#### REVIEW



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## **Recent progress of triboelectric nanogenerators: From** fundamental theory to practical applications

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#### Abstract

For the development of the internet of things (IoTs), big data, and artificial intelligence, widely distributed sensing network is the most essential element, which has to be driven by the energy storage unit, with a limited lifetime and environmental concerns. Given that the wide distribution and high mobility of these numerous sensors, the success of the IoTs and sustainable development of human society call for renewable distributed energy sources. Since triboelectrification effect is ubiquitous and universal in our living environment, the triboelectric nanogenerator (TENG) for mechanical energy harvesting and self-powered sensing developed by Wang and co-workers is one of the best choices for this energy for the new era. In this review, the recent progress of TENGs from fundamental theory to practical applications is systematically summarized. First, the mechanism of contact electrification, first principle theory, working principle, working modes, and figure of merits of the TENG are introduced. Furthermore, recent important progress in four major TENG applications, including micro/nano power sources, active self-powered sensors, large-scale blue energy, and direct high-voltage power sources are reviewed. In the end, some perspectives and challenges for the future development of TENG are also discussed.

#### **KEYWORDS**

blue energy, contact electrification, energy harvesting, self-powered, triboelectric nanogenerators

#### 1 INTRODUCTION

As an ancient and ubiquitous phenomenon, triboelectric effect has been known since more than 2600 years ago during ancient Greek civilization, and it exists at anytime and anywhere in our daily life. However, this universal phenomenon has long been considered an adverse effect that needed to be avoided in people's production and life. In 2012, triboelectric nanogenerator (TENG, also called Wang generator) was first invented as a powerful energy harvesting and self-powered sensing technology.<sup>1</sup> Based on the coupling effect of contact electrification (CE) and electrostatic induction, TENG is capable of converting irregular, distributed, and wasted mechanical energy into

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electric power, and it has lots of merits including low cost, simple structure, lightweight, high efficiency, and diverse material options.<sup>2-6</sup>

With the rapid development of internet of things (IoTs),<sup>7,8</sup> portable electronics,<sup>9-11</sup> and sensor networks,<sup>12,13</sup> the demand for sustainable, renewable, and eco-friendly energy is becoming increasingly important. Compared with other forms of renewable energy, mechanical energy would be the most widely distributed form in the environment and is almost independent of the working environment and weather conditions. Since first reported in 2012, the TENG has shown its powerful ability for harvesting ambient mechanical energy, with

an areal output power density reaching 500 W/m<sup>2</sup>.<sup>14</sup> With versatile operation modes, the TENG can be applied to a wide range of situations and harvest various kinds of mechanical energy for realizing the self-powered electronics networks on a large scale. So far, the applications of the TENG have infiltrated into many aspects of our daily life and can be categorized into four major areas, including micro/nano power sources, self-powered sensors, blue energy, and direct high-voltage (HV) power sources (Figure 1). Considering the huge number of small electronic devices required for IoTs, the existing high replacement costs and environmental concerns of using the battery, TENG will potentially serve as a promising



**FIGURE 1** A summary of the four major application fields of TENGs as micro/nano power sources, active self-powered sensors, blue energy, and direct high-voltage power sources. Wearable electronics: Reproduced with permission.<sup>15</sup> Copyright 2020, The American Association for the Advancement of Science. Implantable device: Reproduced with permission.<sup>16</sup> Copyright 2014, Wiley-VCH. Self-charging power cell: Reproduced with permission.<sup>17</sup> Copyright 2015, Springer Nature. Self-powered system: Reproduced with permission.<sup>18</sup> Copyright 2015, Nature Publishing Group. Robotics: Reproduced with permission.<sup>19</sup> Copyright 2020, Wiley-VCH. Intelligent sports: Reproduced with permission.<sup>20</sup> Copyright 2019, Nature Publishing Group. Health monitoring: Reproduced with permission.<sup>21</sup> Copyright 2015, Wiley-VCH. Security: Reproduced with permission.<sup>22</sup> Copyright 2015, American Chemical Society. Micromotor: Reproduced with permission.<sup>23</sup> Copyright 2019, Nature Publishing Group. Microplasma: Reproduced with permission.<sup>24</sup> Copyright 2018, Nature Publishing Group. Electrospinning: Reproduced with permission.<sup>25</sup> Copyright 2017, American Chemical Society. Air-filtering: Reproduced with permission.<sup>26</sup> Copyright 2015, American Chemical Society. Air-filtering: Reproduced with permission.<sup>26</sup> Copyright 2015, American Chemical Society. Air-filtering: Reproduced with permission.<sup>26</sup> Copyright 2015, American Chemical Society. Fully enclosed TENG: Reproduced with permission.<sup>27</sup> Copyright 2020, Wiley-VCH. Liquid-solid contact electrification TENG: Reproduced with permission.<sup>28</sup> Copyright 2014, American Chemical Society. Hybrid nanogenerator: Reproduced with permission.<sup>29</sup> Copyright 2016, American Chemical Society. TENG network: Reproduced with permission.<sup>30</sup> Copyright 2019, Elsevier B.V

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alternative energy source and thus has been proposed as "the energy for the new era."<sup>31</sup>

Benefit from its superior performance and tremendous potential, the research field of TENG has been developed very rapidly and attracted extensive attention on an international scale.<sup>32-39</sup> According to the literature survey, there are over 56 countries and regions, 830 units, and more than 4700 scientists engaged in TENG research (as of July 2020). Furthermore, an exponential increase is shown in both the number of published articles and citations in the TENG field (Figure 2). These statistics indicate that TENG research is in the stage of vigorous development. The motivation of this review is to summarize the latest development of TENGs and provide a guideline for future research. Herein, the basic knowledge and fundamental theory of TENG are first discussed, including the mechanism of contact electrification, first principle theory, working principle, working modes, and figure of merits. Subsequently, recent critical progress in four major application fields of TENG is also introduced. Finally, based on the road map of TENG research, some remaining challenges and open opportunities for the future development of TENG are discussed.

