Chapter

Triboelectric Nanogenerators: Design, Fabrication, Energy Harvesting, and Portable-Wearable Applications

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Abstract

Scavenging energy from our day-to-day activity into useful electrical energy be the best solution to solve the energy crisis. This concept entirely reduces the usage of batteries, which have a complex issue in recycling and disposal. For electrical harvesting energy from vibration energy, there are few energy harvesters available, but the fabrication, implementation, and maintenances are quite complicated. Triboelectric nanogenerators (TENG) having the advantage of accessible design, less fabrication cost, and high energy efficiency can replace the battery in low-power electronic devices. TENGs can operate in various working modes such as contact-separation mode, sliding mode, single-electrode mode, and free-standing mode. The design of TENGs with the respective operating modes employed in generating electric power as well as can be utilized as a portable and wearable power source. The fabrication of triboelectric layers with micro-roughness could enhance the triboelectric charge generation. The objective of this chapter is to deal with the design of triboelectric layers, creating micro structured roughness using the soft-lithographic technique, fabrication of TENGs using different working modes, energy harvesting performance analysis, powering up commercial devices (LEDs, displays, and capacitors), and portable-wearable applications.

Keywords: triboelectric nanogenerators, micro-roughness, soft-lithography, TENG working modes, portable-wearable

1. Introduction

In the last few decades, the boom in consumer electronics rapidly creates the need for a sustainable portable and wearable power source. There are too many low-power electronic devices that are introduced to enhance the quality of our life, such as sensors, communication devices, GPS devices, implantable, and health monitoring devices [1–4]. All these electronic gadgets require electric power in the range of few microwatts to milliwatts. With the invention of batteries, these devices can use in various portable applications. However, the drawback in batteries limits the purpose and be an obstacle to miniaturize the sensors. As per the batteries in concern, the batteries require periodical replacement, and the recycling of batteries is still a significant challenge. The precursor used for the fabrication of the batteries is highly hazards to human life and creates pollution to the environment [5]. The disposal has many concerns regarding soil and water contamination as they contain a lot of heavy metals. The future of electronics depends on the portable and wearable sensors such as flexible electronics [6, 7], e-skin-based sensor devices [8], and implantable bio-medical electronic systems [9]. Operating the low-power electronic devices, a sustainable and highly reliable power source is required. The power sources should scavenge power from waste mechanical energy. The majority of energy that we consume today is from many nonrenewable sources such as thermal power plants that operate on coal, and diesel power plants operating with the help of oil. These natural resources are limited in supply, and it takes thousands of years to regenerate. The usage of fossil fuels such as coal and oil in the generation of electricity creates massive pollution, and it leads to the reduction of life span to humans. To overcome this issue, an alternative energy harvesting approach had been introduced across the globe to protect humanity and overcome the growing energy crisis.

The conventional approach to generate electrical energy is by using an electromagnetic generator (EMG). These generators harvest effectively under the high frequency of mechanical energy inputs [10]. However, there is an abundant low-frequency mechanical energy around the globe as well as from various sources such as vibration, wind, water wave, human motions, and vehicle motions. These low-frequency motions cannot be harvested effectively using an EMG. The solution to this problem addressed in 2006 with the invention of nanogenerators (NGs) [11]. The NGs with various classifications and effects such as piezoelectric nanogenerator (PNG) [12–15], triboelectric nanogenerator (TENG) [16], thermoelectric generator (TEG) [17], and pyroelectric generator (PYG) [18] had been introduced in the past decades for a variety of energy harvesting and self-powered applications.

Furthermore, the energy harvesters are performing some real-time applications by integrating it with battery or other storage devices. Apart from energy harvesting, these NG can work as a self-powered sensors such as pH sensors [19], glucose sensors [20], chemical sensors [21], humidity sensors [22, 23], temperature sensors [24], air pressure sensors [25], motion sensor [26], optical sensor [27, 28], and strain sensors [29]. To enhance the output power of the TENG devices, researchers across the globe performed the hybridization of these devices and studied the possibility of its use in extensive applications. To be used for a wide range of applications, TENG-PENG [30] hybrid had been reported with high instantaneous power density. Similarly, there are many reports for scavenging the water wave energy by TENG-EMG hybrid configuration [31]. The generated output is much higher and can use for GPS tracking and positioning system. A similar concept is demonstrating by using magnetic particles instead of magnets in the EMG component [32]. The motion of particles activates the triboelectric part of the hybrid device. The issues that TENGs have faced so far are its bio-compatibility, performance reduction concerning humidity. The problems rectified by introducing a biodegradable, edible TENG [33], and a fully packed water-resistant TENG. The fully packed TENG [34] can protect the device from humidity issues and maintains its performance for a more extended period. The further advancements in NGs lead to the design of flexible electronic-skin-based devices for sensing various parameters, microfluidic-based devices [35], and other portable-wearable devices making NGs a sustainable power source. This chapter covers the basics of TENG, fundamental working modes of TENG and fabrication, and energy harvesting and its application in portable and wearable technologies.

