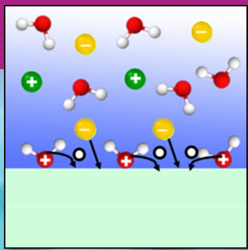

Smart textile triboelectric nanogenerators: Current status and perspectives

Kai Dong, Youfan Hu, Jin Yang, Sang-Woo Kim, Weiguo Hu, and Zhong Lin Wang*

Textile triboelectric nanogenerator (TENG) is a kind of smart textile technology that integrates traditional flexible and wearable textile materials with emerging and advanced TENG science, which not only embraces the capabilities of autonomous energy harvesting and active self-powered sensing, but also maintains original wearability and desired comfortability. With the help of the burden-free and self-sufficient wearable intelligent system, individuals can achieve convenient acquisition and efficient utilization of electric energy, which will help to promote the future development of human-oriented on-body electronics and artificial intelligence. Here, some fundamental knowledge and core elements, including the operational modes and corresponding service occasions, charge generation and transfer mechanisms, remaining challenges and potential solutions are comprehensively summarized and systematically discussed. Based on these analyses, a roadmap toward the scientific research and large-scale commercial application of textile TENGs in the next decade is highlighted at the end of the article. We believe that textile TENGs will become an indispensable part of daily clothing in the future, thus benefiting all humankind and human civilization.

Introduction

With the advent of the era of the Internet of Things and artificial intelligence, an enormous number of on-body wearable electronics and wireless sensor networks call for new energy supply modes and more convenient human–machine interactive mediums. Given the existing environmental concerns related to large-scale replacement and disposal of batteries, triboelectric nanogenerators (TENGs) that can directly convert useless mechanical energy into valuable electrical power will potentially serve as a new alternative energy source, which has also been proposed as "the energy for the new era."[1] With the advantages of facile preparation, low cost, universal availability, and high energy conversion efficiency at low frequency, TENGs show great potentials for future micro-/nanoenergy sources and self-powered sensors.

However, due to the operation modes and structural characteristics of TENG, its merits are difficult to coordinate with human daily activities/movements. Fortunately, present textiles are no longer satisfied with the traditional esthetic, protective and warm keeping purposes.[2,3] To meet the versatile human-oriented intelligent demands, a new kind of textiles (i.e., smart textiles or electronic textiles that can perceive, communicate, respond to or adapt to various external stimuli, such as electrical, thermal, chemical, magnetic, or other origins) emerge as the times require.[4–6] After decades of development, smart textiles with a variety of functions have been reported, such as energy harvesting,[7,8] energy storage,[9,10] signal sensing,[11,12] responsive actuating,[13,14] data processing,[15,16] light emitting,[17,18] and color changing.[19,20] In particular, through the seamless integration of the advanced TENG science and traditional textile technology, a new type of smart textiles (i.e., smart textile TENGs) have been developed, which are endowed with two outstanding functions of mechanical energy harvesting and self-powered sensing. The

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doi:10.1557/s43577-021-00123-2

combination of textiles and TENGs can realize the complementary advantages of them. On one hand, textiles provide a diversified design carrier and broad service platform for the development of TENGs. On the other hand, TENGs offer textiles the abilities of electricity generation and autonomous sensing response. Therefore, smart textile TENGs not only maintain the original softness and comfort of clothing, but also are able to provide continuous, stable, and green electricity, or regular, orderly and real-time electrical signals, which have broad application prospects in wearable micro-/nano-power sources, self-powered sensing, healthcare monitoring, biomimetic systems, human–machine interfaces, and artificial intelligence.

With the thriving development of textile TENGs, it is necessary to make a comprehensive investigation on their current research status and future development prospects. In recent years, although there have been some articles on the existing research works of textile TENGs,[21,22] their bottlenecks and future development trends are still unclear, which makes us confused about what direction to take in the next few decades. In this article, the basic working modes and electricity generation mechanisms of TENGs are introduced, with a special focus on textile structures. Next, the state-of-the-art progress in textile TENGs is tabulated until the end of 2020 through statistical analysis. Five developing tendencies of textile TENGs are highlighted and discussed in detail, which include improving output power density, expanding self-powered application scopes, achieving better wearability and more functionalities, integrating energy harvesting with energy storage, and matching high performance with mature productions (**Figure 1**). Because of these achievements, the remaining challenges that are classified into 10 categories in the future research and large-scale application of textile TENGs are briefly discussed to provide possible solutions and some insights for the desired improvements. Finally, a future roadmap is proposed for the research and commercialization of textile TENGs in the next decade, which identifies key priority directions and key challenges.

