Chemical Engineering Journal 452 (2023) 139060

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Review

Electrospun nanofiber based TENGs for wearable electronics and self-powered sensing

Aswathy Babu [a,b,*], Irthasa Aazem [a,b], Ryan Walden [a,b], Satyaranjan Bairagi [c], Daniel M. Mulvihill [c], Suresh C. Pillai [a,b,*]

[a] Nanotechnology and Bio-Engineering Research Group, Department of Environmental Science, Faculty of Science, Atlantic Technological University, ATU Sligo, Ash Lane, Sligo F91 YW50, Ireland
[b] Health and Biomedical (HEAL) Strategic Research Centre, Atlantic Technological University, ATU Sligo, Ash Lane, Sligo F91 YW50, Ireland
[c] Materials and Manufacturing Research Group, James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

ARTICLE INFO

Keywords:
Triboelectric
Electrospinning
Self-powered sensors
Wearable electronics

ABSTRACT

There has been much recent interest in developing triboelectric nanogenerators (TENGs) to scavenge freely available mechanical energy to address future requirements for clean and sustainable technologies. The macroscale performance of TENGs is determined by the multifaceted role of surface and material properties at the nanoscale, which must be understood for future TENG development. To achieve the desired TENG performance, various protocols for the fabrication and tuning of surfaces and materials are required. A particularly viable application area for TENGs is the energy source for relatively low powered wearable electronic sensors and devices *via* textile or fibrous TENGs. Therefore, this review focuses on recent advances in TENGs prepared by electrospinning from various material combinations and in terms of material design, function, and performance to obtain next generation nanofiber-based TENG devices. The remarkable physical and chemical characteristics of a wide range of electrospun nanostructured materials for achieving optimised TENG performance is discussed. Recent developments in electrospun TENGs for flexible and wearable electronics, and self-powered sensors are also discussed in detail.

1. Introduction

Our digital era is defined by increased demand and interest in personalized and handheld electronics and innovations in sensing devices and the internet of things (IoT). One of the most intriguing possibilities is the development of electronic devices that may be worn as clothing, accessories, or even as part of the body. Industrial, personal, wearable and biomedical electronics are examples of IoT devices that have emerged in recent years. With the arrival of the information age, billions of objects will need to be connected to sensors for various measurements, perceptions, controls, and data exchanges [1]. A corresponding power supply system is also required for these portable, human-oriented, dynamically, and widely dispersed sensor networks. Consequently, the challenges in current development relate mostly to inefficient energy structures and a misaligned supply pattern. Energy harvesting is a potential solution that could allow IoT devices to scavenge self-sustaining bio-mechanical energy from ambient environmental sources. By combining well-developed energy harvesters with energy storage, self-sustaining systems could be explored as a battery replacement option. To meet these requirements, novel energy harvesting techniques with improved wearability, stretchability, durability, washability, and mass production capability are required.

Mechanical energy is one of the most prevalent energies in our surroundings (e.g. wind, machine vibrations or human actions). It has the advantages of consistency, independence, accessibility, and reliability. However, it is frequently overlooked and squandered because of its scattered nature, low energy density, low frequency, and poor utilization rate. Nanogenerators (NGs) offer a possible solution: these are a type of mechanical energy harvester made feasible by advances in nanotechnology and allow mechanical energy to be recycled quickly and effectively. Nanogenerators were first developed by Z. L. Wang in 2006, and since then, numerous nanogenerators have emerged focusing on triboelectric, piezoelectric, and pyroelectric mechanism of electricity generation [2]. Triboelectric nanogenerators (TENGs), for example, are renowned for their high output power (500 W/m^2) and efficiency (85 %) [3] compared to its competitor nanogenerators. TENGs collect

* Corresponding authors.
E-mail addresses: aswathy.babu@atu.ie (A. Babu), suresh.pillai@atu.ie (S.C. Pillai).

https://doi.org/10.1016/j.cej.2022.139060
Received 26 June 2022; Received in revised form 14 August 2022; Accepted 2 September 2022
Available online 9 September 2022

mechanical energy from the environment and generate power, allowing portable or wearable devices to function endlessly.

Two distinct mechanics facilitate the energy harvesting ability of TENGs: triboelectrification (i.e. generation of tribo-charges at the interface) and electrostatic induction (modification in the distribution of electric charge) [4]. When two materials come into contact, electrons from one contact surface are injected into another because of the difference in electron affinity between two different materials. Their separation causes the generation of an electric potential difference. Throughout the external circuit, electrons will circulate back and forth if mechanical triggering is used to cause repeated interaction and release of the two charged surfaces. Four TENG modes have been devised based on this concept: vertical contact–separation, lateral sliding, single-electrode, and freestanding triboelectric layers [5]. The interface is identified as a major component of TENGs, implying that the development of high-performance devices requires the optimization and development of functional interfaces. Key properties include interfacial contact area, surface work function or dielectric constant, surface charge density and tribo-polarities. All of these variables are interrelated, excluding the interfacial contact area, which increases other "metrics" and improves TENG performance when increased. Approaches to boosting contact area are possible via tailoring of surface roughness and interfacial material properties and/or by application of high contact pressures. Contact of two very smooth surfaces can yield a high contact area, but so can a hard rough (or patterned) surface can be pushed into a much softer material. Surface charge density, dielectric constant, device thickness and charge-polarities are important features of the triboelectrification process which limit the efficacy of TENGs [6–9]. Usually, it is advisable to select materials from opposing extremes on the triboelectric series. However, final energy output is determined by a combination of factors (some mentioned above) rendering the design process somewhat challenging.

Various materials and system design studies have been conducted looking at different combinations of materials and TENG designs. The high surface-to-volume ratio and molecular alignment made possible by electrospinning in the production of micro/nanofiber materials significantly influences the TENG device performance. Electrospinning, a low-cost, efficient, and large-scale method, has potential to produce nanofiber-based devices with fascinating mechanical and electrical properties such as high surface area, conductivity, and ultrahigh flexibility [10]. Since wearable electronics demand flexibility, softness, light weightiness, and tiny device designs, the electrospun nanofiber based TENG offers the benefits of high performance, breathability, wearability, ecological sustainability, and compatibility. Wearable electronics based on electrospun-TENGs have found a wide range of applications, from smart garments to health monitoring devices and from health protection to sensors, etc [11]. In order to create thin, soft, light, breathable, and conformable electronic devices, it is important to use a variety of nanofiber assemblies. Fibers with diameters less than 500 nm (down to a maximum 20 nm) and lengths of several meters can be produced using this method [12]. Previous reviews on nanofiber based energy harvesters [13] focused on the applications of electrospun materials in piezoelectric and triboelectric nanogenerators, based on the selected functional polymeric material. However, a detailed investigation in terms of material design, function, and performance of the TENG device using electrospun nanomaterials has been lacking. The current review presents the latest advances in TENGs prepared by electrospinning from various material combinations such as organic and inorganic polymers, and their composites with various nanomaterials to obtain next generation nanofiber-based TENG devices. The electrospinning process is briefly discussed, various functional electrospun tribomaterials are explored and different strategies to prepare the electrospun materials based TENGs are summarised. Soft electronics applications such as self-powered devices, flexible/wearable electronics, strain and pressure sensors and motion/respiration monitoring are detailed. Finally, the challenges and prognosis for future applications are presented.

1.1. TENGs: Basic theoretical background

As mentioned, the two main operating principals behind TENGs are the triboelectric effect and electrostatic induction. However, these two principals are restricted in effectiveness by the materials used as has been explained in depth in a review paper by Zhang et al., [14] based on theoretical evaluation of the materials applied in TENGs.

The underlying physics behind energy harvesting by the triboelectric effect was explained by Wang et al. [15]. This article explains, in detail, the relationship between TENG output and Maxwell's displacement current. According to Maxwell, the electric displacement vector is:

$$D = \varepsilon_0 E + P \tag{1}$$

Where, ε_0 is the permittivity in vacuum, E is the electric field and P is the polarization vector. But in TENGs, where the displacement current is the crucial parameter influencing their output, a new term P_s is introduced. This is because, unlike in classic electromagnetic generators, the surface charges generated in nanogenerators are independent of an external electric field, and the displacement vector can be denoted as;

$$D = \varepsilon_0 E + P + P_s \tag{2}$$

Therefore, the displacement current density of a TENG can be expressed as.

$$J_D = \frac{\partial D}{\partial t} + \frac{\partial P_s}{\partial t} \tag{3}$$

In TENGs the determination of the current density depends mostly upon the surface charge density (σ_T) and dielectric constants (ε_1, ε_2) of the triboelectrification layers. Therefore, the current density at short circuit can be expressed as.

$$J_D \approx \sigma_T \frac{dH}{dt} \frac{\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon_0}{\varepsilon_1}}{\left(\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon 0}{\varepsilon_1} + z\right)^2} \tag{4}$$

Where dH/dt denotes the contact/separation of two media (H is a function of time), d_1 and d_2 are the thicknesses of two media, ε_0 is the permittivity of vacuum and z is the gap between two triboelectric layers.

The equation for output current from a TENG with an area A can be derived from Eq. (4) as.

$$I \approx A\sigma_T \frac{dH}{dt} \frac{\frac{d_1\varepsilon_0}{\varepsilon 1} + \frac{d_2\varepsilon_0}{\varepsilon 1}}{\left(\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon_0}{\varepsilon_1} + z\right)^2} \tag{5}$$

For a clearer understanding, Eq. (5) can be viewed as three separate parts. The first part, P_1 denotes surface tribo-charge density (σ_T) which depends on the material properties of the contact pair. Whereas, the second part P_2 (dH/dt) is attributed to the mode of operation of the TENG of interest. The third part P_3 explains the electrostatic induction aspect and illustrates how the charges induced on the back electrodes by the tribo-charges is governed by the permittivity of the material and the thicknesses of the layers.

$$P_3 = \frac{\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon_0}{\varepsilon_1}}{\left(\frac{d_1\varepsilon_0}{\varepsilon_1} + \frac{d_2\varepsilon_0}{\varepsilon_1} + z\right)^2} \tag{6}$$

From this equation, the effectiveness of a given TENG structure can be estimated.

Well before Maxwell's displacement current was proven to be the theoretical foundation of TENGs in 2017, all theoretical calculations were based on the capacitor model [16]. The governing equation and fundamental output characteristics for the contact-mode TENG may be calculated using the infinitely-large parallel-plate capacitor model.

$$V = -\frac{Q}{S\varepsilon_0}(d_0 + x(t)) + \frac{\sigma x(t)}{\varepsilon_0} \quad (7)$$

where σ is the surface charge density, $x(t)$ is the separation distance, Q is the transferred amount of charge, S is the tribo-surface area and d_0 is the effective dielectric thickness defined as the sum of all dielectric thicknesses divided by their respective dielectric constants.

1.2. Operational modes in TENGs

There have been four novel TENG modes developed in terms of device operation: vertical contact–separation, lateral sliding, single electrode and free-standing mode. As shown in Fig. 1A, each of these modes elaborates on the interaction of triboelectric layers and so depicts the underlying structure and motion necessary to generate electricity.

1.2.1. Vertical contact–separation mode

As shown in Fig. 1A(a), the operating mechanism of this mode is the potential difference resulting from the contact and separation of the opposing surfaces [5]. The gap between the two surfaces shrinks when an external force is applied to the device, causing charge transfer between the top and bottom surfaces of the stacked structure, resulting in positive charges on one surface and negative charges on the other. The inherent characteristics of certain materials are primarily responsible for this triboelectric effect. As the force is released, a small gap occurs between the two surfaces, creating a potential difference between the top and bottom surfaces, allowing free electrons to flow between the two connected electrodes and balancing the electrostatic field. The transferred charges will then flow back *via* the external load when the force is applied again.

1.2.2. Lateral sliding mode

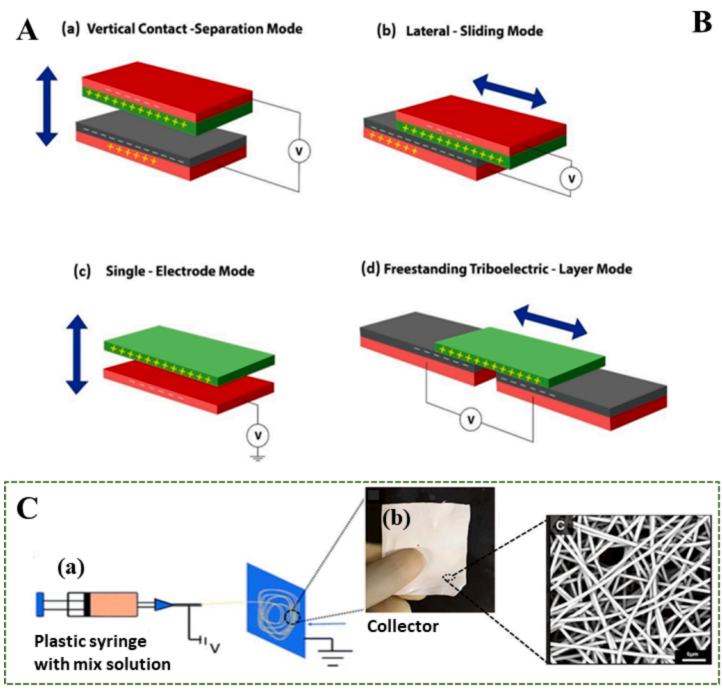
In terms of construction, the vertical contact-separation mode is quite similar to this mode, but the sliding mode TENG operates via frictional siding between the tribo-contact surfaces. As depicted in Fig. 1A(b), the charges on both dielectric-connected surfaces are no longer balanced in the initial condition, resulting in a rise in generated triboelectric charges as the contact area of the two surfaces diminishes [17]. Furthermore, these generated charges can be pushed through an external circuit to balance the potential difference. When the two surfaces return to their former positions, the charges from the preceding electrode will flow back in the same way. Periodic sliding between two dielectric materials again produces an AC signal. Compared to the vertical contact–separation mode, devices with a lateral sliding mode tend to have higher energy harvesting efficiency. Because of the different sliding movements that occur in fabrics during human movement, this mode has much potential in wearable applications.

1.2.3. Single-electrode mode

This mode, unlike others, has only one electrode and a single dielectric substance, as seen in Fig. 1A(c). The local electric field distribution of the TENG device (with limited size) will effectively change with the contact–separation movement of a freely moving object (such as human skin, resulting from electron exchanges between the electrode and the ground in order to balance the potential at the electrode, according to the triboelectric series [18]. The output of this mode is reduced compared to other modes because there is only one electrode in the system. On the other hand, the single-electrode TENG is more suited to specific applications, such as fingertip-driven energy harvesting.

1.2.4. Free-standing mode

Fig. 1A(d), depicts the freestanding mode TENG. Here, the device is mainly composed of two separated dielectric layers on one side (aligned horizontally or vertically) with a single upper layer capable of making contact with both lower layer surfaces. Because of the imbalanced charge distribution, a flow of electrons will take place from one electrode to another to restore balance to the local potential distribution [19]. The possibility of keeping the surface charges on some materials for hours can effectively decrease material abrasion and heat generation. The cycled forward, and backward movement between the paired electrodes produces electrical power through the external circuit. It



B

Insulator Name	Charge Affinity (nC/J)	Insulator Name	Charge Affinity (nC/J)
Polyurethane foam	+60	Sorbothane	+58
Hair, oily skin	+45	Solid polyurethane	+40
Magnesium fluoride	+35	Nylon, dry skin	+30
Machine oil	+29	Nylatron	+28
Glass (soda)	+25	Paper	+10
Wood (pine)	+7	Cotton	+5
Nitrile rubber	+3	Wool	0
Polycarbonate	-5	Acrylic	-10
Epoxy	-32	Styrene-butadiene rubber	-35
PET (mylar) solid	-40	EVA rubber	-55
Gum rubber	-60	Polystyrene	-70
Polyimide	-70	Silicones	-72
Vinyl: flexible	-75	LDPE	-90
Polypropylene	-90	HDPE	-90
Cellulose nitrate	-93	UHMWPE	-95
Polychloroprene	-98	PVC (rigid vinyl)	-100
Latex (natural rubber)	-105	Viton, filled	-117
Epichlorohydrin rubber	-118	Santoprene rubber	-120
Hypalon rubber, filled	-130	Butyl rubber, filled	-135
EDPM rubber, filled	-140	PTFE (Teflon)	-190

Fig. 1. (A) Basic operational modes for TENGs: (a) vertical contact-separation mode, (b) lateral sliding mode, (c) single-electrode mode and (d) freestanding triboelectric-layer mode. **(B)** Triboelectric table developed by AlphaLab. Reproduced with permission [18]. Copyright 2017, Cell Press. **(C)** Figure illustrating: (a) a basic electrospinning set-up, (b) electrospun polyurethane (PU) fiber mesh and (c) SEM image of the electrospun PU fiber mesh. Reproduced with permission [20]. Copyright 2017, John Wiley & Sons.

should be noted that this mode shows excellent performance due to the potential change between two stationary electrodes; moreover, there is no shielding effect.

1.3. Triboelectric materials

There are a wide range of triboelectric materials which can be utilized to construct a suitable TENG device. Their polarity (either positive or negative) and charge density are the key features for dictating their ability to gain and/or loose electrons. Therefore, selection of the triboelectric material is an important step to develop an efficient TENG device. In this regard, a series of triboelectric materials was first explored by John Carl Wilcke in 1757 [9]. The triboelectric series in a chart that classifies triboelectric materials based on their polarities and charge densities. Materials listed further away from the middle of the chart are either more positively or negatively charged. The table shown in Fig. 1B highlights the charge affinities of some of the materials possessing triboelectric capabilities.

2. Introduction to electrospinning

Electrospinning is a versatile and efficient way of producing polymer-based nanofibers and composites with a high surface-area-to-volume ratio [21]. Re-popularised in the mid-90s with the increase of research into nanotechnology, the method of electrospinning has remained mostly unaltered since its first conception in the 1700s. Electrospun nanofiber films have prominent properties such as large specific surface area, inherent rough structure, hierarchical porous structure, and intrinsic porosity, which can substantially enhance the effective frictional contact area and breathability, thereby optimizing the overall performance and wearability of the fabric-TENGs. Electrospun-triboelectric materials with a high specific surface area and surface roughness can have a high surface charge density. Furthermore, electrospinning techniques are perfect for aligning nanofillers such as nanotubes and nanowires inside electrospun fibers [22]. In particular, nanofillers can act as oriented nuclei for polymer chains, resulting in improved electrospun fibers with higher surface charge density and mechanical stability, that can be used in TENG-based wearable electronic applications.

The method itself consists of a solvent solution or polymer in melt form [23] being forced through a capillary tube which ends in a metal tip or spinneret (Fig. 1C). As the solution passes through the tip, a huge electrical current is applied. This applied voltage breaks the solution apart and evaporates the solvent. At the same time, the pressure of the tip alongside the electrical field forces the remaining material together into a fiber. This newly formed fiber is pulled through the tip by the electric field onto a usually grounded collection bed. Although the method of electrospinning is straightforward, many variables can impact the resulting nanofiber.

Various electrospinning processes, such as needleless electrospinning, bubble electrospinning, electroblowing, melt electrospinning, multiplejet electrospinning, coaxial electrospinning, etc, have been developed in the past two decades [10]. Coaxial electrospinning is a method that is often used for continuous electrospinning of solutions with poor dispersion and incompatibility. Multi-component nanofibers can be created using bi-component and multi-component electrospinning. They are electrospun from the same spinneret and share the same filament, but are separated by fine planes. Nanofibers with varying cross-sectional forms may be produced using bi-component electrospinning. The solvent, collector, applied voltage, tip-to-collector distance, and solution flow rate all have an effect on fiber diameter, morphology, orientation and alignment. To manage fiber orientation, many collector types have been designed. Rotating drum collectors are the most often utilized collectors for continuous nanofiber manufacturing. Uniaxially aligned fibers are created using rotating disk collectors. In contrast to a drum collector, a disk collector allows for the collection of a large number of fibers at the disk edge and the production of well aligned nanofibers. The fiber length and fiber size may be raised or lowered by raising or decreasing the applied voltage. By adjusting the nozzle-collector distance, the final fiber morphology may be changed from round to flat.

2.1. Electrospinning parameters

There are many different parameters that must be considered when attempting to electrospinning a material or polymer, from sample preparation to processing [24]. The general key processing parameters are summarised in the Table 1 below [23,25–30]. Although the Table 1 lists the main parameters, which for the most part can be controlled while electrospinning, there are also other variables which must be considered and are somewhat less easily controlled. A wide variety of materials can be electrospun from various material combinations such as organic and inorganic polymers, and their composites with various nanomaterials. This also means the basic parameters for precursor solution preparation can widely vary. To manufacture nanofibers via electrospinning, the precursor solution should have low concentration and viscosity. The solution cannot be electrospun and must be electrosprayed at extremely low quantities. The fiber diameter grows as the syringe flow rate increases, and beads develop. Beads can also be formed by utilizing a polymer with a very low molecular weight while maintaining a constant solution concentration. Hence, the % concentration will have to be increased or in some cases a secondary material will have to be added to enhance the linking of the chains. Smooth fibers are formed by increasing the molecular weight of the solution, while fibers with a large diameter are formed by utilizing solutions with a very high molecular weight. Solvents may have high temperature boiling points so increasing the voltage may be necessary. Another important parameter is the viscosity of the initial sample solution. Lower viscosity in this solution has been shown to improve the smoothness of the final fiber to a point, however, decreasing viscosity too much may result in what is known as “electro-spraying” [25], where instead of producing a continuous fiber, small broken fibres spit out of the needle tip. Higher viscosities have been shown to increase fiber diameter and due to the higher surface tension of the solution “beading” is more likely to occur, which is when a polymer builds like a drop and eventually gets pulled away on the fiber and solidifies like a bead. Since polymer electrospinning is unique to each case, the viscosity can be controlled by using different concentration ratios of both polymer and solvent and even by using varying solvent types. The solvent used has an effect on surface tension. A reduced surface tension promotes the formation of nanofibers without beads, although it might not provide optimal electrospinning conditions. Salts added to the electrospinning solution enhance solution conductivity and surface charge density, leading to greater control of fiber diameter and shape.

