energy from temperature fluctuations in the environment [40, 41, 159, 173, 174]. Therefore, the HNG is based on the combination of these effects that can harvest both thermal and mechanical energy. Yang *et al* proposed a hybrid energy unit that consists of a TENG manufactured with a flexible PDMS nanowire array at the top and a

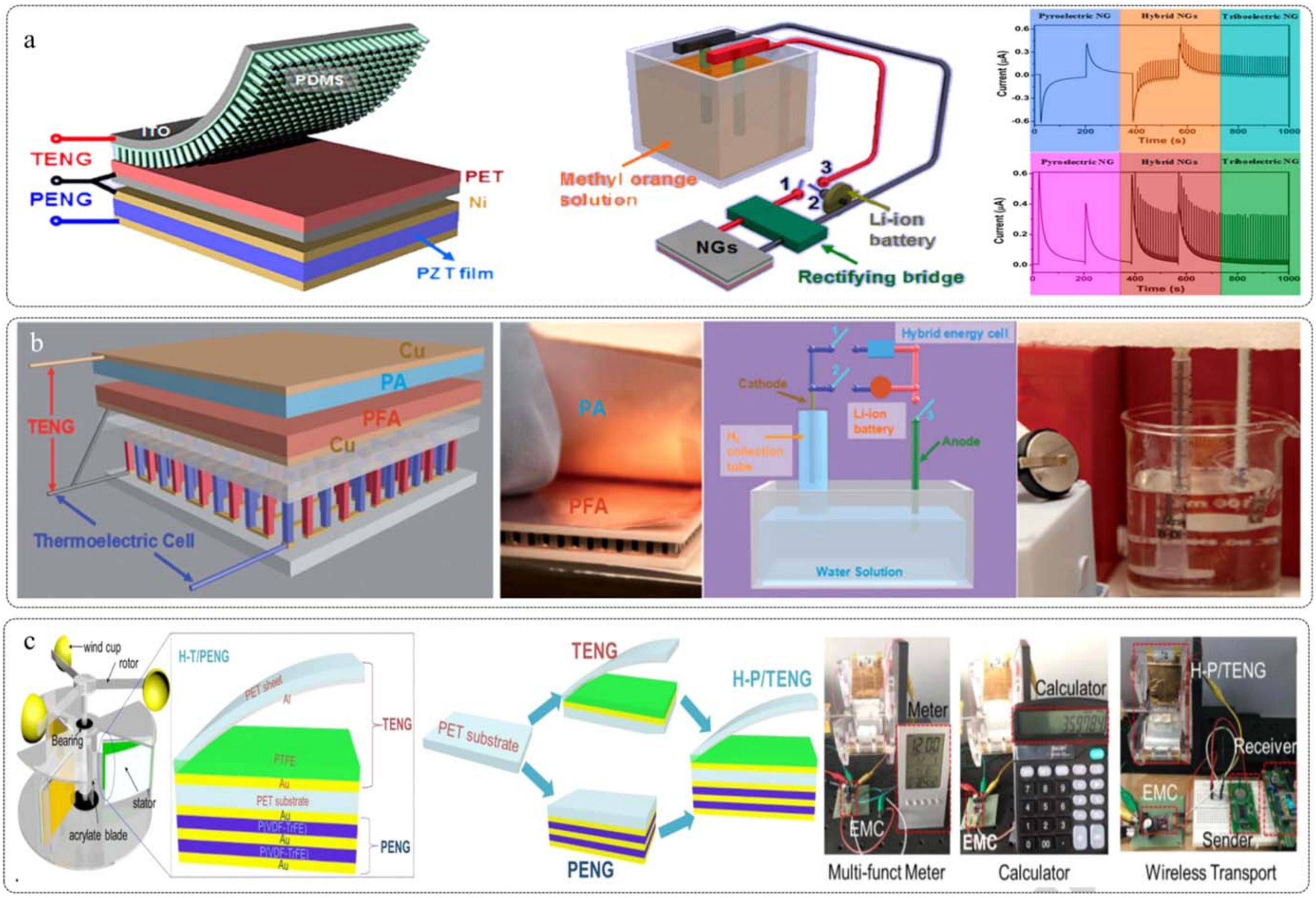

Figure 20. Triboelectric-piezoelectric/pyroelectric nanogenerators. (a) Schematic of a fabricated hybrid energy cell and the self-powered electrodegradation of MO. (Reproduced with permission from [175]. Copyright 2013 American Chemical Society). (b) Schematic of a fabricated hybrid energy cell including a TENG and a thermoelectric cell. Reproduced from [176] with permission from the Royal Society of Chemistry). (c) Fabrication process and schematic illustration of an H-P/TENG. (Reproduced with permission from [177]. Copyright 2018 Elsevier Ltd).