Figure 1. Schematic illustration of the application fields and developing directions of smart textile triboelectric generators (TENGs).

Basic operation modes and fundamental charge generation mechanisms

It is noteworthy that fully mastering the working modes and charge transfer mechanisms of textile TENGs is the premise of deepening its theoretical research and realizing its commercial applications. According to the four basic working modes of TENGs, textile TENGs also have their corresponding operation modes, including single-electrode mode, lateral-sliding mode, vertical contact-separation mode, and freestanding triboelectric layer mode, each of which has its application occasions and fields (**Figure 2**a).[23] However, since textile TENGs are usually made of functional fibers, the in-plane sliding modes are more difficult to achieve than the vertical loading modes, the latter of which seems to be more in line with human movements. In addition, in order to facilitate preparation and operation, the number of fiber electrodes should be reduced as much as possible. Therefore, single-electrode mode is one of the most popular working modes of textile TENGs.

Contact electrification or triboelectrification is a universal and ancient phenomenon existing between any two materials. However, its underlying mechanism is still ambiguous and controversial. Recently, some possible physical models, such as electron/current transfer model,[24] surface state model,[25] electron cloud-potential well model,[26] and electric double-layer model[27] (Figure 2b) have been tentatively proposed to explain this complex mechanism, which provides beneficial guidance to unravel the electricity generation theory of textile TENGs. The triboelectrification of textile should consider its special structural effects in addition to the general factors that have been reported. For example, how is the charge transfer between fibers realized in the step-by-step contact

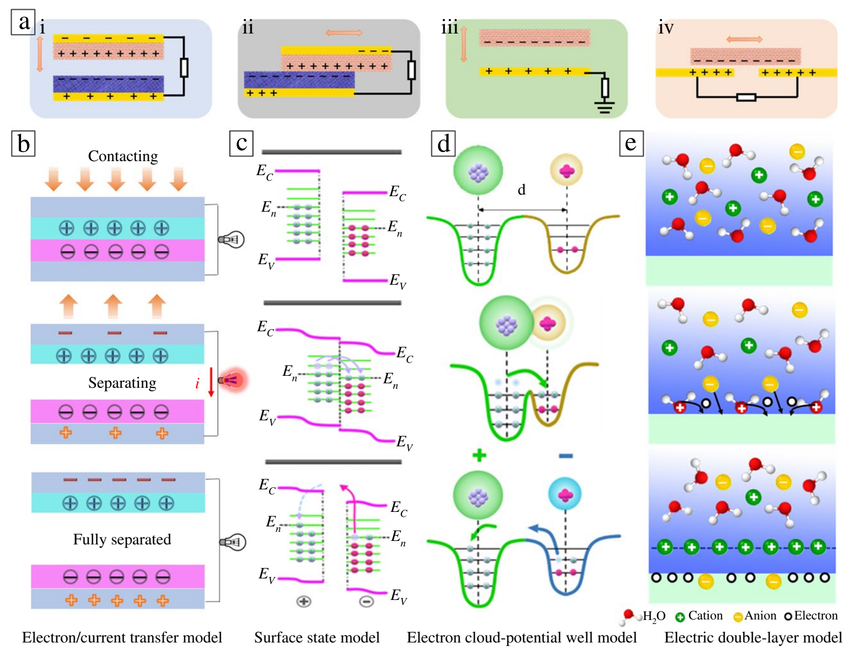

Figure 2. Basic operation modes and fundamental charge generation mechanisms of textile triboelectric nanogenerator (TENG). (a) Four working modes of TENG, including (i) vertical contact-separation mode, (ii) contact-sliding mode, (iii) single-electrode mode, and (iv) free-standing triboelectric layer mode. Potential electricity generation modes of TENG, including (b) electron/current transfer mode, (c) surface state model, (d) electron cloud-potential well mode, and (e) electric double-layer model. E_C: conductive band, E_n: neutral level of surface states, and E_V: valence band.

process from point to line and then to surface? What's the difference in the ability of fiber triboelectrification in its transverse or longitudinal direction? And whether the micro-/nano-holes or humps distributed on the surface of fibers will inhibit or accelerate the charge transfer or not? It is expected to solve these issues with the help of more accurate detection tools in micro-/nanoscale and related simulation software.

