



Flexible Ferroelectric Materials-Based Triboelectric Nanogenerators for Mechanical Energy Harvesting

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Triboelectric nanogenerators are widely used in a variety of applications including wearable electronics, self-driven sensors, electrochemistry, and other fields. A lot of work has been done by researchers to increase the performance of triboelectric nanogenerators. Changing device structure, physical surface engineering and chemical composition modification are common effective methods. Some recent studies have found that the polarization of ferroelectric materials can regulate the output of triboelectric nanogenerators. Compared with other materials, ferroelectric materials have the advantages of polarization characteristics and large dielectric constant, which can improve the output performance by regulating the electric potential on the surface of the material, and can also collect the pyroelectric-piezoelectric-triboelectric coupling energy. However, most ferroelectric materials are rigid and therefore difficult to apply to flexible wearable electronics. In this paper, we briefly describe the mechanism of ferroelectric polarization triboelectric output and the working mechanism of coupled generators, then introduce some flexible ferroelectric materials and finally introduce some of their recent applications.

Keywords: flexible ferroelectric material, triboelectric nanogenerator, micro nano energy, self-driven sensing system, mechanical energy harvesting

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INTRODUCTION

Triboelectrification effect is a kind of charged effect caused by contact, that is, in the process of triboelectric between a material and another material, one will take electrons and the other one will lost electrons, triboelectrification effect is the basic source of static charges in our life (Fan et al., 2012). The sign of a material's charge depends on its relative polarity with the material in contact with it (Wang et al., 2013). Triboelectricity has been known for more than 2,600 years, but its effects have been largely negative (Xu et al., 2018). For example, an aircraft in flight will generate static charges due to triboelectric between the skin and the air, which will interfere with radio frequency signal transmission. In warehouses where flammable and explosive objects are stored, static charges can cause explosions and also create safety hazards. Some electronic components, such as semiconductor field-effect transistors, can be damaged by the high voltage generated by the electrostatic discharge on the gloves. Therefore, triboelectric electrification in our life is mostly regarded as a negative effect, has not been effectively used (Fan et al., 2016). Feng-Ru Fan et al. proposed the concept of triboelectric nanogenerator, which is the first time to use the triboelectric

electrification effect to convert mechanical energy into electrical energy (Fan et al., 2012). The benefits of a triboelectric nanogenerator are its tiny size, light weight, and cheap cost, and it has a wide application promise in the future generation of portable wearable electronic gadgets.

With the development of research, the output performance of triboelectric nanogenerator has been greatly improved (Sahatiya et al., 2018; Zhang et al., 2021; Chai et al., 2022). Changing device structure, physical surface engineering and chemical composition modification are common effective methods (Li H. Y. et al., 2015; Shin et al., 2017; Singh and Khare, 2019). The triboelectric charge density generated between the contact surfaces of two different materials is the key factor to determine the output performance. The larger the potential difference between the contact surfaces of two materials, the easier it is to create a triboelectric charge, which boosts the output performance (Xu et al., 2018). Ferroelectric material is a kind of material with polarization orientation, which can change the polarization direction under the action of external electric field, so as to change the surface potential and improve the triboelectric output (Park et al., 2018; Zhang et al., 2021; Li B. et al., 2022). Peng Bai et al. proposed a method to regulate the output performance of triboelectric generators by polarization (Bai et al., 2014). By changing the polarization direction of PVDF, the output voltage can be increased to 240% or reduced to 70%. This paper proposes a novel way for controlling the output of triboelectric nanogenerators. Jie Wang et al. reported a method to increase triboelectric charge density. A triboelectric charge density of $1003 \mu\text{C}/\text{cm}^2$ is obtained, by coupling vacuum conditions with surface polarizing of ferroelectric materials, without the limitation of air breakdown, approaching dielectric breakdown limit (Wang et al., 2017). These works indicate the great application prospect of ferroelectric materials in triboelectric generators.

In this paper, we briefly describe the mechanism of ferroelectric polarization boosts triboelectric output and the working mechanism of coupled generators, then introduce some flexible ferroelectric materials and finally introduce some of their recent applications. We hope this paper can arouse the interest of relevant researchers.

MECHANISM OF THE TENGs

Ferroelectric materials have the characteristics of large residual polarization, dielectric constant, pyroelectric coefficient and electro-optic modulation, and have been widely used in various fields, such as optical modulators, thermal devices, tunable microwave devices and so on (Omote et al., 1997; Trieloff et al., 2003; Acosta et al., 2017). Many research has lately shown that ferroelectric materials offer vast application potential in the realm of triboelectric generators. The output function equation of open circuit voltage (1) and short circuit current (2) of triboelectric nanogenerator is (Wang, 2017).

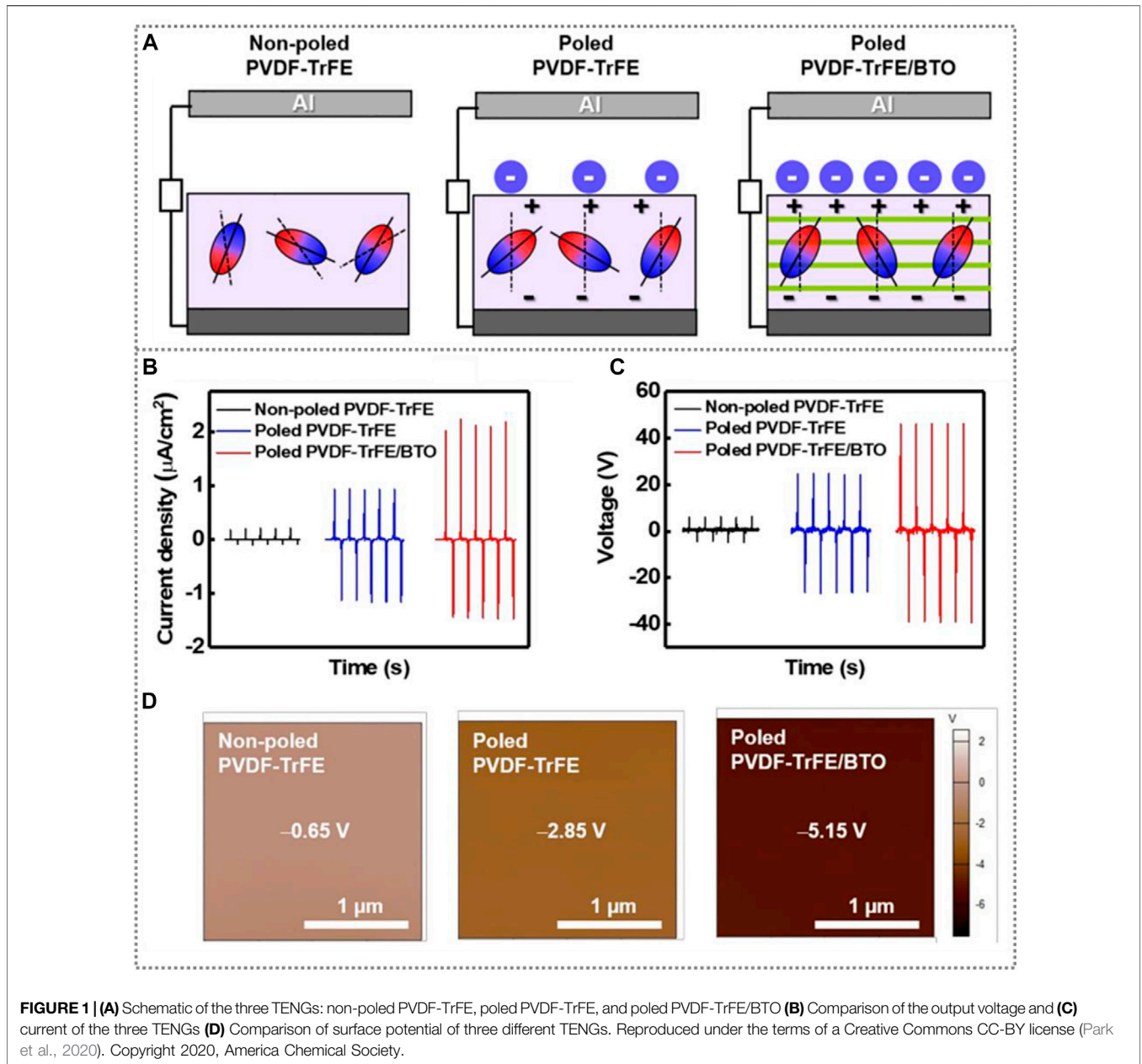
$$V = \sigma_1(z, t) \left[\frac{\mathbf{d}_1}{\epsilon_1} + \frac{\mathbf{d}_2}{\epsilon_2} \right] + \frac{z[\sigma_1(z, t) - \sigma_c]}{\epsilon_0} \quad (1)$$

$$RA \frac{d\sigma_1(z, t)}{dt} = z \frac{\sigma_c}{\epsilon_0} - \sigma_1(z, t) \left[\frac{\mathbf{d}_1}{\epsilon_1} + \frac{\mathbf{d}_2}{\epsilon_2} + \frac{z}{\epsilon_0} \right] \quad (2)$$

Where z is a function of the time t that depends on the dynamic process of applying force, ϵ_1 and ϵ_2 are the relative dielectric constants of two contact materials, \mathbf{d}_1 and \mathbf{d}_2 are the displacements of the motion of the two contact materials, $\sigma_1(z, t)$ is the free electron buildup in the electrode, σ_c is the triboelectric surface charge density, A is contact area size. Therefore, under the same structure and motion state, materials with high polarization strength and dielectric constant will have higher output and are more suitable for triboelectric generators. The polarization of ferroelectric materials can control the surface potential, increase the contact potential difference between two different materials, and make the triboelectric charge density larger.

