Towards Truly Wearable Systems: Optimising and Scaling up Wearable Triboelectric Nanogenerators

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Summary

Triboelectric nanogenerator (TENG) is an upcoming technology to harvest energy from ambient movements. A major focus herein is harvesting energy from human movements through wearable TENGs, which are constructed by integrating nanogenerators into clothing or accessories. Textile based TENGs, which include fibre, yarn and fabric based TENG structures, account for the majority of wearable TENGs, with many designs and applications demonstrated recently. This calls for a comprehensive analysis of textile based TENG technology, and, how the state-of-the-art device optimization concepts can be deployed to construct them efficiently. Concurrently, how advanced engineering concepts and industrial manufacturing techniques, which are bound with fibre, yarn, and fabric-related developments, can be applied into the TENG context for their output enhancement is still under investigation. Herein, we fill this vital gap by analysing the state-of-the-art developments, upcoming trends, output optimisation strategies, scalability, and prospects of the textile based TENG technology, presenting a textile engineering perspective.

1. Introduction

Upcoming technologies such as the Internet of Things (IoT) and 5G technology are reshaping the future role of textiles and apparels (Dharmasena and Silva, 2019). The next generation of smart textiles will have advanced capabilities of interacting with the user and the environment, creating a broad range of applications in communication, healthcare, security, sports, education, and consumer electronics (Stoppa and Chiolero, 2014; X. Wang et al., 2015; Ruchira Nalinga Wijesena et al., 2016; Weng et al., 2016; Yetisen et al., 2016; Fernando, Dharmasena and Niles, 2017; Dharmasena and Silva, 2019; Dharmasena et al., 2019). In recent examples, smart textiles have been used in real-time to monitor body motion, muscle behaviour, and, to diagnose physiological parameters such as temperature, blood pressure, heart rate, etc. with the detected signals incorporated into electrocardiogram (ECG), electroencephalography (EEG), and electromyography (EMG), and, observed via IoT and smart electronic devices (Koo et al., 2014; Stoppa and Chiolero, 2014; Ahn, Song and Yun, 2015; Manero et al., 2016).

The electronic components integrated within smart textiles and wearable electronics consume varying degrees of power, ranging from microwatts to milliwatts (Fig. 1a). Finding methods to power these devices while maintaining their wearable and electronic performances is challenging (Dharmasena and Silva, 2019; Dharmasena et al., 2019; Paosangthong, Torah and Beeby, 2019; Wu et al., 2019). Conventionally, wired power supplies and rechargeable or replaceable energy storage units were used for this purpose, however, with increasing performance requirements, these are becoming obsolete. Energy harvesting, which captures freely available energy from the ambient environment and converts into electricity, has emerged as a potential candidate to replace, or combine with, the existing energy technologies (Fig. 1b) (X. Wang et al., 2015; Tian et al., 2017; Wu et al., 2019).

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Dharmasena et al., 2019). Among available energy sources, human motion generates considerable mechanical power (Fig. 1c), and, is closely related to wearable technologies, drawing significant attention worldwide as a viable energy source for wearable electronics (Fig. 1c) (Dharmasena and Silva, 2019).

Triboelectric nanogenerators (TENGs) have emerged at the forefront of harvesting human motion to power wearable technologies, due to their many unique features such as high outputs and efficiency, flexibility, durability, ease of fabrication and low cost. First reported by Z. L. Wang’s research group in 2012 (Fan, Tian and Lin Wang, 2012) TENG research has experienced a rapid expansion in recent years (Ding et al., 2019). TENGs are especially useful in textile-based energy harvesting applications, as they can be readily designed and integrated into clothing. Many of the conventional textile materials listed in the triboelectric series (J. Zhou et al., 2014; Pu et al., 2015; Dong et al., 2018; Guo et al., 2018) have been demonstrated to produce wearable TENGs with desirable output performances and wearable characteristics. In addition, TENGs have been integrated into textiles using common manufacturing techniques such as weaving, knitting, braiding, embroidery, etc (Dong, Wang, et al., 2017; Chen et al., 2018; Dharmasena and Silva, 2019). To this end, the properties of textile materials, textile structures, and, processing techniques, play a pivotal role in influencing wearable TENG performances.

Despite many device examples, only a limited number of reports exist which help to systematically understand the behaviour of textile based TENGs and their optimization strategies. The relationship between the fibre, yarn, fabric, and garment behaviour, their production techniques, and how these affect the electrical and mechanical performance of wearable TENGs are yet to be studied. Such investigations would be critical since the successful development of wearable energy generation units and their mass-scale production depend on the detailed understanding of the interrelationship between the textiles and the electronic components.