Current research status of textile TENGs

The current research status and global impact of TENGs have been investigated based on the publications and their geographical distribution.[28] On the basis of similar statistical analysis, the present development of textile TENGs is studied in the period from the first invention of TENG in 2012[29] to the end of 2020 (**Figure 3**). It can be found that the number of retrieval articles on textile TENGs is increasing year by year since the first combination of TENGs and textiles was realized in 2014 (Figure 3a).[30] In terms of regional distribution, the research of textile TENGs has been extended to major countries in our world, among which the People's Republic of China, the USA, and the Republic of Korea are in the top three (Figure 3b). In addition, according to the sequence of the number of publications, the top four independent research institutes are arranged as follows: Chinese Academy of Sciences, Georgia Institute of Technology, University of Chinese Academy of Sciences, and Donghua University (Figure 3c). According to the previously discussed objective analysis data, it turns out that textile TENGs are currently in a period of rapid development, and will present a stronger upward momentum in the next few years. In this trend, China has played an important role in promoting the new smart textile technology, and is expected to become the research and application center in this field in the future.

Developing trends or research directions of textile TENGs

High electromechanical conversion efficiency and excellent wearability are the unremitting pursuits of textile TENGs. According to the previously discussed retrospective analysis of the current research status of textile TENGs, we classify their research and development trends into five categories, as shown next. We hope that the systematic and standardized classification of textile TENGs can help future researchers and market analysts to accurately grasp the existing research basis and quickly obtain the directions that need further breakthroughs.

Improving energy harvesting power output density

The electricity converted from textile TENGs can first be used as the power source to drive various wearable electronics. However, due to the bottleneck of low power output resulting from low current, it is difficult for textile TENG-based power sources to realize practical applications. Nowadays, researchers have adopted a variety of approaches, especially multidimensional fabric structural designs, to steadily improve the output power density of textile TENGs. For example, through further nanostructure modification of the interleaved fibers, a high power output fabric TENG with an instantaneous power output of 4 mW was prepared by inserting Al wires with nanowires into poly(dimethylsiloxane) (PDMS) tubes (**Figure 4**a[i]).[31] High performance textile TENGs can also be presented in the in-plane sliding modes. A grating-structured fabric TENG with the maximum output power density of 3.2 W m^{-2} was composed of the stator fabric with two interdigitated metal electrodes and the slider fabric provided with a series of parallel grating segments (Figure 4a[ii]).[32] In order

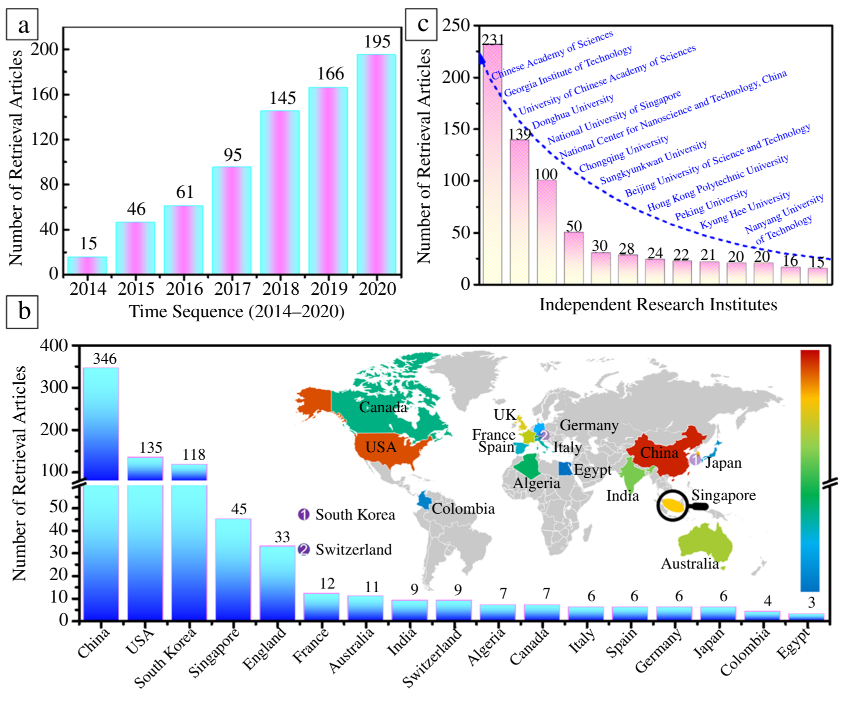

Figure 3. Current research status of textile triboelectric nanogenerators (TENGs) from the viewpoint of literature retrieval from 2012 to the end of 2020 in the Web of Science (WOS). (a–c) Number of published articles on textile TENGs retrieved by (a) years, (b) countries, or (c) independent research institutes, respectively. Retrieval method in WOS is that TS = (fiber OR nanofiber OR yarn OR thread OR wire OR string OR fabric OR cloth OR textile OR woven OR knit OR braid OR nonwoven OR electrospinning OR spinning) AND TS = (TENG OR triboelectric OR triboelectricity OR biomechanical energy harvesting) NOT TS = (piezoelectric OR piezoelectricity).