2. Working modes of TENG

The mechanism behind TENG is triboelectrification and electrostatic induction effects; with the rapid advancement in the field of nanogenerators and TENG, the exploration leads to the investigation of fundamental working modes of TENG, which covers four basic modes. The modes include a vertical contact separation mode, linear sliding mode, single-electrode mode, and free-standing mode. These modes require two different triboelectric materials with proper electrode connections with proper insulation between each layer. The combination may be either dielectric-dielectric or metal-dielectric arrangements. The basic principle behind all the four modes is that whenever there is a displacement in any of the triboelectric layers, the electrostatic charge movements break the electrostatic status present, leading to the development of potential difference between the electrodes. In the repeated mechanical actuation of layers with forward and reverse direction makes the triboelectric layer to generate forward and reverse potential between the electrodes, making the positive and negative peaks in the TENG output generating the AC signal. The four different working modes are shown schematically in **Figure 1**.

2.1 Contact separation mode

In the contact separation mode TENG, the triboelectrification occurs by the contact and separation process of two triboelectric materials or layers, as shown in **Figure 1a**. The process may either happen between two different dielectric materials or may be a dielectric and metallic layers. This model has a significant advantage with its simple design, easy fabrication, and low cost. This mode of TENG is also the first developed and demonstrated for powering low-power electronics. This mode of TENG can also make as a multi-unit stacking for the enhanced output performance.