Herein, we conduct a detailed investigation of the available literature for textile based TENGs, with regards to the various stages of the textile manufacturing process. Firstly, we provide a generic introduction into TENG basics including their types, working principles and optimisation methods. Next, a brief overview of the textile manufacturing process and textile based wearable TENGs is provided. For the first time, we present a categorisation of textile based TENGs according to different stages of the textile manufacturing process. Within this classification, key features of current textile based TENGs, potential optimization strategies, and, scalability are discussed in detail, providing a textile engineering perspective on how to overcome major challenges in this research area. A series of guidelines are provided for fibre, yarn and fabric based TENGs to make them compatible with the established textile techniques and processes. Finally, the measurement techniques, standardization strategies and prospects of the textile based TENGs are examined, paving the way towards sustainable future wearable applications.

2. From TENG Basics

A number of fundamental working modes were introduced for TENGs, depending on their structure and motion profile, namely vertical contact separation mode (VCSTENG), lateral sliding mode (LSTENG), single electrode mode (SETENG), and free-standing triboelectric layer mode (FSTENG) (Fig. 2a) (Wang, Chen and Lin, 2015). The working principles of all the TENG categories rely on two fundamental phenomena; triboelectric charging, and, electrostatic induction.

2.1. Triboelectric Charging and Material Selection

Triboelectric charging is the static charge separation between two material surfaces when contacted with each other (Baytekin et al., 2011a; Galembeck et al., 2014; Dharmasena and Silva, 2019; R D I G Dharmasena and Silva, 2019). The origin of triboelectric charging is assumed to be due to electron (Liu and Bard, 2008; Xu et al., 2018), ion (McCarty and Whitesides, 2008) or charged material transfer (Baytekin et al., 2011b, 2012), or, several of these charge types (Galembeck et al., 2014).
The ability of a surface to be triboelectrically charged with respect to a reference surface is empirically utilized to construct the triboelectric series (Diaz and Felix-Navarro, 2004; Zou et al., 2019). Incidentally, triboelectric series contains a large number of common textile polymers and materials (Fig. 2b), (S. Liu et al., 2018) which facilities the use of existing textile materials for TENG applications (Zou et al., 2019). For instance, textile substrates composed of dielectric polymers such as cotton, (Chen et al., 2018; Ning et al., 2018) silk, (Choi et al., 2017; He et al., 2020; Ye, Dong, et al., 2020) nylon, (Gong et al., 2017) polyester, (Pu, Li, et al., 2016; Dong, Deng, et al., 2017) polyethylene terephthalate (PET), (Zhizhen Zhao et al., 2016; Xiong et al., 2018) polyactic acid (PLA), (Pan et al., 2018) polyurethane (PU), (Kim, Park and Kim, 2019) and, carbon fibres (Chen et al., 2018) have been used as wearable TENG contact surfaces. In some cases, additional triboelectric coatings using materials such as polytetrafluoroethylene(PTFE), (Cheng et al., 2017; Ning et al., 2018) polydimethylsiloxane(PDMS), (Lee et al., 2015; Dong, Deng, et al., 2017) silicone rubber, (Pan et al., 2018) perylene (Zhenfu Zhao et al., 2016) and polyvinylidene fluoride(PVDF), (Guo et al., 2018) which are also associated with textiles, were used to enhance triboelectric performance. On the other hand, TENG electrodes and conductive interfaces have been constructed using metals and metal nanoparticles, (Lee et al., 2015; Seung et al., 2015) carbon-based materials such as carbon nanotubes (CNT), (He et al., 2017) and conductive polymers such as polyaniline, (Dudem et al., 2019) in forms of embedded wires or surface coatings.

Material selection for triboelectric contact surfaces is critical, as it primarily affects triboelectric charging. We previously demonstrated the effect of triboelectric charging on the output optimization of TENGs, where the power output increased quadratically against increasing triboelectric charge density, (Dharmasena, Deane and Silva, 2018) while the optimum resistance (i.e. the external load which extracts the maximum power from the TENG) remained constant (Fig. 2c). Selecting material types further apart in the triboelectric series, providing sufficient contact between triboelectric surfaces, enhancing triboelectric contact area by increasing surface roughness are some of the commonly used techniques for triboelectric charge density enhancement, which are applicable for optimizing textile-based TENGs (Dharmasena, Deane and Silva, 2018; Dharmasena and Silva, 2019). On the other hand, selecting high conductivity materials for TENG electrodes is essential to keep the device impedance low, efficiently induce device outputs, and, to effectively extract output power. In terms of wearable TENG applications, the material selection process should target to achieve a balance between electrical performances as well as wearable characteristics.