Regulation Mechanism of Polarization on Surface Potential

The polarization of ferroelectric materials will change the electric potential of the material surface (Lee et al., 2016). Yoojeong Park et al. investigated the effect of polarization on surface potential (Park et al., 2020). **Figure 1A** shows the induced charge on surface of PVDF-TrFE non-poled, poled, and with BTO poled. The induced charge on the surface increases with the increase of polarization intensity. **Figures 1B,C** shows the impact of ferroelectric polarization increases the voltage and current of poled PVDF-TrFE by roughly 450 and 400%, respectively, as compared to unpoled PVDF-TrFE. The TENG results are consistent with the surface potential study. **Figure 1D** shows the surface potential of the poled PVDF-TrFE is greater (-2.85 V) than that of the non-poled PVDF-TrFE film (-0.65 V). The total of all dipole moments is little because the dipoles of non-poled PVDF-TrFE are randomly oriented. Deahoon Park et al. suggested a triboelectric generator (TENG) consisting of a P(VDF-TrFE) layer sandwiched by PDMS layers to increase TENG performance. (Park et al., 2021). They demonstrated that the structure and polarization orientation of PVDF-TrFE had a significant impact on the TENG's output performance. The output performance of TENGs is improved because of the greater surface potential difference. The suggested design generates a peak output current and voltage of $50 \mu\text{A}/\text{cm}^2$ and 420 V , respectively. Lingxiao Gao et al. presented a DHS-TENG to drive temperature monitoring and smart-home management (Gao et al., 2018). Using the ferroelectric properties of PVDF, the DHS-TENG increases the triboelectric charge density of the contact area. The DHS-TENG can generate a maximum output power of 9.03 mW . It also provides improved output voltage and current of 460 V , $140 \mu\text{A}$, with a force of 40 N , respectively. Huidrom Hemojit Singh et al. designed a PVDF- NaNbO_3 film-based TENG and exhibited a great tuning (64 percent) of the TENG's performance by modifying its electrical polarization orientation (Singh et al., 2021). Kelvin probe force microscopy experiments were performed to investigate the reason of the difference in output with polarization orientation of the films. The surface electric potential of the film was discovered to modify



with polarization, leading to changes in output. The present study proved the benefit of employing ferroelectric materials for triboelectric nanogenerator systems, since the output properties of triboelectric nanogenerators can be adjusted according to the needs.

Working Mechanism of Hybrid Generators

The output power of triboelectric nanogenerators has increased significantly compared to the beginning, however, there are still output power limitations for further use in large-scale energy harvesting (Bhatta et al., 2022). As a result, the coupling of triboelectric electricity with other qualities is critical, and special attention should be made to the coupling of triboelectric electricity with many other effects. (Sun et al.,

2020). In daily life, there is triboelectric electricity as well as pressure and temperature changes, which often occur simultaneously. Sliding triboelectric generators, for example, often generate triboelectric heat in the triboelectric process, especially in high-frequency sliding, but it is usually lost in waste. In addition, the work done by the unavoidable forces in the vertical direction leads to additional energy loss. Therefore, it is important to collect these energies at the same time.

Ferroelectric materials have excellent piezoelectric and pyroelectric coefficients and can convert piezoelectric and thermal energy into electrical energy. Yunlong Zi et al. proposed a piezoelectric-pyroelectric-triboelectric hybrid cell for harvesting coupled energy, as shown in **Figure 2A** (Zi et al., 2015). **Figure 2B** shows that triboelectric heat and