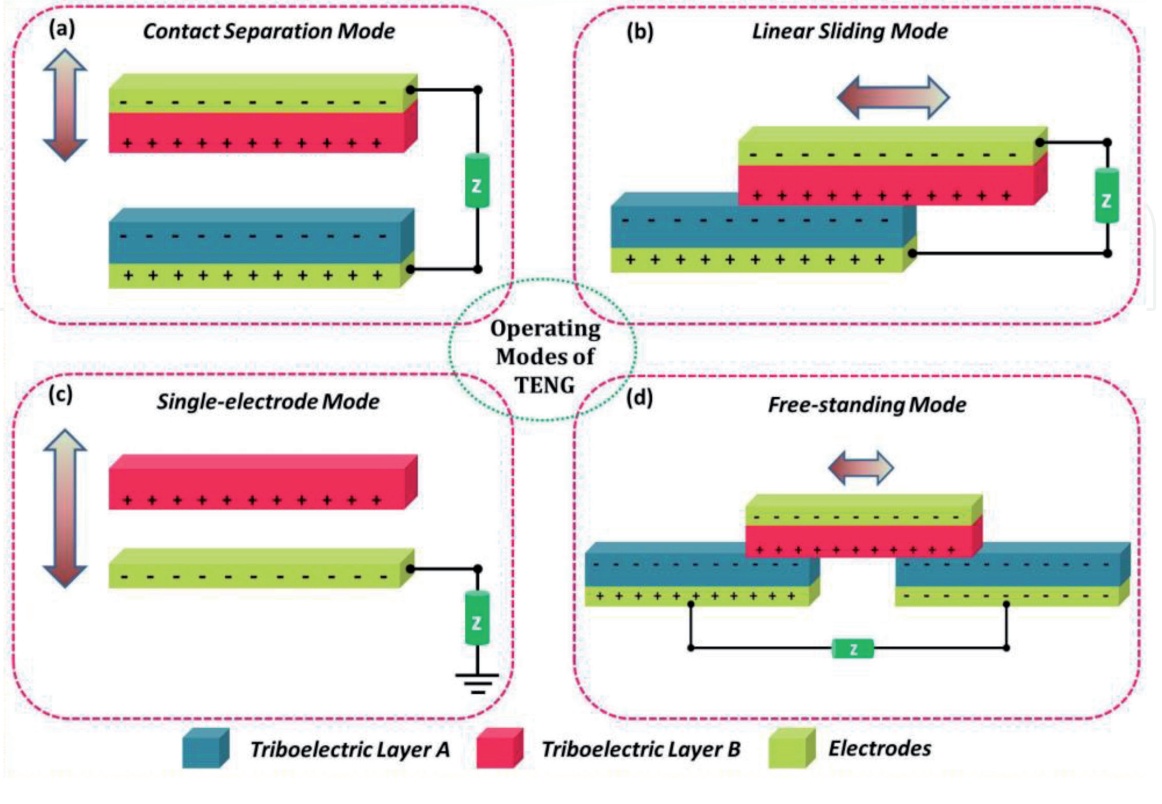

Figure 1.
Schematic representation of the four fundamental operating modes of TENG.

2.2 Linear sliding mode

In the linear sliding mode, the charge generation is by the relative to and from sliding between the layers of TENG. The construction is almost similar to the contact separation mode with electrodes attached to the back of the triboelectric layers, but the displacement is in sideward, as shown in **Figure 1b**. The sliding mode has a low figure-of-merits compared with the vertical contact separation mode due to its protracted displacement in the sliding process. The advantage of this mode is that it can generate more charge density with a highly effective charge generation due to its high contact area. Also, by introducing more grating structures, the output performance can be enhanced. The sliding mode TENG can also be able to operate rotationally with cylindrical grating structures.

2.3 Single-electrode mode

The simplest structure of TENG is the single-electrode mode TENG, but the output performance is too low due to the small charge transfer, making the generated voltage and current to be less, but it is highly suitable for self-powered applications. The advantage of this device is that it overcomes the application limitation due to the contact wire obstructing at both sides in the contact separation mode and sliding mode TENG devices. The basic arrangement of a single-electrode mode TENG is shown in **Figure 1c**.

2.4 Free-standing mode

The free-standing model has one electrode move freely between the two electrodes or triboelectric layers. The electrodes are in a static position, and a triboelectric layer without electrode can move over it. This mode of TENG device has a high figure-of-merits and has demonstrated high output efficiency and electrical output. Also, this type of device can be fabricated easily and integrated into various real-time applications. The necessary arrangement of a single-electrode mode TENG is shown in **Figure 1d**.

3. Progress in TENG

After the invention of TENG in 2012, the field becomes an extensive investigated field with a vast number of researchers working and improving it until today [36]. The first developed TENG device is a contact separation mode device with kapton and polyester as the active layers [7]. Further investigation TENG leads to the invention of other modes in 2013 [37]. The research trend on NGs started moving forward from energy harvesting to self-powered sensing and actuation. The transparent and flexible nanogenerators were fabricated and tested in the later stage with the application in e-skin and tactile sensing. The researchers' then working towards hybridizing the TENG with other energy harvesters such as PENG and EMG for scavenging wind and water wave energy efficiently and also had performed various real-time applications connected to environmental monitoring. Very recently, by adopting these explored TENG design and operation, liquid–solid interface TENGs and liquid–liquid TENGs had introduced for scavenging water droplet energy [38]. There had been a problem in TENGs and its electrical output concerning external factors such as temperature and humidity. Recently, the humidity issues got rectified by introducing a fully packed, waterproof TENG device by our group in 2019. In addition to biodegradable TENGs, an edible TENG made of regular food items

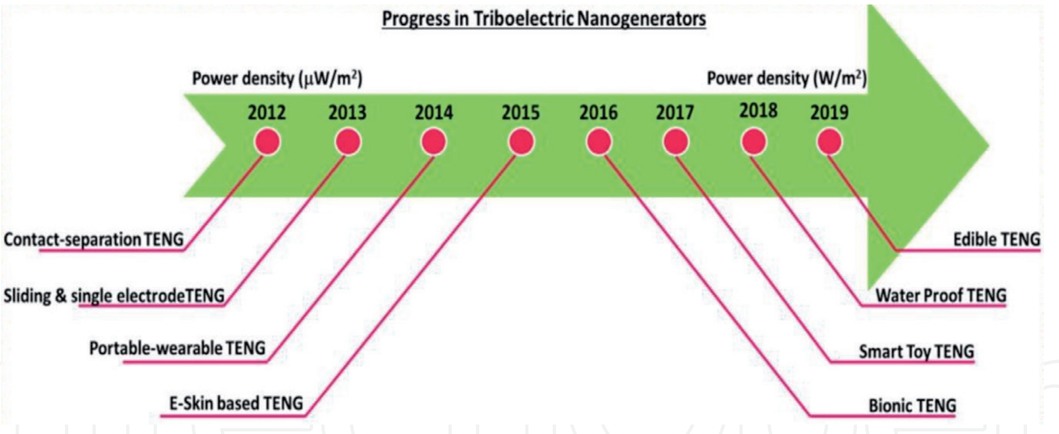

Figure 2.
Design and development of TENGs from its origin to date, with various device structures, applications, and performances.