Another key parameter is the electric field that surrounds the fiber as it is extruded from the spinneret to the collection table. By manipulating this electric field, the deposition of the resulting fiber can be influenced to become aligned or patterned. This electric field is also heavily influenced by the applied voltage to the spinneret and any applied voltage to the collection table. The applied voltage and polymer flow rate in the syringe are other important parameters. At higher voltages, the fiber diameter is much more quickly shortened, and bead production is more common in some instances. The final variable is the sample to be electrospun itself. Some polymers such as PDMS are not spinnable by themselves and require a co-polymer to be spun with them. This addition of a second polymer significantly increases the difficulty when spinning as there can be multiple solvents with different boiling points and different polymers with different melting points.

Table 1
Summary table of main parameters to be considered before electrospinning, and the corresponding effect.

Major Parameter for Electrospinning				
No.	**Parameter**	**Effects**	**Reported Ranges**	**Ref**
1	Flow Rate	The speed of the flow rate can directly affect the diameter and uniformity of the resulting fiber. Generally, the slower the flow rate, the thinner and more uniform the fiber.	0.5–4 mL/hr	[23,25,29,30]
2	Voltage	The voltage applied must be high enough to cause solvent evaporation and polymer cohesion, but if too high, it can cause irregularities in the fiber like beading.	1–18 kV	[23,29,30]
3	Substrate Type	The type of substrate onto which the fibers are deposited will affect the adhesion and stability of the fibers	Aluminium	[23,29]
4	Collector Type	The type of collector used can affect how aligned the resulting fiber will be as multiple different collectors are available.	Roller / Plate collector	[28,31]
5	Needle / Spinneret Gauge	The size of the needle/spinneret gauge can ultimately affect the diameter of the resulting fiber. It can also be a reason for multiple jets forming.	21 G	[25,27,29]
6	Distance of the Collector form the Spinneret	This has been shown to directly affect the diameter of the fiber as well as its dryness. Too short and the fiber doesn't have enough time to dry; too long and it can cause beading in the fiber.	8–16 cm	[23,29,30]
7	Ambient Conditions	These are conditions like temperature and humidity, which can adversely affect the ability of a solvent to evaporate.	room temperature (25 °C) Humidity less than 40 %	[23,30]

3. Strategies to design electrospun triboelectric nanofiber based wearable TENGs

Electrospinning is a highly effective method for producing multifunctional or multicomponent nanofibrous membranes due of the considerable benefits of ease of processing and cheap cost. Major factors governing contact electrification in TENGs, such as high triboelectric surface contact area, layer thickness and surface charge density could be effectively tuned by the electrospinning process [32]. Moreover, the possibility offered by this method for controlling the shape and surface characteristics of the nanofibers and membranes, such as porosity and roughness at the nanoscale is highly beneficial for developing efficient triboelectric layers [13,33–39]. It can also process different materials (natural polymers, synthetic polymers, ceramics, inorganic nanoparticles, active agents etc.). More negative charges will be created when material from the bottom of the triboelectric series touches a material near the top of the series, as mentioned in the triboelectric series first published by John Carl Wickle [40]. As a result, many polymers can be employed to create nanofiber-based TENG devices. Metals such as Al, Ni, Cu, and Ag, as well as organic materials such as nylon, cotton, silk, and polyurethane (PU), can be used to manufacture a high efficiency positive triboelectric layer based on their positions in the triboelectric series [40–42]. Polymers such as polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF), polydimethylsiloxane (PDMS), fluorinated ethylene propylene (FEP), polyethylene terephthalate (PET), polyimide, parylene, silicone, and rubber are examples of negative triboelectric layers [43,44]. Furthermore, diverse materials, such as nanoscale metals, carbon-based materials and 2D materials can be electrospun into triboelectric materials to improve TENG output performance [45–48].

Nanofiber-based wearable TENGs have received considerable recent interest for use in wearable TENGs. To be successfully worn by humans, the constituent materials must allow flexibility, breathability and even washability. The balance between high output performance, functionality, and wearability remains challenging. They must also be non-toxic. This further leads us to the major challenge raised by these devices, which is to balance the required sustainable conductivity and flexibility of the various components of the device. Consequently, the requirement for stretchable power sources to power such devices has increased. Apart from flexibility, light weight, softness, and compact size are also essential requirements of a self-powered wearable TENG device. In light of these concerns, the recent research on wearable and flexible TENGs has been aligned towards developing appropriate multifunctional materials and suitable fabrication strategies to meet their underlying requirements. This goal was achieved through material designs and device fabrication strategies which yielded nanostructures with high surface potential exhibiting efficient generation and transfer of triboelectric charges [6]. Wearable TENG devices can benefit from electrospun membranes with a high specific surface area and rough structure - this may result in a greater charge density [49]. As a result, a wide variety of fiber-based TENGs with distinctive properties have been successfully built for wearable applications by effective electrospinning parameter optimization.

In electrospun nanofiber-based TENGs, various parameters related to the electrospinning process and that of the spinning solution influence the TENG device's power output performance. This is mainly due to the enhancement in surface potential of the electrospun membranes which consequently improves the triboelectric surface charge generation [45,50]. As discussed in the previous sections, by modulating the applied spinning voltage, solution flow rate, deposition time, nozzle parameters, speed of rotation of the collector drum, factors such as diameter of the obtained fibers, coating thickness and fiber alignment can be modified. Additionally, the porosity, surface roughness and continuity of the fibers depends upon the molecular weight of the polymers, solvent type, concentration of the polymer solutions and the crystallinity of the polymer matrix. Moreover, the flexibility offered by the electrospinning process in easily altering the instrument set up and accessories is also helpful in fabricating membranes with various morphologies. These changes will also help TENGs attain the ideal mix of mechanical endurance and flexibility, as well as enhanced current density. Moreover, electrospinning facilitates tailorability of the triboelectric yarn properties across long fibers and has potential to facilitate a large surface area. Electrospun fibers have been shown to boost the triboelectric effect, and their vast surface area allows for the creation of additional charges. Jang et al. [26] demonstrated that well-optimized

process conditions and a correctly selected counter material could significantly improve TENG performance. Because of its thin nanofibers and compact structure, a longer working distance would enhance the charge density of the nanofiber mat, resulting in increased electrical performance. The triboelectric series-based contact material selection also had a substantial impact. In addition, a larger needle gauge and an extended electrospinning time could also raise the open circuit voltage. Indeed, the multi-scale micro-nano structures in the friction layer structure have the potential to increase not only the output performance of TENGs, but also their mechanical attributes and wearing comfort.

3.1. Single polymeric nanofiber based TENGs

The high uniformity and orientation obtained by electrospun polymer nano fibers compared to their non-electrospun analog are beneficial for fabricating high-performance wearable and stretchable TENG devices. In a recent investigation by Kim et al. [51], a comparative study on the triboelectric performance of friction layers made of electrospun polyimide (PI) nanofibers and PI films was performed (Fig. 2A). The study showed that continuous and uniform nanofibers of PI were obtained with 15 wt% and 20 wt% of PI in DMAc solvent, which was notably influenced by the polymer molecular weight and polymer concentration. The electrical output of the friction layers was evaluated under continuous contact and separation cycles by delivering a ~ 10 N compressive force at a frequency of 2 Hz. A considerably higher value of $V_{oc} = 366$ V and $I_{sc} = 6.52$ μA was obtained for electrospun PI nanofibers compared to that of screen printed (V_{oc} = 45.6 V, 1.61 μA) and commercial (V_{oc} = 66.1 V, 1.68 μA) PI films. This was attributed to the increased surface area of the electrospun nanofiber PI layer compared to that of the PI films which showed an almost flat surface morphology. Moreover, charges were induced both on the surface of the nano fibrous membrane and on the inner fibers. The current density of electrospun PI nanofiber membrane was found to be higher than that of commercial PI films. It was also proved that it can harvest stable electrical energy from human body movements and power small electronic devices.

One of the major findings that led to electrospinning for producing polymer-based components for wearable TENGs is the emergence of a highly crystalline β-phase in PVDF [52]. This is attributed to the high degree of dipole moment obtained in PVDF owing to the arrangement of fluorine and hydrogen atoms in the opposite direction. Consequently, this leads to the higher output of the device since the triboelectric charge generation and transfer relies greatly upon the dipole moment within a single triboelectric layer and the difference in polarity between the two different contact layers. Additionally, the incorporation of certain additives has also been found to stabilize the β-phase and to enhance the transformation to this phase [53,54]. As is evident from Table 2, though, output from PVDF is highly subject to the choice of the opposing triboelectric layer. Mi et al., [55] used electrospun PVDF against a cellulose nanofibril/polyethyleneimine aerogel layer (Fig. 2B) and achieved a V_{OC} of 106.2 V, while Yu et al., [56] (Fig. 2C) used electrospun PVDF against electrospun poly(3-hydroxybutyrate-*co*-3-hydro-xyvalerate) (PHBV) and was able to achieve a V_{OC} of 695 V. Despite the fabricated TENG devices in both cases being of similar proportions, the TENG by Yu et al. was almost seven times more effective than Mi et al.'s. Although material selection can be attributed to this, the effective contact surface area of both the triboelectric layers of Yu's TENG was far greater than that of Mi's, allowing far more electron transfer points to occur [55,56].

In a paper by Kim et al., [58] electrospun PVDF was also used, alongside electrospun polyurethane (PU), to create a humidity-resistant TENG device capable of producing an impressive output V_{OC} of 45.1 V when subjected to 20 % relative humidity. This output, although seeming low, is a good achievement at that level of humidity as most TENG devices exhibit a V_{OC} retention of only 20 % while this device was

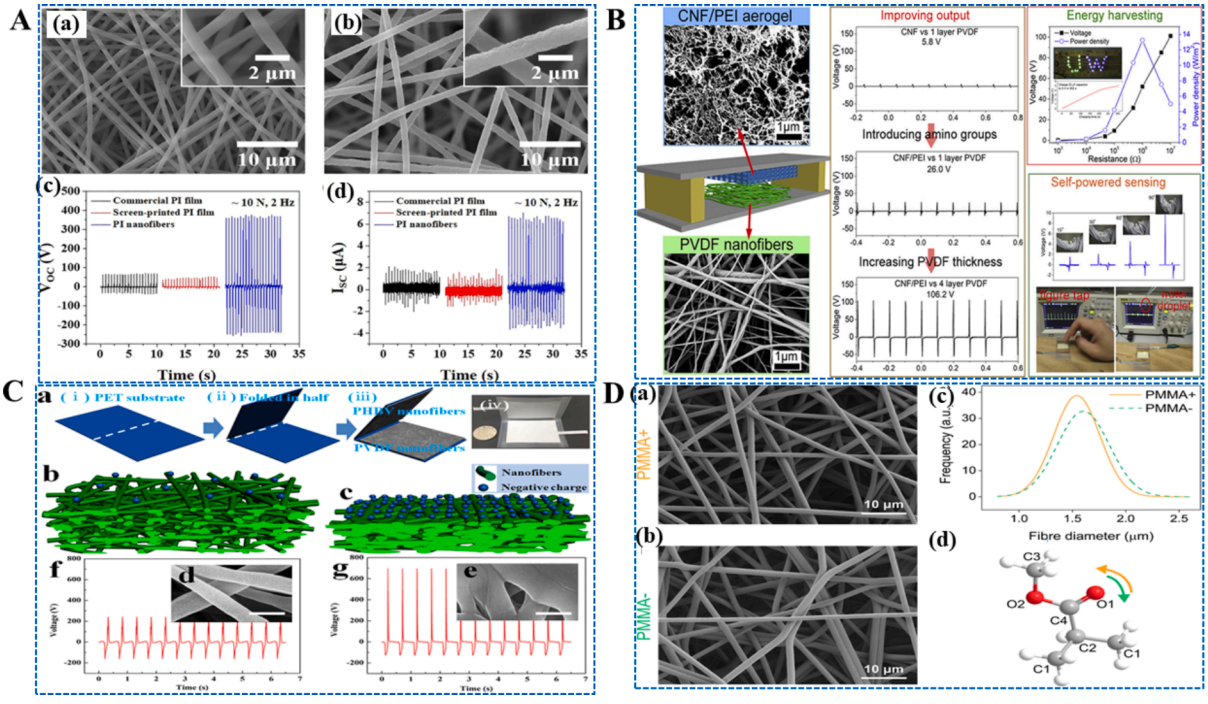


Fig. 2. **(A)** (a-b) The microstructures of electrospun PI nanofiber membranes: Effect of friction layer types on (c) V_{OC} and (d) I_{SC}. Open Access, 2020 [51]. **(B)** Flexible triboelectric nanogenerator for energy harvesting and sensitive self-powered sensing based on porous aerogels and electrospun nanofibers. Reproduced with permission [55]. Copyright 2018, Elsevier. **(C)** (a) Schematic diagrams of the TENG fabrication based on a closed-nanopore electrospun mat, (b-c) schematic diagrams of electrospun polymer mats with varying surface charges before and after post treatment on PVDF and PHBV mats, (d-e) FE-SEM images of electrospun polymer mats before and after post treatment on PVDF and PHBV mats, (f-g) optimal output voltages of SP-TENGs on PVDF and PHBV mats before and after post treatment. Reproduced with permission [56]. Copyright 2017, Elsevier. **(D)** SEM image of electrospun PMMA fibers with (a) positive polarity and (b) negative polarity (c) histograms of fiber average diameter and (d) schematic structure of a single PMMA polymer chain unit. Open Access, 2019 [57].

Table 2
Comparison of maximum device outputs for TENGs fabricated using electrospun single polymer materials for use in the triboelectric layers. N/R = not reported.

	Electrospun Single Polymer Materials for TENGs							
No.	Polymer Base	Effective Area (cm^2)	Resistance (MΩ)	V_{OC} (V)	I_{SC} (μA)	Power Density (W/m^2)	Stability/ Durability (number of cycles)	Reference
1	Polyimide	N/R	100	753	10.79	2.62	10,000	[51]
2	PMMA +	N/R	40	46.6	N/R	N/R	N/R	[57]
	PMMA -		80	234.4				
3	PTFE / PEO	N/R	N/R	900	N/R	N/R	30,000	[60]
4	PVDF/ Cellulose	2 × 2	10	106.2	9.2	13.3	10,000	[55]
5	PVDF/ PHBV	4 × 5.5	N/R	695	58	3.1	N/R	[56]
6	PVDF/ PU	5 × 5	N/R	45.1	10.38	N/R	324,000	[58]

able to retain almost double that. This was attributed to the use of both electrospun triboelectric layers, among other lesser factors. Kim et al. again investigated the different electrospinning methods in a later paper [59] to determine which method would result in the best triboelectric layer for TENGs. Different nozzle systems were used to fabricate polyimide (PI) nanofibers and PVDF-trifluoroethylene (TrFE) composite nanofibers. The study showed that the most effective set of fibers was created using a multinozzle-drum method of electrospinning, resulting in a TENG capable of producing an output V_{OC} = 364 V, I_{SC} = 17.2 μA and power density = 2.56 W/m^2.

In another study, Jang et al., [26] investigated the effects of spinneret gauge, electrospinning time and distance of the collector from the spinneret through the fabrication of a ES PVDF-TrFE / PI film TENG. Various PVDF-TrFE nanofibrous mats were created using different electrospinning parameters and compared. The study showed that a greater distance between the spinneret and the collector resulted in a thinner and more compact nanofiber mat, leading to a proportional increase in charge density. However, the increase of both time and gauge size resulted in a thicker fiber which harmed the charge density. The optimal combination of investigated parameters was shown to be 27 G, 3 h and 150 mm respectively which resulted in a TENG output V_{OC} = 578 V and a power density = 2.39 W/m^2, which is a reported increase of 5.7 and 54.8 times, respectively, on the worst reported set of parameters. The effect of smaller diameter fibers creating larger triboelectric charges is also observed in a paper by Kim et al. [58], where the same effect is seen when spinning PVDF nanofibrous materials. However, instead of the distance between the spinneret and collector being attributed, the spinneret gauge is. PDVF material spun with a 20G spinneret was shown to produce fibers which were thinner than those spun with a 30G, and thus had a greater electrical output (shown in Table 2).

The rapid spread of coronavirus (COVID-19) has resulted in significant deaths and economic losses, highlighting the critical need for technology solutions in medical preventative efforts. The use of face masks has been required in many countries following the emergence of SARS-CoV-2, and its effectiveness in controlling the pandemic is well established. Liu et al. [61] proposed a face mask in which a basic TENG with an electrocution layer could fulfil the goal of filtering and deactivation of SARS-CoV-2. Their paper develops a unique self-powered electrostatic adsorption face mask based on a PVDF electrospun nanofiber film and a TENG powered by breathing. It can electrostatically adsorb ultrafine particles, and could continuously deliver electrostatic charges in this adsorption process through breathing. The TENG face mask demonstrated the removal effectiveness of coarse and fine particles greater than 99.2 wt%, and the removal efficiency of ultrafine particulates is as high as 86.9 wt% after 240 min of continuous use and a 30-day interval. This research has presented a novel approach to air filtration, which might have significant implications in human health, self-powered electronics, and wearable technologies.

The possibility offered by polymeric materials to tune their surface chemistry to improve their triboelectric performance has enabled the utilization of certain other electrospun polymeric membranes and nanofibers in wearable TENGs. These include Polymethymethacrylate (PMMA), Polyurethane (PU), Polytetraflouroethylene (PTFE), Polyamide (PA) and Polyvinyl alcohol (PVA) etc [57,60,62–64]. A paper by Busolo et al. [57] revealed that the charge type supplied to the polymer in the electrospinning process can influence the triboelectric charge of the polymer fiber (Fig. 2D). By subjecting PMMA solutions to either a positive or negative electrical current, it was found that the fiber will mimic the traits of the applied current. Although it was seen that PMMA which was subjected to a negative current adapted better and thus created a TENG with much greater output, than that of the PMMA subjected to a positive current (shown in Table 2). It was found that the surface potential of PMMA fibers was directly correlated to the change in surface morphology of the fibers. Depending upon the electrospinning voltage applied, more O_2 containing groups were available on the surface of PMMA nanofibers, resulting in the potential surface enhancement of the fibers. This work also showed the positive impact of electrospinning on the triboelectric performance of the nanofibers in comparison with that of other techniques.

PTFE is widely accepted as one of the most tribo-negative polymers due to its high number of fluorine groups. Zhao et al. prepared PTFE/PEO membranes for high-performance TENGs using an emulsion electrospinning technique [60]. However, as shown by Zhao et al., it is not easily electrospun due to its high chemical and thermal stability. To successfully electrospin PTFE, it must be spun alongside a polyethylene oxide (PEO) co-polymer and then sintered. Although the method of electrospinning is not as straight forward as other methods, Zhao et al. have shown that it can produce a fiber. They were able to achieve a stable open-circuit voltage of 900 V, a short-circuit current density of 20 mA/m^2, and even a charge density of 149 $\mu C/m^2$ [60]. A self-restoring, waterproof, tunable shape memory polyurethane (SMP) microstructural mat-based TENG with long lifetime was developed by Xiong et al. [63]. Different micro-architectures of the shape memory polymer such as microspheres and nanospheres were achieved by changing the electrospinning settings. High surface area and tunable microarchitecture enhanced the triboelectric properties of the device, while the durability was improved by the recoverable microstructures. Moreover, the ability of scalable rough microstructure on the surface of electrospun membranes to improve TENG performance was demonstrated in this work by tuning the viscosity of the polymer solution. The excellent electrical output of 320 V open circuit voltage and 0.04 mA/m^2 current density was obtained for these electrospun mats. Apart from that, the SMP mats were suitable for skin contact driven TENGs due to the variable microstructures possible. Surface roughness gradients during structural recovery provide distinct triboelectric outputs, which enable a water energy harvester with temperature sensing capability (25 °C to 95 °C) that might be used for self-powered waterproof wearable electronics and smart wastewater management.