# 2 | FUNDAMENTAL THEORY OF TENGs

The study of basic theory lays an essential foundation for the establishment of a discipline. In the recent 2 years, some significant breakthroughs in the fundamental physics of the TENG have been achieved. This section will systematically discuss the latest advances in fundamental theory and basic knowledge of the TENG.



**FIGURE 2** A literature survey in the field of TENG from the SCI database by July 15, 2019. A, TENG research conducted by universities and research institutes globally. B, The number of TENG research articles published each year. C, The number of citations on TENG research articles each year

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# 2.1 | Mechanism of contact electrification

Although triboelectrification (TF) has been known for over 2600 years, it is debatable whether CE is the result of ion transfer, electron transfer, or materials species transfer. CE is a common physical phenomenon and occurs between all phases, including solid-solid, solid-liquid, liquid-liquid, liquid-gas, gas-gas, and gas-solid. Studying the fundamental mechanism of CE will play a significant part in the development of physics, chemistry, and biology.

Recently, Wang and co-workers found that is the dominant mechanism for CE between solid-solid cases is electron transfer.<sup>40</sup> CE between dielectric and metal could be well described by using the surface states model and Fermi level model for dielectric and metal, respectively. If the distance of two materials is larger than the bonding length, the two atoms tend to attract each other (Figure 3A). It was experimentally found that CE will occur only if the interatomic distance is shorter than the

bonding length, in the repulsive force region in the interaction potential of two atoms, as shown in Figure 3B. To explain the electron transition for a general case, the overlapped electron cloud model was innovatively proposed.<sup>42</sup> Figure 3C shows the electron clouds of two materials remain separated prior to their atomic-scale contact. When the two atoms get close to and contact with each other, a strong electron cloud overlap between two atoms under stress leads to a lowered potential barrier, subsequently allowing electron transition between these two atoms (Figure 3D). Mechanical pressure is required to shorten the interatomic distance and maximize the overlap of the electron cloud. Such a model is regarded as the universal model for understanding CE between any two materials, which could be extended to other cases of CE. For simplicity of referring and description, this electron transition model is named as the Wang transition for CE. Additionally, it is expected that photon emission exists in this process, which remains to be experimentally verified.



FIGURE 3 The overlapped electron-cloud model proposed for explaining CE and charge transfer between two atoms for a general case. A,B, Interatomic interaction potential between two atoms when the force between the two is attractive and repulsive, respectively. C,D, Schematic of the electron cloud and potential energy well model of two atoms belonging to two materials A and B when they are separated and in close contact, respectively. Electron transition from atom A to atom B is possible due to the lowered potential barrier by the external force, resulting in the occurrence of CE. Reproduced with permission.<sup>41</sup> Copyright 2020, Wiley-VCH

CE between solid-liquid is the formation of the electric double layer (EDL). Wang recently proposed that the EDL formation consists of two steps, which is also called the Wang model for EDL. The first step is an electron exchange process between solid and liquid surfaces, and the second step is the interaction between different ions in the liquid. Thus, the traditional model could be modified by adding the first step, which makes the atoms on the solid surface to be ions. In practice, recent experiments have verified that ion adsorption and electron exchange simultaneously occur and coexist in the solidliquid interaction.<sup>43,44</sup> Such a revision may influence some related understanding about the cellular-level interactions electrochemistry, and interface chemistry.

#### 2.2 | The first principle theory of TENGs

As the theoretical origin of the TENG, Maxwell's displacement current is caused by the time variation of the electric field plus a media polarization term. Concerning power generation, the polarization should contain a term contributed by the strain field such as CE and piezoelectric effect. To explain the contribution made by the CEinduced electrostatic charges in Maxwell's equations, an additional term  $P_{\rm S}$  was added in displacement vector *D* by Wang in 2017.<sup>45</sup> that is

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} + \boldsymbol{P}_{\mathrm{S}} \tag{1}$$

Here, the first-term polarization vector P is attributed to the existent external electric field, and the added term  $P_S$  is primarily associated with the existent surface charges, which are independent of the electric field. Substituting Equation (1) into Maxwell's equations, and define

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

Then, Maxwell's equations can be reformulated as follows:

$$\nabla \cdot \boldsymbol{D}' = \rho' \tag{3}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{4}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{5}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}' + \frac{\partial \boldsymbol{D}'}{\partial t} \tag{6}$$

where the density of volume charge and the current density could be redefined as

$$\rho' = \rho - \nabla \cdot \boldsymbol{P}_{\mathrm{S}} \tag{7}$$

$$\boldsymbol{J}' = \boldsymbol{J} + \nabla \cdot \frac{\partial \boldsymbol{P}_{\mathrm{S}}}{\partial t} \tag{8}$$

From Equations (1) and (2), the newly Maxwell's displacement current can be revised as:

$$\boldsymbol{J}_{\mathrm{D}} = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_{\mathrm{S}}}{\partial t}$$
(9)

Here, the first term  $\varepsilon \frac{\partial E}{\partial t}$  is the displacement current due to the time varying electric field and its induced medium polarization. It gives the birth of electromagnetic wave theory and causes the emergence of wireless communication, radar, antenna, TV, radio, microwave, telegram, and space technology. While the second term  $\frac{\partial P_s}{\partial t}$ , which is referred to as Wang term, represents the displacement current due to the nonelectric field but owing to the external strain field. It leads to the invention of nanogenerators, which are named as the energy for the new era-the era of internet of things, big data, and artificial intelligence. The primary fundamental science, practical impacts, and technologies derived from these two components of Maxwell's displacement current are presented in Figure 4.46 This "tree" idea is expected to grow larger, stronger, and taller for the foreseeable future, and may lead to great technological breakthroughs for human society.