2.2. Electrostatic Induction and Output Enhancement

The relative movement of triboelectrically charged surfaces induces an output on the TENG electrodes (Dharmasena et al., 2017, 2018; Deane, Dharmasena and Gentile, 2018; Dharmasena, Deane and Silva, 2018; Dharmasena and Silva, 2019). This behaviour is governed by the variation of the electric fields acting on the electrode interfaces of TENG units, resulting in the generation of Maxwell’s displacement current, as described by, (Wang, 2017)

\[ J_D = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_S}{\partial t} \]  

(1)

Where \( J_D \) is displacement current density, \( D \) is displacement field, \( t \) is time, \( E \) is the electric field, \( \varepsilon \) is permittivity, and \( P_S \) is the polarization of the medium.

The output behaviour of TENG was initially explained using a capacitor-based circuit model, via developing a relationship between voltage \( V \), charge \( Q \) and TENG layer separation \( x \), (known as the V-Q-x relationship) given by; (Niu et al., 2013)

\[ V = -\frac{1}{c(x)} Q + V_{OC}(x) \]  

(2)

where \( V_{OC}(x) \) represents the open-circuit voltage and \( c(x) \) represents the capacity. This model contained several drawbacks including the difficulty in fully explaining TENG working principles and closely approximating output trends of practical TENG devices. Consequently, we presented the
distance-dependent electric field (DDEF) model based on Maxwell’s equations, to fully describe the working principles of TENGs (Dharmasena et al., 2017; Dharmasena, Deane and Silva, 2018). This model accounts for the finite dimensions of triboelectrically charged sheets to predict their electric field behaviour. For instance, the fundamental electric field equation for the DDEF model approximates the electric field of a charged sheet with length \( L \), width \( W \), charge density \( \sigma \), dielectric constant \( \varepsilon \), against distance \( z \), using; (Dharmasena et al., 2017)

\[
E_z = \frac{\sigma}{\pi \varepsilon} \arctan \left( \frac{L/W}{2(z/W)^{1/4} + (L/W)^{3/4} + 1} \right) = \frac{\sigma}{\pi \varepsilon} f(z)
\]

Considering the electric fields of the triboelectrically charged layers and output charge layers, the overall electric field at the electrode interfaces can be calculated, which is used to evaluate the potential of the electrodes (Dharmasena et al., 2017). Consequently, the voltage, current, charge, and power outputs of the TENG can be predicted using the DDEF model with a relatively higher accuracy (Dharmasena et al., 2017, 2018; Dharmasena, Deane and Silva, 2018; Dharmasena, 2019).

Based on the DDEF model, we presented optimisation criteria to significantly enhance the structural, material, and motion parameters of a TENG, that can act as a guideline to improve textile based TENG performances. Considering structural parameters, larger triboelectric contact surface areas are favourable for higher power generation and to reduce TENG internal impedance (Fig. 2d). Lower thicknesses of triboelectric layers provide favourable output trends, given that the thickness is sufficient for the stable accumulation of triboelectric charges (Fig. 2e). Textiles are available in a variety of thicknesses (microns to millimetres) and sizes (up to several square meters for clothing), therefore, can be engineered to fit the energy harvesting applications. In terms of material parameters, the dielectric constant is again a key material parameter affecting TENG performances. As evident from Fig. 2b, a large number of textile materials are available for TENGs, enabling both charge density improvement and engineering of the dielectric constant. With regards to motion parameters, faster relative movements (Fig. 2f) (Dharmasena, Deane and Silva, 2018) higher motion amplitudes (Fig. 2g), ensuring adequate contact between triboelectric surfaces (Fig. 2h) are critical in improving the power output of a TENG. Therefore, textile techniques which introduce elasticity, flexibility, and rapid movement to textile structures via material selection and fabric structuring (that will be discussed in future sections of this work) are extremely beneficial in constructing highly efficient TENG designs.