3.2. Polymer nanocomposite fiber based TENGs

The excellent dielectric and mechanical properties exhibited by

polymers make them one of the prime choices for fabricating TENG devices [34]. Most of the nanofiber-based TENGs described can be categorized as polymer composites since they are made by electrospinning one or more components into a polymer matrix, which changes the material's surface electrification and permittivity [32]. Furthermore, a broad variety of materials (nano/micro metals and carbon-based materials have been tested in conjunction with nano/microfibers in order to increase the output performance of energy harvesting devices [65–69], including Ag nanowire (AgNW), graphene, iron, and ZnO nanoparticles and 2D nanomaterials [22,45,52–54,70–77]. Some recent studies have observed the promotion of a highly polar β-phase in PVDF by incorporating suitable additives. Electrospun PVDF nanofibers composited with AgNWs were fabricated by Cheon et al. [78]. They were combined with nylon nanofibers to study the triboelectric effect of a polymer-metallic nanofiber design. Fig. 3A shows how a 3 wt% increase in Ag NWs resulted in a significant rise in output voltage (from 156 V to 240 V. The PVDF–Ag NW demonstrated a homogeneous and bead-free fibrous structure across a vast area at concentrations up to 3 wt%. This work also suggests that the uniaxial stretching of the nanofibers in conjunction with the charge trapping mechanism of the Ag NWs added to the performance capability of the device. The study also showed an enhancement in the mechanical stability of the nanofibers through thermal annealing without affecting TENG performance. The enhancement of β-phase, increased dipole moment and high degree of orientation in electrospun PVDF nanofibers through the incorporation of conductive fillers was further confirmed by studies featuring metallic and carbonaceous nanoparticles [75,79,80]. In addition, most of the fillers that enhance the dipole moment and triboelectric charge generation in the electrospun PVDF nanofiber-based TENGs were found to be ferroelectric in nature, which is also found to be beneficial for improving the charge density of the TENGs through effective polarization in the triboelectric layers [81]. Using Ag nanowires (NW) in the PVDF–TrFE matrix during electrospinning, Kim et al. [81] developed a nanofibrous membrane with an extremely high power production single-electrode triboelectric nanogenerator (SETENG). As the Ag NW content grew from 0 % to 2 %, the output performance improved and a rise in SETENG's output power from 13 mW to 22 mW was observed. Short-circuit current and open-circuit voltage were also boosted by adding 2 wt% Ag NWs to the circuit. Wearable applications, trajectory tracking, external physical sensing, and chemical stimuli sensing are all possible with this special nanofiber-based SETENG.

In another investigation, Choi et al. [79] developed PVDF/graphene quantum dot (GQD) composite nanofibers (NFs) with better triboelectric nanogenerator (TENG) performance (Fig. 3B). When an appropriate amount of GQDs were added, structural and chemical studies revealed that the GQDs supported the development of the polar β-phase in PVDF. The maximum output power of TENG devices rose from 35 to 97 μW, as the GQD content climbed from 0 to 5 vol%, but declined as the GQD content increased further. The increased GQD content improved and degraded TENG performance due to the greater development of polar β-phase and the deleterious influence of conductive GQDs on charge trapping, respectively. Similarly, Bhatta et al., [71] investigated the incorporation of MXene nanosheets into the PVDF matrix before being electrospun to increase the dielectric property and surface charge density of the nanofiber, which significantly improved triboelectric performance (Fig. 3C). A triboelectric nanogenerator (TENG) based on PVDF/MXene composite (PMC) nanofiber and Nylon 6/6 nanofiber could provide a power density of 11.21 W/m^2 at a matched load of 2 ΩM, with extremely stable (greater than 60 K cycles) output signals that charge the storage capacitors fast and operate the low power electronics and commercial LEDs sustainably. In addition to energy harvesting, the TENG has been successfully shown as a self-powered foot motion sensor,

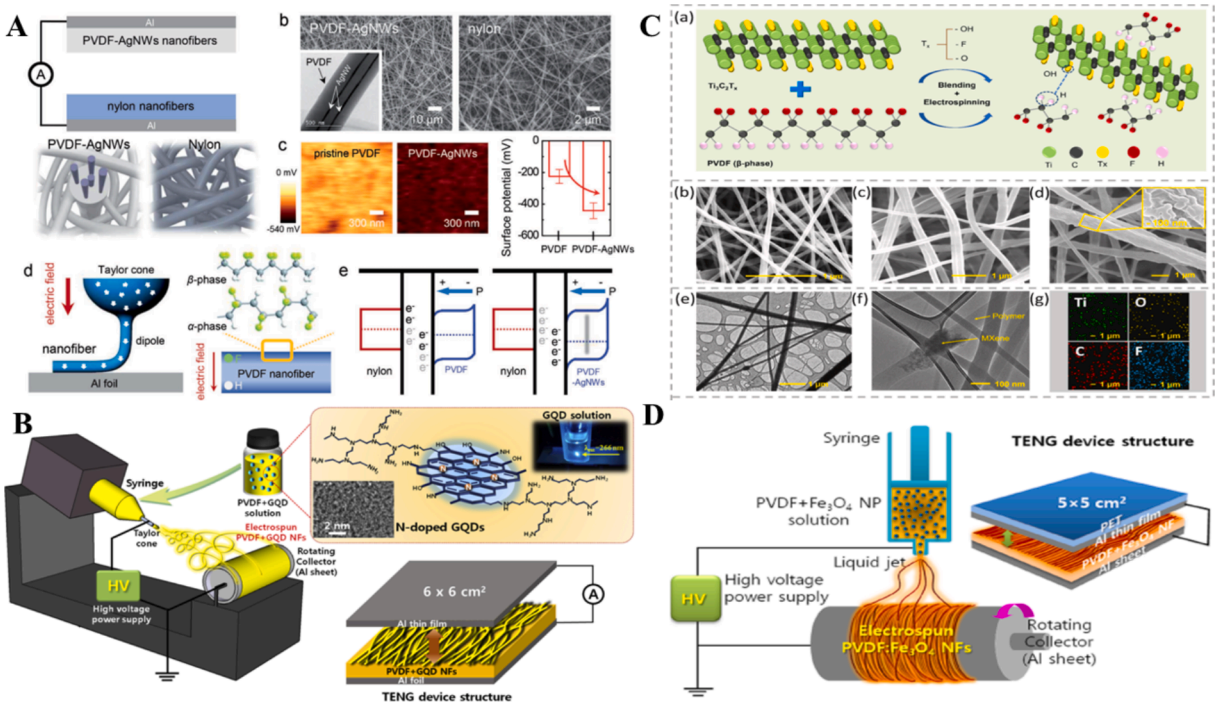


Fig. 3. **(A)** Schematic diagram, morphology (SEM and TEM images), surface potential, schematic illustration of the electrospinning procedure as applied to the PVDF solution and schematic of working mode of the PVDF–AgNW and Nylon nanofiber based electrospun TENG device. Reproduced with permission [78]. Copyright 2017, John Wiley & Sons. **(B)** Fabrication process and structure of PVDF/GQD composite NFs based TENG device by the electrospinning method. Reproduced with permission [79]. Copyright 2019, Elsevier. **(C)** (a) The chemical structure and scheme depicting the effect of MXene integrating into the PVDF matrix, FESEM images of (b) electrospun Nylon 6/6 nanofiber, (c) electrospun PVDF nanofiber and (d) PMC nanofiber and (e-f) TEM images of the PMC nanofiber demonstrating intercalation of MXene nanosheets within the PVDF matrix, (g) EDS elemental mapping image of a PMC nanofiber containing MXene. Reproduced with permission [71]. Copyright 2021, Elsevier. **(D)** Electrospinning method for fabricating Fe_3O_4 NP/PVDF composite NFs and TENG device structure. Reproduced with permission [82]. Copyright 2018, American Chemical Society.

which can control the step lights depending on human foot motion over the stair. In a study conducted by Im et al., [82] electrospun membranes of Fe_3O_4 embedded PVDF were developed (Fig. 3D). The ion–dipole interaction observed between the PVDF polymeric chains and oxo or hydroxyl groups in Fe_3O_4 enhanced the β-phase of PVDF. Also, random orientation of embedded Fe_3O_4 on the electrospun PVDF nanofibers was observed without any agglomeration at a concentration up to 11.3 wt% of Fe_3O_4 in the PVDF matrix. These attributes and a maximum *V*oc of 134 V with a maximum *I*sc of 5.68 μA make the system suitable for a stretchable TENG device. Apart from that, the robust mechanical strength of the nanofibers were ascribed to the hindrance given to the crack propagation by the Fe_3O_4 nanoparticles.

High flexibility obtained for electrospun polymeric nanofiber-based TENGs was also demonstrated in some of the recent studies. Furthermore, the easy incorporation of functional materials into polymer matrices during the electrospinning process has hugely benefited the fabrication of surface modified nanofibrous membrane based TENGs. A study conducted by Jiang et. al. [64] which includes MXene nanosheets embedded PVA nanofibers justifies this. The electrospun nanofibrous membranes of MXene/PVA when contacted with a silk fibroin exhibited exceptional and stable electrical output in combination with stability and durability. The high performance of the TENG assembly was ascribed to the nanostructure and high surface area achieved by this surface modified design achieved through electrospinning. For the tribo negative layer, MXene nanosheets were incorporated into a poly(vinyl alcohol) (PVA) matrix for ensuring wearability, while electrospun silk fibroin acted as the electron-donating layer. A tip-to-collector distance of 11 cm was maintained constant and the electrospinning time was varied to achieve different thicknesses. The instantaneous output power reached a maximum with a *V*oc of 118 V and output power density of ~1.09 W/m^2 with a load resistance of 5 MΩ. Furthermore, the PVA/MXene-based TENG was capable of charging a 22 μF capacitor to a voltage of 2.9 V. In another study, Ozen et al. [62] utilized electrospinning to develop a modified polyacrylonitrile (PAN) and ethyl cellulose/PVP nanofibers as opposite polarity triboelectric layers. The electrospinning technique facilitated high power density with highly flexible dielectric contact layers. Through doping with sepiolite improved the tribo potential in electrospun PAN nanofiber. The maximum voltage and power density produced were 486 V and 28.1 W/m^2 for the sepiolites doped fibers. The developed nanofibers are appropriate dielectric layers for self-powered stretchable TENG devices.

In recent investigations, various modifications to the electrospinning process were also found to be highly beneficial for high-performance TENGs. PVDF nanofibers with improved triboelectric properties were developed by Shaikh et al. [52], by employing a far-field centrifugal electrospinning (CE) process which was further doped with multi walled carbon nanotubes (MWCNTs) (Fig. 4A). The spinning solution consisted of 7 wt% semi-crystalline PVDF in a 39:1 solution of Dimethyl formamide (DMF) to Tetrahydrofuran (THF) which was electrospun using the CE setup at a steady flow rate of 45 shots per minute. The obtained ultrafine PVDF nanofibers with smooth and porous surfaces were observed to have a diameter ranging from 100 to 300 nm with a high porosity of around 70 % – 80 %. Additionally, to provide crystalline β-phase growth and improve the surface charge density of the nanofibers, they were doped with functionalized MWCNTs. The PVDF nanofiber-based fabric was then woven to a nylon fabric to obtain a woven triboelectric nanogenerator (WTENG) with a total nominal area of about 60 mm^2. The electrical properties of the WTENG were evaluated from its periodic contact with a freestanding PDMS sheet under a force of 5 N at varying frequencies from 1 to 5 Hz. The maximum voltage, current, and power density values obtained were 7 V, 700 nA and 0.85 mW/m^2, respectively. By encouraging the formation of crystalline β-phase, which increases the surface charge density of the fibers during contact electrification, this work shows an enhancement in the triboelectric characteristics of an electrospun PVDF nanofiber-based fabric [52]. This design was demonstrated to be suitable for energy harvesting from human body motions by integrating it with human clothing and floor mats.

The positive impact of the orientation of polymer nanofibers on surface area and output performance was found to be further enhanced

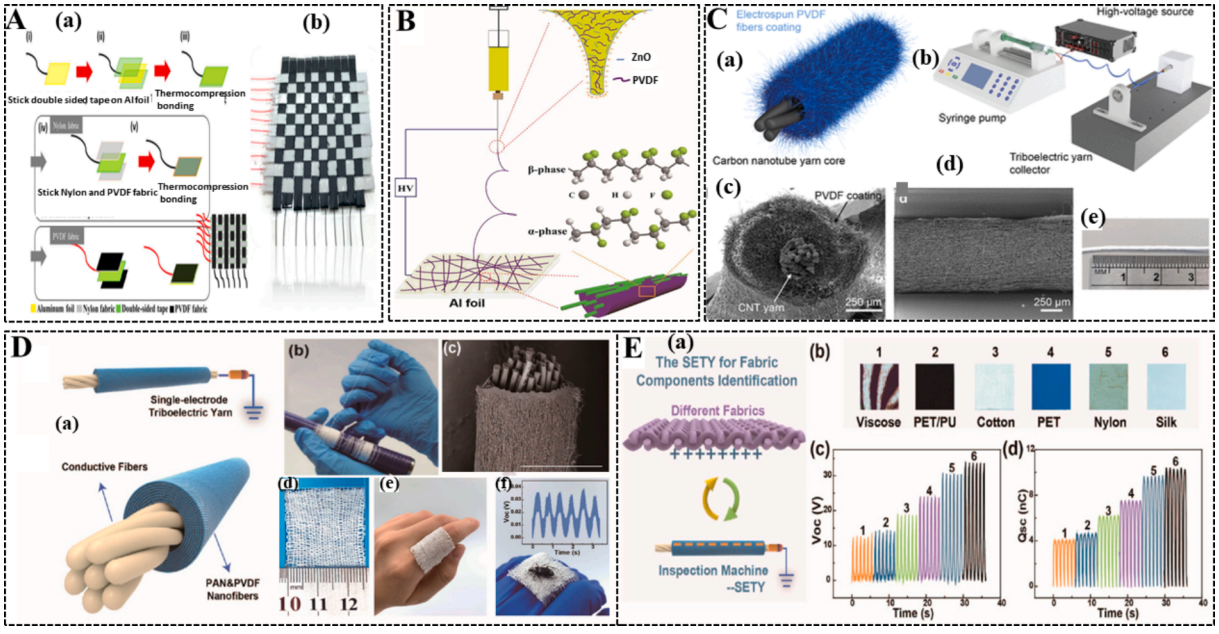


Fig. 4. **(A)** (a) Flow-chart of woven fabric TENG fabrication based on PVDF electrospun nanofibers, (b) image of the woven fabric made of PVDF electrospun fibers [52].Open Access 2019, MDPI. **(B)** Fabrication of PVDF/ZnO NWs based electrospun nanocomposite. Reproduced with permission [22].Copyright 2020, Elsevier. **(C)** (a) A triboelectric yarn based on core–shell structure, (b) electrospinning set up, (c-d) morphology of the prepared core–shell yarn and (e) actual image of the core–shell yarn. Reproduced with permission [75]. Copyright 2021, American Chemical Society. **(D)** (a) SETY's working principle and schematic illustration, (b) stretchable SETY, (c) SETY cross section as seen using a scanning electron microscope, (e-f) plain fabric fabricated by the SETY, (f) sensitivity measurement of the fabric touched by an insect. **(E)** (a) Textile component examination with SETY, (b) swatches of cloth and (c-d) electric output of different fabric samples. Reproduced with permission [84]. Copyright 2020, American Chemical Society.

by the alignment of fillers incorporated in the electrospinning polymer solution, in the same axis as that of the electrospun nanofiber. Apart from the high orientation of the fillers, their high dielectric characteristics and surface area also helped improve performance. This was demonstrated in work by Pu et al., [22] (Fig. 4B) where a TENG device with triboelectric layers of ZnO nanowires (ZnO NWs) with electrospun PVDF and Nylon 11 were created. The stretching of nanofibers during the high voltage electrospinning process and the presence of ZnO NWs in the PVDF matrix induced β-phase PVDF formation. They improved the orientation of the ZnO on the surface as well as inside of both PVDF and Nylon 11. In another study, Yar et al. [83] fabricated PAN/ZnO and PAN/$B(OH)_3$ nanofiber based triboelectric layers with higher power output performance than that of pure PAN-based TENG layers. 10 w/v% of PAN in DMF was electrospun with a DC power supply maintaining a distance of 15 cm between the collector and needle tip. Additionally, the solution flow rate was maintained at 1 mL/h, and 18 kV voltage was applied between the syringe and collector. The incorporation of ZnO nanoparticles and boric acid ions in the PAN matrix hindered the homogeneous fiberization, due to which the obtained fibers exhibited a wider size distribution. The study shows that the surface area of the dielectric materials and load conditions influences the power density of TENGs. The 3 × 3 cm^2 PAN/$B(OH)_3$ exhibited a power density of 6.67 W/m^2 when the resistive load was 33 MΩ.

Other advanced structural modifications are also possible via the electrospinning process. This was exemplified in a study by Busolo et al., [75] (Fig. 4C) were an extremely durable core–shell structured triboelectric yarn with an approximate diameter of 850 μm was obtained by coating electrospun PVDF fibers over conductive carbon nanotubes (CNTs). CNT yarns replaced the standard electrospinning unit drum collector, over which a uniform coating of PVDF fibers were formed. The work focused on the influence of relative humidity of the electrospinning process on the fiber formation and the PVDF fibers were electrospun at 60 % (PVDF 60) and 30 % (PVDF 30) relative humidity. It was observed that a higher tribonegativity and surface roughness was obtained for the PVDF 60 based nanofiber as compared to that of the PVDF 30. The vapor-induced phase separation observed in the hydrophobic polymer at high relative humidity was responsible for the increase in surface roughness and internal porosity of the fibers. Additionally, under the vertical contact separation working mode, these electrospun yarns produced a V_{OC} and I_{SC} of 2.6 and 465 nA, high resistance to wear and high flexibility. After 180,000 tapping cycles at a force of 10 N with 2 Hz frequency, the PVDF fibers were observed to have aggregated to form a film-like structure significantly enhancing the power output of the device. Also, a peak power density of 0.207 W/m^2 was obtained by this yarn for a contact area of 0.096 cm^2 even after 200,000 cycles. It is also noteworthy that the constraints associated with metal overlaid designs could be eliminated by such core–shell structured conducting and mechanically durable triboelectric yarns. The critical problem is mass-producing thin yarns with an excellent triboelectric output in a steady production process. Hence, the positive effect of core–shell structured electrospun fibers is further explored by Ma et al. [84] (Fig. 4D-E). Electrospun single electrode triboelectric yarns (SETY) with an approximate diameter of 350 μm consisting of polyacrylonitrile (PAN) and PVDF in combination with conductive silver were fabricated. The core–shell structured helical fiber bundles exhibited good triboelectric properties with a maximum output performance for the fibers with PAN: PVDF ratio of 1:3. The yarns were electrospun at an applied voltage of ± 12 kV between the two needles with a solution flow rate of 0.8 mL/h to achieve a yield of 60 mL/ h. At low frequency of 1 Hz, the open-circuit voltage, short circuit current and the short-circuit charge obtained were 33.4 V, 0.49 μA and 11.2 nC, respectively. Additionally, this yarn, yielded high outputs of 40.8 V, 7.05 × 10^{-3} mA/m^2 and 9.513 nC/cm^2 under an applied mechanical driving frequency of 2.5 Hz.

The voltage at which the electrospinning process is carried out plays a crucial role. An electrospun fibrous composite surface based on the ferroelectric copolymer, poly (vinylidene fluoride-*co*-trifluoroethylene) (P(VDF-TrFE)) dispersed with $BaTiO_3$ (BTO) was developed by Min et. al. [74] (Fig. 5A). The electrospinning was carried out at a voltage of 17 kV with a flow rate of 0.5 mL/h collected by a drum collector rotating at 1500 rpm to obtain electrospun mats with a thickness of around 8 μm. The developed tribonegative surface exhibited higher surface polarization and yielded a maximum *V*oc, *J*sc and optimum power density of 315 V, 0.067 mA/m^2 and 2.75 W/m^2, respectively. These values were found to be higher than those obtained for the spin-coated (PVDF-TrFE))/BTO composite. This was attributed to the improved dipole alignment caused by higher voltage and uniaxial fiber stretching during electrospinning. Apart from that, it was also observed that the incorporation of $BaTiO_3$ fillers improved the crystallinity of the beta phase of the polymer matrix which further increases dipolar moment per unit cell compared to other phases. Also, the homogeneous dispersion of BTO in the P(VDF-TrFE) had dramatically improved the matrix's permittivity, leading to an increase in the capacitance of the TENG. Moreover, this enhancement in crystallinity in conjunction with the polarization induced by the electrospinning process leads to increased surface potential, and hence, the ability to transfer more charges and raise TENG output.

Building porous nanostructures could also be an excellent way to boost the charge density of nanofibers [55,56,85–87]. Porous tribomaterials in TENGs can be challenging to produce because of the complexity of constructing nano-scale structures. With a wide surface area and high porosity, porous materials are ideal for applications that need high surface area. TENG charge density will rise if the contacting material is porous, since the effective contact area will grow and more charge traps will absorb electrons [88]. The solvent is utilized directly as a liquid template in the electrospinning process for creating porous materials on nanofibers because it volatilizes easily after electrospinning at ambient temperature and pressure. Since no further templates or washing solutions are required, the nanoporous structure may be created in a single process. Yu and colleagues [85] constructed a TENG based on biomimetic nanofibers of water hyacinth petiole (BWHP) and PVDF nanofibers through a two-component coaxial electrospinning method. The honeycomb structure was created by pressing the PVDF nanofiber mat (Fig. 5B-C). The nanofibers have a rough surface because the PVDF solution is mixed with mineral oil during the electrospinning process. Charge loss is prevented by the hexagon structures of the pressure-treated PVDF nanofiber mat. The max output voltage, charge density and power density of the developed TENGs were 1000 V, 364 $\mu C/cm^2$ and 6 W/m^2 respectively – enough to operate some wearable devices and charge a commercial Li-ion battery.