pyroelectric nanogenerator based on PZT membrane at the bottom (see figure 20(a)), which can harvest mechanical energy and thermal energy, respectively [175]. The Isc of the hybrid energy cell is shown in figure 20(a), while the TENG and pyroelectric nanogenerator can work independently. This composite energy unit has potential applications in the electrodegradation of methyl orange and corrosion protection. Yang *et al* also proposed an integrated system which combines three basic principles of triboelectrification from the contact-separation mode of a TENG's different materials, Seebeck effects from thermoelectric cells, and optoelectronic effects from SCs (see figure 20(b)) [176]. In addition to harvesting mechanical energy and solar energy in the environment, it can harvest thermal energy as well. Besides, the self-powered water decomposition system has proved that the hybrid energy battery can be directly used to decompose water to produce hydrogen. One of the important factors hindering the output performances of HNGs is a mismatched impedance, which can be solved by a hybrid piezo/triboelectric nanogenerator (H-P/TENG), as shown in figure 20(c). The impedance can be adjusted based on the selection and the combination of different piezoelectric polymers/composites/nanofibers. Moreover, the H-P/TENG can be used to scavenge wind energy with cups and provide a high output voltage and current of 210 V and 395 μA [177].

8. Summary and outlook

In this review, a TENG for harvesting environmental energy is systematically summarized from the material selection, the structures of the device, the working principle, and the development as well as its applications for varied situations. The TENG technology that targets various environmental energies is widely used in the application of the energy storage unit, which can be omnipresent in the era of the IoT and sensor networks. Besides, hybrid nanogenerators of a TENG and other forms of power generators have also been developed for breaking technology boundaries and providing an innovative approach. On the other hand, some common qualities and challenges exist simultaneously. Generally speaking, the advantages shared by these TENG-based energy harvesters including easy fabrication, being an abundant natural source, and high output, make them potentially preferable for energy conversion and harvesting. Moreover, the distinguishing features and the unique advantages of TENG

Table 1. A summary of the triboelectric materials and output performance of various WD-TENGs.

Structures	Triboelectric materials	Voltage (V)	Current (μA)	Power	Wind speed ($m\ s^{-1}$)	References
Rotational sweeping mode	Al and PTFE	250	250	12 mW	15	[94]
Double-side-fixed mode	Kapton and PTFE	342	140	$9\ kW\ m^{-3}$	15	[79]
Single-side-fixed mode	Al/Ti and Kapton	396	75	5.5 mW	18.4	[78]
Double-side-fixed mode	Al/Ti and PTFE	342	66	3.4 mW	18.4	[80]
Contact-sliding mode	Al and PTFE	90	$0.5\ mA\ m^{-2}$	$16\ mW\ m^{-2}$		[20]
Single-side-fixed mode	Al and FEP	100	1.6	0.16 mW	10	[21]
Pendulum inspired TENG	Cu and PTFE	56	3.4		>2	[22]
Rotating TENG	Cu and Kapton	320	3.4 mA			[88]
Double-side-fixed mode	Ag and nylon	130	7.5	0.22 mW		[23]
Leaves based TENG	Cu/leaf powder and PVDF	1000	150	17.9 mW	7	[90]
Vertically stacked thin TENG	AI and PDMS	21	0.14	0.903μW	25	[91]
Single-side-fixed mode	ITO and PET	98	16.3	2.76 mW		[93]
Venturi triboelectric energy harvester	Cu and PTFE	150	16	4.5 mW	5	[95]
Diversely evolved hyper-branched structure	Cu and feather	64.3	6.55	263 mW	7	[96]
Single-side-fixed mode	Au and PTFE	200	60	0.86 mW	15	[97]

harvesting different environmental energy are summarized in the following.

8.1. Wind energy

The conventional electromagnetic wind generator was developed many years ago, while a complete and mature system for harvesting wind energy had already been established. In comparison with a conventional wind generator, the WD-TENG has excellent advantages including low cost, lightweight, and flexible assembly, although the output power is lower. More importantly, the conventional electromagnetic wind generator cannot work efficiently with low-speed wind ($< 5\ m\ s^{-1}$), while a TENG can effectively harvest energy from this tiny and discontinuous wind. Up to now, the output voltage and current ranges of a WD-TENG are 21∼1000 V and 0.14 μA∼3.4 mA (according to table 1), respectively. Researchers have proposed an assumption: if multideck lawn structured TENGs can be installed on the tops of houses, the entire mechanism is expected to reach a power density of $23.7\ W\ m^{-2}$ which can supply the power needed for domestic electronics.