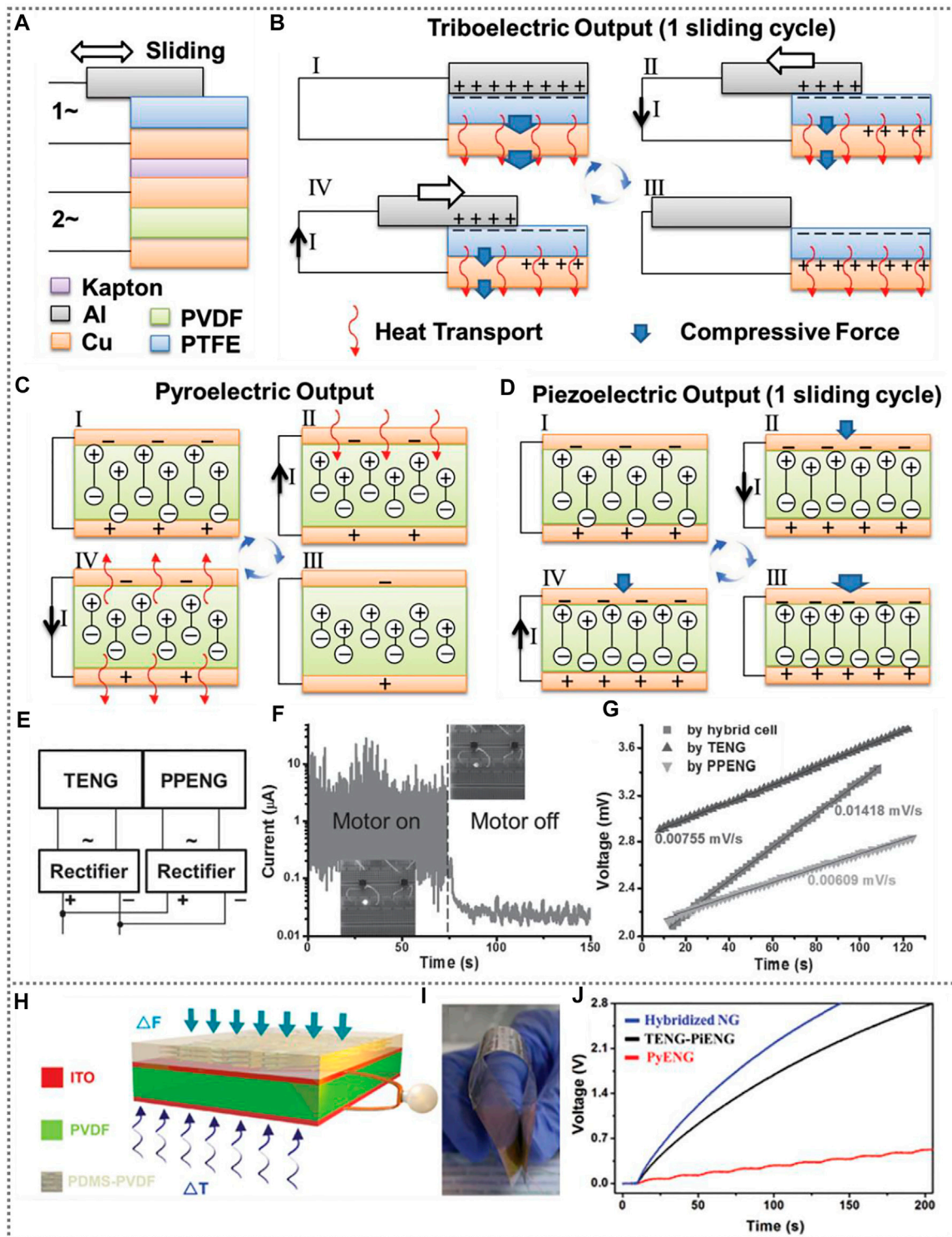


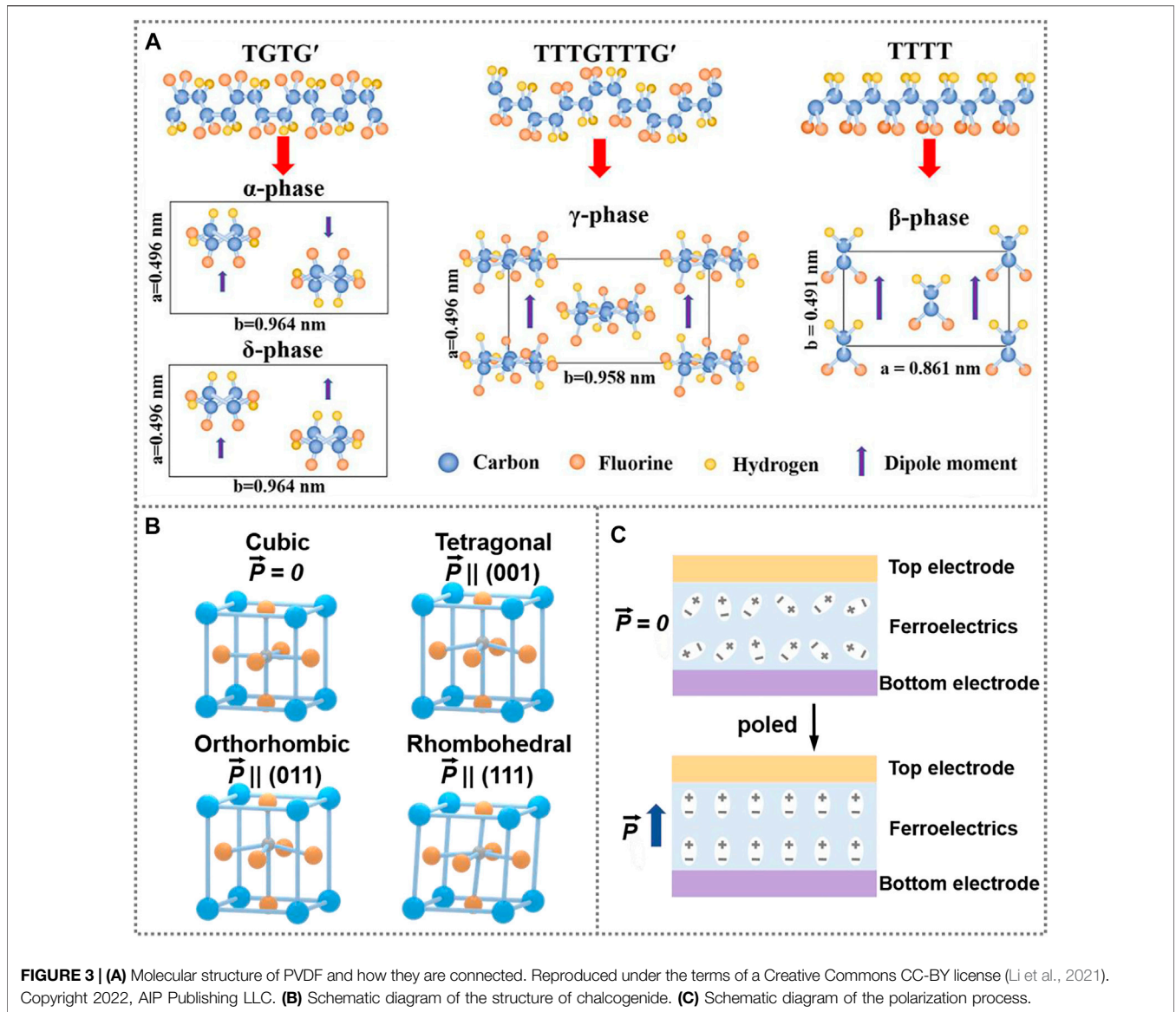
FIGURE 2 | (A) Schematic diagram of the structure of the hybrid generator (B) Schematic diagram of a sliding triboelectric process. (C) Schematic of a piezoelectric output process (D) Schematic of a pyroelectric output process. (E) External circuit of the hybrid generator. (F) The hybridized output current, with the LED illuminated by the hybridization output when the motor was turned on and off, as illustrated in the insets. (G) Comparison of hybridized output and single output. Reproduced with permission (Zi et al., 2015). Copyright 2015, Wiley-VCH. (H) Device schematic. (I) Schematic diagram of device bending. (J) Hybridized output is much higher than single output. Reproduced with permission (Wang S. et al., 2016). Copyright 2016, Wiley-VCH.

pressure are inevitably generated during the operation of a sliding triboelectric generator. **Figure 2C** demonstrates the operating principle of pyroelectric generators. When heated, the polarization strength of the ferroelectric material decreases and electrons run from the top electrode to the bottom to balance the bound charges on both sides, thus generating an external current, and when the heat dissipates, the polarization strength increases and electrons run from the bottom electrode and to the top, generating the opposite current. This is the pyroelectric output. **Figure 2D** illustrates the operating principle of a piezoelectric generator. When the applied pressure becomes smaller, the polarization intensity increases and electrons run from the bottom to the top to balance the bound charges on both sides, thus generating an external current, when the pressure becomes larger, the polarization intensity increases and electrons run from the top to the bottom, generating the opposite current. This is the piezoelectric output. **Figure 2E** shows the hybridization circuits for TENG and PPENG outputs. As illustrated in **Figure 2F**, with the LED lit by the hybridization output while the motor was on and after the motor was turned off. **Figure 2G** shows that there is a significant increase in output power in the coupled output state. As illustrated in **Figure 2H**, Shuhua Wang et al. prepared coupled generators for the collection of pyroelectric-piezoelectric-triboelectric coupling energy using PVDF/PVDF-PDMS composites (Wang S. et al., 2016). As shown in **Figure 2J**, the hybrid nanogenerator offers superior charging performance than the energy harvesting unit alone (TENG-PIENG or PyENG) when both TENG-PIENG and PyENG are active. Energy harvesters that are environmentally safe and have a high output performance for successfully capturing mechanical energy across a wide temperature range are desired. Sun Yanhua et al. reported a coupled generator based on BFO-BTO ceramic powder and polyimide (PI) matrix, the output voltage and current are 175 V and 0.6 μ A, respectively, and output power of 4.1 mW/cm³ is achieved (Sun et al., 2020). Jihye Kim et al. proposed a P(VDF-TrFE)-based coupled generators demonstrate that the higher polarization strength significantly improves the output of the nanogenerators, the improved performance is approximately 24 percent and 82 percent in output voltage and current, respectively, compare with piezoelectric nanogenerator (Kim et al., 2017). Abu Musa Abdullah et al. reported a hybrid generator based on KNN-PVDF (Abdullah et al., 2021). The voltage and current of the hybrid piezoelectric-triboelectric output were increased by 153 and 186%, respectively, over that of piezoelectricity alone. It can charge a 100 nF capacitor to 9.4 V within 60 s. The optimal output power is 0.164 W. These works demonstrate the superiority and great potential of coupled generators for energy harvesting.

INTRODUCTION OF FLEXIBLE FERROELECTRIC MATERIALS

Ferroelectric materials are divided into two categories: organic and inorganic. The organic ferroelectric materials mainly include PVDF, PVDF-TrFE, nylon 11, nylon 7 and so on (Chang et al.,