A waterproof and breathable TENG (WB-TENG) designed by Lan et al. [89], consisted of an active triboelectric layer comprised of an electrospun poly (vinylidene fluoride-*co*-hexafluoropropylene) and electro sprayed fluorinated carbon nanotubes. The simultaneous electrospraying of F-CNT onto the electrospun PVDF-HFP resulted in the embedding of F-CNT within composite nanofibers (Fig. 6A). This electrospun PVDF-HFP solution formed a porous and hydrophobic nanofibrous network with excellent durability and breathability. Moreover, the presence of fluorinated groups in the microspheres resulted in increased surface roughness and tribonegativity of the composite film leading to enhancement of the WB-TENG output performance. The combination of electrospinning and electrospraying of different components was a reliable method for developing tunable nanostructured fibers where functional components are embedded between the nanofibers. The triboelectric performance of the TENG was evaluated under single-electrode mode and was found to have achieved a V_{oc} of around 500 V and J_{sc} of around 0.05 mA/m^2 at a 15 wt% loading of F-CNT under a contact force of 30 N and frequency of 5 Hz. Additionally, the study reveals that this WB-TENG with strong electro-static adhesion could be used in plant leaves for energy harvesting from wind and rain- drops. Electrospun PVDF-graphene nanofiber (PVDF/G NFs) composites with excellent triboelectric performance were prepared by Shi et al., from hybrid PVDF-graphene solutions with varying concentrations of

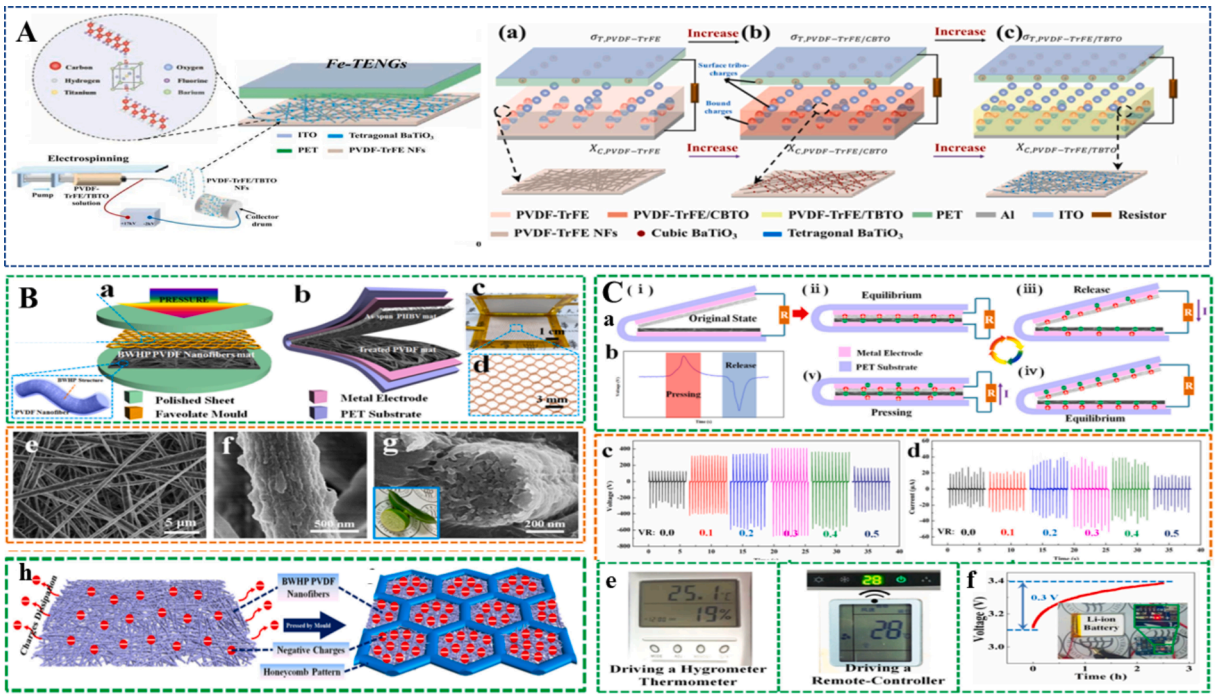


Fig. 5. **(A)** The effect of ferroelectric polarization in the triboelectric surface potential and charge density, (a-c) schematic of Fe-TENG having different electro-negative materials. Reproduced with permission [74].Copyright 2021, Elsevier. **(B)** (a-d) schematic illustration, (e-g) SEM images, and (h) working principle of pressure-treated PVDF nanofibers in the BN-TENG. **(C)** (a-d) operational mechanism and electrical output of BN-TENGs and (e-f) BN-TENG can power electronic equipment such as: a calculator, a thermometer, remote control and a Li-ion battery. Reproduced with permission [85].Copyright 2018, Elsevier.

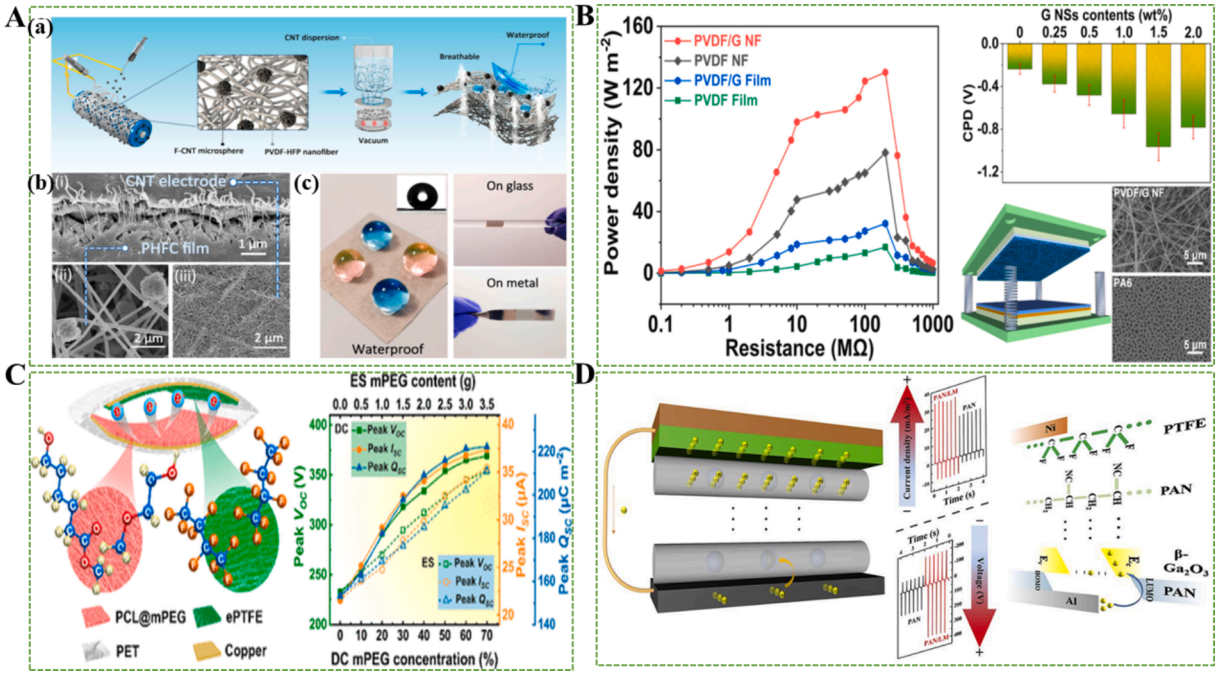


Fig. 6. **(A)** (a) Schematic illustration of the WB-TENG fabrication process, (b) SEM images of the WB-TENG and (c) images illustrating the hydrophobic properties of the PHFC film. Reproduced with permission [89]. Copyright 2021, American Chemical Society. **(B)** Schematic illustration of the TENG energy harvesting based on electrospun PVDF-graphene nanosheet composite nanofiber. Reproduced with permission [7]. Copyright 2021, Elsevier. **(C)** Illustration of electrospun positive tribomaterials with oxygen-rich polymers as mechanical energy harvesters. Reproduced with permission [90]. Copyright 2019, American Chemical Society. **(D)** Schematic diagram of charge trapping and effect of liquid metal particles in electrospun polymers for TENG applications. Reproduced with permission [91]. Copyright 2019, Elsevier.

graphene nanosheets [7]. It was observed that with a 2.0 wt% loading of graphene nano sheets in the PVDF matrix, smooth and highly porous bead free fibers were obtained without aggregation of the nanosheets (Fig. 6B). The triboelectric performance of the nanofibers was evaluated under a contact force of 50 N and working frequency of 5 Hz, with PVDF/G NFs as the tribonegative layer and Polyamide 6 (PA6) as the

tribopositive layer. Four times higher values of voltage (~1511 V), short-circuit current density (~189 mA/m^2), and peak power density (~130.2 W/m^2) compared to that of pristine PVDF nanofibers were observed. This is the highest power output among the papers reviewed in the present paper. The inclusion of graphene nanosheets in addition to the electrospinning process resulted in the creation of polar crystalline-β-phase, which was identified as the primary explanation for the exceptional qualities achieved. Apart from that, the improved surface potential and charge trapping sites increased the output performance of the PVDF/G NFs – PA-6 TENG [7].

In another study, Zhang and co-workers developed a TENG combining an electrospun poly-Ɛ -caprolactone (PCL) nanofibrous membrane with an extended polytetrafluoroethylene (ePTFE) membrane [90]. This TENG assembly in which the PCL membrane acts as the tribopositive layer and ePTFE as the tribonegative layer, exhibited excellent performance owing to the ability of the oxygen atom donors present in PCL (Fig. 6C). Compared to a conventional PA6/ePTFE TENG, 28 % increment in the electrical output was observed with a maximum V_{OC} of 265.71 V and a power density of 53.87 W/m^2. Furthermore, the incorporation of methyl-PEG with PCL membrane improved the tribopositivity of PCL and thereby achieved a 40 % increment in the electrical output of the TENG. Additionally, this study revealed the positive impact of oxygen-rich polymers on enhancing electron affinity in tribopositive layers [90]. Similarly, by adding liquid metal (LM) particles (Gallium), Ye et al. was able to produce a TENG device that was able to produce a $V_{OC} = 375$ V and a charge density = 35 mA/m^2 [91]. The high output was attributed to the LM particles which are not only cheaper than other nanomaterials, but due to their liquid state, are more evenly dispersed within the fiber (Fig. 6D). Table 3 gives a comparison of the electrical outputs of TENGs fabricated using electrospun polymer nanocomposite materials.

3.3. Multi-layered TENGs

The amount of charge density on both sides of the interface controls the performance of TENGs [92]. For most cases, charge generation, charge transfer and storage, and charge dissipation all play a role in the triboelectrification process. According to the position of triboelectric materials on the triboelectric series, positive and negative charges collect first on the contact surfaces. Once separation occurs, an electrical potential difference is generated between the triboelectric layers. On the other hand, the triboelectric charges that have already been created in the friction component will prevent new charges from entering. TENG output performance will remain constant as a result of the accumulation of charge in the friction component [93]. In addition, a materials triboelectric charges rapidly diminish over time if they are not fully used. TENG performance will significantly improve if these concerns are solved. Composing the contact materials for TENGs by using both charging layers and charge storage layers is the most efficient way to increase the density of charged particles in order to accomplish structural optimization of the composite structure [94]. Electrospinning is equally suitable for fabricating different components of the TENGs, such as the charge generating layer, charge storage layer, and the conductive layer [34,95–98]. Moreover, the technique can also fabricate multi-layered structures with good compatibility and adhesion between layers [99,100]. Hence, a multi-layered TENG composed of a charge-transport layer and a charge-storage layer in the friction components, the composite three-layered structure displayed much greater electric output performance due to the accumulation of charge density than the single-layer structured TENG. This attribute is highly suitable for wearable devices since it helps to reduce the number of separate components in the device and improves wearability. Additionally, it helps to rule out the possibilities of delamination of different layers over continuous mechanical deformations and frequent washing (in textile TENGs). Illustrated in Fig. 7(A-C) is a TENG constructed using electrospun PES and cellulose acetate (CA) nanofibers as the tribo-layers. PS nanofibers were chosen as the charge storage layer [92]. A composite PS–carbon black nanofiber layer was chosen to transmit the charge and to make the device more efficient. All four membranes are depicted in SEM pictures in Fig. 7A, which demonstrate their morphologies and water contact angles, as seen in the photographs. Adding a charge transport and storage layer to the nanofiber-based TENG device may significantly increase its output performance. As a result, the multi-layered structures current and voltage output were 3 and 2.6 times, respectively compared with the single-layer structured TENG and demonstrated a power density of 0.13 W/m^2 during the contact–separation process. Even after 600 cycles of running, the TENG proved to be exceptionally robust, steady, and flexible. Thus, it is ideal for gathering biomechanical energy from human motions, as it can be embedded into the fabric.

Electromagnetic pollution protection and multifunctionality are becoming increasingly crucial as wearable electronics proliferate. It is still challenging to find EMI shielding materials that may be used in various applications. Du and co-workers created an increscent EMI shielding multi-layered MXene/PLA composite membrane by using MXene to be alternately constructed onto electrospun PLA nanofiber mats [99]. The multi-layered membrane attained optimal shielding effectiveness (SE) of 55.4 dB, which may be attributed to the MXene layers intact conduction and the multiple-reflection–absorption effect. The fast temperature rises from 31 °C to 52.8 °C at a low trigger voltage of 1.5 V was achieved due to the MXene-based multi-layered membrane's exceptional Joule heating capability. Based on the multi-layered membrane, the triboelectric nanogenerator generated 0.46 W/m^2 of peak power density, as a result of which it is capable of force sensing and energy harvesting. It is possible to make bio-based EMI shielding membranes using this method, and the results offer a new framework for

Table 3
Comparison table of maximum device outputs for TENGs fabricated using electrospun nanocomposite polymer materials as one of the triboelectric layers.

Electrospun Nanocomposite Materials for TENGs								
No.	**Polymer Base**	**Nano composite**	**Effective Area (cm^2)**	**Resistance (MΩ)**	***Voc* (V)**	***Isc* (μA)**	**Power Density (W/m^2)**	**Reference**
1	PVDF	GrO NPs	4 × 5	0.1	340	78	N/R	[53]
2	PVDF	AgNWs	2 × 2	N/R	240	~12.5	N/R	[73]
3	Polyacrylonitrile	Gallium	N/R	N/R	375	N/R	N/R	[91]
4	PVDF	TrFE	3 × 4	100	576.7	N/R	2.39	[26]
5	Nylon 11	ZnO NWs	N/R	10–20	330	10	3	[22]
6	PVDF							
7	PVDF	Graphene NSs	0 × 2	100	1511	N/R	130.2	[7]
8	Polyimide	PVDF + TrFE	N/R	100	364	17.2	2.56	[59]
9	PA6	PVDF–HFP/rGO	3 × 3	1 × 10^3	80	1.67	0.45	[49]
10	PET	Fe_3O_4//PVDF	5 × 5	N/R	138	5.68	N/R	[82]
11	Polyvinyl alcohol (PVA)	PVA/MXene	28.3 (circular)	5	118.4	N/R	1.0876	[64]
12	PVDF	TrFE-MXene	0.3	4	270	N/R	N/R	[54]
13	PAN	ZnO	3 × 3	33	166	N/R	6.67	[83]
14	PVDF	CNT	0.096	400	2.6	0.46	0.207	[75]

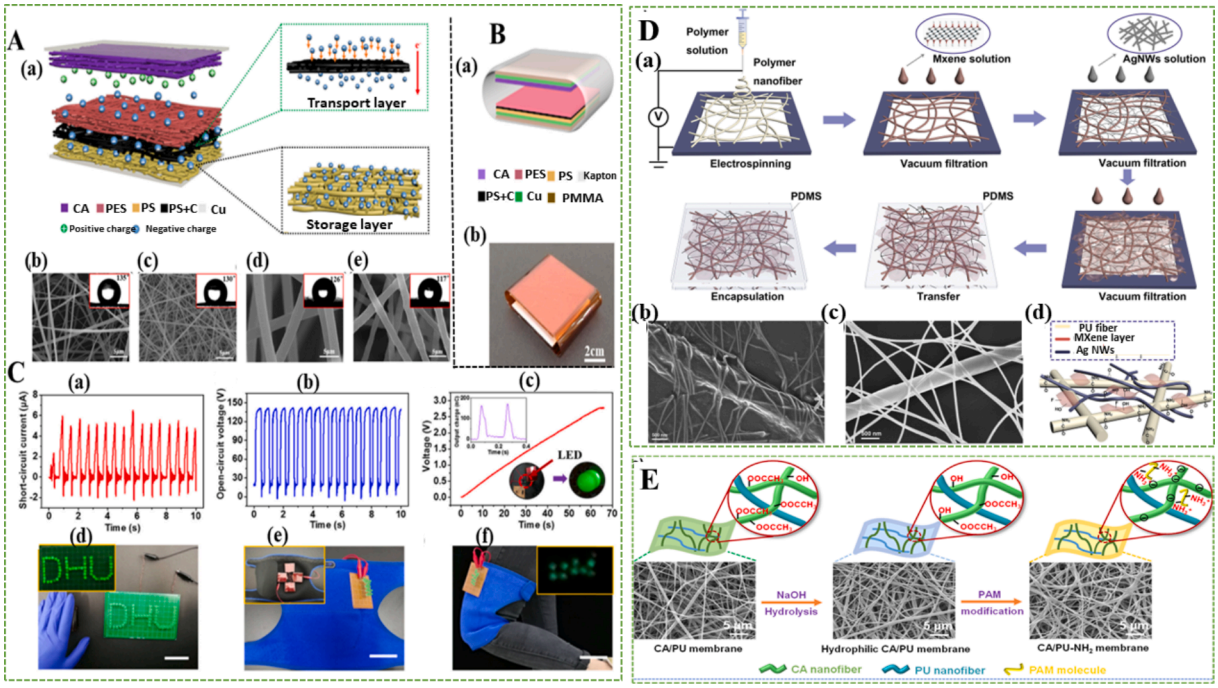


Fig. 7. **(A)** (a) The triboelectric charge transfer and storage process in the multi-layered TENG, (b-e) SEM image of carbon black-containing electrospun CA, PES, and PS nanofibers. **(B)** Multi-layered composite TENG schematic drawing and optical image. **(C)** (a-c) multi-layered TENG electrical output characteristics and (d-f) demonstrations for diverse human biomechanical energy harvesting applications. Reproduced with permission [92].Copyright 2018, Elsevier. **(D)** (a) Diagram of the fabrication process of stretchable and transparent TENG, SEM images of (b) a hybrid electrode of MXene-AgNWs-MXene-PU nanofibers and (c) AgNWs-PU nanofibers electrode and (d) interfacial interaction mechanism diagram of MXene, AgNWs, and PU nanofibers. Reproduced with permission [76].Copyright 2020, Elsevier. **(E)** Surface amino modification of nanofibrous membranes as a strategy for increasing hydrophobicity. Reproduced with permission [101].Copyright 2017, Elsevier.

the design of functional devices that are integrated. Multi-layered antibacterial nanofiber air filters were made using a rotating triboelectric nanogenerator (R-TENG) [100]. The multi-layered polyimide nanofiber filter is superior to single-layered nanofiber filters in removing bigger particulate matter (PM) particles and enhancing the removal of smaller PM particles. Linking R-TENG increases the filters ability to remove ultrafine particles. For ultrafine particulate matter, the greatest significant percentage removal is 94.1 %, while the average removal efficiency is 89.9 %. It was found that despite an increase in the number of layers, each layer's thickness reduced; as a result, the filters total pressure drop reduced rather than increased. The presence of a small quantity of silver nanoparticles in the nanofiber film, resulted in an antibacterial effect. This technology's minimal pressure drop and zero ozone emission make it ideal for cleansing air, haze removal, and bacterial control.

The enhancement of surface charge density is observed in triboelectric charge generating layers of the multi-layer electrospun TENG designs. This was exemplified in a work by Hao et al. [34] where an electrospun multi-layered structure of PVDF and polystyrene doped with carbon black (PVDF/PSC/PS) nanofibers were used in combination with PVA nanomembranes. On comparing with the PVDF only tribo-layer, the PVDF/PSC/PF membrane showed a 695 % increase on the output performance. The surface roughness and high specific surface area obtained in addition to the uniform distribution of carbon black nanoparticles in the polystyrene nanofiber is a result of the electrospinning method used for developing the membrane. Apart from that, the improvement in charge trapping ability observed in this multi-layered membrane along with increased charge transfer rate, helped to enhance the surface charge density in this design. This TENG assembly also sheds light on the importance of the right combination of materials with multiple functionalities in attaining higher output performance in TENGs. Similar to the enhanced properties observed in multi-layered friction membranes, this strategy is also found to be beneficial for the electrode component of TENGs especially in terms of the stretchability and durability of the device. This is justified by the higher strain rate of 180 % over 1000 cycles of stretching achieved in an electrode design featuring multiple layers of MXene solutions and AgNW dispersions laid over an electrospun TPU polymer membrane [76] (Fig. 7D). Additionally, it was also observed that there were no significant variations in the output voltage even after 500 cycles of stretching at a strain rate of 65 %. Moreover, this highly stretchable and transparent electrode in combination with a PDMS tribo-negative layer produced a *Voc* of 38 V and current density of 1.67 mA/m^2.