#### 2.3 | Working principle of TENGs

Although triboelectric effect has been documented for thousands of years, it is usually considered as a negative effect in industrial applications because its induced electrostatic charges could cause dust explosions, ignition, electronic damage, dielectric breakdown, and so on. In 2012, this effect was first applied for developing the TENG as a new mechanical energy harvesting technology. Based on the coupling effect of CE and electrostatic induction, TENG was first invented by Wang and coworkers to effectively harvest ambient mechanical energy, which is widespread but generally wasted in our daily life. Figure 5 illustrates the detailed working principle of the TENG, using contact-separation mode TENG as an example. In the original state, no charge is generated or inducted (Figure 5 I). When the surfaces of two different materials are brought into physical contact, triboelectric charges on the two contacted surfaces will be created (Figure 5 II). Then a potential difference can be established once the two contacted surfaces are separated, resulting in an instantaneous electron flow from

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**FIGURE 4** A tree idea illustrating the revised Maxwell's displacement current: the first term  $\varepsilon \frac{\partial E}{\partial t}$  is responsible for the electromagnetic waves theory; and the newly added term  $\frac{\partial P_s}{\partial t}$  is the energy and sensing applications about nanogenerators derived from Maxwell's equations. Reproduced with permission.<sup>46</sup> Copyright 2020, Elsevier B.V

bottom electrode to top electrode (Figure 5 III), finally reaching equilibrium when the two surfaces are fully separated (Figure 5 IV). Once the two surfaces are pressed again, the electrostatic induced charges will flow back through the external load to compensate for the electric potential difference (Figure 5 V). In this whole working cycle, the generated current signal is shown in the top right corner of Figure 5.

#### 2.4 | Four working modes of TENGs

Since its first report in 2012, TENG's output power density has been reported to be up to 500 W/m<sup>2</sup>, and the instantaneous energy conversion efficiency of about 70% has been demonstrated.<sup>47</sup> Depending on the direction of the polarization change and electrode configuration, four basic working modes of the TENG have been proposed, including vertical contact-separation (CS) mode, lateral sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode, as shown in Figure 6.<sup>48</sup> As the most basic structure, the vertical CS mode utilizes the relative movement perpendicular to the interface. During the contact-separation process, the potential changes between the two electrodes, and an external current flow will then be created for balancing the potential difference. The LS mode utilizes the relative displacement parallel to the contact interface, and the potential changes between the two electrodes, and thus electrical output is generated through the external circuit. This mode can also be implemented by employing the rotation-induced sliding. The SE mode is invented for harnessing mechanical energy from the moving object without using a conduction line, with the ground serving as the reference electrode. The FT mode is designed upon the SE mode, but using two pair of symmetric electrodes. When the position of a freely moving object changes, electrical output will be produced from the asymmetric charge distribution. Moreover, the theoretical models of these four fundamental working modes have also been extensively studied.<sup>49</sup> It is worth noting that the TENG is not limited to one single mode in practical applications, and different modes are usually combined to make full use of their advantages.

#### 2.5 | Figure of merits of TENGs

With the development of four fundamental working modes and applicable materials of TENGs, a common



FIGURE 6 The four fundamental working modes of TENGs. A, Vertical contact-separation mode. B, Linear sliding mode. C, Singleelectrode mode. D, Freestanding triboelectric-layer mode

standard for comparing and evaluating the output performance of TENGs is urgently required. In 2015, Zi et al proposed a performance figure of merit (FOM<sub>P</sub>) for quantifying the output performance of TENGs, which is composed of a structural figure of merit (FOM<sub>s</sub>) and a material figure of merit  $(FOM_M)$ .<sup>50</sup> Just like the Carnot efficiency for engines, ZT factor for thermoelectric materials, and energy-conversion efficiency for solar cells, the

 $\mathrm{FOM}_{\mathrm{P}}$  can be used for characterizing the performance of a TENG.

The authors first investigate the output characteristic of the LS mode TENG (Figure 7A) and found the energy output of the TENG can be represented by the plot of built-up voltage V against the transferred charges Q. From the encircled area of the V-Q curve, the output energy per cycle can be calculated. As shown in Figure 7B, by employing instantaneous short-circuit conditions during TENG operation using a switch in parallel with the external load, cycles for maximized energy output (CMEO) are proposed. During step 1 and step 3, the switch is turn off, while the triboelectric layers displace from x = 0 to  $x = x_{max}$ , and vice versa. Then the switch is turn on during step 2 and step 4 to enable Q to reach the maximum transferred charges Q<sub>SC.max</sub> and 0. From the CEMOs for different load resistances, it can be noticed that the maximized output energy  $E_{\rm m}$  can be realized at  $R = +\infty$ . Thus, the  $E_{\rm m}$  can be calculated as:

$$E_{\rm m} = \frac{1}{2} Q_{\rm SC,max} \left( V_{\rm OC,max} + V'_{\rm max} \right) \tag{10}$$

Considering that the average output power and energy-conversion efficiency at the CMEO are proportional to  $E_{\rm m}/Ax_{\rm max}$ , a structural FOM is proposed as:

$$FOM_{S} = \frac{2\varepsilon_{0}}{\sigma^{2}} \frac{E_{m}}{Ax_{max}}$$
(11)

where  $\varepsilon_0$  is the permittivity of vacuum and *A* is the TF area of the TENG. And then the performance FOM can be defined as:

$$FOM_{P} = FOM_{S} \cdot \sigma^{2} = 2\varepsilon_{0} \frac{E_{m}}{Ax_{max}}$$
(12)

where  $\sigma^2$  can be defined as the FOM<sub>M</sub>, which is the only component related to the material properties.

For quantifying the triboelectric performance of various polymers, Zou et al developed a standard method for evaluating their triboelectric charge densities (TECDs).<sup>51</sup> To ensure sufficient surface contact with the tested materials, liquid metal was used as the reference material, which is shape adaptable and soft. Through accurately measuring the TECD in a glove box under well-defined conditions, a quantitative triboelectric series for over 50 polymers were constructed. Subsequently, a quantified triboelectric series for a broad variety of inorganic nonmetallic materials was also measured.<sup>52</sup> These quantitative triboelectric series can reveal the intrinsic physical property of general materials for gaining or losing electrons and may serve as a textbook standard for scientific



**FIGURE 7** Figure of merits for TENGs. A, Schematic illustration of the LS mode TENG. B, The CMEO of the TENG with a load resistance of 100 M $\Omega$ . C, The CMEO of the TENG with different load resistances. A-C, Reproduced with permission.<sup>50</sup> Copyright 2015, Nature Publishing Group. D, The *V-Q* plot showing the negative part as the breakdown area and the positive part as the nonbreakdown area. E, Circuit of the universal method for assessing the effective output capability of TENGs. F, The CMEO with the breakdown curve compared with the theoretical curve based on Paschen's law. D-F, Reproduced with permission.<sup>51</sup> Copyright 2019, Nature Publishing Group

research and practical applications in energy harvesting and self-powered sensing.