was designed and fabricated by our group and demonstrated powering low-power electronic devices. Also, the first developed TENG device has a power density in the range of micro watts, and today, the device had reached the power density in watts. The increasing power density shows that the TENGs are reliable energy harvester and self-powered sensors which can able to commercialize shortly and to have a high possibility to replace batteries. **Figure 2** shows the road map, explaining the advancement of TENGs for various applications.

4. Fabrication of TENG device

The fabrication of a TENG device requires precise handling of the arrangement of triboelectric layers and electrodes. The improvement in the design of the TENG device is improving day-by-day. The triboelectric layer with a high surface roughness delivers high electrical output. The phenomenon is that the rough surfaces increase the contact points of the TENG device. Each micro/nano scale roughness interacts with the other triboelectric layer during its mechanical actuation. Therefore, the contact point multiplies the generated output as compared with the flat surface where the contact point is single. There are various approaches to creating surface roughness of the triboelectric layers, such as inductively coupled plasma etching, wet etching, lithographic technique, and casting. These techniques involve various advantages as well as disadvantages. The high-end lithographic and plasma etching techniques involve high-cost instruments and skilled operator, which is a disadvantage. There are various reports on simply creating surface roughness using cost-effective techniques such as using sandpaper as a mold. The sandpaper with more roughness as a mold for fabricating roughness created triboelectric layer, and the polymers such as PDMS and other silicon elastomer-based polymers poured on it, and with heat treatment, the polymer solution is then cured to form a polymeric film with microscale surface roughness. The other cost-effective technique reported is the surface modification of a used acrylonitrile butadiene styrene (ABS) polymer petri dish. The surface modification is done through wet etching using acetone as an etchant. The technique involves less time and a simple preparation process.

The ABS polymer petri dish is first washed with water and dipped in a beaker full of acetone for 90 s, as shown in **Figure 3a**, and the petri dish dried in an air atmosphere at room temperature. By this time, acetone etches the surface of the petri dish, creating micro-roughness on its surface, as shown in **Figure 3b**. The PDMS polymer is poured into the petri dish and cured in a hot air oven to get a polymeric film.