A sound-driven TENG was fabricated by Qiu et. al., [102] which comprised of a Cu foam, PVDF nanofibers and Nylon fabric. This sandwich-like TENG design enabled the conversion of vibration from acoustic waves with bandwidth ranging from 25 Hz to 425 Hz, to electrical energy. Electrospun PVDF nanofibers formed the three-layered TENG on the surface of a porous Cu foam and PEDOT:PSS was coated on the nylon fabric. The electrospun PVDF nanofibers improved the Cu foam's surface area and enhanced the output performance during the contact electrification process. The light weight flexible PVDF nanofibers and the nylon fabric attached to the Cu foam acted as the vibration films that facilitated enhanced soundwave propagation with reduced loss of sound energy and, in-turn enhanced the electrical output. The electrical outputs were 523 V, 60.5 μA and 25.01 mA/m^2 respectively under a 125 Hz and 110 dB sound wave. The benefits of multi-layered design in both the charge generating layer and the electrode component of TENGs have been reflected in the output performance and durability of the devices developed in the aforementioned studies. The synergy between charge storage and charge generation attained through the utilization of multi-functional materials in multi-layered membranes is the basis for increased surface charge density in friction layers. Whereas, in the case of the TENG electrodes, the main advantage of the multi-layered design is the retention of continuity of conductive networks to ensure the stability of the output. Also, it has been proved to be the reliable approach for replacing the commonly use rigid conductive materials in electrodes, which lead to somewhat inflexible devices.

Furthermore, the integrity and continuity between different layers achieved through the electrospinning process helps to improve the service life of the device.

3.4. Surface modified electrospun nanofiber based TENGs

To improve the interface contact characteristics, most contact materials for TENGs are subjected to either chemical or physical modification [103,104]. Physical surface alterations that improve the roughness of the layers can help triboelectric materials have more contact area. Micro/nanostructured materials have been placed onto the surface of tribo-contact layers to increase surface roughness in TENGs [105,106]. Complex processes, long processing times, restricted manufacturing area, and high treatment costs are all difficulties with these technologies. As opposed to physical surface modification, chemical surface modification is easier and can better regulate the contact area, change chemical characteristics, and even increase charge carrying sites without modifying the substrate [104,107]. Many materials that tend to gain or lose electrons [4] have been employed to functionalize the triboelectric friction layers, such as fluorinating surfaces, ion injection, and molecular targeting [108,109]. Chemical modification can solve a variety of concerns, such as poor mechanical characteristics and low inherent hydrophobicity, in addition to increasing the contact area of triboelectric materials [104].

Electrospinning and surface chemical amino modification were used by Shen et al. [101] to create a high-performance humidity-resistant triboelectric nanogenerator (HR-TENG). The electrospun CA/PU membrane is initially hydrolyzed in NaOH solution and then immersed in varying concentrations of polyacrylamide (PAM) solution. Amino groups were added to the treated CA/PU membrane following electrostatic self-assembly (Fig. 7E). The TENG device's output rose in proportion to the rise in PAM concentration. A power density as high as 1.3 W/m^2 was attained with a current and voltage output of 28 μA and 345 V, respectively (however, relative humidity was high at 55 %). As a result of its high output stability in humid environments, this device might function as a long-term source of power for electronic gears worn by athletes. Apart from chemically modifying the electrospinning solution or functionalising the electrospun fiber, spraying nanostructured materials directly over the surface of the fabric has also been observed as a feasible approach. This was exemplified in work by Qiu et. al. featuring an all fabric wearable TENG [110]. Both electrospinning and electro spraying methods were used to coat a PET fabric with polymeric nanofibers. This sandwich structured textile TENG with PVDF and PTFE nanofiber coated fabric attained excellent flexibility, breathability and washability. Moreover, a 16 cm^2 area of this textile generated a power density of 0.080 W/m^2 at a load of 50 MΩ.

4. Applications of electrospun nanofiber based TENGs in wearable electronics and self-powered sensing

Wearable TENGs have been deemed ideal substitutes for regular batteries which have clear limitations as a power supply for electronic devices. Sustainable material selection and structural design optimization are two critical aspects for improving the output performance of wearable TENGs. Recent research has proved that flexible and wearable electronics hold applications of numerous kinds such as electronic skin, e-fabrics, electronic watches, prosthetics, human–machine systems etc. [11,15,111–113]. The simple, reliable, and cost-effective electrospinning technique can produce highly flexible and stretchable nanofiber and nanocomposite membranes suitable for high-performance wearable TENGs [7,52,74]. However, there has been rather little study on achieving stretchability and transparency in TENGs simultaneously [112,114].

4.1. Electrospinning based stretchable and wearable TENGs

Among the new developments in wearable TENGs, highly flexible membranes and substrates developed by the electrospinning technique hold a significant place [45,52,64,115–120]. The effective surface-to-volume ratio and feasibility of molecular level orientations and excellent flexibility offered by electrospun fiber materials, can contribute greatly to the output efficiency of the device [66,115,120–123]. Moreover, this technique is proved to be most reliable, cost-effective, and promising for fabricating wearable TENG devices over the other lithography techniques such as photo-lithography, nanoimprinting, and laser interference [96,124,125].

Liu et al. [76] created a flexible and transparent TENG employing electrospun fibers of MXene and AgNWs with polyurethane nanofiber electrodes, having excellent optoelectronic characteristics with 87.6 % transmittance. A maximum strain of 180 % and a 42 % variation in resistance were observed after 1000 compression cycles at a 65 % strain on the as-prepared electrode, due to the MXene's improved adhesion between the conductive network and elastic matrix. With just a few taps, the TENG can produce 38 V of output voltage and 1.67 mA/m^2 of current density, making it a powerful energy harvester and motion sensor as well. Its combination of a stable power source and motion sensor together with stretchability and transparency make it an attractive candidate for wearable gadgets and human–machine systems. In a study by Zhang et al. [86], an electrospun PVDF triboelectric negative layer with super hydrophobicity and natural rubber (NR) (tribo-positive) were contacted to obtain outstanding TENG properties under humid conditions. The nanoporous structure of the electrospun layer enabled the trapping of more charges in their interior, which eventually enlarged the surface area of the electrospun fibers and thereby the contact area between the tribo layers. Moreover, an excellent power output density of up to 56.9 W/m^2 and a high *Voc* of 2209 V, obtained for this TENG electrospun nanofiber-based TENG assembly makes it a suitable option for biomechanical energy harvesters for use as human body movement detectors.

Sustainable, and wearable power sources are confronting major hurdles in tandem with the growth in multipurpose wearable devices. Jiang et al. [126] fabricated a skin-inspired triboelectric nanogenerator (SI-TENG) that is washable, flexible, and ultrathin and described as an extremely sensitive self-powered haptic sensor (Fig. 8A). The SI-TENG had various advantages, such as stretchability and light-weight, and adherence on human skin without disrupting its interface. Nanofiber networks of thermoplastic polyurethane (TPU) and silver nanowires intertwine to generate a flexible composite electrode that is electrospun and electrosprayed simultaneously. 8 N applied force resulted in a triboelectrification effect of 95 V, 0.3 μA, and 6 mW/m^2 for the SI-TENG. Signal processing circuits have been integrated within the sensor array to showcase its potential to identify human actions *via* energy harvesting and active sensing. The SI-TENG has a broad spectrum of uses in the domains of human–machine interfaces and security devices.

Nanofibers with high surface area superior softness are excellent possibilities for wearable TENGs, even if deformability and durability are difficult to seamlessly integrate with ordinary textiles/clothing. Li and group [127] suggested a physical interlocking technique based on nanofibers of Polyvinylidene fluoride-*co*-hexafluoropropylene (PVDF) electrosprayed with styrene-ethylene-butylene-styrene (SEBS) to make them a breathable, waterproof and stretchable nanofibrous membrane (Fig. 8B). The SEBS microspheres offer elasticity and hydrophobicity, increasing the electrospun PVDF-HFP fiber network's stretchability and waterproofness. A single electrode nanofiber TENG was demonstrated using a printable electrode formed of liquid metal containing gallium-indium-tin particles and silver flakes which were shown to be able to harvest energy from flowing water and human movements. It could power 200 commercial LEDs and an electronic watch at 85 V, 219.66 mW/m^2 triboelectric output. Mechanical resistance was high in the membrane made of stretchy nanofibers. To make textile-TENGs suitable

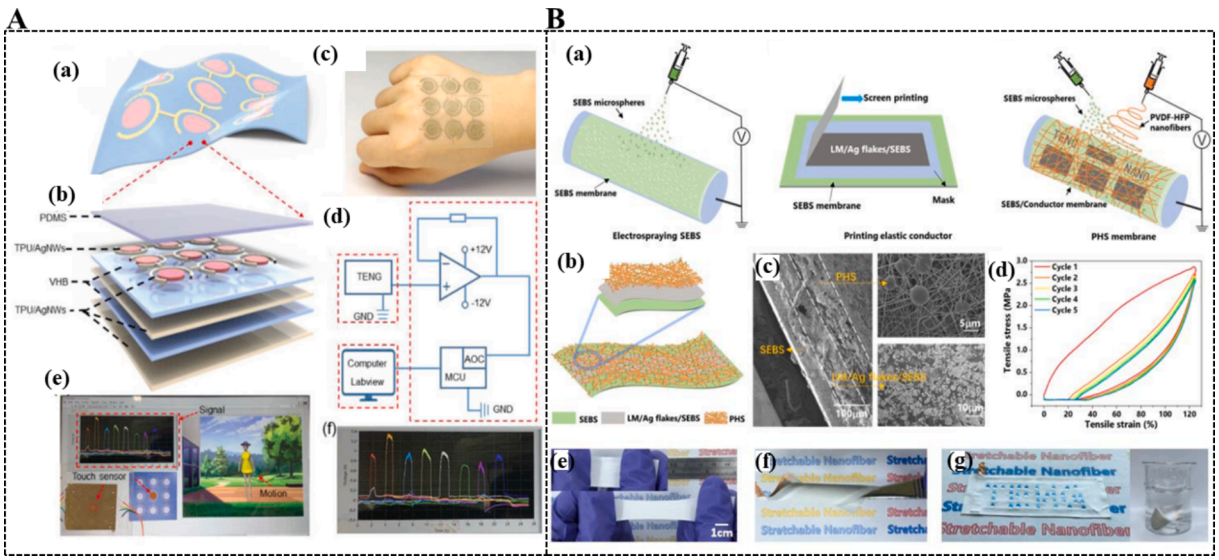


Fig. 8. **(A)** The SI-TENG as a haptic sensor for amusement games is demonstrated: (a) schematic of the 3 × 3SI-TENG array, (b) the 3 × 3SI-TENG array's structure, (c) illustration of the SI-TENG coupled to the hand, (d) schematic of sensor system circuit, (e) demonstration of how the SI-TENG array controls the movement of game characters and (f) screenshot of the output voltage in real time. Reproduced with permission [126].Copyright 2021, John Wiley & Sons. **(B)** TENG structure and characteristics based on self-interlocked stretchy nanofibers (SNF-TENG): (a) schematic depiction of the SNF-TENG fabrication process, (b) the sandwich-like construction of the SNF-TENG structure, (c) surface morphology and cross-sectional SEM picture, (d) cyclic tensile characteristics, (e–g) photographs exhibiting-stretchability, flexibility, hydrophobicity, and washability of SNF-TENGS. Reproduced with permission [127]. Copyright 2021, Elsevier.

for power sources, smart raincoats, self-powered e-skin, and haptic dynamic surfaces, it could be simply incorporated into the flexible textile.

4.2. Self-powered active sensors

Self-powered active sensors that can detect mechanical motions such as pressure, touches, vibration, or acceleration have been shown to be a novel source of power for wearable electronic devices [68]. TENGs based on electrospun materials have also been employed in toxic gas detection [128,129]. Motion and pulse detection in real-time is critical for health evaluation and medical diagnosis [130]. However, developing a pressure sensor having remarkable sensitivity and breathability that is also lightweight, flexible, and energy-efficient is still a major challenge [118,130,131]. Lou et al. used a simple electrospinning approach to create a pressure sensor TENG with complete fiber-structure [130] (Fig. 9A). Nanofibrous membranes comprising of PVDF/Ag nanowire and ethyl cellulose, and two conductive textile layers make up the sensor textile's composite structure. Using nanofibers with a rough structure, this wearable device demonstrated exceptional sensing capabilities in the pressure ranges of 3 to 332 kPa, the sensitivity can reach as high as 1.67 and 0.20 $VkPa^{-1}$, respectively. After 7200 cycles of continuous operation, the textile sensor demonstrated exceptional mechanical stability. The textile sensor was quickly conformable to many desirable body locations for dynamic motion sensing and active pulse monitoring. Future wearable electronics and multifunctional pressure sensors are likely to benefit from this research. Garcia et al. [132] reported another cost-effective electrospinning technology consisting of nanofibers of polyvinylidene fluoride and a polypropylene sheet to create an impact sensor (Fig. 9B). The influence of a free-falling ball released from different heights on TENG outputs was investigated. The purpose of this experiment was to see if there was any correlation with the electric output of the nanogenerator and the energy of the hit. Voltage and current outputs increased in a linear fashion as impact energy increased, according to the research. In addition, the electric responses exhibit exceptional sensitivity (14 V/J) and excellent reproducibility. Garcia et al. [133] also developed a novel triboelectric nanogenerator using electrospun PVDF and polyvinylpyrrolidone (PVP) submicron fibers. The TENG uses PVP, which rapidly loses electrons, whereas PVDF attracts electrons well. This study proposes employing a dynamic mechanical analyzer to evaluate the mechanical–electrical response connection. Voltage and current signals were proportional to the amount of pressure being exerted. As a sensor, the proposed nanogenerator has good sensitivity and minimum experimental error, making it ideal for use in real-time applications. The study's main achievements are an electrospun PVDF/PVP nanogenerator and its prospective use as a self-powered pressure sensor.

Li and his colleagues have created a triboelectric nanogenerator that is completely stretchable [134], by employing a PDMS friction layer with an anti-nickel foam structure over an electrospun electrode (Fig. 9C-D). The optimal output voltage was 92 V, which represents a tenfold increase over the voltage of a TENG based on flat PDMS films. Even at a stretching ratio of 50 %, the stretchable TENG retained steady output performance. Given its impressive features and ease of use as a self-driven sensor, the fully stretchable TENG was developed to monitor the bending and walking conditions of fingers. It was also successfully mounted to a leaf to measure wind speed in the natural setting where no external power supply is required. In another study, the authors described a method for creating a novel type of woven-structured triboelectric nanogenerator using scalable electrospinning technology [119]. The TENG is manufactured from industrial stainless-steel yarns encased in electrospun polyamide 66 nanofiber and P(VDF-TrFE) nanofibers. Also, the WS-TENG's electric output is capable of reaching 166.5 V, 8.5 μA, and 0.093 mW/m^2, when actuated by various friction materials in a standalone mode. The produced WS-TENG has demonstrated itself capable of lighting up 58 LEDs in series, charging commercial capacitance, and powering portable devices such as smartphones, tablets, and laptops. Sewn WS-TENGs in a smart glove allows tracking of finger motions in a wide range of scenarios. Wearable electronics and human motion tracking are likely to benefit from the new method to self-power textiles introduced in this study.

Huang and co-workers [135] have developed an all-fiber TENG insole that harvests energy from human walking by using electrospun piezoelectric PVDF nanofibers placed between two conducting fabric electrodes. A secondary nanostructure roughens the nanofibers surface to increase the insoles performance. At a maximum output voltage of 210 V, the insoles maximum output current is 45 μA, while its

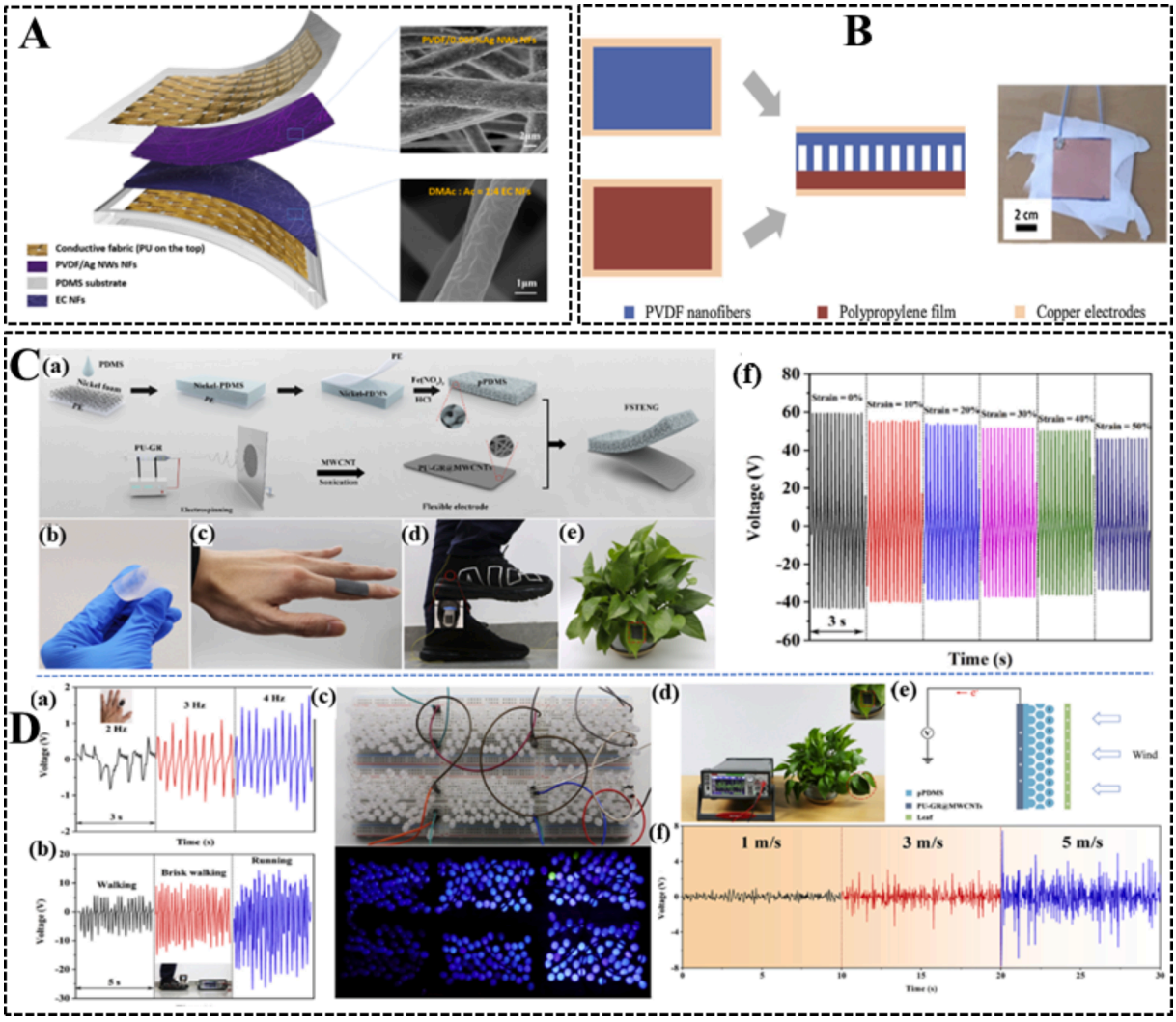


Fig. 9. (**A**) Design and structure of the pressure sensor based on PVDF/Ag NWs. Reproduced with permission [130]. Copyright 2019, American chemical Society. (**B**) fabrication of PVDF electrospun nanofiber based TENG. Reproduced with permission [132]. Copyright 2019, Elsevier. **(C)** (a) schematic representation of the FSTENG fabrication process, (b) photograph of the as-fabricated pPDMS film, (c) photo showing the FSTENG affixed to the finger joint, (d) photo showing the FSTENG affixed to the insole, and (e) photo showing the FSTENG affixed to a leaf surface, (f) electrical response of FSTENG to tensile strain. (**D**) FSTENG's application: FSTENG voltage output signals for (a) different frequencies of finger bending and (b) different walking states, (c) FSTENG optical images of 348 LEDs before and after lighting, (d-e) FSTENG's functioning mechanism as a wind speed sensor and (f) FSTENG output voltage signals at various wind speeds. Reproduced with permission [134]. Copyright 2019, Elsevier.

instantaneous power output is 2 mW. This invention has been proven to be a consistent supply of power that can quickly light up 214 serially connected LEDs. This nano fiber-based electrical power production approach may meet wearable device requirements for energy conversion efficiency and durability. In another work, Lin et al. [136] synthesized core–shell nanofibers by utilizing PDMS ion gel and PVDF-HFP nanofibers. They built static and dynamic pressure sensors by selectively utilizing changes in capacitance and triboelectric phenomena. There was also good performance as an ultrahigh-precision pressure sensor using a PDMS ion gel and PVDF-HFP nanofiber mat, with an extremely sensitive linear response of 0.068 V kPa^{-1} exhibited from 100 kPa to 700 kPa. This is the best linear response recorded thus far. With its higher inductive charges and enhanced dielectric capacitance than pure PVDF-HFP nanofiber, core–shell nanofiber showed that up to 0.9 W/m^2 TENG output power density is sufficient to rapidly illuminate several hundred LEDs.