Due to the high voltage output of the TENG, the breakdown effect will seriously affect its maximized effective energy output  $(E_{em})$  of the TENG. Xia et al proposed a standardized method considering the breakdown effect, and developed a revised FOM for assessing the output capability of the TENG.<sup>53</sup> Figure 7D shows the air breakdown exists in the CS mode TENG with a regular surface charge density of  $50 \,\mu\text{C/m}$ ,<sup>2</sup> indicating that about half area is unreachable due to the air breakdown. To accurately reveal the limited  $E_{\rm em}$  of all kinds of TENGs, a standardized assessment method was designed, with TENG1 being the target device and TENG2 being the power source (Figure 7E). As illustrated in Figure 7F, the measured  $E_{\rm em}$  is close to the theoretical calculation result from Paschen's law. To make the FOM more suitable for practical situations with the universally existed breakdown effect, FOM<sub>S</sub> and FOM<sub>P</sub> of the TENG can be redefined based on the  $E_{\rm em}$  as:

$$FOM_{S} = \frac{2\varepsilon_{0}}{\sigma^{2}} \frac{E_{em}}{Ax_{max}}$$
(13)

$$FOM_{P} = FOM_{S} \cdot \sigma^{2} = 2\varepsilon_{0} \frac{E_{em}}{Ax_{max}}$$
(14)

### 3 | RECENT PROGRESS OF TENG APPLICATIONS

Based on the four basic operation modes, the TENG could be used as a powerful technology for energy harvesting and self-powered sensing in a broad range of scenarios. The applications of the TENG can be divided into four major fields: micro/nano power sources for self-powered systems; active self-powered sensors for human-machine interfacing (HMI), infrastructures, medical, and environmental monitoring; basic network units for harvesting water wave energy toward large-scale blue energy; and direct power sources for HV applications. The most recent remarkable progress for TENGs in these areas will be discussed in this section.

#### 3.1 | Micro/nano power sources

Owning to its advantages such as high efficiency, low cost, lightweight, abundant structural, and material choices, the TENG has found vast applications as micro/ nano power source by harvesting various kinds of mechanical energy from the external environment, such

as human walking, vibration, heartbeats, wind, and so on.<sup>54-62</sup> Biomechanical energy is widespread but usually wasted in our daily life, and plenty of researches have been explored by using TENGs for harvesting this lowfrequency energy. Recently, Yi et al reported a shapeadaptive TENG consisting of an elastic polymer cover and a conductive liquid (Figure 8A).<sup>63</sup> Taking advantage of the unique deformability of the liquid electrode, and the excellent flexibility of the rubber cover, this stretchable TENG can be conformed to any curvilinear surface. As shown in Figure 8B, the shape-adaptive TENG can be mounted under the shoe to harvest the human walking energy. For harvesting the tapping energy, a bracelet-like shape-adaptive TENG was also fabricated and worn on the wrist (Figure 8C). Apart from in vitro energy harvesting, an implantable TENG (iTENG) was developed by Ouyang et al for in vivo biomechanical energy conversion.<sup>64</sup> By integrating with the power management and pacemaker unit, a self-powered symbiotic pacemaker (SPM) was constructed and achieved cardiac pacing in large animal scale successfully (Figure 8d). As shown in Figure 8E, the core-shell structured iTENG is composed of the supporting structure, two triboelectric layers, and the shell with two encapsulation layers. Thanks to the excellent in vivo output power of the iTENG, the harvested energy from each cycle reaches 0.495 µJ, which is higher than the pacing threshold energy of humans (0.377 µJ). Several other TENGs for harvesting in vitro or in vivo mechanical energy were also reported.69-76

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To improve the energy harvesting capability, TENGs can be integrated with other energy harvesting technologies, so that various kinds of environmental energy could be scavenged simultaneously.77-80 Chen et al developed a hybrid power textile which composed of a photovoltaic textile and fabric TENG, as illustrated in Figure 8F.<sup>65</sup> The hybrid textile can simultaneously harvest mechanical energy and solar energy, which hugely improved its output power and expanded its working circumstances. This hybrid textile was also successfully demonstrated to charge small electronics such as mobile phone and watch (Figure 8G). Due to its irregular alternating current output characteristic, TENGs cannot be directly used for driving most of the elecdevices. Consequently, TENG-based selftronic charging power systems have been developed by integrating TENGs with energy storage devices.<sup>81-84</sup> For instance, Pu et al designed a solid-state yarn supercapacitor (SC) using reduced graphene oxide as active materials, and a TENG fabric woven by Ni-coated and parylene-Ni-coated polyester straps (Figure 8H,i).<sup>66</sup> By integrating three yarn SCs with a TENG fabric, a wearable self-charging power textile was successfully fabricated (Figure 8J).

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**FIGURE 8** Applications of TENGs as micro/nano power sources. A, Schematic diagram and photograph of the shape-adaptive TENG. B, Photograph of the pedal-like shape-adaptive TENG sited under the shoe. C, Photographs showing 80 LEDs driven by the bracelet-like shape-adaptive TENG. A-C, Reproduced with permission.<sup>63</sup> Copyright 2016, The American Association for the Advancement of Science. D, Schematic diagram of the symbiotic cardiac pacemaker system. E, Structure diagram of the implantable TENG. D, E, Reproduced with permission.<sup>64</sup> Copyright 2019, Nature Publishing Group. F, Schematic diagram of fabric TENG (top) and photovoltaic textile (bottom). G, Demonstration of the hybrid power textile for driving small electronic devices. F,G, Reproduced with permission.<sup>65</sup> Copyright 2016, Nature Publishing Group. H,I, Schematic diagram of the all-solid-state yarn SC, H, and TENG cloth, I. J, Photograph of the self-charging power textile. H-J, Reproduced with permission.<sup>66</sup> Copyright 2016, Wiley-VCH. K, Schematic illustration of the whirligig-inspired TENG based self-powered glucose meter. K,L, Reproduced with permission.<sup>67</sup> Copyright 2018, Elsevier B.V. M, Construction of the dual-TENG and self-powered electrocatalytic ammonia synthesis system. Reproduced with permission.<sup>68</sup> Copyright 2020, RSC Publishing