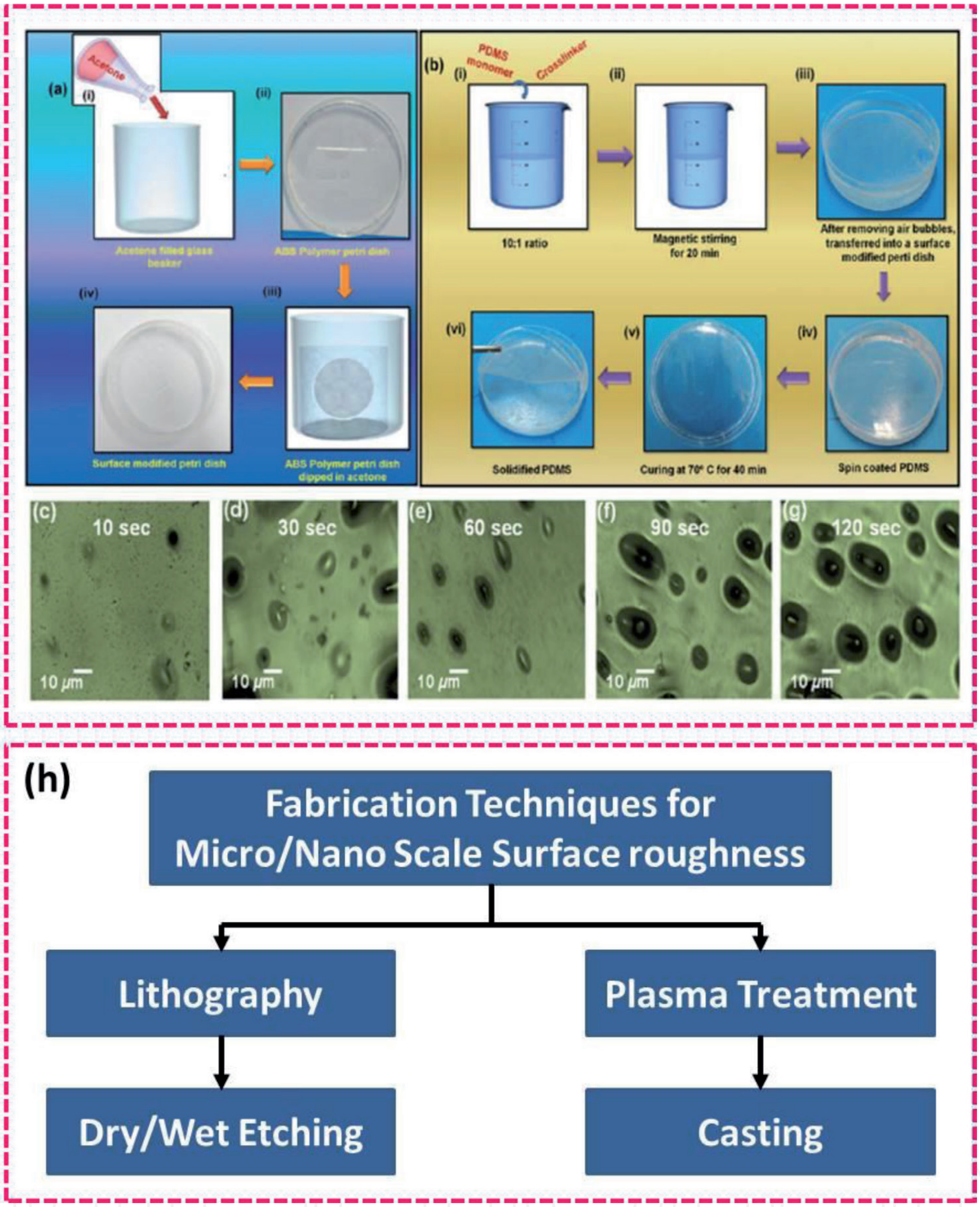

Figure 3.
(a, b) Wet etching of an ABS polymer petri dish using acetone as an etchant and fabrication of mold. The PDMS monomer is then poured on the surface-etched mold and cured to form a roughness patterned PDMS film. (c–g) FE-SEM morphology showing the surface roughness of PDMS film cured in a petri dish with different acetone treated time and their corresponding surface roughness. (h) Fabrication techniques for micro/nanoscale surface roughness [39].

Figure 3c–g shows the FE-SEM morphology of the surface of the PDMS polymer film made using roughness created petri dish mold. The petri dish with acetone treatment for a period of 90 s shows good roughness. **Figure 3h** shows the fabrication techniques involved in the fabrication of different micro or nanoscale surface roughness.

5. TENGs as a biomechanical energy harvester

The primary purpose of a TENG device is that it can harvest mechanical energy from the environment. The mechanical energy can be in any form ranging from vibration, vehicle motion, and human body motion. To scavenge the biomechanical energy and use effectively for a variety of applications, an H-TENG and SS-TENG devices report the fabrication of wearable TENG and its performance to applications. **Figure 4** shows the H-TENG device and its electrical performances with the application of an emergency exit system. The H-TENG device made up of polymeric materials by collecting the polymeric waste materials from the house garbage bin, as shown in **Figure 4a**. The positive material is cooking aluminum foil, and the harmful triboelectric materials are random plastics, and the spacer material is the utensil cleaning sponge. The entire TENG device made of household waste shows its easy fabrication and competitive cost development process. The layer-by-layer schematic of H-TENG is shown in **Figure 4b**. The statistics of plastic wastes generated and creating adverse effect to the environment is shown in **Figure 4c**. The device works on vertical contact separation mode, as shown in **Figure 4d**. The device successfully used for scavenging waste mechanical energy from the human finger, palm, hand, and leg motions, as shown in **Figure 4e** with their corresponding electrical response. The electrical output of the H-TENG device made of various polymers was measured in the laboratory using a linear motor, and their corresponding voltage and current responses are shown in **Figure 4f**. The devices were constantly powering at a maximum of 20 V/300 nA response. At last, the fabricated H-TENG device was used for an emergency exit LED lighting system, indicating the exit direction, as shown in **Figure 4g**.