2018; Ram et al., 2019). At present, PVDF-based materials are the most widely used materials (Yao et al., 2020). **Figure 3A** illustrates the molecular structure of PVDF and the different linkages, TG⁺TG, TTTGTTT^{G'}, and TTTT, corresponding to the α -phase, β -phase, and β -phase, respectively. Among them, β phase has the highest polarization intensity, so to improve the ferroelectric properties of PVDF, the content of β phase should be increased (Horiuchi and Tokura, 2008). PVDF-based materials can be easily crystallized directly from melt or solution into polar β -phase under ambient conditions by introducing a certain percentage of structurally similar molecules such as trifluoro ethylene (TrFE) (Owczarek et al., 2016). TrFE, which one of the hydrogens is substituted with a slightly larger fluorine to form a stable copolymer with VDF. Due to spatial site resistance, the TrFE defect forces the copolymer chain into an all-trans conformation, resulting in a ferroelectric β -phase, which is the only stable crystalline phase of P(VDF-TrFE). Inorganic ferroelectric materials mainly include BTO, PZT, etc (Liu et al., 2016; Acosta et al., 2017). Their molecular structures are all chalcogenide structures, as shown in **Figure 3B**. They have four phase structures as cubic, tetragonal, orthorhombic and rhombohedral, where the cubic phase is non-ferroelectric and the remaining three are ferroelectric with spontaneous polarization directions along (001) (011), and (111), respectively (Martin and Rappe, 2017). The temperature at which the transition from the ferroelectric to the non-ferroelectric occurs is called the Curie temperature (Bersuker, 1981). Inorganic ferroelectric materials have large residual polarization strengths and large dielectric constants, much larger than organic ferroelectric materials, yet are mostly rigid (Tsagarakis et al., 2006). The development of the preparation process allows the preparation of inorganic ferroelectric materials on flexible substrates, such as PLD, ALD, dissolution sacrificial layer, laser lift-off (LLO), etc (Yao et al., 2020). However, the lack of flexibility and wear resistance makes it difficult to be used in triboelectric electric generators (Lan et al., 2020). **Figure 3C** illustrates the principle of ferroelectric material polarization, in which the ferroelectric domains appear in a disordered state when unpolarized, when the macroscopic polarization intensity of the material is zero. After the electric field is applied, the ferroelectric domains are aligned in one direction under the action of the electric field and are in a state of macroscopic polarization, with the direction of polarization along with the applied electric field. The magnitude of the applied electric field depends on the magnitude of the coercivity field of the material itself. Researchers mixed inorganic ferroelectric materials with organic ferroelectric materials to enhance the polarization strength and dielectric constant of organic ferroelectric materials. Xiang Tao et al. reported a method to increase the performance adding BTO nanoparticles into the PVDF film, with a contact force and spacing distance of 180N and 100mm, respectively (Tao et al., 2019). At a contact frequency of 5Hz, peak voltage and charge density increased by 234 percent and 130 percent, respectively. The higher piezoelectric characteristic and permittivity are important for the greatly improved output of the TENGs, according to detailed analyses of the PVDF-BTO films. Daehoon Park et al. reported a TENG by constructing BaTiO₃



nanoparticles (NPs) embedded sponge structures. The BaTiO₃(NPs) serve a key role in raising surface charge density via polarization strength, allowing TENGs to be packaged with a small spacing gap (Park et al., 2018). An output voltage of 370 V and current of 10 μ A were obtained. Even in adverse environments, the TENGs can dependably capture energy. The method presented here is a simple, practical, and repeatable method for fabricating tiny and packed TENGs for use in mechanical energy harvesting systems. Hyun Soo Kim et al. proposed a triboelectric generator consisting of PVDF and PDMS with ITO as the electrode (Kim H. S. et al., 2019). Compared to under-polarized and unpolarized PVDF, up-polarized PVDF creates large triboelectric charges, fast saturation voltages/currents, and large residual charges due to modulated surface potential and increased capacitance. Bin Li et al. proposed a TENG by adding BNT-BS/NN-ST nano powder into PDMS (Li B. et al., 2022). In instance, we discovered that

BNT-BS/NN-ST/PDMS had much greater output voltages than pure PDMS. A maximum output voltage of 370V was obtained when the addition amount was 15%. Harishkumarreddy Patnam et al. reported a composite film by adding Ca-BZT nano particles into PDMS (Patnam et al., 2020). The films' surface unevenness and charge, and dielectric constants are all greatly improved, leads to the increase in the Hybrid generator's output properties. The max output voltage, current, and power density values are 550 V, 34 μ A, and 23.6 W/m². Woo-Suk Jung et al. reported a coupled generator made of PVDF and PTFE (Jung et al., 2015). The coupled generator generates 370 V and 12 μ A/cm², with a corresponding output power density of 4.4 mW/cm², it can light 600 LEDs under a force of 0.2N, and can charge a capacitor of 10 μ F to 9.4 V in 25 s. This is achieved by using both piezoelectric and triboelectric processes at the same in a single cycle. In addition to inorganic ferroelectric materials, some additives can also enhance the ferroelectricity of organic ferroelectric

TABLE 1 | Some triboelectric nanogenerators based on flexible ferroelectric materials.

Materials	Mechanisms	Output Voltage (V)	I_{sc} ($\mu\text{A}/\text{cm}^2$)	Output power (W/m^2)	Charge density ($\mu\text{C}/\text{m}^2$)	Cycles (n)	References
PVDF/PMMA	TENG	810	0.86	13.8@5M Ω	-	10000	Xia et al. (2022)
PVDF-TrFE/PDMS	TENG	420	50	33@10M Ω	-	-	Park et al. (2021)
P(VDF-TrFE) PDMS/MWCNT	TENG	25	6.5	19.8@6M Ω	-	-	Wang et al. (2016b)
PVDF-HFP-SEBS	TENG-PENG	400	1.63	2.34@M Ω	250	-	Jiang et al. (2022)
PVDF	TENG	400	8.75	7@2M Ω	-	-	Chen et al. (2019)
BTO/P(VDF-TrFE)	TENG	190	6.15	7.21@M Ω	105	-	Chai et al. (2022)
ZnO/PVDF-PTFE	TENG-PENG	119	0.21	0.106@150M Ω	-	-	Singh and Khare, (2019)
PVDF-MS@PVA	TENG	230	1.5	3.1@20M Ω	-	-	Patnam et al. (2021)
PVDF-ZnSnO ₃ /PA-6	TENG	520	0.27	0.47@50M Ω	62	-	Soin et al. (2016)
PVDF/PA-6	TENG	1140	9.17	-	490	150000	Cheng et al. (2018)
BiFeO ₃ film	TENG-PENG	110	3.7	1.51@250M Ω	-	1800	Liu et al. (2021)
BaTiO ₃ NP/PDMS	TENG-PENG	13	18	-	~	-	Suo et al. (2016)
Ca-BZT/PDMS	TENG-PENG	550	8.5	23.6@20M Ω	-	-	Patnam et al. (2020)
BaTiO ₃ -Nanorods/Chitosan	TENG-PENG	270.2	36.7	156.8@50M Ω	35.3	-	Pongampai et al. (2021)
P(VDF-TrFE)/TBTO	TENG	315	6.7	2.75@10M Ω	-	10000	Min et al. (2021)
Nylon 11/PMMA- PVDF-TrFE/ZrO	TENG	500	500	420@10M Ω	220	-	Cao et al. (2020)

materials. Moon Hyun Chung et al. reported a TENG made of P(VDF-TrFE) and PEDOT:PSS (Chung et al., 2022). The peak output voltage and current are ~ 15 V and ~ 2.3 μA , respectively, under 1 Hz oscillation. The findings show that adding PEDOT:PSS nanofiller to PVDF-TrFE improves its ferroelectric characteristics.

APPLICATIONS OF HYBRID TENGs

By the increasing environmental problems, the search for green and renewable energy is particularly important for the sustainable development of human beings. There are four main research areas of triboelectric nanogenerators, micro and nano energy, self-driven sensing systems and blue energy, high voltage electrical power source (Wu et al., 2019). Flexible ferroelectric triboelectric generators for blue energy and high-voltage electrical power are still relatively little studied, so they are not described here. We present some generators made of flexible ferroelectric materials and compare their performance, as shown in **Table 1**. This section focuses on the application of flexible ferroelectric triboelectric nanogenerators to micro and nano energy and self-driven sensing systems.

Micro Nano Energy

In the future, everyone has several or even dozens of portable mobile electronic devices on them. Size and power supply problems limit the development of next-generation portable electronic devices, and the discarded batteries will bring pollution to the environment (Wang, 2008). As a simple and efficient alternative for converting mechanical energy into electrical energy, triboelectric nanogenerators have the potential to significantly reduce not just energy consumption but also the pollution created by discarded batteries (Kim et al., 2022). The availability, conversion efficiency, and stability of

micro-nano energy are some of the most important performance factors (Fan et al., 2016). The use of solar energy is an obvious option when the device is in an open area with enough light. In situations when the device is adjacent to an engine but not illuminated, collecting energy through mechanical vibrations is the most effective method of generating power (Li H. Y. et al., 2015). In biological applications, collecting the deformation energy produced by muscle stretching is an effective method of doing this (Sim et al., 2016). Solar cells are very efficient, however when light is restricted due to environmental circumstances, high-efficiency solar cells may not be the ideal option for such devices, despite their great efficiency (Sun et al., 2020). So the sort of energy collected relies on the stability of the energy source, which is essential for the device to function well over an extended period of time (Singh and Khare, 2018). The performance of solar cells, for example, is impacted by a variety of elements including the time of day and night, meteorological conditions, and even the season. This is the reason why the triboelectric nanogenerator was selected as the energy source for the self-driven sensor and why it was utilised in the first place (Niu et al., 2013). Charge density is one of the most essential factors of TENG since it significantly influences output property, yet, it is severely limited by the phenomena of air breakdown, which occurs when the nanogenerator is exposed to air. Li Cheng et al. proposed a triboelectric nanogenerator that has a high charge density (Cheng et al., 2018). A peak triboelectric charge density of $490 \mu\text{C}/\text{m}^2$ is produced, as shown in **Figure 4A**. The generator is composed of two parts, the first of which contains a triboelectric layer made of PVDF and PA-6 film and the second part has two PET films. The output can be further enhanced by connecting multiple second part devices to the first SI-TENG device, as shown in **Figure 4C**. As introduced in **Figure 4D**, Minje Kim et al. described a way for successfully increasing the output current density of TENGs via the use of polarised ferroelectric