Furthermore, TENGs can be used as portable energy sources, and many related self-powered systems have been demonstrated, such as health inspection,<sup>85</sup> water disinfection,<sup>86</sup> personal electronics,<sup>87,88</sup> electrochemical degradation, and synthesis.<sup>89,90</sup> Recently, Guo et al reported an ultralight whirligig-inspired TENG (Wi-TENG) for transforming low-frequency pulling motion into ultra-fast rotation (Figure 8K).<sup>67</sup> With advantages of lightweight and high output power, the Wi-TENG could be used as a reliable, sustainable, and portable power

source for driving a household blood glucose meter, as shown in Figure 8l. Han et al developed a self-powered electrocatalytic ammonia synthesis system operated by the dual TENG (Figure 8m).<sup>68</sup> Nitrogen was first fixed into  $NO_X$  by utilizing the TENG induced air discharge. Meanwhile, the generated  $NO_X$  was used for synthesizing ammonia in the electrochemical cell, with TiO<sub>2</sub> serving as the catalyst. Under a gas flow rate of 3.5 m<sup>3</sup>/min, the ammonia production of the self-powered system reaches 2.4 µg/h. Compared with traditional ammonia synthetic

methods, such a synthesis system possesses the merits of facile-fabrication, scalable, low-cost, and eco-friendly, demonstrating its great potential for self-powered ammonia synthesis.

#### 3.2 | Self-powered sensors

Since the TENG can directly convert mechanical stimuli into electrical signals without any additional transducers, it has outstanding potential for developing self-powered sensors without using external power sources, such as pressure sensors,<sup>91-93</sup> tactile sensors,<sup>94-96</sup> motion sensors,<sup>100-102</sup> sensors.97-99 acceleration chemical sensors,<sup>103-105</sup> acoustic sensors,<sup>106-108</sup> and photoelectric sensors.<sup>109,110</sup> Meanwhile, HMI is a field that utilizes various kinds of techniques to realize the interfaces between users and machines, and it has become increasingly important in a broad range of application domains, such as security, information communication, and healthcare. As an effective mechanical-to-electric signal transformation technology, TENGs have been successfully used for realizing many kinds of HMI.<sup>111-115</sup> For example, Pu et al developed a TENG-based HMI system that can translate



**FIGURE 9** Applications of TENGs as self-powered sensors. A, Schematic structures and photographs of the mechnosensational TENG. Reproduced with permission.<sup>116</sup> Copyright 2017, The American Association for the Advancement of Science. B, Schematic illustration of the natural wood-based intelligent table tennis table. C, Photograph of the self-powered falling point distribution statistical system. D, Screenshot demonstrating the statistical result of the self-powered system. B-D, Reproduced with permission.<sup>20</sup> Copyright 2019, Nature Publishing Group. E, Illustration of the self-powered underwater wireless motion monitoring system based on the bionic stretchable TENG. F, Output signals of the bionic stretchable TENG fixed on the elbow at various curvature motion. G, Photographs of integrated TENGs worn on the arthrosis of humans. E-G, Reproduced with permission.<sup>117</sup> Copyright 2019, Nature Publishing Group. H, Illustration of two all-textile TENGs integrated into a shirt for real-time monitoring the pulse and respiratory signals. I, Schematic diagram of the combination of TENG and clothes. J, Photograph showing the display of the all-textile TENG placed on the chest. K, Decomposition of the voltage signal for the all-textile TENG mounted on the chest into the heartbeat and the respiratory waveform. H-K, Reproduced with permission.<sup>118</sup> Copyright 2020, The American Association for the Advancement of Science

real-time eye blink micromotions into control commands.<sup>116</sup> The structure design and photographs of the fabricated mechanosensational TENG (msTENG) are shown in Figure 9A. This circular msTENG was designed in single-electrode mode with a multilayered structure, and it can be flexibly mounted on an eyeglass arm for monitoring the eye motions. By integrating the msTENG with a simple signal processing circuit and wireless transceiver module, a smart home control system and a hands-free typing system were successfully developed. With the growing concern about network security, the demand for effective authentication solutions is becoming more and more important. Using the behavioral biometric of keystroke dynamics, Chen et al first established a self-powered Authentication system based on the single-electrode contact separation mode TENG arrays.<sup>22</sup> Subsequently, to make it more applicable to versatile working environments, a two-factor, pressure-enhanced keystroke-dynamics-based security system was developed by Wu et al<sup>119</sup> It can be used for authenticating and identifying users through their characteristic typing behavior, with high accuracy of 98.7%. This system consists of a triboelectric keystroke device for collecting typing behavior reflected in keystroke dynamics, a signal processing program for extracting feature information, and a support vector machine software platform for user authentication. Its promising applications in the financial and computing industry may push the network security to a new level.

Considering that mechanical motions are ubiquitous in sports activities, TENGs have shown great potential in developing self-powered athletic sensing systems, including smart sports facility and wearable equipment.<sup>118,120-122</sup> As shown in Figure 9B, a flexible and durable wood-based TENG for fabricating a smart pingpong table was developed by Luo et al, which could directly convert the impactions between the ping-pong ball and the table surface into electrical signals.<sup>20</sup> By setting a TENG array on the table, a self-powered falling point distribution statistical system that could perform motion path tracking, velocity sensing, and distribution statistics was successfully realized (Figure 9C,D). Through precisely detecting and collecting the training data for big data analytics, scientifically training evaluation and guidance can be provided for athletes. Moreover, a self-powered edge ball judgement system was also designed for assisting referees' decision in real-time. This work not only expands the application domain of the self-powered system to intelligent sports training and monitoring, but also significantly promotes the development of big data analytics in the smart sports industry. With regard to wearable equipment, Zou et al reported a bionic stretchable TENG by mimics the structure of ion channels in an electric eel for constructing an underwater wireless human motion monitoring system (Figure 9E).<sup>117</sup> Figure 9F shows the relationship between the bending angle of the elbow and voltage output of the TENG fixed on a human's arm. Through wearing four stretchable TENGs on the knees and elbows, respectively, the real-time swimming motion signals can be acquired for sports training and safety (Figure 9G). Besides, Fan et al designed an all-textile TENG array that can be directly incorporated into various sites of the fabric for monitoring the physiological signals (Figure 9H).<sup>118</sup> Figure 9I shows the all-textile TENG stitched into a piece of cloth, which was knitted with nylon and conductive yarns using the full cardigan stitch. By stitching into an elastic strap, the TENG can be directly mounted on the chest for monitoring the respiration information, as shown in Figure 9J. After signal processing, the respiratory and heartbeat waveforms were obtained simultaneously and precisely (Figure 9K).