Guo et al. [137] (Fig. 10A) outlined a whole fiber blended piezoelectric augmented TENG made of electrospun nanofibers of silk fibroin as the tribopositive part and electronegative PVDF nanofibers on conductive fabrics. The hybrid nanogenerator reached a power density of 3.1 W/m^2 benefitting from the enhanced surface area and the electropositive nature of silk fibroin during triboelectrification. This new all-fiber structure delivers all of the benefits of conventional textiles, as a result, clothes of any shape or size may benefit from the flexibility and exceptional air permeability of these materials. Additionally, the created gadget enables the identification of various body motions *via* a link between the gesture and the related electrical output. A versatile sustainable TENG sensor fabricated from cellulose nanofibrils was exhibited by Mi et al. [55] using PEI aerogel film, and PVDF nanofiber mats (Fig. 2B). Not only does modifying nanocellulose with PEI improve the aerogels mechanical characteristics, but it also increases the power density towards 14.4 times enabled by the higher electron donating tendency. Additionally, the triboelectric performance is enhanced by use of numerous layers of PVDF mats. It demonstrated an improvement in power density as well as output voltage of 18.3 and 97.6 times, respectively compared to the TENG composed of a single layer of PVDF mat and the peak output power density was 13.3 W/m^2. Additionally, in the role of self-sustaining sensor, the unique TENG exhibits exceptional

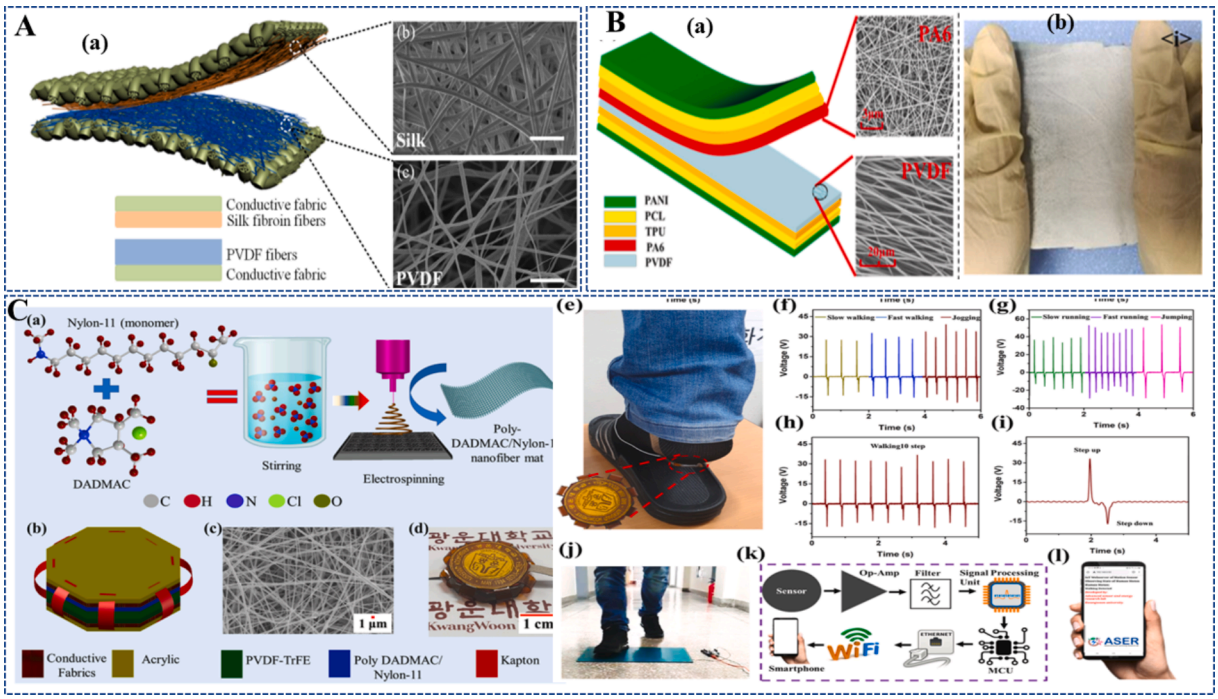


Fig. 10. **(A)** (a) Schematic of an all-fiber hybrid-triboelectric nanogenerator, (b) SEM image of silk nanofiber. Reproduced with permission [137]. Copyright 2018, Elsevier. **(B)** (a) structural design and (b) flexibility of the wearable TENG. Reproduced with permission [138]. Copyright 2019, Elsevier. **(C)** (a-d) Fabrication and characterization of poly-DADMAC/nylon-11 nanofiber mat, (e) TENG testing on a sock, (f-i) human motion voltage output, (j) set-up of self-powered motion monitoring, (k) human motion tracking for IoT applications and (l) a smartphone enabled active human movement sensor. Reproduced with permission [139]. Copyright 2021, Elsevier.

sensitivity. In addition to detecting human motion, such as arm folding or footfall, it could also detect tiny movements such as finger touching, liquid dropping, and substrate motion.

Due to the use of metal electrodes with no gas permeability, wearable devices have a particular hardness affecting comfort. Furthermore, the electrode does not stick to the frictional layer substance, resulting in a decreased electrical performance. Qiu et al. [138] developed a TENG, in which Polyaniline (PANI) electrodes and polycaprolactone (PCL) contacting materials are used (Fig. 10B). For smart wearable health monitoring, the TENG offers outstanding flexibility and gas permeability with electrical output reaching up to 200 μA and 1000 V. A 10 × 10 cm^2 wearable TENG can power approximately 1000 LEDs. Furthermore, it is able to track the patient's respiration in real time and notify them if they stop breathing. Patients with linguistic communication difficulties, on the other hand, can use Morse code to communicate messages by tapping their fingers. The self-powered sensor can function correctly with greater contact resistance, ensuring the device's long-term reliability in a variable environment.

Rana et al. [139] reported that TENG performance could be improved by an electrospun composite nanofibrous mat consisting of poly(diallyldimethylammonium chloride) (PDDA) and nylon-11 (Fig. 10C). A threefold boost in the composite materials charge trapping capabilities significantly enhanced the TENG's relative dielectric constant. When poly-DADMAC was introduced, the composite materials had six times the mechanical strength of nylon-11. The TENG produced long-term power for reduced electrical equipment with a power density of 7.6 W/m^2. Using the recommended TENG, a pressure sensor with 1.01 V/kPa sensitivity was successfully tested. For other purposes, the TENG was used as an active motion sensor to track a person's movements in real-time. Also, the TENG was successfully used in IoT to track human movement *via* a mobile web-based application. Development of high-performance TENGs and self-sustaining, wearable electronics and sensors is expected to benefit from the findings of this study.

Wearable electronics may be enhanced by adding extra features and functionalities that will increase their value and practicality. A self-cleaning, self-powered, UV-protected, and antibacterial TENG has been reported utilizing Ag nanowires/TPU nanofibers and TiO_2@PAN electrospun networks to capture mechanical energy [140]. TiO_2 NPs provided a UV protection factor (UPF) of 204, UVA transmittance (TUVA) of 0.0574, and UVB transmittance (TUVB) of 0.107. The TENG was a highly potent antibacterial agent against Staphylococcus aureus because of the combination of TiO_2 NPs and Ag NWs. The all-nanofiber-based pedometers micro-to-nano porosity structure enables them to self-power. An all-fiber-structured TENG was constructed using an electrospinning approach that was simple, scalable, and one-pot [68]. MXene sheet was used as the triboelectric negative material, while electrospun ethylcellulose and polyamide 6 mixture was used as the tribopositive part. When the TENG was manufactured using all-fiber components and a load resistance of 100 MΩ, it demonstrated exceptional durability and stability, along with good output performance, which peaked at 0.29 W/m^2. A vital feature of the TENG was its ability to capture the energy and use it to power multiple LEDs while acting as a self-powered motion sensor.

The passivity and sensitivity of an acceleration sensor are critical to its utilization as a vibration measuring tool. Zhang et al. [141] described a TENG made up of liquid metal mercury droplets and PVDF nanofibers to form an acceleration sensor. The electrical output reached 15.5 V and 300nA owing to the PVDF film's high surface tension and good elastic and mechanical resilience. The output voltage and current only dropped slightly over 200,000 cycles, exhibiting outstanding stability. Use of high-speed cameras allowed the acceleration sensor to be dynamically captured for future examination. It was also demonstrated that the acceleration sensor could detect real-time vibrations from mechanical equipment and human motions, which might be useful for equipment monitoring and troubleshooting. You et al. [142] demonstrated a SE-TENG (single-electrode triboelectric nanogenerator) with ability to detect human motion as well as extract biomechanical energy. In order to create the SE-TENG, a polydimethylsiloxane (PDMS) elastomer was

infused with Ag-coated polyethylene terephthalate (PET). Its flexible architecture responded to external pressure with alternating electrical impulses with an output voltage and current up to 50 V and 200 nA respectively. Human movements may be detected, and the device can simultaneously harvest electrical energy. For example, an electronic timepiece and LEDs could be powered by the captured energy.

A simple electrospinning technique and cold-pressing were used to create sustainable poly L-lactic acid and ethyl cellulose fiber film triboelectric layers and the nanofiber based thin films were shown to detect human movements [143]. Triboelectric output was greatest (19 V, 630 nA at 3.5 Hz) and life was longest in the brain-like structure among the three TENGs built to study the impact on different triboelectric layers. The developed sensor, which is self-powered, was used to detect human walking states and limb motions with high sensitivity. Because of its straightforward manufacturing process and biocompatible components, wearable and portable sensors based on nanofibrous TENGs could be the future of personal-healthcare and medical monitoring. A wearable TENG made entirely of Janus electrospun nanofiber sheets is created by Qin et al. [144]. This all-nanofiber-based TENG is not only lightweight and flexible, but it also breathes well due to its porous nature. Furthermore, the asymmetric conductive Janus structure provides an efficient method of improving the low adhesion force between the electrode and the electrification layer. It can create a peak voltage of 140 V, a current of 3.8 μA, and an instantaneous power of 0.75 mW as a self-powered device with an effective contact area of 2×2 cm^2. This basic yet flexible and breathable TENG has enormous application potential in self-powered wearable devices that can harvest diverse mechanical energies from daily living and accomplish real-time monitoring of human movements.

5. Challenges

Even though electrospun nanomaterials in TENGs have produced remarkable output, there are still a few challenges to overcome if we are to move electrospun TENGs from the laboratory to the real world. These challenges (explored below) are all interlinked with each other; they are challenging to overcome and present the greatest obstacle to the progression of TENGs to full scale industrialisation.

- *Electrospinning parameters and spinnability of functional polymers:* Even though electrospinning is one of the most versatile techniques available, it has a few limitations. These include the need for high voltage and conducting targets, the challenge of achieving *in situ* deposition, the difficulty of scaling production up, the difficulties of producing nanofibers with diameters less than 50 nm and the requirement of highly specialized equipment and repeatable systems for commercialization. Electrospinning organic conducting and semiconducting polymers utilized in traditional energy devices is extremely tough. Poly aniline (PANI) and PEDOT: PSS nanofibers have been used in energy devices; however, spinnable active polymers are still in short supply. New polymers and polymer blends should be developed in order to create flexible/stretchable functional polymers suitable for TENG applications.
- *TENG materials and structural design:* Identifying appropriate TENG materials with optimum structural properties is one of the most important decisions when attempting to fabricate new TENG devices. This combination of materials will not only ultimately influence the device's output, but also how the TENG device can be utilised. To begin with, most nanofiber-membrane-based TENGs have a sandwich-like multi-layer structure which includes triboelectric layers, spacers, electrodes, a supporting substrate, a protective/encapsulating layer, and so on, which is difficult to construct. Another drawback of nanofiber-based TENGs is the requirement for two separate triboelectric membranes in order to execute contact-separation motion [119]. Nanofiber-based TENGs, comprising metal plate electrode, binder/tape, PET substrate, and silicone protective encapsulating layer, all have a significant impact on the device's flexibility and breathability. Finally, the multi-layer planar structure is unable to withstand complicated deformations generated by human movement, making it unsuitable for application in wearable devices. One of the problems in future study will be to strike a careful balance between obtaining a high charge density while retaining the flexibility of the nanofibers and devices.
- *Low Output:* Although some TENG devices have reported exceptional outputs, these outputs are recorded under laboratory conditions where all variables are optimised. For TENGs to be cost effective, they would have to have similar output when tested under realistic conditions, where the variables such as humidity, ambient temperature, consistent load, and uniform contact cannot be assured. The low output power of electrospun fiber based TENGs, particularly flexible ones, is a key issue for wearable nanogenerators. One contributor is the lack of proper electrode materials [13]. Furthermore, investigations show that the electrical outputs of nanogenerators based on randomly oriented fiber webs are poor, which might be related to larger air gaps between the nano fiber webs. In particular, the low contact area presently achievable with textile TENGs is a critical limiting factor. The challenge is to figure out how to increase contact area in textile contact.
- *Flexibility and stretchability:* Improving the flexibility and stretchability of electrospun nanofibers in wearable TENGs is critical. Despite the fact that existing electrospun nanofiber-based soft electronics have some mechanical flexibility owing to the intrinsic flexibility of nanofibers, a few electrospun nanomaterials, like carbon nanofibers and metallic oxide nanofibers, have limited mechanical flexibility, resulting in inferior mechanical properties of TENG devices. Furthermore, careful control of the density, orientation, and porosity of the nanofibers is required in order to increase flexibility/stretchability while retaining the electrical performance of the TENG devices. Furthermore, various nanofiber assembly techniques should be integrated, and novel device assembly techniques should be developed to accomplish necessary flexibility/stretchability in wearable electronics. Furthermore, maintaining adequate conductivity of the components as they are stretched has been difficult for wearable TENG devices.
- *Durability and stability:* Nanogenerators with improved output performance may be made using fiber-based materials. Electrospun fibers, on the other hand, may distort and undermine the device's stability over time. As a result, while designing high-stability devices, the choice of material is a significant consideration. Hence, the usage of nanofiber based nanogenerators in wearable electronics and the identification of operating parameters need a methodical investigation. At the material level, first and foremost, the mechanical stability, durability and breathability of the devices must be greatly increased in order to meet the criteria for long-term operation. Brittleness of electrospun nanofibers is also a significant drawback for a variety of applications, which has become another motivating element for future research, particularly on generating extremely flexible continuous fibers. The addition of nanofillers to the fiber matrix has become another important field of study for biomedical and energy-related applications in order to get synergistic chemical and physical features.
- *Scalability:* Although electrospinning has advanced considerably in recent years, the transition to reasonably large-scale manufacturing is always a hurdle. The majority of past research on electrospun nanofibers and flexible TENG devices has been conducted at the lab scale. The entire cost, power usage, and environmental consequences must all be considered in order to accomplish industrial-scale manufacturing. Essentially, production costs would have to be reduced and overall performance and service life would have to be improved. The use of multi-spinneret or needle-free electrospinning, for example, appears to be hampered by their high industrial costs. As a result, increasing yield and lowering one-time manufacturing

costs will aid in the acceleration of the lab-to-commercialization shift.

6. Future perspectives

- *Interfacial engineering:* Interfaces have mostly been employed in TENG devices to alter surface morphology, which has resulted in increased electrical output power. Future research, on the other hand, is expected to focus on the design of interfacial regions, the fabrication of interfaces with greater active contact areas, the precise inclusion of surface imperfections and dopants, and more sensitive interface manipulation toward high-performance TENGs. In the case of nanofiber based TENGs, if the contacting material is porous, TENG charge density will increase [88]. Electrospinning procedures allow for the creation of porous materials on nanofibers so that the effective contact area will increase and more charge traps will absorb electrons. Because it volatilizes quickly after electrospinning at ambient temperature and pressure, the nanoporous structure may be generated in a single step because no further templates or washing solutions are necessary. Using two component electrospinning and inspiration from water hyacinth's internal structure and bionic technology, Yu et al., created biomimetic nanofiber tribo-contact materials [85]. With a 1000 V output voltage, a transfer charge density of 364 $\mu C/m^2$, and a power density of up to 6 W/m^2, this improved TENG is perfect for power generation: Using the one-component electrospinning technique, Zhang et al., created microfibers with a bionic petiole structure [86]. Internal nanopores and rough surface nanostructures improve surface charge density. Power density was 56.9 W/m^2, peak output voltage was 2209 V, and current density was 597.5 mA/m^2 in the optimized TENG design.
- *Development of new materials*: For many years, piezoelectric polymers such as polyvinylidene fluoride (PVDF) and its copolymers have been investigated for electrospinning purposes because the β-phase of PVDF has the maximum piezoelectric activity. At normal temperature, nylon 11 has good piezoelectric properties equivalent to PVDF among odd-numbered nylons. P(VDFTrFE) is an excellent tribo-negative material with low toxicity, and adaptable mechanical qualities, it has been extensively employed as a contact material for TENGs. Electrospinning may be the best method for modifying the P (VDF-TrFE) structure since it can continually create long and thin nanofibers. Despite significant achievement in the selection of triboelectric materials, many more materials remain undiscovered. To expand the use of TENGs, new green materials such as bio-derived materials, functionalized materials, inorganic materials, and composite materials are in great demand. In addition, it is highly desirable to develop bio-derived electrospun triboelectric materials with co-optimized mechanical and triboelectric properties, as well as compatible electrode materials with superior fracture resistance, flexibility, biocompatibility, and durability. In energy devices, on the other hand, one of the forthcoming primary targets is to synthesize nanofiber-based electrodes with optimum porosity and pore distance for boosting ion carrying and storing capacity, which will subsequently improve both energy and power density. Besides that, by incorporating and optimizing intelligent functional materials and their interactions with the basic fibrous structures produced by electrospinning, TENGs can be multi-functionalized which is critical in efforts to broaden the application scope of these one-dimensional nanomaterials produced by electrospinning.
- *3D printed TENGs:* The development of TENGs is making significant progress thanks to the latest 3D printing techniques. Wearable electronics, wireless networks, and biomedical implants may all be self-powered using 3DP-TENGs, which can scavenge ambient mechanical and vibrational energy. The utilization of triboelectric components that are elastic, flexible, and malleable considerably enhances the design options and integration abilities of the devices. It is possible to employ electrospun fibers as fillers in extruded 3D printing or to incorporate them into 3D printed frameworks. Electrospun fibers may be collected on a 3D printed pre-stressed or stretched substrate to create extremely stretchy fibrous membranes [145]. To create multidimensional materials with many micro/macro structures, electrospinning and 3D printing may be combined. Comfortable wear, even tribo-contact per foot pressure, and more crucially, enhanced tribo-effect from strain-mismatching contact were all given by the conformal 3D tailored interface. The tribo-interface, when squeezed during foot stepping, can create extra lateral friction as a result of the strain differential between the flexible and stiff components at the contacting interface. As a consequence, the output voltage and current of the 3D-customized TENG would be very high.
- *IoT devices:* "Internet of Things (IoT)" has recently attracted a lot of interest in remote health care monitoring systems, notably infectious illnesses (e.g. pneumonia, COVID-19). Modern IoT-based remote health care systems rely on ultra-sensitive pressure–temperature dual functional pressure sensors. It is utilized to transform applied force and temperature variations into an electrical signal, or other perceived signal output, from various regions of our body. Using these sensors, it is possible to monitor our health and activities in real time by attaching them to our clothing. In this context, electrospun materials based TENG devices would be excellent for real-world use because of their ultra-flexibility, light weight, and ability to adhere to any body surface while also requiring no external bias for operation. In order to avoid the transmission of viruses, a clinician can use this device to monitor many physiological signals such as heartbeat and respiratory rate as well as body temperature and coughing signal wirelessly without direct physical contact with the patient, even in a quarantine situation. Electronic skin and other artificial intelligence applications might use electrospun-TENG devices in the near future to monitor dynamic tactile and strain information because of their integrated device architecture, portability, and greater thermal and mechanical sensing capabilities.
- *Environmental sustainability:* The combustion of fossil fuels accounts for more than 80 % of primary energy consumption, and current profiles show that the globe remains heavily reliant on carbon-based power generation, resulting in record levels of carbon dioxide emissions (CO_2). TENGs have been hailed as having enormous potential for producing localised low-carbon, non-fossil fuel energy [146]. TENGs gather and convert mechanical energy from, among other things, body motion, vibration, wind, and waves to harvest electricity; thereby, reducing world fossil fuel usage. The development of a green electrospinning technique to manufacture nanofibers will make the process more environmentally friendly and pave the way to industrial production and sustainability. If further development can achieve a higher performance ratio and a longer lifetime, electrospun materials-based TENG might be one of the most ecologically sustainable energy harvesters. TENG lifespan is predicted to improve significantly in the future because of advancements in material optimization; thereby, cutting CO_2 emissions. TENGs are the most recent energy harvester technology with significant promise for enhanced production processes, increased efficiency, more consistent performance, and a longer operating lifetime. At the time of writing, only a decade has passed since the publication of the first TENG paper in 2012; therefore, the TENG is still at an early stage of development and much research remains to be done.