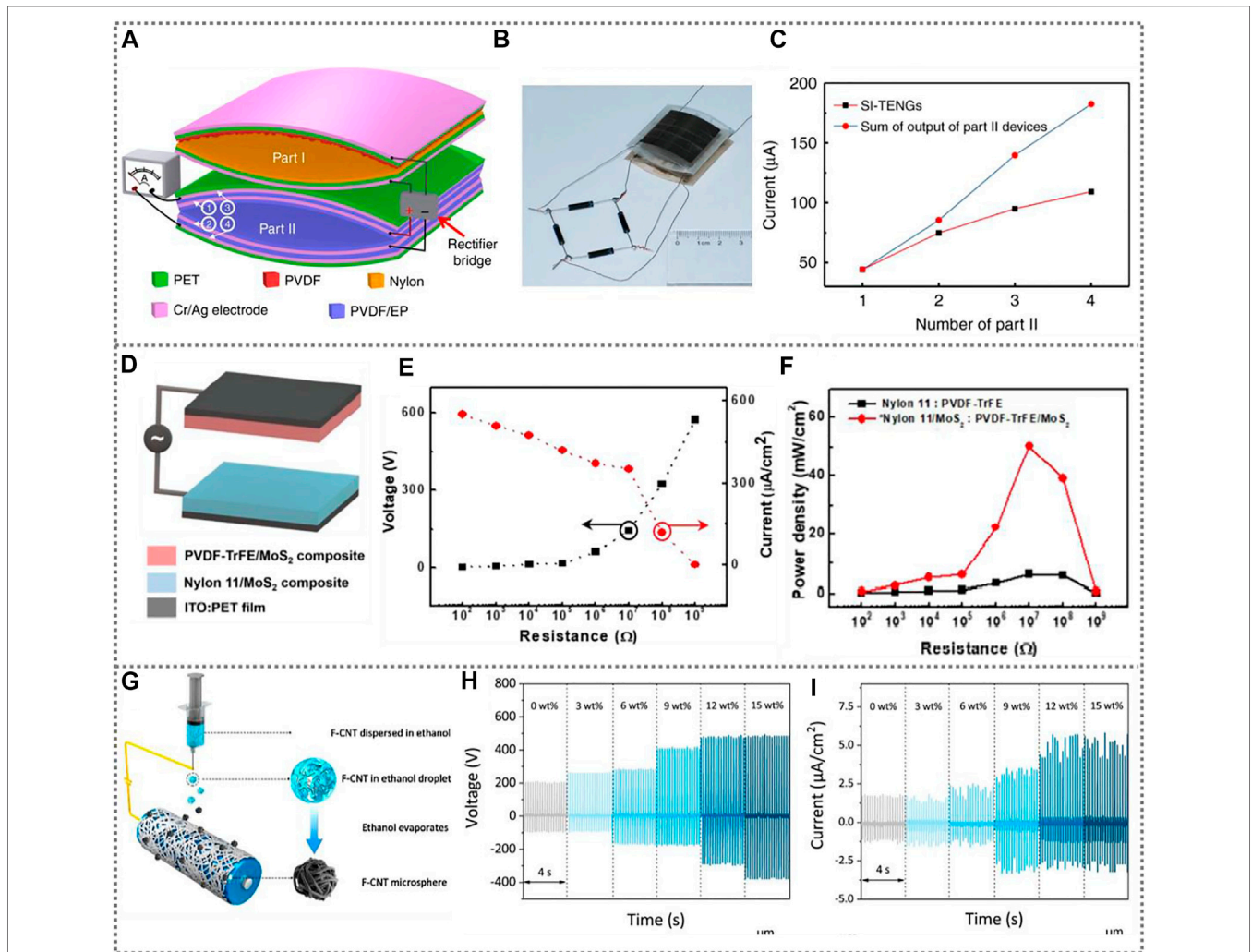


FIGURE 4 | (A) Schematic diagram of the generator. (B) Physical picture of the generator. (C) As the number of second parts increases, the output also increases. Reproduced under the terms of a Creative Commons CC-BY license (Cheng et al., 2018). Copyright 2018, Springer Nature. (D) Schematic diagram of generator structure. (E) Variation of output voltage and current with load resistance. (F) Comparison of the output of the two types of generators. Reproduced under the terms of a Creative Commons CC-BY license (Kim M. et al., 2019). Copyright 2019, America Chemical Society. (G) Schematic diagram of the structure of a water-drop friction generator. (H) Output Voltage and (I) Current of TENG with varying F-CNT concentrations. Reproduced under the terms of a Creative Commons CC-BY license (Lan et al., 2021). Copyright 2021, America Chemical Society.

polymers and MoS₂ composite materials (Kim M. et al., 2019). As an additional benefit of having the right polarisation of both ferroelectric composite layers, the charge density has increased by a further factor of two. By optimising the manufacturing process, it is possible to obtain output voltages and current densities of up to 145 V and 350 mA/cm², respectively, in the output circuit. As a result, the TENG has a high output power density of around 50 mW/cm² as shown in **Figure 4F**.

Triboelectric nanogenerators based on flexible ferroelectric material also has important applications in agriculture (Chen et al., 2021; Li X. et al., 2022). Plants are crucial to agricultural productivity. The continual presence of abiotic stressors such as drought, salt, incidence sunlight, and temperature fluctuations, on the other hand, may possibly harm plant viability and consequently contribute to poor production (Torquebiau, 2017). As a result,

effective and timely plant health monitoring has become an essential tool for increasing agricultural yields. However, sustaining power supply for these electrical devices remains a critical concern. Batteries are now mostly employed as temporary power sources (Wang, 2008). Conventional batteries must be changed or recharged on a regular basis, which may cause maintenance issues and environmental issues. As a result, it is preferable to develop maintenance-free and long-term power sources in order to build “smart agriculture” systems that run continuously. Zong-Hong Lin et al. showed that contact between water and polymer may be helpful for triboelectric nanogenerator, resulting in a novel use of triboelectric nanogenerator, particularly in liquid conditions for sensing (Lin et al., 2013). Zong-Hong Lin et al. created the water-TENG with PTFE to collect water-related energy derived from moving water and water droplets, which differs