#### 3.3 | Blue energy

Widely distributed across the earth, water wave energy is one of the most important renewable and clean energy sources. However, it has not yet been well exploited on account of the technological limitations of the currently used electromagnetic generator (EMG). Compared with traditional EMG, the newly developed TENG exhibits distinct advantages in harvesting energy from irregular and low-frequency water wave motions.<sup>123,124</sup> By integrating many of TENG units into a network, large-scale water wave energy harvesting can be realized, that is blue energy.<sup>31,125</sup> In order to effectively collect the water wave energy, TENGs with various structure design have been proposed, including spring-based structure,<sup>126</sup> wavystructure,<sup>127,128</sup> duck-shaped structure,<sup>129</sup> electrode rolling spherical structure,130,131 and air-driven membrane structure,<sup>132</sup> swing structure.<sup>27,133</sup> Spring-based structure is capable of transforming instantaneous mechanical impact energy into elastic potential energy, so that low-frequency output power of the TENG can be improved. Jiang et al designed a spring-assisted TENG for harvesting water wave energy, which is composed of two spring-connected acrylic blocks and an acrylic box (Figure 10A).<sup>134</sup> The influences of spring rigidity, motor acceleration, and spring length were systematically investigated. Under optimized conditions, the voltage and current output of the TENGs with or without spring are compared in Figure 10B,C. It can be noted that the accumulated charge was improved from about 351.03 nC to 747 nC (by 113.0%), and more current peaks could be observed when using the spring structure. The calculated



FIGURE 10 Applications of TENGs in blue energy harvesting. A, Schematic illustration of the spring-assisted TENG. B,C, Comparison of the accumulated charge (B) and output current (C) for the TENGs with and without spring. A-C, Reproduced with permission.<sup>134</sup> Copyright 2017, Elsevier B.V. D.E. Schematic structure (D) and photograph (E) of the encapsulated 3D electrode structured TENG. F. Schematic diagram of a TENG network agitated by water waves. G, Photograph showing the self-assembled TENG network in water. H, Photograph of 300 LEDs lighted by the TENG network. D-H, Reproduced with permission.<sup>30</sup> Copyright 2019, Elsevier B.V. I) Schematic illustration of the spherical multilayered TENG floating on the surface of ocean water. J) Framework for the self-powered marine information monitoring system driven by the power-managed TENG. I,J, Reproduced with permission.<sup>135</sup> Copyright 2020, RSC Publishing, K, Structural design of the pendulum inspired TENG, L, Schematics of the operation mechanism of the pendulum inspired TENG. M, Output voltage of the proposed pendulum inspired TENG for an external mechanical excitation. K-M, Reproduced with permission.<sup>136</sup> Copyright 2019, Elsevier B.V

electric energy per cycle can also be improved by up to 150.3%. This work provides an effective strategy for enhancing the efficiency and output power of TENG in water wave energy harvesting. Since the rolling spherical

PTFE Cotton thread

iv

Acrylic

Copper

structure can harvest energy from all directions, it is considered as the most promising for blue energy harvesting. An encapsulated 3D electrode structured TENG was designed by Yang et al.<sup>30</sup> The structure and photograph

0

ò

20 40 60 80

Time (s)

100

120

13

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of a single TENG unit are presented in Figure 10D,E. A group of electrode plates is connected together to form the 3D electrodes and sealed by a spherical shell, and FEP pellets are inserted into the inner channels of the ball as triboelectric material. The average power density of the TENG unit reaches up  $8.69 \text{ W/m}^3$ , which is over 18 times of the reported rolling spherical structured devices. Based on the capsulated high-performance units, a macroscopic self-assembly TENG network was further proposed, which is realized using a self-adaptive magnetic joint (Figure 10F,G). As a demonstration, the TENG network containing 18 units can easily light up hundreds of LEDs when agitated by the water waves.

For practical applications, the energy conversion efficiency and mechanical durability of TENGs still need to be further improved. Power management module (PMM) has been proved as an effective strategy to maximize the energy transfer of the TENG, and some relevant works for blue energy harvesting have also been reported.<sup>137,138</sup> Recently, Liang et al designed a spherical TENG based on the spring-assisted multilayered structure for collecting water wave energy in multiple directions, and a PMM was integrated for output energy management (Figure 10).<sup>135</sup> Compared with direct charging by the TENG, the charging speed for an SC can be hugely improved by 100 times when integrating with a PMM. As application demonstrations, a water level detection/alarm system and a water thermometer were successfully powered by the TENG (Figure 10J). Moreover, through the PMM, the irregular and random electrical output of the TENG can be converted into a steady direct current (DC) voltage, which could better meet the voltage demands of electronic devices. To enhance the durability of the TENG, a pendulum inspired TENG (P-TENG) was designed by Lin et al, which could not only improve the output frequency but also boost the energy harvesting efficiency through converting the impact kinetic energy into potential energy.<sup>136</sup> Figure 10K shows the structural diagram of the P-TENG, consisting of a pendulum triboelectric layer, an electrode layer, and thin stripes. The fundamental working principle of the P-TENG is schematically depicted in Figure 10l. Benefit from the pendulum structural design, the P-TENG can work without any frictional resistance at the free-standing mode, which is contributed to the excellent device durability and robustness. As illustrated in Figure 10M, when the pendulum triboelectric layer swings forth and back, the voltage output of the P-TENG can last more than 120 seconds, indicating its outstanding frequency-multiplied performance. A P-TENGs network was also successfully adopted to harvest water wave energy for driving electronics. Subsequently, Jiang et al reported a robust swing-structured TENG for efficient blue energy harvesting.<sup>27</sup> An air gap

between the triboelectric layers and electrodes, and flexible insulative brushes were employed to reduce the frictional resistance and maintain surface charges, thereby improving the durability and stability of the TENG. Under one triggering, a swing time of 88 seconds can be achieved by the TENG device, and its transferred charge remains nearly unchanged after 400 000 cycles. These novel designs will provide a new insight for the development of TENGs toward practical applications in blue energy.