8.2. Raindrop energy

So far, the best option for collecting mechanical energy from the motion of the raindrop is the TENG-based harvester, since the TENG has the advantages needed to collect these tiny and random motions. The hydrophobic surface, which is a key factor in obtaining continuous and rapid rolling of raindrops on the RD-TENG, is the basic treatment for a TENG to collect raindrop energy. Meanwhile, a surface with many other special functions, including self-cleaning, anti-sticking, anti-contamination, and so on, can all be applied for an RD-TENG. Among the papers referred in this review, the power density of the TENG is usually on the scale of a dozen milliwatts per square meter, which is enough to support some low consumption devices.

8.3. Sonic energy

In addition to power generation, the SD-TENG with the higher conversion efficiency can be used as self-powered acoustic sensors with a very high sensitivity to micro-vibration. The application of a TENG-based sonic sensor may have greater application prospects than pure energy generation applications. According the paper by Chen *et al* published in 2019 [31], the output power density of an SD-TENG can reach $7\ W\ m^{-2}$ under a sonic wave of 170 Hz and 115 dB, which is so far the highest output value in this review. The self-powered capability and ultrahigh sensitivity of a TENG can be applied in safety monitoring, sensor networks, military surveillance, and environmental noise reduction.

8.4. Ocean energy

The TENG for ocean energy harvesting has attracted the attention of many researchers and has resulted in a series of breakthroughs in structural designs, output performance as well as the network optimization has been continuously reported in recent years. The most significant characteristic of ocean energy is related to its low motion frequency, which can also be considered as the ultimate application of the TENG. So far, the highest output power density from the ocean TENG reaches $12.4\ W\ m^{-3}$ which is noteworthy, and may be further increased in near future.

8.5. Hybrid energy

This work presents a new stage of hybrid generators aimed toward multiple energy harvesting as a practical portable power source, which has the potential problems in the coupling effect and impedance matching as well. Based on different physical effects and mechanisms, different energy units are generally combined by parallel connections or a rectifier circuit to achieve the energy density of 2.04~42.6 W m^{-2} that is higher than a single unit. Therefore, designing a hybrid energy device is also significant for simultaneously or individually harvesting environmental energy to the maximum extent and compensating for the drawbacks of each method.

In the future direction of the development of TENGs in large-scale energy harvesting from the environment, TENGs are not expected to be used to replace current mature energy-harvesting technologies, but are expected to complementarily solve future energy needs as new technological approaches. Toward achieving energy demand, future research on the following aspects of technical obstacles need to be resolved primarily:

(1) The selection and durability of materials should be addressed. The fundamental performance of materials determines the work range and the output power of devices. The abrasion of materials during triboelectrification, especially in some harsh environments, reduces the life of the equipment. The efficiency of the charge transfer to the dielectric and the capability of charge retention in the dielectric are both related to material selection. More importantly, polymer thin films are often used as friction layers for a TENG, which are difficult to degrade naturally and may cause irreversible damage to the ecological environment. The use of environmentally friendly and degradable materials for a green TENG design is also important to cater to the contemporary theme of energy conservation and environmental protection.
(2) Low output performance is the bottleneck for practicability of TENGs. Various methods that can improve the output power have been deliberate and reported, such as increasing the number of energy cycles by designing the number and pitch of grid electrodes, reducing the thickness of the dielectric layer, designing the structure of spacers, and so on. In addition, the output power density can be decided by the mismatch impedance of hybrid generators which can be settled by using a commercial transformer and abundant selections of various piezoelectric polymers/composites/nanofibers to adjust the impedance of the TENG. Other critical factors affecting the output performances like the driving frequency and phase difference should also be further developed with better solutions.
(3) The study of the conversion of natural energy to electricity should not only focus on the input conversion efficiency which depends on the optimization of materials and structural designs but also concentrate on the power management of output signals. According to different current parameters and TENG systems, effective power management can achieve maximum energy transfer and power management during the process of energy storage and management, and transportation is the key point for achieving an effective self-powered functional system. Meanwhile, competent power management can offset some of the energy loss caused by the TENG's high output impedance, which is conducive to the effective integration of a TENG with other energy collection technologies.

Although these unresolved issues and tough challenges have seriously hindered the development process of TENGs, their potential prosperity and promising distributed applications make their development a compelling trend of this era. Through showing an overview of this technology, the TENG is expected to attract more attention in this field and encourage more in-depth investigations and profound discoveries.

Acknowledgments

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