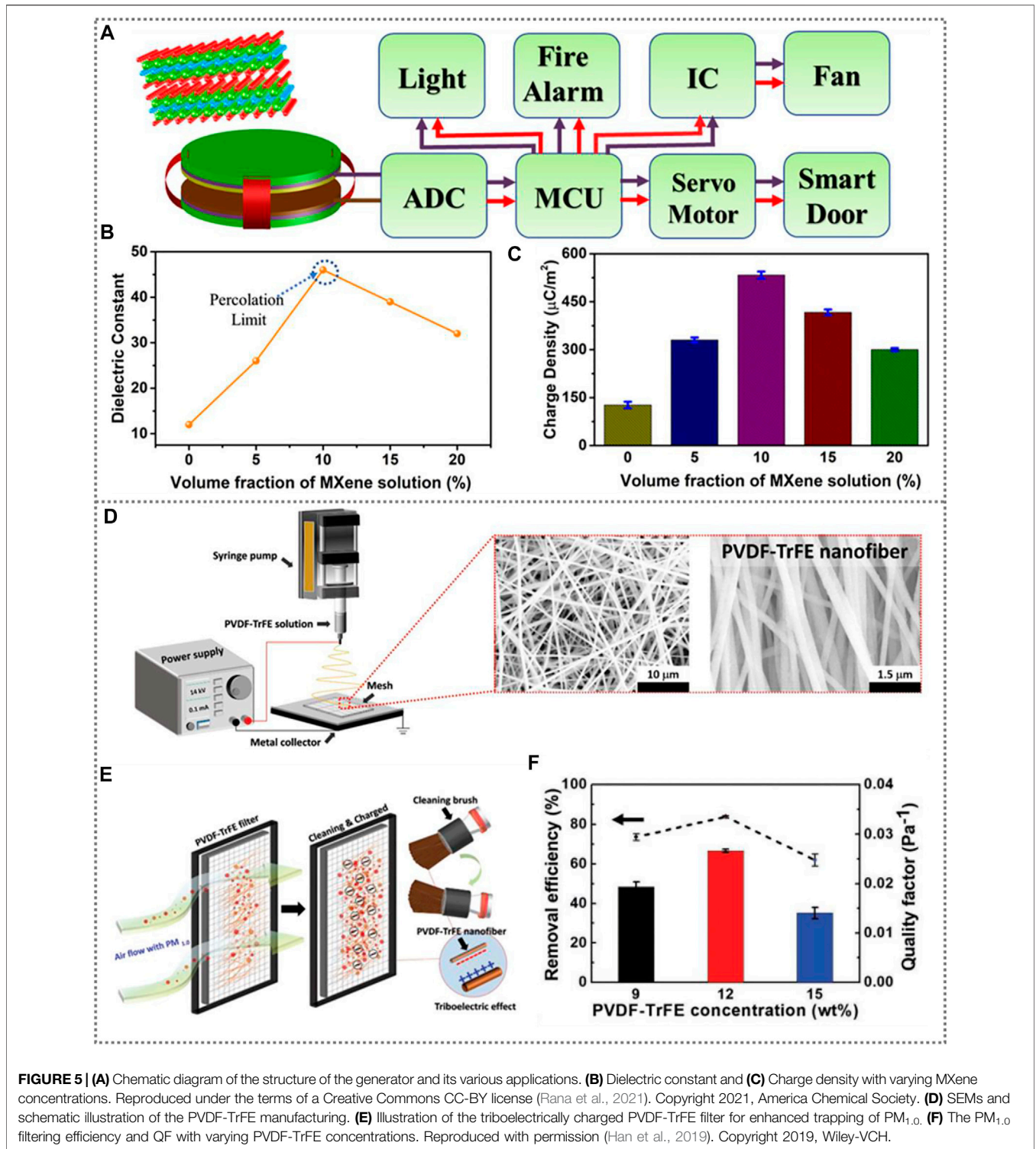
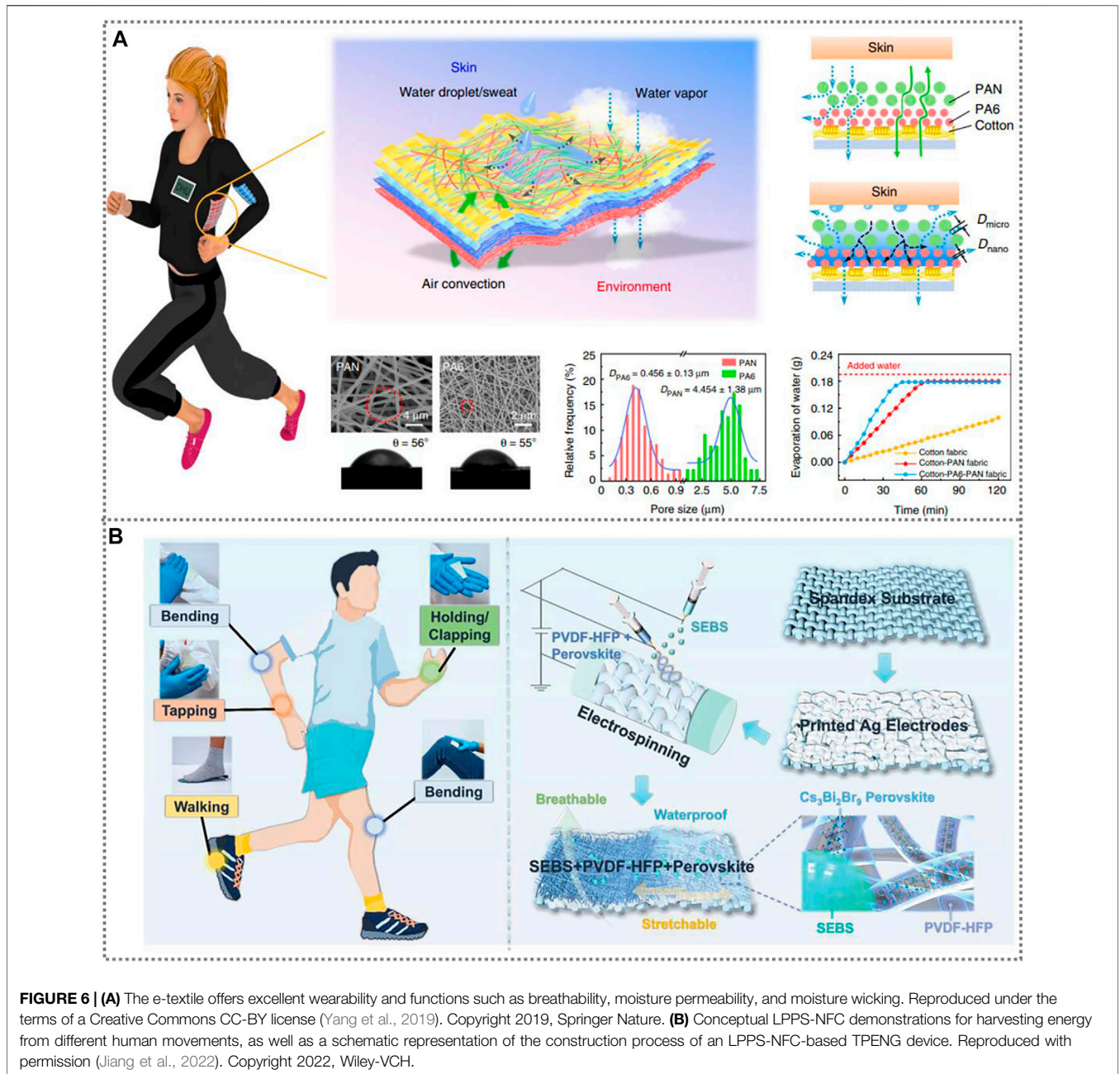


FIGURE 5 | (A) Schematic diagram of the structure of the generator and its various applications. (B) Dielectric constant and (C) Charge density with varying MXene concentrations. Reproduced under the terms of a Creative Commons CC-BY license (Rana et al., 2021). Copyright 2021, America Chemical Society. (D) SEMs and schematic illustration of the PVDF-TrFE manufacturing. (E) Illustration of the triboelectrically charged PVDF-TrFE filter for enhanced trapping of $\text{PM}_{1.0}$. (F) The $\text{PM}_{1.0}$ filtering efficiency and QF with varying PVDF-TrFE concentrations. Reproduced with permission (Han et al., 2019). Copyright 2019, Wiley-VCH.

significantly from the Kelvin water dropper’s operating mechanism (Lin et al., 2014). The output of a 30 μL water drops water-TEG produce a max output voltage of 9.3 V and max output current of 17 μA . When the device is loading a 5 M Ω resistor, it produces a peak output power of 145 μW . Wanghui Xu et al. created a device that harvests energy from impinging water droplets by combining a

polytetrafluoroethylene film on an ITO substrate with an Al electrode (Xu et al., 2020) (171) Several orders of magnitude increase in the production of water droplet triboelectric electricity. These works demonstrate the great potential of water droplet triboelectric electricity. Water droplet triboelectric electricity is a significant source of triboelectric electricity in agricultural



systems, both in rain and in watering, where energy may be gathered from water droplets (Chen et al., 2021). As shown in Figure 4G, Lingyi Lan et al. proposed a nanogenerator for collecting triboelectric electricity from water droplets (Lan et al., 2021). It has great output power of $330.6 \mu\text{W}/\text{cm}^2$, permeability and hydrophobicity, and it was fabricated using (PVDF-HFP) and F-CNT). The device is capable of harvesting energy during rain and watering to drive sensors that detect plant health without damaging the plant's physiological activity. This allows the sensors used to detect the health of crops to function without additional power, eliminating the need for maintenance. Fibbers made of ferroelectric materials have a variety of application scenarios, such as wearable power supplies,

motion sensors, etc (Wang et al., 2015; Sebastian et al., 2017; Eom et al., 2020). As shown in Figure 5A, S M Sohel Rana et al. reported a triboelectric generator made of PVDF-TrFE)/MXene used to harvest energy from human movement to drive small electronic devices (Rana et al., 2021). It produces the maximum output power of $4.02 \text{ W}/\text{m}^2$ with a resistor of $4 \text{ M}\Omega$. It can capture energy from the smallest movement of the human body, allowing it to power tiny electrical equipment in the house.