3. Textile based TENGs

3.1. Overview of the Textile Manufacturing Process

The starting point of textile products is ‘fibre’. Fibres are distinguished by their high length to diameter ratio, (McIntyre and Daniels, 1995) which is typically over several hundred times for textile fibres. Natural fibres used for textiles include plant-based seed fibres (e.g.: cotton, kapok), bast fibres (e.g.: flax, jute, hemp), leaf fibres (e.g.: abaca, manila), and, animal-based fibres (e.g.: wool, silk, alpaca) (Eichhorn et al., 2009; Todor et al., 2018). Prominent man-made fibres include synthetic fibres such as polyamide (PA), PET, polyvinyl alcohol (PVA), polypropylene (PP), polyvinyl chloride (PVC), polyethylene (PE), regenerated cellulose fibres such as lyocell, viscose, modal, and, other high performance fibres (Wanasekara et al., 2012, 2016; C. Zhu et al., 2016; Wanasekara and Eichhorn, 2017; Foster et al., 2018). Depending on their length, fibres are divided into staple fibres (short in length) and filaments (continuous fibre strands). Common textile manufacturing process follows the steps of fibres (Fig. 3a), yarns (Fig. 3b-d), fabrics (Fig. 3e-i) & garments (Fig. 3m-q).

Conversion of fibres into yarns is realised through spinning or extrusion. Spinning is predominantly used for the conversion of staple fibres into yarns. Considering the example of a natural fibre (cotton), several sub-stages are involved in this process known as ginning (removing fibres from seed), bailing (Fig. 3c(1)), opening (Fig. 3c(2)), carding (Fig. 3c(3)) (opening into individual fibres), (Lee and Ockendon, 2006) drawing (Fig. 3c(4,5)) (orientation of the fibres) and twisting (Fig. 3c(6)) (to...
increase fibre cohesion) (Lawrence, 2010). Ring spinning technique used in this example enables strong fibre binding via a uniform twist, and, produces hairy yarns with fibre protrusions, which could be important to increase yarn surface area. There are other techniques such as rotor, air-jet, friction, and wrap spinning, providing various degrees of strength, uniformness, and extensibility (Lawrence, 2010). Yarn parameters such as composition, count, twist, production mechanism and life span would influence the mechanical and electrical performance of wearable TENGs.

Filament fibres can be directly converted into yarns using different extrusion techniques (Lawrence, 2010). Common extrusion techniques include wet spinning (polymer dissolved in a solvent and extruded from spinneret submerged in a chemical bath), dry spinning (polymer dissolved in a solvent which is evaporated with hot air after extrusion), melt spinning (George, 1982)( Fig. 3b) (polymer melted before extruding), and, gel spinning (polymer is in gel form, which passes through the air, followed by a liquid bath) (Elsevier, 2005).

Common methods of manufacturing fabrics from yarns include non-woven (Fig. 3e), weaving (De Pauw et al., 2020) (Fig. 3f), and, knitting (Fig. 3g), after which the fabrics are subjected to dyeing (Fig. 3h-k), finishing (Fig. 3l) and garment manufacturing processes (Fig. 3m, n), along with additional operations such as printing (Fig. 3o, p) and embroidery (Fig. 3q) for special requirements.

Woven fabrics are formed by interlacing two sets of yarns known as warps (lengthwise) and wefts (width-wise), in a right angle. Some of the weaving designs include plain weave (Fig. 4a), twill (Fig. 4b), sateen (Fig. 4c) and satin (Fig. 4d) (Adanur, 2000). The manufacturing techniques for weaving include single-phase and multi-phase methods. Single-phase weaving includes shuttle weaving, and, shuttle-less weaving methods (e.g.: air jet, water jet, rapier, and projectile). In the multi-phase category, circular and flat weaving techniques are prominent. Advanced weaving methods such as 3-dimensional (3D) weaving has become increasingly popular, adding structural functionalities to textiles, (Harvey et al., 2019; Schegner et al., 2019) which could be useful in developing custom made high-performance TENGs.

Knitted fabrics are manufactured by inter-looping yarns using weft knitting (Fig. 4e) or warp knitting (Fig. 4f). Weft knitting uses yarns to produce the loops in the horizontal direction (width direction) of the fabric (courses). Some of the common weft-knitted fabric structures include plain (Fig. 4g), rib (Fig. 4h), interlock (Fig. 4i), and purl (Fig. 4j). Speciality knitted fabrics such as 3D knitted and spacer fabrics (M. Zhu et al., 2016) are interesting prospects for textile TENGs due to their desired structural and mechanical functionalities.