In a similar approach, an SS-TENG device fabricated for scavenging biomechanical energy by placing it on the seating chair. The whole process of SS-TENG from the schematic, electrical response and applications are shown in **Figure 5**. The device consists of interdigitated electrodes (IDE) made of aluminum is attached to the bottom side of a Kapton film. The kapton film acts as a negative triboelectric layer, and the contact materials were bus cards, polyethylene cover, jeans cloth,

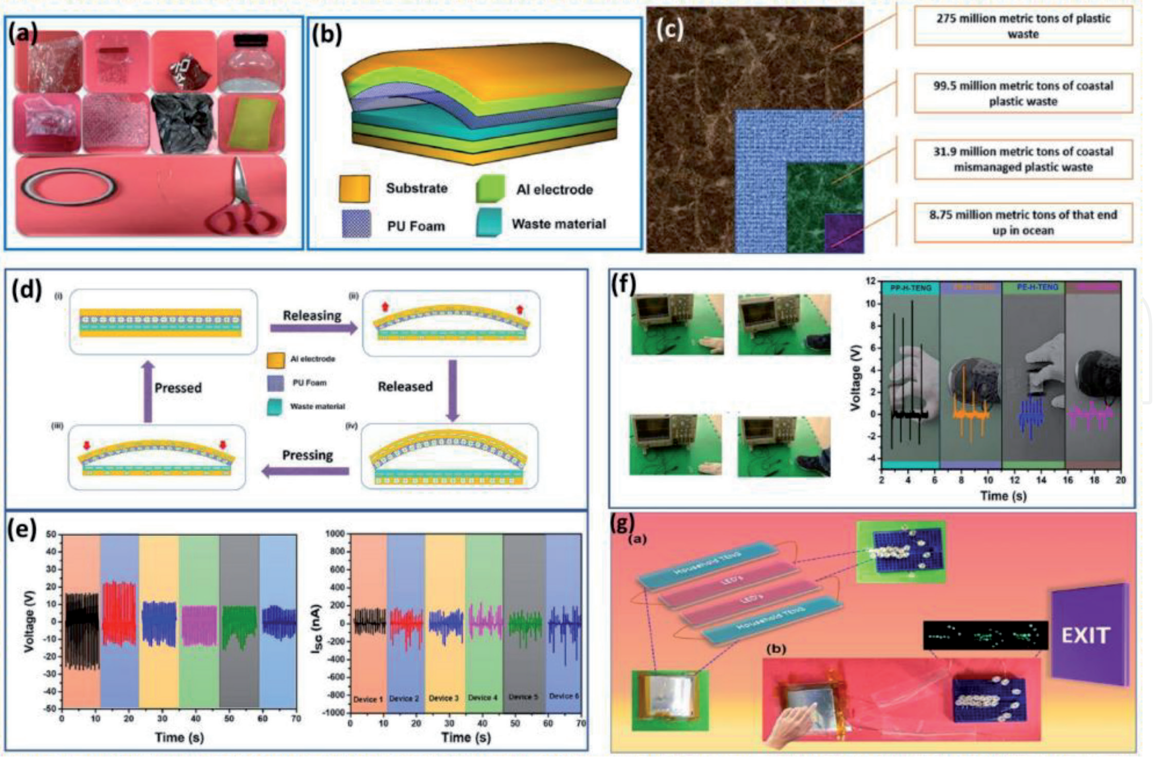

Figure 4.
(a) Fabrication materials of TENG device using recycled waste polymer wrappers from household things. (b) Schematic of the household H-TENG device. (c) Statistics of generated plastic waste all over the world. (d) Contact-separation working mechanism of H-TENG device. (e) Scavenging waste mechanical energy from H-TENG device. (f) Voltage and current response of the H-TENG devices made with different type of polymers. (g) Applications of H-TENG device showing the emergency exit with LED indication [40].