#### 3.4 | High-voltage power sources

Given that the output characteristics of low current and high voltage, the TENG can be directly used as highvoltage power sources. The open-circuit voltage from the TENG can easily reach several kilovolts, which could be used to effectively control or drive some electrically responsive materials or devices, such as dielectric elastomers,<sup>139,140</sup> ferroelectric materials,<sup>141,142</sup> piezoelectric materials,<sup>143</sup> electrostatic air cleaners,<sup>144,145</sup> electrostatic manipulators,146,147 and field emitters.148 Compared with traditional HV power sources, TENG-based HV power sources only output a small current and usually do not require sophisticated power converters, making them have various unique advantages including safety, portability, simple structure, and cost-effectiveness. By combining a planar sliding TENG and piezoelectric ceramics, an active piezoelectric micro-actuator for two-dimensional (2D) optical direction modulation was designed by Zhang et al (Figure 11A).<sup>143</sup> Driven by the dual-channel output voltages of the TENG, the two micro-actuators were orthogonally positioned, and the optical direction can be modulated by the mechanical energy. In addition, the high output voltage of the TENG was utilized to generate nanoelectrospray ionization (nanoESI) for highly sensitive analysis.149 spectrometric As presented in mass Figure 11B, the sliding freestanding TENG (SF-TENG) was used to produce alternating-polarity charge pulses, which were supplied to the nanoESI. Figure 11C shows the photograph of an electrospray plume induced by the TENG charge flow. The frequency, duration, and polarity of generated ion pulses were all controllable via the TENG actuation, and the TENG high output voltage provided nanoESI with higher sensitivity at low concentrations, as verified by the signature fragment ion  $(m/z \ 182.118)$  only detectable in the TENG-driven nanoESI mass spectrometry when analyzing a 10 pg/mL cocaine solution (Figure 11D). Recently, Bai et al developed a multilayered washable triboelectric air filter (TAF) which is composed of nylon fabrics and PTFE fabrics.<sup>150</sup> Figure 11E shows the schematic diagram of the measuring setup for determining



FIGURE 11 Applications of TENGs as direct high-voltage power sources. A, Schematic diagram of a 2D direction modulator driven by the TENG. Reproduced with permission.<sup>143</sup> Copyright 2015, Wiley-VCH. B, Scheme of the ionization charges generation mechanism with sliding freestanding mode TENG. C, Dark-field image showing the TENG charge flow-induced electrospray plume. D, Signature fragment ion (m/z 182.118) can only be observed by the SF-TENG when analyzing a 10 pg/mL cocaine solution in nanoESI mass spectrometry. B-D, Reproduced with permission.<sup>149</sup> Copyright 2017, Nature Publishing Group, E, Schematic illustration of the setup for the measurement PM removal efficiency. F, Schematic diagram of the filtration mechanism of the charged triboelectric air filter. E,F, Reproduced with permission.<sup>150</sup> Copyright 2018, Wiley-VCH. G, Schematic diagram and photograph of the triboelectric plasma. H, A luminescence photograph showing a patterned electrode driven by the TENG. I, A plasma disk powered by freestanding rotary TENGs. G-I, Reproduced with permission.<sup>24</sup> Copyright 2018, Nature Publishing Group. J, Structure diagram of the self-powered electroadhesion system. K, Photographs of the self-powered electroadhesion system handling various objects. J,K, Reproduced with permission.<sup>151</sup> Copyright 2018, American Chemical Society. L, Structural design of the sustainable high-voltage TENG with a charge accumulation strategy. Reproduced with permission.<sup>152</sup> Copyright 2020, RSC Publishing

the PM removal efficiency of the TAF. This TAF can be easily charged by rubbing the nylon and PTFE fabrics against each other, and its filtration mechanism is illustrated in Figure 11F. After charging, the TAF realized a removal efficiency of 84.7 and 96.0% for PM<sub>0.5</sub> and PM<sub>2.5</sub>, demonstrating the great potential of TENG-based air cleaning.

By integrating with the voltage boosting circuits, the voltage output of TENGs can be further improved, which is capable of driving many other HV applications such as microplasma,<sup>24</sup> electrospinning,<sup>26,153</sup> and electroadhesion.<sup>151</sup> Recently, a concept of triboelectric microplasma by combining TENGs with plasma source was proposed by Cheng et al, and atmospheric-pressure plasma driven by mechanical stimuli was successfully achieved (Figure 11G).<sup>24</sup> When directly powered by the TENG, both filamentary discharge and arc discharge can be observed, as demonstrated in Figure 11H. To prove its

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system feasibility, the triboelectric microplasma has also been applied to surface treatment and patterned luminescence. For example, a plasma disk can be successfully powered by the TENG, and photographs with different exposure time are shown in Figure 11I. This work is believed to enrich the diversity of plasma applications by offering a portable and facile supplement to traditional plasma sources. By introducing a triboelectric charge supplement channel (CSC), Xu et al boosted the output voltage of the CS mode TENG by over 10 times (Figure 11J).<sup>151</sup> Such CSC takes effect through a replenishing mechanism for dissipated charges, maintaining the optimal charge distribution throughout TENG electrodes, which enables the highest output voltage under given device configuration and surface charge density. Based on this boosted voltage, a self-powered electroadhesion system was constructed and used for manipulating various kinds of objects (Al plate, silicon wafer, glass, and metal block) via straightforward and easy operations, as shown in Figure 11K. Additionally, Lei et al proposed a sustainable high-voltage TENG (SH-TENG) with a charge accumulation strategy (Figure 111).<sup>152</sup> With a sustainable voltage output of over 20 kV, the SH-TENG can trigger continuous dielectrophoresis and electrophoresis effects in oil, and realize a self-powered oil purification system, which could satisfy the global needs of environmental protection and energy conservation.