In warp knitting, a set of yarns is used to construct loops in the vertical direction (length direction) of the fabric (wales) (Spencer, 2001). Tricot and Raschel are the two main types of warp knit fabric structures. Knitted fabrics allow more design capabilities, along with properties such as stretchability, and conformity, demonstrating the potential to be popular in next-generation smart textile applications (Kwak et al., 2017). A performance comparison between woven and knitted fabrics, which are critical for most of the TENG developments, is provided in Supplemental note 1.

Non-woven process directly converts fibres into fabrics through mechanical or chemical processes, bypassing yarn manufacturing. Nonwoven fabrics have found a variety of applications, especially as technical textiles. These fabrics are produced using techniques such as dry-laid (fibres bonded by mechanical, thermal or chemical processes), wet-laid (similar to paper production) and polymer laid (Fig. 3d) (synthetic filaments extruded by molten polymer) (Russell, 2007) methods, and their physical properties vary according to the production method.

Once a fabric is produced, it is subjected to finishing operations. This includes major steps such as coloration of the fabrics through techniques such as dyeing and printing (Wardman, 2017). The type of colourants and the coloration processes vary significantly depending on the fibre type as summarised in Supplemental note 2. Following textile production, internationally recognised standards are used to evaluate their quality.
3.2. Overview of Textile Based Wearable TENGs

A large variety of wearable TENG designs have been reported in the literature using flexible polymer-based architectures, and, textile-based architectures. In this paper, we focus on textile based TENG developments. Supplemental Note 3 summarises some of the significant textile based TENG developments, based on common textile materials.

From a textile engineering perspective, these TENGs can be linked to different stages of the textile manufacturing process summarised in Fig. 3. Therefore, in the upcoming sections of this work (section 4 and section 5), we categorize the textile-based TENGs into fibre/yarn related developments (relevant to processes depicted in Fig. 3a-d), and fabric related developments (relevant to processes depicted in Fig. 3e-q), to analyse their performance, optimisation procedures, scaling up and potential performance improvement methods. The main parameter that we use for this classification is the stage at which the textile material is triboelectrically functionalised, providing a logical basis for the categorization of textile based TENGs.

However, it is important to note that the TENG technology is still in its early stages, therefore, almost all the fabrication methods are laboratory-based processes which are comparable with the manufacturing techniques described in Fig. 3. Typically, such fabrications take place in forms of triboelectric modifications in yarn or fabric form. For instance, the fibre/yarn based TENG fabrication methods include lab scale electrospinning (Li et al., 2020), wrapping or coiling with a motor (Lou et al., 2020; Ye, Dong, et al., 2020) and twisting techniques (Zhou et al., 2014) etc. These yarns and fibres are typically embedded or converted into fabrics using sewing (Lai et al., 2017; He et al., 2019), hand weaving (Zhang et al., 2016; J. Liu et al., 2019), shuttle weaving (Chen et al., 2016), hand knitting (Dong, Wang, et al., 2017), pilot scale nonwoven techniques (Peng et al., 2019), and embroidery (Sala de Medeiros et al., 2019) methods. On the other hand, fabric based TENG developments utilise techniques such as dip coating and dyeing (Ko, Nagaraju and Yu, 2015; Pu et al., 2015; Seung et al., 2015; Chen et al., 2018), spin coating (Lee et al., 2015), plasma treatment (Matsunaga et al., 2020), screen printing (Paosangthong et al., 2019), electrodeposition (Zhu et al., 2012), reactive ion etching (Ye, Xu, et al., 2020) and lithography (Zhang et al., 2019) etc to triboelectrically modify the contact surface or fabric structure. With this review, we also develop a link between the laboratory-based processes and the industry-based processes explained in Fig. 3, through a detailed discussion on optimisation and scaling up of textile based TENG technology (section 4.4 and section 5.5).

4. Fibre/Yarn related TENG Developments

In our classification, fibre and yarn-based TENGs include the TENG designs in which the major triboelectrically active modifications correspond to one of the stages depicted in Fig. 3a-d of the textile manufacturing process. Considering their structure, fibre/yarn related TENGs are divided into two sub-categories; core-shell and sandwiched structures. TENG developments at fibre/yarn stage allow for maximum control and modification capabilities of the energy generators, (Yu et al., 2017; J. Liu et al., 2019; Ma et al., 2020; Ye, Dong, et al., 2020) however, their handling and processing have been difficult due to small size and weak mechanical properties.