Air quality is currently a serious social and environmental problem, factory emissions, car exhaust pollution, etc. all bring serious challenges to air quality (Wang et al., 2022). Diseases due to air problems are on the increase year by year (Barkjohn et al.,

2020). In poorer air conditions, the use of air filters has become the choice of many people (Zhang et al., 2020). As shown in **Figure 5B**, Kyung Seok Han makes a triboelectric generator to filter air with PVDF-TrFE nanofibers (Han et al., 2019). Following polarisation, this air filter has a PM_{1.0} filtering effectiveness of more than 88 percent, which improves to 94 percent after triboelectric commencement. This work provides a simple and effective way to improve the air quality at home. The triboelectric electricity generated by walking, running, and other motions in the body provides a rich source of triboelectric electricity. Static electricity on our clothing used to worry us, but today we can utilise triboelectric energy to power tiny wearable electrical devices. By making ferroelectric fibbers into textiles, energy can be collected from the body during movement. As shown in **Figure 6A**, Weifeng Yang et al. reports on a textile made from PVDF fibbers (Yang et al., 2019). This textile has excellent comfort properties. Under the slow movement of the human body, it can generate an output power of 5 W/cm² to drive portable low power electronic devices. As shown in **Figure 6B**, Feng Jiang prepared a triboelectric generator from a fibber material made of PVDF-HFP and SEBS (Jiang et al., 2022). The fibber material has excellent comfort and stretchability. Generators made of this fibber material have an output voltage of 400 V, a current of 1.63 μA/cm², and a power density of 2.34 W/m², and has excellent water resistance. It can collect energy from bending, tapping, walking/holding and other actions.

In addition to being used to harvest human motion energy, ferroelectric polymer fibbers can also be used to harvest acoustic energy. Airport noise, traffic noise, and building site noise have all been identified as issues that must be addressed. However, they may also be utilised as a source of energy. The energy created by sound is all around us, yet it is often squandered. As a result, we need a good method of collecting sound energy. Qichen Fang et al. proposed a triboelectric nanogenerator made of PVDF fibbers that can collect sound energy and sensing (Chen et al., 2019). The device generates a peak voltage of 400 V and a peak current of 170 μA/cm². At 170 Hz and 115 dB, the device can provide an output power of 7 W/m². This work provides a low-cost, simple and effective method for harvesting sound energy. Jiadong Liu et al. proposed a generator made of BFO-GFF/PDMS composite for collecting piezoelectric and triboelectric energy (Liu et al., 2021). The device's maximum output voltage and current at 1 Hz are 110 V and 3.67 μA/cm², respectively. Xingzhao Wang et al. prepared P(VDF-TrFe) nanofibers for triboelectric nanogenerator and obtained an output performance of 25 V, 98.56 μW and 1.98 mW/cm³ at a force of 5 N (Wang X. et al., 2016). These works show great promise for ferroelectric fibbers in smart textiles and wearable power.

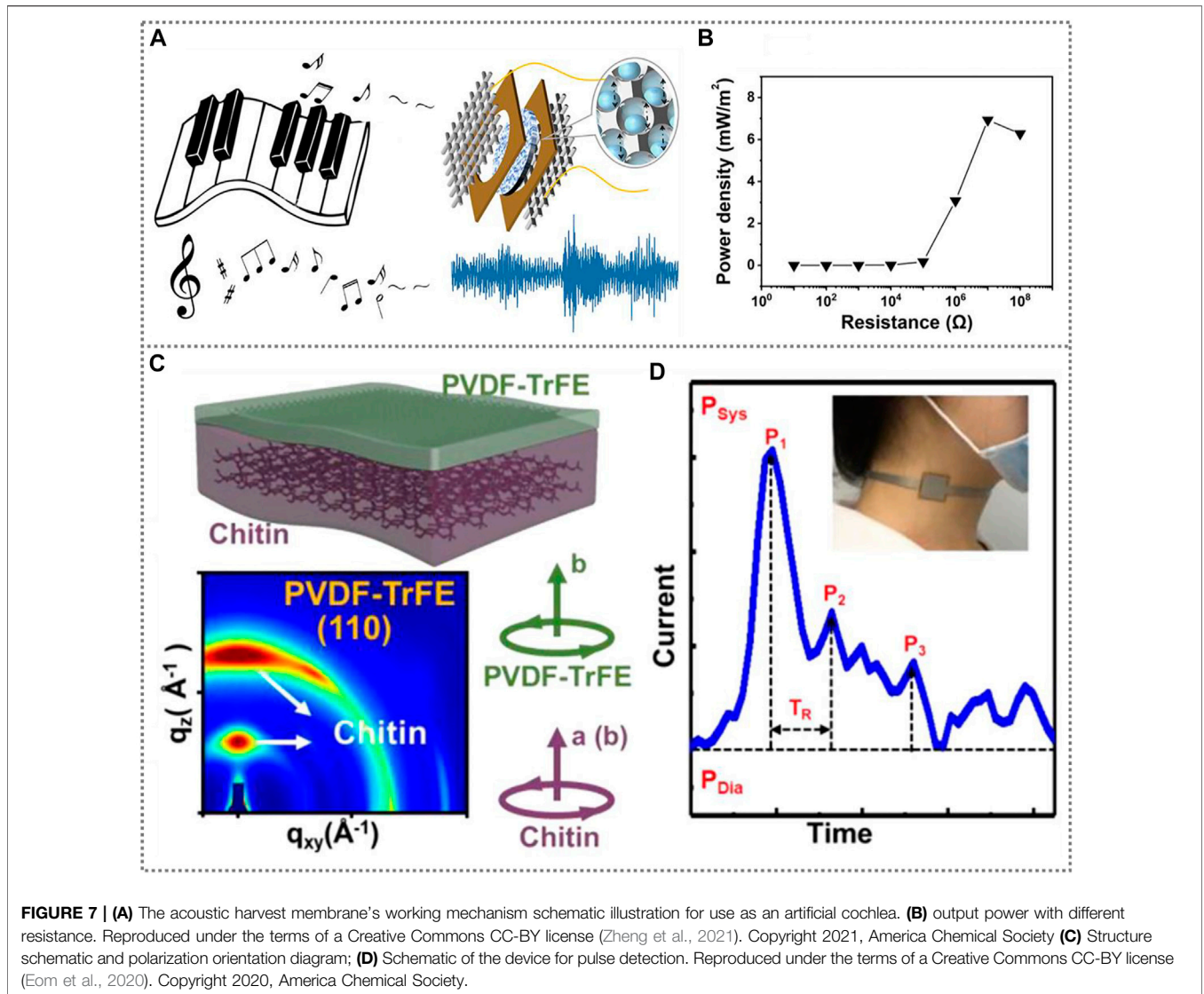
Self-Driven Sensing System

In the future era of Internet of Everything, achieving object-to-object connectivity is the foundation of IoT intelligence. If a network of sensors were installed in every corner of the globe, a huge number of sensors would be located in every corner of the world and it's unlikely that batteries could power such a staggering number of trillions of sensors. Because people

need to find the location of the battery from time to time, replace the battery and test whether the battery is working properly. In this case, a possible alternative is to harvest the energy present in the environment where the sensor is located (Wang, 2017). This is a new field. Because it translates mechanical inputs directly into electrical impulses without the need of extra transducers, the TENG offers a lot of promise in the area of active sensing and self-powered sensors. It requires simpler control circuit transistors and less standby power than conventional passive. Haptic touch sensors, acoustic sensors, motion and acceleration sensors (Zhang et al., 2017), and chemical sensors (Li Z. et al., 2015; Wen et al., 2015) are examples of related ground-breaking work.

A cochlear implant is a piece of electronic equipment that transforms external sound into electrical impulses. It repairs, enhances, and rebuilds deaf people's hearing function. Cochlear implants have advanced fast in the last two decades, thanks to advances in high technology, going from experimental research to clinical use. Cochlear implants are being utilised as a standard therapy for severe to complete deafness all around the globe. The cochlear implant is the most successful biomedical engineering device in use today. The demand for adaptable, efficient, and self-powered cochlear implants is still pressing. As shown in **Figure 7A**, Jiaqi Zheng et al. proposed a cochlear implant based on the piezoelectric-triboelectric effect made of BTO and PVDF (Zheng et al., 2021). By dispersing the BTO nano powder in PVDF, a shell-core structure is formed that enhances the piezoelectric and triboelectric response. The device can produce an open circuit voltage of 15.24 V and a maximum short circuit of 9.22 mA/m². With the improvement of living standard, people pay more and more attention to their health condition. Green, healthy life concept is deeply rooted. It is important for timely monitoring of health conditions. However, the majority of existing health monitoring devices are battery-powered and need periodic battery change, which is inconvenient. Therefore, it is particularly important to develop self-driven wearable sensors that can be used for medical health detection. As shown in **Figure 7C**, Kijoo Eom et al. demonstrated that PVDF-TrFE prepared on chitin film has a high degree of orientation and excellent stability beyond expectations (Eom et al., 2020). Triboelectric generators made by this method have superior performance and can detect fine pressure. They applied this device to detect the human pulse.