### 4 | SUMMARYAND PERSPECTIVES

In this review, we have systematically summarized the recent progress of TENGs, from its fundamental theory to practical applications. The basic knowledge and fundamental theory of TENG are first discussed, which mainly include mechanism of contact electrification, first principle theory, working principle, working modes, and figure of merits. Then, the major application fields of TENG are also discussed. First, with the ability to harvest the mechanical energy from the external environment, the TENG can serve as a micro/nano power source for small, distributed, and possibly wearable electronics. By integrating TENGs with existing commercial sensors, a concept of self-powered system has been developed. Second, the TENG itself can also operate as an active selfpowered sensor for sensing various kinds of mechanical motion and agitation, which will have a wide range of applications in internet of things, artificial intelligence, big data, and sensor networks. Third, in comparison with the EMG, TENG has an excellent output efficiency at the low working frequency, which is particularly suitable for harvesting water wave energy. By connecting many units of TENGs into a network, it is possible to harness the

energy from ocean waves, which is referred to as the blue energy. Finally, with the merits of controllability, portability, safety, cost-effectiveness, and high efficiency, the TENG can be directly used as an HV power source for specific HV applications, such as mass spectrometry, electron field emission, and so on. Based on the above four major application areas, a road map for TENG has been proposed in 2018 to identify the key directions and provide a timeframe for TENG development (Figure 12).<sup>154</sup>

Even though great progress related to fundamental theory and technological applications of the TENG has been achieved, there are still some certain problems and issues that need to be addressed for the future development of this research area.

(1) Further investigation in the fundamental physics of contact electrification. Although some progresses have been made in this area, more research works remain to explore CE in both nanoscale and microscale. Especially, CE between liquid-liquid interface different to probe and has not yet been studied. Recent work shows that it may be a promising method to use small tip shaped TENG as a probe for studying the charging behavior at the liquidliquid interface. Besides, during the process of CE, electron transfer occurs on the surface of the triboelectric materials may cause interface catalysis. It is an interesting scientific issue to investigate how the generated CE charges could affect the redox reaction at the interface.

(2) Improving the output energy of the TENG. From the point of the internal structure of the TENG, various strategies including improving the surface charge density by modifying materials or creating surface micro/ nanostructures, enhancing the contact intimacy, designing innovative structure would be promising choices to improve the output performance. Besides, the TENG's output energy can be improved through external methods such as optimizing the working environment, introducing the power management circuit. In addition, charge pumping<sup>155-157</sup> and self-charge excitation<sup>158</sup> are two newly developed effective mechanisms for improving the output power of the TENG.

(3) Enhancing the durability of materials and devices. Long-term stability is a vital issue for the practical application of the TENG. During the operation process, material abrasion will lead to a serious decline in the performance of the TENG, especially for the sliding mode TENG. To tackle this problem, the first solution is using a working mode transition for the TENG. It has been proved that the produced charges in the first few cycles of mechanical contacts can remain for some time without dissipation. By designing a "switchable" structure for the TENG mode transition between contact and noncontact mode, high output performance, and durability could be simultaneously obtained. The second one is developing



FIGURE 12 Road map for the development of TENG from 2017 to 2027. Reproduced with permission.<sup>154</sup> Copyright 2019, Wiley-VCH

materials with robust mechanical durability. Studies about composite materials and chemical modification would be helpful.

(4) Most of the materials for fabricating TENGs are nondegradable synthetic polymers, which would possibly cause environmental pollution. In this context, developing biodegradable and renewable materials could be a good choice. However, such materials often have insufficient triboelectric and mechanical properties. Future strategies could focus on exploring more natural materials and improving their properties by physical and chemical modifications, which may greatly promote the development of TENGs and have a significant impact on the sustainable development of society, economy, and environment.

(5) With regard to large-scale blue energy harvesting, although the output performance of the TENG for harnessing water wave energy has improved a lot, there are two issues that need to be solved for its practical application. First, due to the intrinsic instability and randomness of the water wave energy, how to fix the TENG network across the sea is essentially important for energy harvesting. Therefore, reasonable structure design for connecting the TENG network plays a key role in solving this problem. Second, since the shielding effect caused by the conductive seawater, the output performance of the TENG will drastically decrease when working in the water environment. How to minimize or avoid this negative effect is another critical problem for the development of blue energy harvesting. Future researches could focus on developing advanced connecting and packaging

technologies for the TENG networks working in the marine environment.

(6) Effective energy storage for the TENG. Traditional energy storage devices are usually charged using a DC input. Given the pulsed output characteristic of TENGs, it is important for studying the ion transport and diffusion under the pulsed driving force across the isolating membrane in the Li batteries.<sup>159</sup> As for the super-capacitors, the leakage problem could severely reduce the storage efficiency due to the relatively low current of TENGs.<sup>160</sup> More efforts should be dedicated to suppressing the self-discharge of the supercapacitors in the future.

(7) As a self-powered sensing technology, TENGs can be widely distributed in every corner of the environment for collecting various types of mechanical signals in real time. Combining with artificial intelligence and cloud computing, TENG-based big data analytics could be developed as a new branch of self-powered systems to automatically analyze the collected data and provide scientific guidance. Based on TENG-based big data analytics, smart sensing systems can be built for a wide range of fields, such as environment monitoring, healthcare, sports, safety, and more. This new branch will greatly expand the TENG application range for IoTs. Additionally, the sensing accuracy of TENGs is usually neglected at the current research stage of TENG-based self-powered sensing systems. With the rapid development of the selfpowered sensing field, the sensing accuracy of TENG will be vitally important in the process of its commercialization, which can be improved by structural design,

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material modification, and power management. In addition, signal processing circuits can also be used for improving the sensing accuracy.

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#### **CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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