4.1. Core-shell fibre/yarn based TENG

Core-shell fibre and yarn structures are popular for energy harvesting and self-powered sensing. Some of the core-shell TENGs operate in single-electrode mode in which the human skin acts as the counter triboelectric surface, (Dong, Wang, et al., 2017; Park et al., 2017; Dong et al., 2018) whereas some reports indicate dual core-shell structures which contain two triboelectric layers and two electrodes (Tian et al., 2018; J. Liu et al., 2019; Ye, Dong, et al., 2020; Ye, Xu, et al., 2020). Core-shell structure allows the core material to be protected within the surrounding sheath structure, (Cheng et al., 2017; He et al., 2017) with additional advantages such as ease of fabrication and ability to withstand mechanical stresses.
Considering device examples for energy harvesting, Ye et al. (Ye, Dong, et al., 2020) developed an energy harvesting textile by wrapping silk and PTFE fibres (triboelectric surfaces) around stainless steel core yarns (electrodes) (Fig. 5a). Shuttle loom weaving and embroidery techniques were used to construct a fabric using these functional yarns, producing a peak $V_{OC}$~45 V, peak $J_{SC}$~0.2 mA/m$^2$, and, peak power density of 3.5 mW/m$^2$ through a load of 50 MΩ, under a contact separation movement at 2 Hz.

He et al. (He et al., 2017) constructed a multi-layered stretchable and flexible fibre-like TENG (Fig. 5b). A silicone rubber fibre was coated with a CNT based conductive composite ink which acted as an electrode. This was covered by another silicone layer. A copper microwire was wrapped around the outer silicone layer, which acted as the second electrode. Triboelectric charging, in this case, took place between the copper wire and the silicone rubber surface. When relaxed, the copper electrode and the silicone layer are in contact, however, when the fibre is stretched, a gap is created between these two surfaces. This creates a contact and separation action during the stretch and recovery of the fibre, and correspondingly, a current is driven between the copper wire and the CNT electrode. When subjected to 50 % stretch (no. of coils 22 cm$^{-1}$ and 5 Hz frequency, 10 cm length), the device produced peak performances of $V_{OC}$~140 V, $I_{SC}$~0.18 µA/cm, and, the charge density of 6.1 nC/cm. Peak power of 5.5 µW was obtained through a 320 MΩ load, when the fibre was subjected to 50 % stretch at 2 Hz frequency. The applicability of the TENG in energy harvesting was demonstrated by powering a digital watch and a calculator.

Core-shell TENG fibres have also been demonstrated in a number of self-powered sensing applications (Ha et al., 2015; Wang, Lin and Wang, 2015; He et al., 2019). Ma et al. developed a triboelectric yarn using a silver yarn as the core. The shell was fabricated with PVDF/polyacrylonitrile (PAN) hybrid nanofibers via electrospinning (Fig. 5c) (Ma et al., 2020). The triboelectric yarn indicated low weight (0.33 mg/cm), softness, and low diameter (350.66 µm). This yarn was processed into a TENG fabric using weaving, and, operated in SETENG mode, generating a voltage of 40.8 V, current of 0.705 µA/cm and charge density of 9.513 nC/cm$^2$ under a movement of 2.5 Hz and 5 N force. Furthermore, a power output of 336.2 µW/m was generated at 1 Hz operating frequency. A load sensor was constructed using the triboelectric yarn by developing a woven 8x8 pixel array, capable of detecting pressure, location, and magnitude of the applied load.

In another sensing example, Sim et al. developed a stretchable multi-layered core-shell and wrinkled TENG fibre (Fig. 5d) (Sim et al., 2016). Herein, a silver-coated nylon yarn wrapped around a PU fibre acted as an electrode and positive triboelectric layer. An electro-spun PVDF-TrFE mat was wrapped around this fibre, which acted as the native triboelectric material, whereas the outer electrode consisted of CNT sheets. When the strain was increased from 10% to 50% under a 10 Hz movement, this sensor demonstrated an increase of voltage from 13 mV to 24 mV, current from 3 nA to 8 nA and charge from 5.5 pC to 10 pC. A TENG sensor consisting of multiple of these fibres was constructed via weaving, and, demonstrated in sensing mechanical stretch and bending.

Gong et al. (Gong et al., 2017) developed a wearable kinematic sensor based on a stretchable core-sheath structured yarn. A conductive metal core fibre was covered with nylon fibres (Fig. 5e), which acted as the electrode and positive triboelectric surface, respectively. This was placed inside a silicone rubber tube which acted as the negative triboelectric layer. A bamboo fibre/Ag nanowire coating was deposited on the outside of silicone tube which acted as the other electrode, with a layer of PDMS being deposited as the outermost layer of the structure. This device was demonstrated for human motion monitoring, capable of identifying characteristic walking patterns when connected as a knee pad.