to increase the effective contact-separation area as much as possible, 3D fabric structures are gradually used to design high performance textile TENGs. A 3D orthogonal woven TENG was fabricated with conductive metal fibers as the warp yarn, rubber-coated energy harvesting fibers as the weft yarn, and cotton fibers as the Z-direction binding yarn, whose maximum peak power density could reach 270 mW m^{-2} (Figure 4a[iii]).[33] Recently, a 3D braided TENG with the merits of shape adaptability and high resilience was fabricated through four-step rectangular braiding technology, which was easy to achieve a peak power of 150 μW (Figure 4a[iv]).[34] It is worth noting that although it is difficult or impossible to quantitatively compare the power output of the previously discussed research works due to varied test conditions, they can provide a simple, efficient, and easy-to-scale strategy to improve the electrical output performance of textile TENGs.

Expanding self-powered sensing application scopes

Textile TENGs can also work as self-powered sensors in response to pressure or deformation, which can be seamlessly integrated into wearable garments or general fabrics with better comfort and great convenience. The second row in Figure 4b presents several examples to show that the self-powered sensing applications have been greatly expanded along with the rapid development of this technology. In 2014, a wireless body temperature system triggered by a "power shirt" was constructed with a fiber-based textile TENG, a bridge rectifier, and a capacitor (Figure 4b[i]).[35] In 2018, highly stretchable yarn-based TENGs were realized with a novel demonstration of evaluating the features and success of golf swing actions sewn on the arm lateral and medial of a sleeve (Figure 4b[ii]).[36] Most recently, various attractive applications have emerged based on the boosted performance, such as sensitivity, response time, and stability of textile TENGs and sophisticated system designs, including well-designed signal processing modules and proper algorithms. Several represented works are also shown in Figure 2b, including textile TENG sensor arrays for subtle physiological signal monitoring (i.e., arterial pulse waves and respiratory signals) (Figure 4b[iii]),[37] self-powered identity recognition carpets for safeguarding entrance by monitoring human walking trajectories (Figure 4b[iv]),[34] and smart triboelectric floor monitoring systems for identity information associated with walking gait patterns enabled by deep learning-based data analytics.[38] These examples reveal the great potential of textile TENGs for diverse applications, including, but not limited to, smart building/home, intelligent automation, health care, and security.

Achieving better wearability and more functionalities

In addition to electrical properties, wearability and additional functionalities are also particularly important for textile TENGs, which determine whether they can be directly applied to the human body. Wearability is one of the most important characteristics and basic requirements of clothing, which is the intuitive response to comfort and satisfaction. It mainly involves the following features, such as mechanical flexibility, softness, esthetic appearance, gas permeability, moisture wicking, machine washability, tailorability,