7. Conclusions

Exploiting nanofibers to convert mechanical energy into electrical energy for self-powered active systems and devices, was a significant milestone in the nano-energy area. Using readily accessible organic and inorganic electrospun materials offers a potential new technique for collecting ambient energy. Microscale mechanical energy harvesting

with the nanofiber-based TENGs can be scaled up to provide a high-volume power density with a conversion efficiency of up to 85 % at the macroscale. The highest output encountered in our review was a peak power density of 130.2 W/m^2 for electrospun PVDF nanofibers (with graphene nanosheets) in contact with polyamide-6 (PA6) films [7]. Even though this is still lower than the output available with conventional film-based TENGs (which can exceed 500 W/m^2), this is a high output for a fibrous interface. There are a number of appealing properties that make the TENG devices desirable: light weight; flexibility; breathability, shape conformance; and even washability. Human movement, wind vibration, water flow, wave motion and tire rotation etc. can all be utilised for electricity production using next generation TENGs. It is anticipated that the nanofiber-based TENG devices will be used in innovative fabrics and the next generation of wearable electronics on a larger scale. There is still a long way to go before electrospun-based nanogenerators, which have the potential to power wearable electronic gadgets, can be put into practice. A pathway towards generation of more optimised materials and device structures will be described in the near future using the electrospinning technology's flexibility and morphological control capabilities. Improved output performance for nanogenerators may now be achieved by using novel fiber-based materials. However, electrospun fibers may deform and weaken the device with time and the strength of the bond they make with the substrate is an issue. When creating high-stability devices, the material design must be taken into consideration. A thorough investigation of the practical application of nanogenerators in wearable electronics (especially durability) is also necessary. Advancements in all of these challenge areas will likely lead to increased output and durability; thereby, accelerating the roll-out of advanced nanofiber based TENGs as battery replacements in the wearables industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported by Science Foundation Ireland (SFI-20/EPSRC/3710) and also by the UK Engineering and Physical Sciences Research Council (EPSRC) through grant Ref. EP/V003380/1 ('Next Generation Energy Autonomous Textile Fabrics based on Triboelectric Nanogenerators').

References

[1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, M. Ayyash, Internet of things: A survey on enabling technologies, protocols, and applications, IEEE Commun. Surv. Tutorials. 17 (2015) 2347–2376.
[2] Z.L. Wang, J. Song, Piezoelectric nanogenerators based on zinc oxide nanowire arrays, Science 312 (2006) 242–246.
[3] Z.L. Wang, J. Chen, L. Lin, Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors, Energy Environ. Sci. 8 (2015) 2250–2282.
[4] Z.L. Wang, Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors, ACS Nano 7 (2013) 9533–9557.
[5] R. Zhang, M. Hummelgård, J. Örtegren, M. Olsen, H. Andersson, H. Olin, Interaction of the human body with triboelectric nanogenerators, Nano Energy 57 (2019) 279–292.
[6] J.H. Zhang, Y. Zhang, N. Sun, Y. Li, J. Du, L. Zhu, X. Hao, Enhancing output performance of triboelectric nanogenerator via large polarization difference effect, Nano Energy 84 (2021), 105892.
[7] L. Shi, H. Jin, S. Dong, S. Huang, H. Kuang, H. Xu, J. Chen, W. Xuan, S. Zhang, S. Li, X. Wang, J. Luo, High-performance triboelectric nanogenerator based on electrospun PVDF-graphene nanosheet composite nanofibers for energy harvesting, Nano Energy 80 (2021), 105599.
[8] C. Wu, T.W. Kim, J.H. Park, H. An, J. Shao, X. Chen, Z.L. Wang, Enhanced triboelectric nanogenerators based on MoS2 monolayer nanocomposites acting as electron-acceptor layers, ACS Nano 11 (2017) 8356–8363.
[9] S. Wang, L. Lin, Z.L. Wang, Triboelectric nanogenerators as self-powered active sensors, Nano Energy 11 (2015) 436–462.
[10] A. Barhoum, K. Pal, H. Rahier, H. Uludag, I.S. Kim, M. Bechelany, Nanofibers as new-generation materials: From spinning and nano-spinning fabrication techniques to emerging applications, Appl. Mater. Today. 17 (2019) 1–35.
[11] Y. Wang, T. Yokota, T. Someya, Electrospun nanofiber-based soft electronics, NPG Asia Mater. 13 (2021) 1–22.
[12] A. Greiner, J.H. Wendorff, Electrospinning: a fascinating method for the preparation of ultrathin fibers, Angew. Chemie Int. Ed. 46 (2007) 5670–5703.
[13] T.A. Arica, T. Isık, T. Guner, N. Horzum, M.M. Demir, Advances in Electrospun Fiber-Based Flexible Nanogenerators for Wearable Applications, Macromol. Mater. Eng. 306 (2021).
[14] R. Zhang, H. Olin, Material choices for triboelectric nanogenerators: a critical review, EcoMat. 2 (2020) e12062.
[15] Z.L. Wang, On Maxwell's displacement current for energy and sensors: the origin of nanogenerators, Mater. Today. 20 (2017) 74–82.
[16] S. Niu, Z.L. Wang, Theoretical systems of triboelectric nanogenerators, Nano Energy 14 (2015) 161–192.
[17] Z.L. Wang, L. Lin, J. Chen, S. Niu, Y. Zi, Triboelectric nanogenerator: lateral sliding mode, in, Triboelectric Nanogenerators, Springer (2016) 49–90.
[18] J. Chen, Z.L. Wang, Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator, Joule. 1 (2017) 480–521.
[19] L. Zhang, C. Su, X. Cui, P. Li, Z. Wang, L. Gu, Z. Tang, Free-standing triboelectric layer-based full fabric wearable nanogenerator for efficient mechanical energy harvesting, ACS Appl. Electron. Mater. 2 (2020) 3366–3372.
[20] A.P. Kishan, E.M. Cosgriff-Hernandez, Recent advancements in electrospinning design for tissue engineering applications: A review, J. Biomed. Mater. Res. Part A. 105 (2017) 2892–2905.
[21] L. Chen, S. Wang, Q. Yu, P.D. Topham, C. Chen, L. Wang, A comprehensive review of electrospinning block copolymers, Soft Matter 15 (2019) 2490–2510.
[22] X. Pu, J.W. Zha, C.L. Zhao, S.B. Gong, J.F. Gao, R.K.Y. Li, Flexible PVDF/nylon-11 electrospun fibrous membranes with aligned ZnO nanowires as potential triboelectric nanogenerators, Chem. Eng. J. 398 (2020), 125526.
[23] F.E. Ahmed, B.S. Lalia, R. Hashaikeh, A review on electrospinning for membrane fabrication: Challenges and applications, Desalination 356 (2015) 15–30.
[24] H.M. Ibrahim, A. Klingner, A review on electrospun polymeric nanofibers: Production parameters and potential applications, Polym. Test. 90 (2020), 106647.
[25] V. Beachley, X. Wen, Effect of electrospinning parameters on the nanofiber diameter and length, Mater. Sci. Eng. C. 29 (2009) 663–668.
[26] S. Jang, Y. Kim, S. Lee, J.H. Oh, Optimization of electrospinning parameters for electrospun nanofiber-based triboelectric nanogenerators, Int. J. Precis. Eng. Manuf. Technol. 6 (2019) 731–739.
[27] H. Pan, L. Li, L. Hu, X. Cui, Continuous aligned polymer fibers produced by a modified electrospinning method, Polymer (Guildf). 47 (2006) 4901–4904.
[28] Z.-M. Huang, Y.-Z. Zhang, M. Kotaki, S. Ramakrishna, A review on polymer nanofibers by electrospinning and their applications in nanocomposites, Compos. Sci. Technol. 63 (2003) 2223–2253.
[29] W.E. Teo, S. Ramakrishna, A review on electrospinning design and nanofibre assemblies, Nanotechnology. 17 (2006).
[30] Z. Li, C. Wang, Zhenyu LI, Zhenyu Li · Ce Wang One-Dimensional Nanostructures Electrospinning Technique, and Unique Nanofibers, 2016.
[31] R. Pan, W. Xuan, J. Chen, S. Dong, H. Jin, X. Wang, H. Li, J. Luo, Fully biodegradable triboelectric nanogenerators based on electrospun polylactic acid and nanostructured gelatin films, Nano Energy 45 (2018) 193–202.
[32] P. Tofel, K. Částková, D. Říha, D. Sobola, N. Papež, J. Kaštyl, Ş. Ţălu, Z. Hadaš, Triboelectric Response of Electrospun Stratified PVDF and PA Structures, Nanomaterials. 12 (2022) 349.
[33] M.T. Rahman, S.M.S. Rana, M.A. Zahed, S. Lee, E.-S. Yoon, J.Y. Park, Metal-Organic Framework-Derived Nanoporous Carbon Incorporated Nanofibers for High-Performance Triboelectric Nanogenerators and Self-powered Sensors, Nano Energy 106921 (2022).
[34] Y. Hao, J. Huang, S. Liao, D. Chen, Q. Wei, All-electrospun performance-enhanced triboelectric nanogenerator based on the charge-storage process, J. Mater. Sci. 1–12 (2022).
[35] Z. Sha, C. Boyer, G. Li, Y. Yu, F.-M. Allioux, K. Kalantar-Zadeh, C.-H. Wang, J. Zhang, Electrospun liquid metal/PVDF-HFP nanofiber membranes with exceptional triboelectric performance, Nano Energy 92 (2022), 106713.
[36] P. Tofel, K. Částková, D. Říha, D. Sobola, N. Papež, J. Kaštyl, S. Talu, Z. Hadaš, Triboelectric Response of Electrospun Stratified PVDF and PA Structures. Nanomaterials 2022, 12, 349, (2022).
[37] D.-J. Sim, G.-J. Choi, S.-H. Sohn, I.-K. Park, Electronegative polyvinylidene fluoride/C60 composite nanofibers for performance enhancement of triboelectric nanogenerators, J. Alloys Compd. 898 (2022), 162805.
[38] Q. Niu, H. Wei, B.S. Hsiao, Y. Zhang, Biodegradable silk fibroin-based bio-piezoelectric/triboelectric nanogenerators as self-powered electronic devices, Nano Energy 107101 (2022).
[39] J. Xia, Z. Zheng, Y. Guo, Mechanically and electrically robust, electro-spun PVDF/PMMA blend films for durable triboelectric nanogenerators, Compos. Part A Appl. Sci. Manuf. (2022), 106914.

[40] Z. Li, A. Elhassan, I. Abdalla, M. Zhu, J. Yu, B. Ding, Wearable triboelectric nanogenerators constructed from electrospun nanofibers, Energy Harvest. Prop, Electrospun Nanofibers, 2019.

[41] W. Paosangthong, R. Torah, S. Beeby, Recent progress on textile-based triboelectric nanogenerators, Nano Energy 55 (2019) 401–423.

[42] J. Zhang, Y. Zhang, Y. Li, P. Wang, Textile-based flexible pressure sensors: A review, Polym. Rev. 1–31 (2021).

[43] X. Zhang, Overview of Triboelectric Nanogenerators, Flex. Stretchable Triboelectric Nanogenerator Devices Towar, Self-powered Syst. (2019) 1–18.

[44] A. Chen, C. Zhang, G. Zhu, Z.L. Wang, Polymer materials for high-performance triboelectric Nanogenerators, Adv. Sci. 7 (2020) 2000186.

[45] S.-R. Kim, J.-H. Yoo, J.-W. Park, Using electrospun AgNW/P (VDF-TrFE) composite nanofibers to create transparent and wearable single-electrode triboelectric nanogenerators for self-powered touch panels, ACS Appl. Mater. Interfaces. 11 (2019) 15088–15096.

[46] C. Zhang, J. Mo, Q. Fu, Y. Liu, S. Wang, S. Nie, Wood-cellulose-fiber-based functional materials for triboelectric nanogenerators, Nano Energy 81 (2021), 105637.

[47] J.H. Choi, Y. Ra, S. Cho, M. La, S.J. Park, D. Choi, Electrical charge storage effect in carbon based polymer composite for long-term performance enhancement of the triboelectric nanogenerator, Compos. Sci. Technol. 207 (2021), 108680.

[48] M.P. Kim, D.-S. Um, Y.-E. Shin, H. Ko, High-performance triboelectric devices via dielectric polarization: a review, Nanoscale Res. Lett. 16 (2021) 1–14.

[49] Z. Qin, Y. Yin, W. Zhang, C. Li, K. Pan, Wearable and stretchable triboelectric nanogenerator based on crumpled nanofibrous membranes, ACS Appl. Mater. Interfaces. 11 (2019) 12452–12459.

[50] P. Zhao, N. Soin, K. Prashanthi, J. Chen, S. Dong, E. Zhou, Z. Zhu, A. A. Narasimulu, C.D. Montemagno, L. Yu, Emulsion electrospinning of polytetrafluoroethylene (PTFE) nanofibrous membranes for high-performance triboelectric nanogenerators, ACS Appl. Mater. Interfaces. 10 (2018) 5880–5891.

[51] Y. Kim, X. Wu, J.H. Oh, Fabrication of triboelectric nanogenerators based on electrospun polyimide nanofibers membrane, Sci. Rep. 10 (2020) 1–9.

[52] M.O. Shaikh, Y. Bin Huang, C.C. Wang, C.H. Chuang, Wearable woven triboelectric nanogenerator utilizing electrospun PVDF nanofibers for mechanical energy harvesting, Micromachines. 10 (2019).

[53] T. Huang, M. Lu, H. Yu, Q. Zhang, H. Wang, M. Zhu, Enhanced power output of a triboelectric nanogenerator composed of electrospun nanofiber mats doped with graphene oxide, Sci. Rep. 5 (2015) 1–8.

[54] S.M.S. Rana, M.T. Rahman, M. Salauddin, S. Sharma, P. Maharjan, T. Bhatta, H. Cho, C. Park, J.Y. Park, Electrospun PVDF-TrFE/MXene Nanofiber Mat-Based Triboelectric Nanogenerator for Smart Home Appliances, ACS Appl. Mater. Interfaces. 13 (2021) 4955–4967.

[55] H.Y. Mi, X. Jing, Q. Zheng, L. Fang, H.X. Huang, L.S. Turng, S. Gong, High-performance flexible triboelectric nanogenerator based on porous aerogels and electrospun nanofibers for energy harvesting and sensitive self-powered sensing, Nano Energy 48 (2018) 327–336.

[56] B. Yu, H. Yu, H. Wang, Q. Zhang, M. Zhu, High-power triboelectric nanogenerator prepared from electrospun mats with spongy parenchyma-like structure, Nano Energy 34 (2017) 69–75.

[57] T. Busolo, D.P. Ura, S. Kyun, M.M. Marzec, A. Bernasik, Nano Energy Surface potential tailoring of PMMA fibers by electrospinning for enhanced triboelectric performance, Nano Energy 57 (2019) 500–506.

[58] W. Kim, S. Pyo, M.-O. Kim, Y. Oh, D.-S. Kwon, J. Kim, Humidity-resistant triboelectric energy harvester using electrospun PVDF/PU nanofibers for flexibility and air permeability, Nanotechnology. 30 (2019), 275401.

[59] Y. Kim, X. Wu, C. Lee, J.H. Oh, Characterization of PI/PVDF-TrFE composite nanofiber-based triboelectric nanogenerators depending on the type of the electrospinning system, ACS Appl. Mater. Interfaces. 13 (2021) 36967–36975.

[60] P. Zhao, N. Soin, K. Prashanthi, J. Chen, S. Dong, E. Zhou, Z. Zhu, A. A. Narasimulu, C.D. Montemagno, L. Yu, J. Luo, Emulsion electrospinning of polytetrafluoroethylene (PTFE) nanofibrous membranes for high-performance triboelectric nanogenerators ACS Appl, Mater. Interfaces 10 (6) (2018) 5880–5891.

[61] G. Liu, J. Nie, C. Han, T. Jiang, Z. Yang, Y. Pang, L. Xu, T. Guo, T. Bu, C. Zhang, Self-powered electrostatic adsorption face mask based on a triboelectric nanogenerator, ACS Appl. Mater. Interfaces. 10 (2018) 7126–7133.

[62] A. Ozen, F. Ozel, Z. Kınas, A. Karabiber, S. Polat, Spring assisted triboelectric nanogenerator based on sepiolite doped polyacrylonitrile nanofibers, Sustain. Energy Technol. Assessments. 47 (2021), 101492.

[63] J. Xiong, H. Luo, D. Gao, X. Zhou, P. Cui, G. Thangavel, K. Parida, P.S. Lee, Self-restoring, waterproof, tunable microstructural shape memory triboelectric nanogenerator for self-powered water temperature sensor, Nano Energy 61 (2019) 584–593.

[64] C. Jiang, C. Wu, X. Li, Y. Yao, L. Lan, F. Zhao, Z. Ye, Y. Ying, J. Ping, All-electrospun flexible triboelectric nanogenerator based on metallic MXene nanosheets, Nano Energy 59 (2019) 268–276.

[65] A. Yar, Enhanced output performance of tetraethyl orthosilicate and graphene nanoplates-decorated nanofiber-based triboelectric nanogenerators, Colloids Surfaces A Physicochem. Eng. Asp. 631 (2021), 127670.

[66] A.R. Mule, B. Dudem, H. Patnam, S.A. Graham, J.S. Yu, Wearable single-electrode-mode triboelectric nanogenerator via conductive polymer-coated textiles for self-power electronics, ACS Sustain. Chem. Eng. 7 (2019) 16450–16458.

[67] Y. Zou, V. Raveendran, J. Chen, Wearable triboelectric nanogenerators for biomechanical energy harvesting, Nano Energy 77 (2020), 105303.

[68] J. Huang, Y. Hao, M. Zhao, W. Li, F. Huang, Q. Wei, All-fiber-structured triboelectric nanogenerator via one-pot electrospinning for self-powered wearable sensors, ACS Appl. Mater. Interfaces. 13 (2021) 24774–24784.

[69] Q. Zheng, Q. Tang, Z.L. Wang, Z. Li, Self-powered cardiovascular electronic devices and systems, Nat. Rev. Cardiol. 18 (2021) 7–21.

[70] I. Firdous, M. Fahim, L. Wang, W.J. Li, Y. Zi, W.A. Daoud, Boosting current output of triboelectric nanogenerator by two orders of magnitude via hindering interfacial charge recombination, Nano Energy 89 (2021), 106315.

[71] T. Bhatta, P. Maharjan, H. Cho, C. Park, S.H. Yoon, S. Sharma, M. Salauddin, M. T. Rahman, S.S. Rana, J.Y. Park, High-performance triboelectric nanogenerator based on MXene functionalized polyvinylidene fluoride composite nanofibers, Nano Energy 81 (2021), 105670.

[72] P. Zhao, N. Soin, K. Prashanthi, J. Chen, S. Dong, E. Zhou, Z. Zhu, A. A. Narasimulu, C.D. Montemagno, L. Yu, J. Luo, Emulsion Electrospinning of Polytetrafluoroethylene (PTFE) Nanofibrous Membranes for High-Performance Triboelectric Nanogenerators, ACS Appl. Mater. Interfaces. 10 (2018) 5880–5891.

[73] S. Cheon, H. Kang, H. Kim, Y. Son, J.Y. Lee, H.J. Shin, S.W. Kim, J.H. Cho, High-Performance Triboelectric Nanogenerators Based on Electrospun Polyvinylidene Fluoride-Silver Nanowire Composite Nanofibers, Adv. Funct. Mater. 28 (2018) 1–7.

[74] G. Min, A. Pullanchiyodan, A.S. Dahiya, E.S. Hosseini, Y. Xu, D.M. Mulvihill, R. Dahiya, Ferroelectric-assisted high-performance triboelectric nanogenerators based on electrospun P(VDF-TrFE) composite nanofibers with barium titanate nanofillers, Nano Energy 90 (2021), 106600.

[75] T. Busolo, P.K. Szewczyk, M. Nair, U. Stachewicz, S. Kar-Narayan, Triboelectric Yarns with Electrospun Functional Polymer Coatings for Highly Durable and Washable Smart Textile Applications, ACS Appl. Mater. Interfaces. 13 (2021) 16876.

[76] J. Liu, L. Zhang, N. Wang, C. Li, Highly stretchable and transparent triboelectric nanogenerator based on multi-layer structured stable electrode for self-powered wearable sensor, Nano Energy 78 (2020), 105385.

[77] H.S. Kim, I.K. Park, Enhanced output power from triboelectric nanogenerators based on electrospun Eu-doped polyvinylidene fluoride nanofibers, J. Phys. Chem. Solids. 117 (2018) 188–193.

[78] S. Cheon, H. Kang, H. Kim, Y. Son, J.Y. Lee, H. Shin, S. Kim, J.H. Cho, High-Performance Triboelectric Nanogenerators Based on Electrospun Polyvinylidene Fluoride –, Silver Nanowire Composite Nanofibers 1703778 (2017) 1–7.

[79] G. Choi, S. Baek, S. Lee, F. Khan, J. Hyun, I. Park, Performance enhancement of triboelectric nanogenerators based on polyvinylidene fl uoride / graphene quantum dot composite nano fi bers, J. Alloys Compd. 797 (2019) 945–951.

[80] H. Jiang, H. Lei, Z. Wen, J. Shi, D. Bao, C. Chen, J. Jiang, Q. Guan, X. Sun, S. Lee, Nano Energy Charge-trapping-blocking layer for enhanced triboelectric nanogenerators, Nano Energy 75 (2020), 105011.

[81] M. Kim, D. Park, M.M. Alam, S. Lee, P. Park, J. Nah, Remarkable Output Power Density Enhancement of Triboelectric Nanogenerators via Polarized Ferroelectric Polymers and Bulk MoS 2 Composites, ACS Nano 13 (2019) 4640–4646.