Apart from core-shell structures, conductive and non-conductive fibres can be twisted or blended to produce TENGs. For instance, Zhou et al. developed a twisted fibre TENG (Fig. 5f) for wearable applications by twisting cotton threads modified with CNT and PTFE. Cotton thread was coated with CNT using dip coating, obtaining even loading of $\sim$0.207 mg/cm and a conductivity of 1.552
mS/cm. (J. Zhou et al., 2014) An additional coating of PTFE was applied on some of these yarns, and, these two sets of yarns were twisted to construct the TENG, in which CNT and PTFE acted as triboelectric contact surfaces. This device produced an output power density of ~0.1 µW/cm² using finger motion, through a load of 80 MΩ. When combined into a woven fabric and sewn into a lab coat, the TENG was able to charge a 2.2 µF capacitor up to 2.4 V in 27 seconds, under shaking movement.

4.2. Sandwiched fibre/yarn based TENG

Sandwiching fibres or yarns between multiple material layers has been a common strategy used for textile based TENGs. One of the key advantages is that the fibre webs which may not contain required rigidity and durability (e.g.: nanofibers or nanomaterials) can be easily incorporated into TENGs with this method. Electro-spun fibre webs have been a key feature in sandwiched fibre based TENGs.

Among examples for this category, Peng et al. (Peng et al., 2019) developed a TENG based on melt-blown nonwoven fabric for energy harvesting and self-powered sensing (Fig. 6a(i)). This device consisted of nonwoven polypropylene (negative triboelectric surface) and nylon 6,6 (positive triboelectric surface) fabric layers sandwiched between Ni coated nylon fabrics (electrodes) (Fig. 6a(ii)). The optimum output performances of the device were recorded as a peak $V_{OC}$ of 210 V, $J_{SC}$ of 28.3 µA/m², $Q_{SC}$ of 97.3 nC under 6 Hz frequency contact separation movement, for a 60x60 mm² surface area. The peak power density of 901.7 mW/m² was generated through a 70 MΩ resistor. This device was used to charge a 1 µF capacitor to power a digital watch and 124 LEDs by hand tapping. Furthermore, the device was demonstrated for sensing applications, as a pedestrian volume collector and a training monitor.

A hybrid piezoelectric and triboelectric fibre based TENG was developed by Guo et al. (Guo et al., 2018) (Fig. 6b). This device contained silk fibroin and PVDF nanofibers as the two triboelectric surfaces, which were electrospun onto conductive fabrics electrodes. The fibre-based development showed high active surface area and air permeability, and, was capable of being embedded into garments. The peak outputs indicated a $V_{OC}$~500 V, $I_{SC}$~12 µA, and, power density of 310 mW/cm² through a 100 MΩ load when subjected to hand tapping at 2 Hz frequency. This device used to develop a self-powered real-time fall alert system, demonstrating its practical usage.

Number of single electrode mode Fibre type sandwiched TENGs have also been developed. Li et al. (Li et al., 2020) presented a SETENG using carbon nanofibers (electrode) sandwiched between PVDF nanofibers (triboelectric sensing layer) and PU nanofibers (substrate layer) (Fig. 6c). In contact with the skin, the PVDF acquires a negative charge where the skin charges positively, providing the triboelectric charging for the device to operate. This device achieved a peak power density of 85.4 mW/m² through a load of 50 MΩ, under 140 kPa pressure. As a pressure sensor, this device demonstrated a sensitivity of 0.18 V/kPa in the range between 0-175 kPa, retaining almost constant sensitivity up to 50% elastic deformation. An array of these energy harvesters (4 x 4 cm²) were used to illuminate 50 LEDs by hand tapping, while wearing a glove.