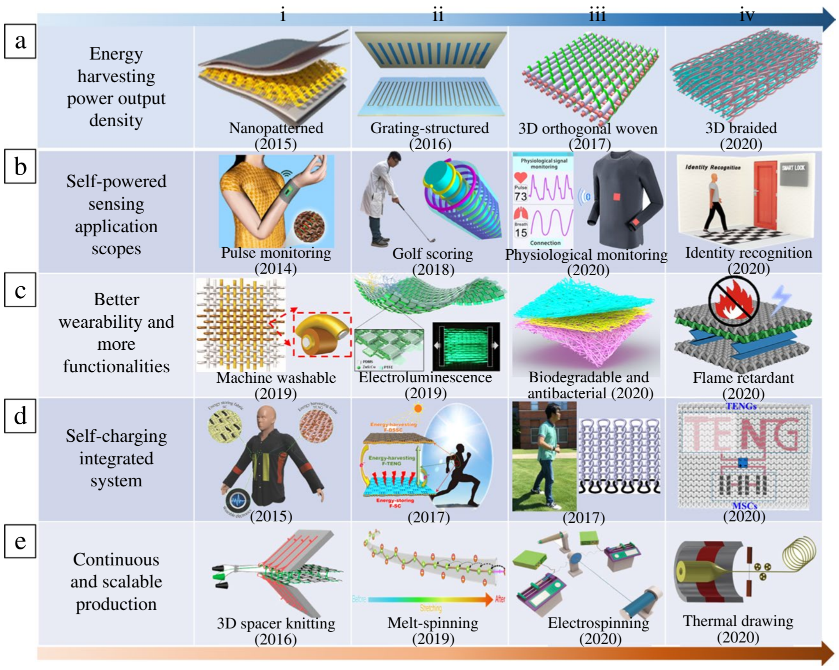

Figure 4. Five main development trends or research directions of smart textile triboelectric nanogenerators (TENGs), including (a) improving energy harvesting power output density. (i) 2D nanostructured fabric TENG. Reprinted with permission from Reference 31. © 2015 American Chemical Society. (ii) 2D in-plane sliding fabric TENG. Reprinted with permission from Reference 32. © 2016 Wiley. (iii) 3D orthogonal woven TENG. Reprinted with permission from Reference 33. © 2017 Wiley. (iv) 3D braided TENG. Reprinted with permission from Reference 34. © 2020 Nature Publishing Group. (b) Expanding self-powered sensing application scopes. (i) Pulse monitoring fiber TENG. Reprinted with permission from Reference 35. © 2014 American Chemical Society. (ii) Golf scoring fiber TENG. Reprinted with permission from Reference 36. © 2018 Wiley. (iii) Physiological monitoring fabric TENG. Reprinted with permission from Reference 37. © 2020 AAAS. (iv) Identity recognition fabric TENG. Reprinted with permission from Reference 38. © 2020 Nature Publishing Group. (c) Achieving better wearability and more functionalities. (i) Machine washable fabric TENG. Reprinted with permission from Reference 39. © 2016 Wiley. (ii) Light-emitting fabric TENG. Reprinted with permission from Reference 41. © 2019 American Chemical Society. (iii) Biodegradable and antibacterial nanofiber TENG. Reprinted with permission from Reference 42. © 2020 AAAS. (iv) Flame-retardant fabric TENG. Reprinted with permission from Reference 43. © 2020 American Chemical Society. (d) Integrating energy harvesting with energy storage. (i) 2D self-charging power woven fabric. Reprinted with permission from Reference 44. © 2015 Wiley. (ii) Self-charging fiber unit with various energy harvesting forms. Reprinted with permission from Reference 45. © 2016 AAAS. (iii) Self-charging knitting power fabric. Reprinted with permission from Reference 46. © 2017 American Chemical Society. (iv) 2D coplanar self-charging fabric. Reprinted with permission from Reference 47. © 2020 American Chemical Society. (e) Matching high performance with mature production. (i) 3D spacer knitting technique. Reprinted with permission from Reference 48. © 2016 Elsevier. (ii) Melt-spinning method. Reprinted with permission from Reference 49. © 2019 Nature Publishing Group. (iii) Electrospinning technique. Reprinted with permission from Reference 50. © 2020 American Chemical Society. (iv) Thermal drawing technology. Reprinted with permission from Reference 52. © 2020 Nature Publishing Group.

recyclability, biocompatibility, and scalability. Functionalities are the embodiments of intelligence, which endow textiles with the attributes of self-management, self-protection and self-response, including superhydrophobicity, self-cleaning, flame retardancy, thermal management, directional liquid transport, UV blocking, self-healing, shape memory, deodorization, disinfection, biodegradation, energy harvesting, energy storage, light-emitting, and anti-counterfeiting. One of the unremitting goals of smart textiles is to achieve better wearability and more functionalities. Recently, the combination of wearability and functionality has received increasing attention in textile TENGs. For example, machine-washable and scalable textile TENGs with stable electrical output were developed on an industrial loom using copper-coated polyester (Cu-PET) warp yarns and polyimide-coated Cu-PET weft yarns (Figure 4c[i]).[39,40] In addition to the hydrophobic property, self-powered motion-driven luminescence can be realized in textile TENGs by fabricating ZnS:Cu embedded PDMS composite fibers and poly(tetrafluoroethylene) (PTFE) fibers in a plain weave pattern (Figure 4c[ii]).[41] Through constructing a multilevel hierarchy and micro-to-nanoporous structure via electrospinning, excellent thermal-moisture comfortability can be achieved in textile TENGs. Through further material selections, other functions, such as breathability, biodegradability, and antibacterial activity can be simultaneously integrated into textile TENGs, which greatly improve the environmental friendliness and practicability (Figure 4c[iii]).[42] In other cases, a flame-retardant textile TENG with excellent fire resistance and outstanding energy harvesting capabilities is developed by a simple and effective layer-to-layer self-assembly method for forest self-rescue and fire alarm systems (Figure 4c[iv]).[43] Based on the unique importance of wearability and comfortability to textile TENGs, more and more attention will undoubtedly be paid to them in the future.