The skin is an organ that is wrapped on the body's surface, in direct touch with the external environment, and has the job of protection, excretion, body temperature management, and sensing external stimuli. It is the biggest organ in the human body. Artificial electronic skin offers a broad variety of potential applications, including prosthetic limbs, robotics, mobile phones and computers touch screens, car steering wheels, medicine, and so on (Ma et al., 2017; Dolbashi et al., 2018; Rahman et al., 2020). As shown in **Figure 8A**, Yu Rim Lee et al. developed a sensitive artificial electronic skin inspired by Merkel cells (Lee et al., 2020). This electronic skin consists of lead-free ferroelectric material barium titanate



powder and organic polymer. As shown in **Figure 8B**, When the finger touches and leaves the device, rising and falling currents are generated, thus enabling the perception of the sense of touch. As shown in **Figure 8C**, Trilochan Bhatta et al. proposed a compressible S-PVDF composite film prepared by electrostatic spinning method for electronic skin, with a power density of 13.25 W/m^2 (Bhatta et al., 2022). As shown in **Figure 8D**, the 2×2 array made by this electronic skin can recognize different users, due to the individual differences of each person, different signal sizes are generated, the recognition accuracy rate reaches 98%. These works demonstrate the superiority and great promise of flexible ferroelectric materials in the field of self-driven artificial electronic skin. Hyeon Jun Sim et al. reported a stretchable fiber with ultra-high stability for triboelectric generators that can be stretched more than 10,000 times (Sim et al., 2016). A sensing system that is not disturbed by the surrounding environment is a key factor in achieving human-machine

interaction (HMI) (Hoc, 2000). Jonghwa Park et al. proposed a sound-tactile sensor for dual-mode human-computer interaction (Park et al., 2022). The sensor is based on the triboelectric electric effect and is made of BTO nanopowder and PVDF with high sensitivity and linearity. In the presence of ambient noise interference, the sensor achieves a speech recognition reliability of 95%. They also utilized the sensor to create a smart glove that recognizes and distinguishes the texture of materials. Acceleration sensors are essential components in vibration monitoring and are used in a variety of applications including global positioning systems, biomedical devices, smart electronics, automobile safety, mechanical equipment vibration monitoring, monitoring for earthquakes, and troubleshooting (Gao and Zhang, 2010; Pang et al., 2015). In general, acceleration sensors are divided into three types: capacitive, piezoelectric, and piezoresistive. (Sobocinski et al., 2014). The piezoelectric sensors is self-powered, but its electrical output is quite modest and

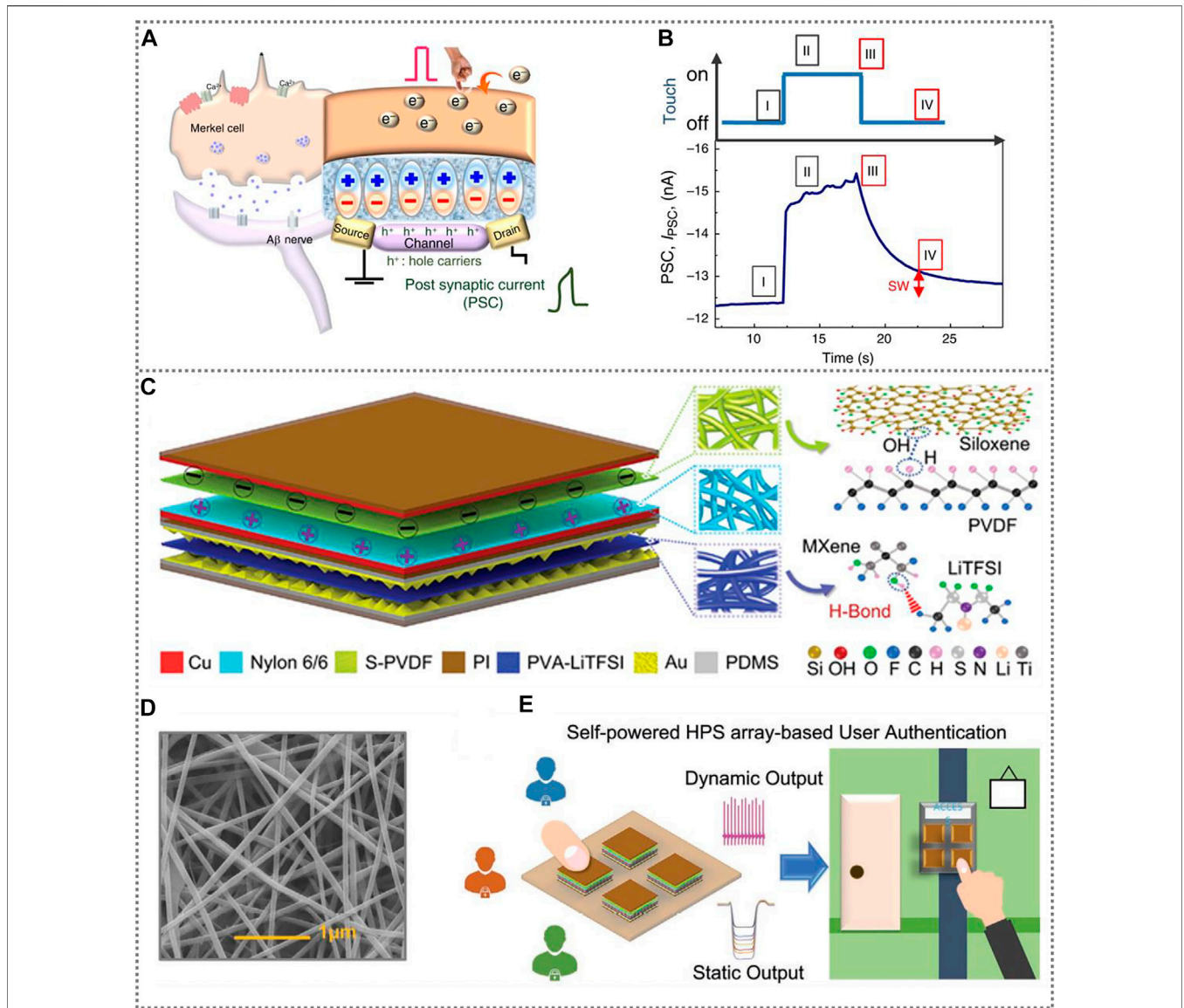


FIGURE 8 | (A) Schematic diagram of the device structure corresponding to human cells. **(B)** PSC during a tactile stimulus. Reproduced under the terms of a Creative Commons CC-BY license (Lee et al., 2020). Copyright 2020, Springer Nature. **(C)** Schematic illustration of the device structure. **(D)** SEM of S-PVDF. **(E)** By merging dual functionality, the SP-HPS array-based user authentication platform for highly protected electronic access systems is created (simultaneous sensing of static and dynamic input features of the user). Reproduced with permission (Bhatta et al., 2022). Copyright 2022, Wiley-VCH.

susceptible to external noise (Shen et al., 2016). Furthermore, capacitive and piezoresistive accelerometers are primarily fueled by traditional power supply units, limiting their possible uses (Roy et al., 2014). As a result, manufacturing acceleration sensors with big output signals and simultaneous self-powered capabilities is desirable. Binbin Zhang et al. demonstrated a self-driven acceleration sensor made of liquid mercury and PVDF nanofibers (Zhang et al., 2017). The sensor has ultra-high stability, and excellent sensitivity. The acceleration sensor detects accelerations ranging from 0 to 60 m/s² and has an excellent sensitivity of 0.26 V·s/m². These works demonstrate the great potential of flexible ferroelectric materials for self-driven sensing systems.

CONCLUSION

In this paper, we demonstrate that flexible ferroelectric materials have a lot of promise in the area of triboelectric generators. The polarization-regulated triboelectric electric output is a distinct benefit of ferroelectric materials over other materials. However, if we want to make flexible ferroelectric materials for further applications in triboelectric electricity, there are still many areas that need to be enhanced. For example, the dielectric constant is relatively low, the polarization strength is substantially lower than in inorganic ceramic ferroelectric materials, and wear resistance and stretchability may still be improved. Therefore, we expect that this work will pique the attention of relevant researchers and encourage the study and

development of flexible ferroelectric materials as well as the creation of novel applications.

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript by discussion of the results. HD and YY wrote this article.

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