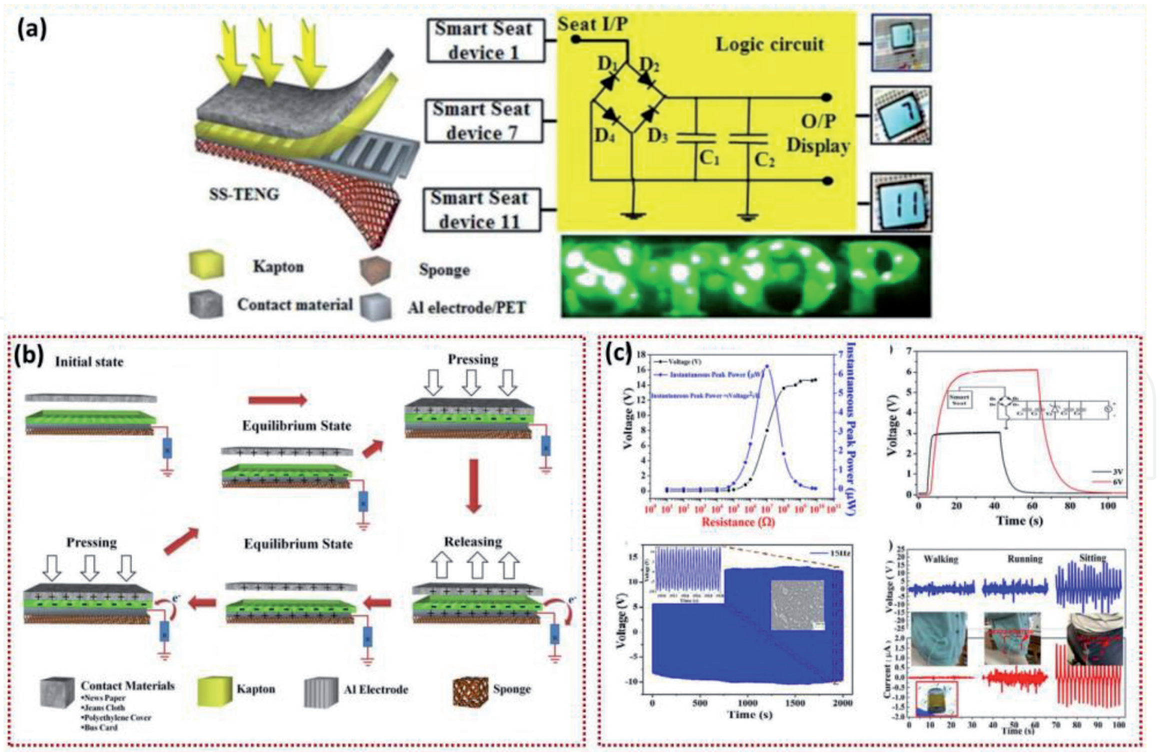

Figure 5.
(a) Schematic of SS-TENG device showing different layers and the logic circuit used for powering electronic displays and LEDs. (b) Working mechanism of SS-TENG device operating with single-electrode mode. (c) Electrical response of SS-TENG and its application as a smart seat [41].

and newspaper. The schematic of the SS-TENG device is shown in **Figure 5a**. The SS-TENG device works on a single-electrode mode triboelectrification. The working mechanism of SS-TENG device with single-electrode mode configuration is shown in **Figure 5b**. **Figure 5c** shows the electrical output response of the device showing a maximum power of 6.5 μW at 10 MΩ resistance. The device also has high stability power continuously for 2000 s without variation in the electrical response. The device is then placed in the pant pocket and measured the electrical response under walking, running, and sitting mechanical motions.

6. TENG for the portable-wearable power source

Besides scavenging biomechanical energy, TENGs can also use as a portable-wearable power sources. By making a design suitable for a portable and wearable process utilizing the appropriate working mode, TENGs can then be used for the mentioned applications. Many researchers have been working on textile-based nanogenerators for wearable applications. These devices use bio-compatible materials as triboelectric layers with the content of fabrics and making it suitable for wearable applications. The advancement in the wearable TENGs can be able to use as a wearable sensor as well as be used as a health monitoring device also. The chapter discusses a smart mobile pouch TENG (SMP-TENG) showing the portable quality of the TENG device. Along with that, a smart backpack TENG (SBP-TENG) demonstrates the energy harvesting and the wearable part.

The SMP-TENG works on the wearable part with the sliding mode. The polymeric layer made of kapton was deposited with the IDE electrode and attached in the mobile phone, which interacts with the triboelectric layer (contact materials) on the mobile pouch. The contact materials tested here are polyester, jeans, cotton, and nylon. **Figure 6a** shows the schematic of the SMP-TENG device with IDE electrode and contact materials. The working mechanism of SMP-TENG is sliding mode, with the contact materials slides over the kapton layer, as shown in **Figure 6b**. **Figure 6c** shows the electrical response of the device with contact materials. Among the four different contact materials, nylon generates a high electrical output of 150 V and 305