Integrating energy harvesting with energy storage

In many cases, energy harvesting and energy-consuming are not synchronous, which requires the effective storage and management of the acquired energy. Self-charging power system means a greatly prolonging or even semi-permanent power supply, which can realize electricity directly and constantly converted from environmental energy, and stored with low loss to power wearable electronics when needed. Self-charging power textiles are developed by integrating energy harvesting textile TENGs and energy storage textile supercapacitors or batteries, which have also been widely reported. The first self-charging power textile system by integrating a whole-textile TENG with a flexible lithium-ion battery was reported in 2015 (Figure 4d[i]).[44] TENGs can be combined with other energy harvesters to simultaneously utilize a variety of energy forms. For example, fiber TENG, fiber dye-sensitized solar cells, and fiber supercapacitors were integrated for simultaneously harvesting body motion biomechanical energy and outdoor solar energy, and then storing them in an energy storage unit (Figure 4d[ii]).[45] Stretchability is a key feature for garment weaving, especially for following human body motions during harvesting biomechanical energy. A highly stretchable and washable all-yarn-based self-charging knitting power textile was fabricated through the weft-knitting technique (Figure 4d[iii]).[46] In addition to fibers or yarns interweaving, self-charging power textiles can also be directly prepared on the fabric substrates. For example, a stretchable self-charging power textile was fabricated with 2D coplanar TENGs and micro-supercapacitors, whose output voltage, power, and maximum areal capacitance do not degrade even at 50% tensile strain (Figure 4d[iv]).[47] These all-in-one self-charging power textiles provide more freedom for designing wearable electronics.

Matching high performance with mature production

In order to promote the mass-scale commercial application process of textile TENGs, it is necessary to expand beyond the laboratory-scale toward mature production and industrialization. Therefore, it also becomes a hot spot of textile TENGs to realize the matching of high output performance and mature industrial production. For example, a mechanical-scalable textile TENG with 3D knitted spacer structure was fabricated by utilizing the PTFE-coated nylon fabric and graphene-coated nylon fabric as the paired tribo-polarities (Figure 4e[i]).[48] By using a modified melt-spinning method, a highly stretchable and scalable manufacture core-sheath triboelectric yarn was prepared by covering the surface of stainless-steel yarn with a blow-molding silicone rubber tube, which showed a large working strain (200%) and superior performance in liquid (Figure 4e[ii]).[49] By a facile electrospinning technology, the continuous and scalable manufacture of micro-nanotriboelectric yarns consisting of poly(vinylidene fluoride) (PVDF) and polyacrylonitrile (PAN) hybrid nanofibers as the shell and conductive silver yarns as the core was fabricated (Figure 4e[iii]).[50] And through a thermal drawing process, a scalable microstructured stretchable triboelectric fiber was fabricated (Figure 4e[iv]).[51,52] The previously discussed large-scale preparation methods are likely to become one of the main approaches for industrial applications of textile TENGs in the future.

Problems and challenges

Ten categories of problems to be continued for textile TENGs have been tentatively listed. These unsolved issues result in low power output and inferior sensing quality of the present textile TENGs, and make them unable to realize large-scale commercial applications.[53]

Charge generation and transfer mechanism between polymer fibers

Compared with common planar membrane-like structure, fiber materials with typical structural features of high aspect ratio, multilevel hierarchical distribution, and micro-to-nanoporosity may have special or different circumstances for the process of contact electrification and/or electrostatic induction. Although there have been many investigations about the charge generation and transfer mechanism in general TENGs,[54,55] similar work is still lacking on textile TENGs and should be carried out with the assistance of mechanical analysis to help understand these processes occurring between polymer fibers.

Fiber material selection criteria and database

It is well known that triboelectrification can occur between any two materials. However, few studies have been done to quantify and standardize the effect of fiber categories on the performance of TENGs. Although specific conductivity or specific resistivity has been widely adopted to evaluate the electrical conductivity of fiber electrodes,[56] there is no universal standard method for normalized triboelectric charge density of fiber materials, which leads to the tremendous differences and irreconcilable contradictions between different triboelectric fiber materials. Therefore, it is paramount to classify and calibrate conductive and dielectric fibers for the standardization research and industrialized promotion of textile TENGs. We are looking forward to quantifying the triboelectric sequence of fiber materials through standardized experimental characterization, such as Kelvin probe force microscope,[55] vacuum-assisted liquid metal contact,[57] and others, so as to establish a selection database of fiber materials for textile TENGs.

Figure-of-merits and performance evaluation standards

Test standards for textiles have been presented by several internationally recognized bodies, such as ISO (International Organization for Standardization), ASTM (American Society for Testing and Materials), and AATCC (American Association of Textile Chemists and Colorists). However, although some possible figure-of-merits (FOM) and standards have been proposed to evaluate the overall performance of TENGs, such as maximum energy output, voltage-charge plot, structural FOM, and material FOM,[58–60] their convenience and universality in practical use still need to be improved. What's more, there is no performance evaluation standard especially for textile TENGs, which makes it difficult to compare the qualities of different devices. The FOM and evaluation standards of textile TENGs should take both the special structural characteristics of textiles and electrical output performance of TENGs into consideration, which requires the experts in the two fields to work together to formulate relevant evaluation standards. For example, we should comprehensively consider the textile material dimension, material FOM, and structural FOM to propose the performance FOM of textile TENGs.