[82] J.-S. Im, I.-K. Park, Mechanically robust magnetic Fe3O4 nanoparticle/polyvinylidene fluoride composite nanofiber and its application in a triboelectric nanogenerator, ACS Appl. Mater. Interfaces. 10 (2018) 25660–25665.

[83] A. Yar, A. Karabiber, A. Ozen, F. Ozel, S. Coskun, Flexible nanofiber based triboelectric nanogenerators with high power conversion, Renew. Energy. 162 (2020) 1428–1437.

[84] L. Ma, M. Zhou, R. Wu, A. Patil, H. Gong, S. Zhu, T. Wang, Y. Zhang, S. Shen, K. Dong, L. Yang, J. Wang, W. Guo, Z.L. Wang, Continuous and Scalable Manufacture of Hybridized Nano-Micro Triboelectric Yarns for Energy Harvesting and Signal Sensing, ACS Nano 14 (2020) 4716–4726.

[85] B. Yu, H. Yu, T. Huang, H. Wang, M. Zhu, A biomimetic nanofiber-based triboelectric nanogenerator with an ultrahigh transfer charge density, Nano Energy 48 (2018) 464–470.

[86] J.-H. Zhang, Y. Li, X. Hao, A high-performance triboelectric nanogenerator with improved output stability by construction of biomimetic superhydrophobic nanoporous fibers, Nanotechnology. 31 (2020), 215401.

[87] N. Wang, X.-X. Wang, K. Yan, W. Song, Z. Fan, M. Yu, Y.-Z. Long, Anisotropic triboelectric nanogenerator based on ordered electrospinning, ACS Appl. Mater. Interfaces. 12 (2020) 46205–46211.

[88] Y. Wang, X. Jin, W. Wang, J. Niu, Z. Zhu, T. Lin, Efficient Triboelectric Nanogenerator (TENG) Output Management for Improving Charge Density and Reducing Charge Loss, ACS Appl. Electron. Mater. 3 (2021) 532–549.

[89] L. Lan, J. Xiong, D. Gao, Y. Li, J. Chen, J. Lv, J. Ping, Y. Ying, P.S. Lee, Breathable Nanogenerators for an On-Plant Self-Powered Sustainable Agriculture System, ACS Nano 15 (2021) 5307–5315.

[90] Z. Zhang, W. Gong, Z. Bai, D. Wang, Y. Xu, Z. Li, J. Guo, L.S. Turng, Oxygen-Rich Polymers as Highly Effective Positive Tribomaterials for Mechanical Energy Harvesting, ACS Nano 13 (2019) 12787–12797.

[91] Q. Ye, Y. Wu, Y. Qi, L. Shi, S. Huang, L. Zhang, M. Li, W. Li, X. Zeng, H. Wo, X. Wang, S. Dong, S. Ramakrishna, J. Luo, Effects of liquid metal particles on performance of triboelectric nanogenerator with electrospun polyacrylonitrile fiber films, Nano Energy 61 (2019) 381–388.

[92] Z. Li, M. Zhu, Q. Qiu, J. Yu, B. Ding, Multi-layered fiber-based triboelectric nanogenerator with high performance for biomechanical energy harvesting, Nano Energy 53 (2018) 726–733.

[93] W. He, W. Liu, J. Chen, Z. Wang, Y. Liu, X. Pu, H. Yang, Q. Tang, H. Yang, H. Guo, Boosting output performance of sliding mode triboelectric nanogenerator by charge space-accumulation effect, Nat. Commun. 11 (2020) 1–8.

[94] I. Firdous, M. Fahim, W.A. Daoud, Performance enhancement of triboelectric nanogenerator through hole and electron blocking layers-based interfacial design, Nano Energy 82 (2021), 105694.
[95] X. Chen, Y. Song, H. Chen, J. Zhang, H. Zhang, An ultrathin stretchable triboelectric nanogenerator with coplanar electrode for energy harvesting and gesture sensing, J. Mater. Chem. A. 5 (2017) 12361–12368.
[96] N. Sun, Z. Wen, F. Zhao, Y. Yang, H. Shao, C. Zhou, Q. Shen, K. Feng, M. Peng, Y. Li, All flexible electrospun papers based self-charging power system, Nano Energy 38 (2017) 210–217.
[97] X. Shi, S. Zhang, S. Gong, A self-powered and arch-structured triboelectric nanogenerator for portable electronics and human-machine communication, J. Mater. Chem. A. 8 (2020) 8997–9005.
[98] H. Wang, H. Sakamoto, H. Asai, J.-H. Zhang, T. Meboso, Y. Uchiyama, E. Kobayashi, E. Takamura, S. Suye, An all-fibrous triboelectric nanogenerator with enhanced outputs depended on the polystyrene charge storage layer, Nano Energy 90 (2021), 106515.
[99] Z. Du, K. Chen, Y. Zhang, Y. Wang, P. He, H.Y. Mi, Y. Wang, C. Liu, C. Shen, Engineering multi-layered MXene/electrospun poly(lactic acid) membrane with increscent electromagnetic interference (EMI) shielding for integrated Joule heating and energy generating, Compos. Commun. 26 (2021), 100770.
[100] G.Q. Gu, C.B. Han, J.J. Tian, T. Jiang, C. He, C.X. Lu, Y. Bai, J.H. Nie, Z. Li, Z. L. Wang, Triboelectric nanogenerator enhanced multi-layered antibacterial nanofiber air filters for efficient removal of ultrafine particulate matter, Nano Res. 11 (2018) 4090–4101.
[101] J. Shen, Z. Li, J. Yu, B. Ding, Humidity-resisting triboelectric nanogenerator for high performance biomechanical energy harvesting, Nano Energy 40 (2017) 282–288.
[102] W. Qiu, Y. Feng, N. Luo, S. Chen, D. Wang, Sandwich-like sound-driven triboelectric nanogenerator for energy harvesting and electrochromic based on Cu foam, Nano Energy 70 (2020).
[103] Z. Fang, K.H. Chan, X. Lu, C.F. Tan, G.W. Ho, Surface texturing and dielectric property tuning toward boosting of triboelectric nanogenerator performance, J. Mater. Chem. A. 6 (2018) 52–57.
[104] Y. Yu, X. Wang, Chemical modification of polymer surfaces for advanced triboelectric nanogenerator development, Extrem. Mech. Lett. 9 (2016) 514–530.
[105] Z. Ren, Q. Zheng, H. Wang, H. Guo, L. Miao, J. Wan, C. Xu, S. Cheng, H. Zhang, Wearable and self-cleaning hybrid energy harvesting system based on micro/nanostructured haze film, Nano Energy 67 (2020), 104243.
[106] X. Chen, J. Xiong, K. Parida, M. Guo, C. Wang, C. Wang, X. Li, J. Shao, P.S. Lee, Transparent and stretchable bimodal triboelectric nanogenerators with hierarchical micro-nanostructures for mechanical and water energy harvesting, Nano Energy 64 (2019), 103904.
[107] L. Zhao, Q. Zheng, H. Ouyang, H. Li, L. Yan, B. Shi, Z. Li, A size-unlimited surface microstructure modification method for achieving high performance triboelectric nanogenerator, Nano Energy 28 (2016) 172–178.
[108] Y. Nurmakanov, G. Kalimuldina, G. Nauryzbayev, D. Adair, Z. Bakenov, Structural and Chemical Modifications Towards High-Performance of Triboelectric Nanogenerators, Nanoscale Res. Lett. 16 (2021) 1–27.
[109] Y.S. Choi, S. Kim, S. Kar-Narayan, Materials-related strategies for highly efficient triboelectric energy generators, Adv. Energy Mater. 11 (2021) 2003802.
[110] Q. Qiu, M. Zhu, Z. Li, K. Qiu, X. Liu, J. Yu, B. Ding, Highly flexible, breathable, tailorable and washable power generation fabrics for wearable electronics, Nano Energy 58 (2019) 750–758.
[111] B. Sun, Y.-Z. Long, Z.-J. Chen, S.-L. Liu, H.-D. Zhang, J.-C. Zhang, W.-P. Han, Recent advances in flexible and stretchable electronic devices via electrospinning, J. Mater. Chem. C. 2 (2014) 1209–1219.
[112] F.R. Fan, W. Tang, Z.L. Wang, Flexible nanogenerators for energy harvesting and self-powered electronics, Adv. Mater. 28 (2016) 4283–4305.
[113] L. Huang, S. Lin, Z. Xu, H. Zhou, J. Duan, B. Hu, J. Zhou, Fiber-based energy conversion devices for human-body energy harvesting, Adv. Mater. 32 (2020) 1902034.
[114] K. Dong, X. Peng, Z.L. Wang, Fiber/Fabric-Based Piezoelectric and Triboelectric Nanogenerators for Flexible/Stretchable and Wearable Electronics and Artificial Intelligence, Adv. Mater. 32 (2020) 1–43.
[115] C. Sun, G. Zu, Y. Wei, X. Song, X. Yang, Flexible Triboelectric Nanogenerators Based on Electrospun Poly (vinylidene fluoride) with MoS2/Carbon Nanotube Composite Nanofibers, Langmuir (2022).
[116] T. Huang, C. Wang, H. Yu, H. Wang, Q. Zhang, M. Zhu, Human walking-driven wearable all-fiber triboelectric nanogenerator containing electrospun polyvinylidene fluoride piezoelectric nanofibers, Nano Energy 14 (2015) 226–235.
[117] X. Wang, B. Yang, J. Liu, Y. Zhu, C. Yang, Q. He, A flexible triboelectric-piezoelectric hybrid nanogenerator based on P (VDF-TrFE) nanofibers and PDMS/MWCNT for wearable devices, Sci. Rep. 6 (2016) 1–10.
[118] M. Chen, Z. Wang, Y. Zheng, Q. Zhang, B. He, J. Yang, M. Qi, L. Wei, Flexible tactile sensor based on patterned Ag-nanofiber electrodes through electrospinning, Sensors. 21 (2021) 2413.
[119] X. Guan, B. Xu, M. Wu, T. Jing, Y. Yang, Y. Gao, Breathable, washable and wearable woven-structured triboelectric nanogenerators utilizing electrospun nanofibers for biomechanical energy harvesting and self-powered sensing, Nano Energy 80 (2021), 105549.
[120] J. Qi, A.C. Wang, W. Yang, M. Zhang, C. Hou, Q. Zhang, Y. Li, H. Wang, Hydrogel-based hierarchically wrinkled stretchable nanofibrous membrane for high performance wearable triboelectric nanogenerator, Nano Energy 67 (2020), 104206.
[121] R. Walden, C. Kumar, D.M. Mulvihill, S.C. Pillai, Opportunities and Challenges in Triboelectric Nanogenerator (TENG) based Sustainable Energy Generation Technologies: A Mini-Review, Chem. Eng. J. Adv. (2021), 100237.
[122] Q. Zheng, Y. Zou, Y. Zhang, Z. Liu, B. Shi, X. Wang, Y. Jin, H. Ouyang, Z. Li, Z. L. Wang, Biodegradable triboelectric nanogenerator as a life-time designed implantable power source, Sci. Adv. 2 (2016) e1501478.
[123] B.U. Ye, B.-J. Kim, J. Ryu, J.Y. Lee, J.M. Baik, K. Hong, Electrospun ion gel nanofibers for flexible triboelectric nanogenerator: electrochemical effect on output power, Nanoscale. 7 (2015) 16189–16194.
[124] J.-H. Zhang, Y. Li, J. Du, X. Hao, H. Huang, A high-power wearable triboelectric nanogenerator prepared from self-assembled electrospun poly (vinylidene fluoride) fibers with a heart-like structure, J. Mater. Chem. A. 7 (2019) 11724–11733.
[125] F. Chen, Y. Wu, Z. Ding, X. Xia, S. Li, H. Zheng, C. Diao, G. Yue, Y. Zi, A novel triboelectric nanogenerator based on electrospun polyvinylidene fluoride nanofibers for effective acoustic energy harvesting and self-powered multifunctional sensing, Nano Energy 56 (2019) 241–251.
[126] Y. Jiang, K. Dong, X. Li, J. An, D. Wu, X. Peng, J. Yi, C. Ning, R. Cheng, P. Yu, Z. L. Wang, Stretchable, Washable, and Ultrathin Triboelectric Nanogenerators as Skin-Like Highly Sensitive Self-Powered Haptic Sensors, Adv. Funct. Mater. 31 (2021) 1–9.
[127] Y. Li, J. Xiong, J. Lv, J. Chen, D. Gao, X. Zhang, P.S. Lee, Mechanically interlocked stretchable nanofibers for multifunctional wearable triboelectric nanogenerator, Nano Energy 78 (2020).
[128] S. Sardana, H. Kaur, B. Arora, D.K. Aswal, A. Mahajan, Self-Powered Monitoring of Ammonia Using an MXene/TiO2/Cellulose Nanofiber Heterojunction-Based Sensor Driven by an Electrospun Triboelectric Nanogenerator, ACS Sensors (2022).
[129] D. Wang, D. Zhang, J. Guo, Y. Hu, Y. Yang, T. Sun, H. Zhang, X. Liu, Multifunctional poly (vinyl alcohol)/Ag nanofibers-based triboelectric nanogenerator for self-powered MXene/tungsten oxide nanohybrid NO2 gas sensor, Nano Energy 89 (2021), 106410.
[130] M. Lou, I. Abdalla, M. Zhu, J. Yu, Z. Li, B. Ding, Hierarchically rough structured and self-powered pressure sensor textile for motion sensing and pulse monitoring, ACS Appl. Mater. Interfaces. 12 (2019) 1597–1605.
[131] C. Garcia, I. Trendafilova, R.G. de Villoria, J.S. del Rio, Self-powered pressure sensor based on the triboelectric effect and its analysis using dynamic mechanical analysis, Nano Energy 50 (2018) 401–409.
[132] C. Garcia, I. Trendafilova, Real-time diagnosis of small energy impacts using a triboelectric nanosensor, Sensors Actuators, A Phys. 291 (2019) 196–203.
[133] C. Garcia, I. Trendafilova, R. Guzman de Villoria, J. Sanchez del Rio, Self-powered pressure sensor based on the triboelectric effect and its analysis using dynamic mechanical analysis, Nano Energy 50 (2018) 401–409.
[134] X. Li, C. Jiang, F. Zhao, L. Lan, Y. Yao, Y. Yu, J. Ping, Y. Ying, Fully stretchable triboelectric nanogenerator for energy harvesting and self-powered sensing, Nano Energy 61 (2019) 78–85.
[135] T. Huang, C. Wang, H. Yu, H. Wang, Q. Zhang, M. Zhu, Human walking-driven wearable all-fiber triboelectric nanogenerator containing electrospun polyvinylidene fluoride piezoelectric nanofibers, Nano Energy 14 (2014) 226–235.
[136] M.F. Lin, J. Xiong, J. Wang, K. Parida, P.S. Lee, Core-shell nanofiber mats for tactile pressure sensor and nanogenerator applications, Nano Energy 44 (2018) 248–255.
[137] Y. Guo, X.S. Zhang, Y. Wang, W. Gong, Q. Zhang, H. Wang, J. Brugger, All-fiber hybrid piezoelectric-enhanced triboelectric nanogenerator for wearable gesture monitoring, Nano Energy 48 (2018) 152–160.
[138] H.J. Qiu, W.Z. Song, X.X. Wang, J. Zhang, Z. Fan, M. Yu, S. Ramakrishna, Y. Z. Long, A calibration-free self-powered sensor for vital sign monitoring and finger tap communication based on wearable triboelectric nanogenerator, Nano Energy 58 (2019) 536–542.
[139] S.M.S. Rana, M.T. Rahman, S. Sharma, M. Salauddin, S.H. Yoon, C. Park, P. Maharjan, T. Bhatta, J.Y. Park, Cation functionalized nylon composite nanofibrous mat as a highly positive friction layer for robust, high output triboelectric nanogenerators and self-powered sensors, Nano Energy 88 (2021), 106300.
[140] Y. Jiang, K. Dong, J. An, F. Liang, J. Yi, X. Peng, C. Ning, C. Ye, Z.L. Wang, UV-Protective, Self-Cleaning, and Antibacterial Nanofiber-Based Triboelectric Nanogenerators for Self-Powered Human Motion Monitoring, ACS Appl. Mater. Interfaces. 13 (2021) 11205–11214.
[141] B. Zhang, L. Zhang, W. Deng, L. Jin, F. Chun, H. Pan, B. Gu, H. Zhang, Z. Lv, W. Yang, Z.L. Wang, Self-Powered Acceleration Sensor Based on Liquid Metal Triboelectric Nanogenerator for Vibration Monitoring, ACS Nano 11 (2017) 7440–7446.
[142] A. You, X. Zhang, X. Peng, K. Dong, Y. Lu, Q. Zhang, A Skin-Inspired Triboelectric Nanogenerator with an Interpenetrating Structure for Motion Sensing and Energy Harvesting, Macromol. Mater. Eng. 306 (2021) 1–9.
[143] G. Zhao, S. Gong, H. Wang, J. Ren, N. Wang, Y. Yang, G. Gao, S. Chen, L. Li, Ultrathin Biocompatible Electrospun Fiber Films for Self-Powered Human Motion Sensor, Int. J. Precis. Eng. Manuf. - Green Technol. 8 (2021) 855–868.

[144] Z. Qin, X. Chen, Y. Yin, G. Ma, Y. Jia, J. Deng, K. Pan, Flexible Janus Electrospun Nanofiber Films for Wearable Triboelectric Nanogenerator, Adv. Mater. Technol. 5 (2020) 1–9.
[145] Y.W. Kim, H.B. Lee, J. Yoon, S.-H. Park, 3D customized triboelectric nanogenerator with high performance achieved via charge-trapping effect and strain-mismatching friction, Nano Energy 107051 (2022).
[146] V. Thavasi, G. Singh, S. Ramakrishna, Electrospun nanofibers in energy and environmental applications, Energy Environ. Sci. 1 (2008) 205–221.

Aswathy Babu obtained her Ph.D. in Chemistry from University of Kerala, India in 2015. After that, she was a KSCSTE post-doctoral fellow at CSIR-NIIST, India, worked on the development of functional plasmonic nanomaterials for SERS applications. Currently, she is a post-doctoral researcher at Atlantic Technological University, Sligo, Ireland working under the project funded by SFI-EPSRC. Her current research interest is in the area of energy materials, especially; the development of textile triboelectric nanogenerators (T-TENGs) for wearable electronic applications and developing functional nanomaterials for advanced oxidation processes.

Irthasa Aazem is currently a post graduate researcher at Atlantic Technological University, Sligo, Ireland under the supervision of Prof. Suresh C Pillai. He has received his M. Tech in Polymer Technology and B. Tech in Polymer Science and Engineering from Cochin University of Science and Technology, India. His research interests include investigation of polymer nanocomposites and nanomaterials for energy applications with special emphasis on Tribo-electric nanogenerators (TENGs).

Ryan Walden is a researcher currently working towards obtaining his PhD in the Atlantic Technological University of Sligo. He obtained a Bachelor of Honours degree in Forensic Science and Investigation in 2019. With industrial experience and an extensive background in analytical chemistry, his research interest currently lies in the area of utilizing various plasma treatments to re-functionalize polymer materials for use in high-output triboelectric nanogenerators.

Satyaranjan Bairagi is a postdoctoral fellow under a project funded by EPSRC (Engineering and Physical Sciences Research Council), at University of Glasgow, United Kingdom. He completed his Ph.D. in Material Science from Indian Institute of Technology- Delhi, India, in 2021. His area of research includes development of piezoelectric and triboelectric nanocomposites for nanogenerators as well as textile based flexible advanced materials for renewable energy harvesting.

Daniel M. Mulvihill is Senior Lecturer (Associate Professor) in Mechanical Engineering at University of Glasgow. He completed a D.Phil. in Engineering Science at the University of Oxford in 2012 and subsequently undertook postdoctoral periods at the University of Limerick, EPFL Switzerland and the University of Cambridge prior to joining Glasgow in 2016. His interests are mainly focused on materials engineering and tribology. Dr Mulvihill is a former Institution of Mechanical Engineers (IMechE) Tribology Trust Bronze Medalist (2013). He presently leads a major £1.5M EPSRC project (EP/V003380/1) on next generation textile triboelectric nanogenerators.

Suresh C. Pillai obtained his Ph.D. from Trinity College Dublin and completed his postdoctoral research at California Institute of Technology (Caltech, USA). He currently heads the Nanotechnology and Bio-Engineering Research Group at the Institute of Technology Sligo, Ireland. His research interests include the synthesis of nanomaterials for energy and environmental applications. He is the recipient of a number of awards including the Boyle-Higgins Award 2019, Linus-Pauling Lecture Award 2020 etc. Suresh is also a recipient of the 'Industrial Technologies Award 2011' for licensing functional coatings to Irish companies. He was also the recipient of the 'Hothouse Commercialisation Award 2009' from the Minister of Science, Technology and Innovation and also the recipient of the 'Enterprise Ireland Research Commercialization Award 2009'. He has also been nominated for the 'One to Watch' award 2009 for commercialising R&D work (Enterprise Ireland). One of the nanomaterials based environmental technologies developed by his research team was selected to demonstrate as one of the fifty 'innovative technologies' (selected after screening over 450 nominations from EU) at the first Innovation Convention organised by the European Commission on 5-6th December 2011.