Impedances and capacities matching with energy storage devices

In self-charging power systems, energy storage devices play a key role as a reservoir for storing the generated charges during motions and releasing them when necessary. However, the output of TENGs is a typical feature of alternating current (AC) with large open-circuit voltage and small short-circuit current. There is a large impedance and capacity mismatch between TENGs (typically 10^5–10^7 Ω) and energy storage devices (typically 10^{-2}–10^2 Ω), which greatly reduces the efficiency of energy transfer or storage in direct use. To this end, power management technology is being developed to overcome this challenge. Although a variety of power management technologies have been developed to achieve impedance or capacitance matching, such as AC rectification-transformer technology,[61] optimization of transformer coil ratio,[62] universal power management circuit,[63] inductor-capacitor (IC) oscillation,[64] inductor-free power management technology,[65] and switched-capacitor-converters,[66] power loss is still unavoidable. In addition, the wearability of the power management system is also a great challenge.

Long-term working stability and durability

Long-term working stability or durability is always a big concern of textile-based electronics, which is related to whether they can meet the actual usage requirement. The mechanical and electrical stability of them are highly related to textile structures, manufactory methods, and applied environments, which are generally not as good as the common planar membrane-like structures. In addition, frequent or excessive external loadings may damage the integrity of the surface material, thus reducing the electrical output performance. Hereafter, the long-term working stability and durability of textile TENGs can be effectively improved by selecting wear-resistant materials, designing compact fabric structures, and even adopting the necessary packaging technology.

Power management for high conversion and low dissipation

Effective power management has always been the difficulty and bottleneck for the practicability of TENGs. Most of the existing solutions are to convert high pulse voltage to low voltage by connecting a DC-DC step-down converter externally to TENGs. However, due to the soft and loose structure of textile TENGs, the resilience of textile TENGs will be affected by the conversion of human motion in different frequencies and amplitudes. Compared with the other types of TENGs, the output signal of textile TENGs is more random and irregular in the energy harvesting of human motion. Moreover, the textile TENGs woven from a long conductive yarn usually have a larger impedance and unbalance matching. Therefore, to maximally extract energy from the textile TENGs and utilize them efficiently, a power management circuit for transformers with higher load resistance and widely working frequency bandwidth needs to be designed.

Effective packaging technology

In many cases, textiles are modified via coating processes. The adhesion between fibers/textiles and the coating layers is a challenge under deformations or during washing tests. Also, corrosion will be a big problem when the textiles directly are in contact with the skin as sweat may be introduced during the sensor operation. Packaging is not carefully considered in current research. But, to achieve long-term working stability and durability, packaging is a must. Proper packaging techniques that can keep the air permeability, water permeability and softness of textiles need to be developed to maintain the superiority of wear comfort of textile TENGs over common ones. For example, textile TENGs are usually made of polymer materials with good hydrophobicity or repellency, high thermal stability, and strong friction electrification ability (such as PVDF, PDMS, PET, and PTFE) as the packaging materials, which are fabricated by thermal drawing, wet-spinning, melt-spinning, spraying, screen printing, and other packaging technologies.

Wearability and comfortability

It is difficult to achieve the combination and collaborative improvement of wearability and functionality because they are often mutually exclusive. For example, micro-/nanostructure functional materials with poor biocompatibility and skin friendliness added into clothing may cause skin itching, hot and cold contact irritation, wound infection, and even inflammation. In addition, the texture of garments will become hard after complicated chemical treatments, which may affect their drape, softness and permeability. Furthermore, the operation of TENGs needs certain contact-separation spaces or external loading forces, which will cause inconvenience to wearing. Therefore, human-friendly materials and easy to move textile structures are desired to design textile TENGs.

Scalable manufacturability compatible with mature industrial production

One of the ultimate goals of textile TENGs is to realize large-scale commercial applications. However, most of the current textile TENGs are reported at the laboratory stage with the features of complex structures, limited dimensions, cumbersome process,

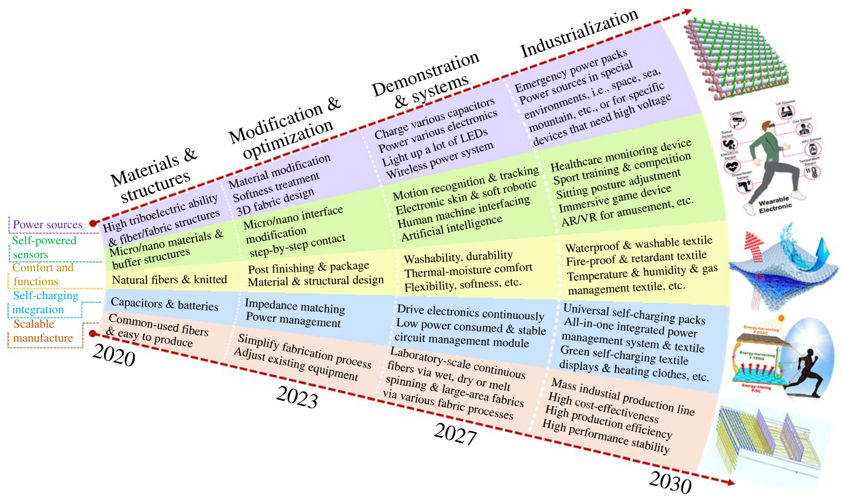

Figure 5. A roadmap of textile triboelectric nanogenerators (TENGs) from 2020 to 2030 toward future research and practical commercial applications. Reprinted with permission from Reference 33. © 2017 Wiley. Reprinted with permission from Reference 68. © 2020 Nature Publishing Group. Reprinted with permission from Reference 69. © 2019 American Chemical Society. Reprinted with permission from Reference 45. © 2016 AAAS. Reprinted with permission from Reference 70. © 2020 Elsevier.

and inferior stability. In the actual industrial production, the shedding or breakage of fiber surface covering material will lead to the exposure or fracture of fiber electrodes or fiber dielectrics, which may result in short-circuit or open-circuit of the whole device.

Comprehensive cost factors

Cost-effectiveness is also worth evaluating in the process of real commercialization of textile TENGs, which runs through their whole life cycles, including manufacturing, maintenance, recycling, and disposal. Functional materials at laboratory level are often expensive, require complex processing crafts and high treatment cost, which can't be quickly expanded to the industrial level. Therefore, there is a trade-off between improving the working performance of textile TENGs and reducing their scalable preparation cost.

Summary and perspectives: A roadmap toward the future

As one of the next-generation smart textiles, smart textile TENGs that are developed through the seamless integration of ancient textile technology with advanced TENG science can make traditional clothing come alive by entrusting them with autonomous mechanical energy harvesting and active self-powered sensing capabilities, which have great potentials in the realm of wearable power sources and multifunctional sensors. Based on the comprehensive overview of the five research trends and 10 remaining issues of textile TENG, a roadmap toward its future development and practical commercial application is proposed, as shown in **Figure 5**, which outlines a bright blueprint of textile TENGs in the next decade. Five priority directions, including power sources, self-powered sensors, comfort and functions, self-charging integration, and scalable manufacture, derived from the current five hot research fields of textile TENGs are highlighted in the four experience stages from materials selection and structural design, to further modification and performance optimization, then to feasibility demonstration and system integration, and finally to industrialization and commercialization.[67] Some preferred approaches, strategies or solutions are listed in each stage to address its key challenges or unresolved issues. In addition, five terminal product prototypes are illustrated at the end of each field to depict what we expect to achieve in the future.[33,45,68–70] Meanwhile, it should also be noted that although the period of each stage is not necessarily in accordance with the marked one, and the space at which each stage proceeds may vary from field to field, the overall progress trend will not change significantly. It is firmly believed that the present critical challenges and insurmountable bottlenecks will be well handled or solved with the advance in some key scientific and technological realms, such as more precise measurement platform, new computing software, higher integrated signal processing modules, and more compatible weaving technologies. We hope that the smart textile TENGs will gradually enter people's daily life through our efforts in the next 10 years, which can provide sustainable all-in-one power supply systems and important interactive tool supports in the era of the Internet of Things and artificial intelligence.

Acknowledgments

The authors are grateful for the support received from the National Key R&D Project from Minister of Science and Technology (Grant No. 2016YFA0202704), the Beijing Municipal Natural Science Foundation (Grant No. 2212052), the Shanghai Sailing Program (Grant No. 19S28101), and the Fundamental Research Funds for the Central Universities (Grant No. 19D128102).

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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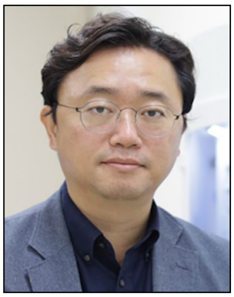

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