In another example, Zhou et al. (Zhou et al., 2020) developed a nanofiber based sandwiched TENG by spraying multiple layers of AgNW and a reduced graphene oxide mixture (electrode), on to thermoplastic PU nanofiber mats (triboelectric surface) (Fig. 6d). This device operated in SETENG mode, using skin as the counter triboelectric layer. The device generated maximum $V_{OC}$~202.4 V, and, instantaneous power density of 6 mW/m² through a 400 MΩ load, when subjected to a movement of 10 Hz, under 10 N contact force. The output performances were stable up to 200 % strain. As a pressure sensor, this device exhibited a sensitivity of 78.4 V kPa⁻¹ in 0-2 kPa range, along with a 1.4 ms response time. A tactile sensor array (5x5) consisting of the TENG units (1 x 1 cm²) was demonstrated to monitor finger motion trajectory.
In a different device architecture, Liu et al. (G. Liu et al., 2018) constructed a TENG based self-powered electrostatic adsorption face mask (Fig. 6e). An electro-spun PVDF nanofiber layer was deposited on the nonwoven substrate, which acted as the negative triboelectric surface. A Cu film was placed opposite to the nanofiber layer to act as the positive triboelectric surface, creating a sandwiched TENG structure. When integrated into a face mask, the inhalation and exhalation actions cause the triboelectric surfaces to contact and separate, which results in triboelectric charging of the two surfaces. According to theoretical simulations, the contact and separation of these triboelectric surfaces resulted in a potential difference of ~2 kV. The TENG based face mask demonstrated removal efficiencies of 99.2 wt. % for coarse and fine particulates, and, 86.9 wt.% for ultrafine particulates, after continually wearing for 4 hours and 30 days interval.

**4.3. Optimization methods for fibre/yarn based TENGs**

The fibre and yarn based TENG developments discussed above, used number of output optimization strategies in material selection and device fabrication, which will be discussed here, in relation to increasing the triboelectric charge density (discussed in Fig. 2c), and, improving electrostatic induction (discussed in Fig. 2d-h).

Considering the charge density improvement, material selection has been a key focus point. Selecting materials further apart in the triboelectric series to obtain higher triboelectric charge separation has been a major strategy (e.g.: polyester and nylon, (J. Liu et al., 2019) silver and PU (Sim et al., 2016)). Moreover, physical and chemical modification of triboelectric fibre/yarn surfaces have been conducted to enhance triboelectric charging. These methods include modifying the triboelectric fibres/yarns by incorporating nanomaterials and nanofibers to improve triboelectric contact areas (Cheon et al., 2018; Guo et al., 2018; Li et al., 2020; Ma et al., 2020; Zhou et al., 2020), and, the development of composite materials related triboelectric fibres and yarns (Kim et al., 2020).

Furthermore, fibre type TENG architectures have been designed to facilitate improved contact between the triboelectric surfaces. For instance, some devices have been constructed with materials such as PU (Sim et al., 2016; Yu et al., 2017; Zhou et al., 2020) and PDMS, (Gong et al., 2017; He et al., 2017) which provide conformal properties during contact and desirable frictional characteristics.

Several output optimization methods have been used to improve electrostatic induction. Controlling the thickness of the dielectric layer of fibre type TENGs, especially in core-shell device architectures, has been shown to increase the electrical outputs (W. Gong et al., 2019). Similarly, larger TENG surfaces were shown to increase the output performances (Li et al., 2020). The importance of dielectric constant during material selection and environmental conditions such as the medium in which the TENGs are operating, towards enhancing TENG outputs has been highlighted in fibre based TENG studies (W. Gong et al., 2019). The motion parameters critically affect the output enhancement to fibre type TENGs, where, increasing the operating frequency and amplitude of the TENG increased current, voltage, and power outputs (Li et al., 2020; Zhou et al., 2020).

**4.4. Future perspectives of fibre/yarn based TENG**

Early fibre/yarn based TENG developments used traditional textile materials (cotton (J. Zhou et al., 2014), nylon (Gong et al., 2017)) and rigid structures in synergy to enhance the power output of wearable TENGs, with less focus on wearer comfort. However, more recent TENG developments focussed on obtaining improved performances in both electrical and wearable aspects. For instance, some developments focussed on flexible TENG designs with core-shell architectures, using soft core filaments (He et al., 2019; Lou et al., 2020; Ye, Dong, et al., 2020) and micro-fibrous shell materials, (Ma et al., 2020) as opposed to conventional rigid metallic filaments. Several of these devices (Yu et al., 2017; Lou et al., 2020) showed acceptable levels of washability, while other important wearable properties like moisture management and breathability are yet to be investigated. There has been an increasing interest in using nanofibrous structures to enhance the surface area of sandwich structured TENGs, which act favourably on moisture management properties (e.g.: water vapour transmission rate of 10.26 kg m⁻²d⁻¹) and air permeability (Li et al., 2020; Zhou et al., 2020).
that utilize thin coatings using atomic deposition methods have been fabricated, however, these
coatings exhibited poor washability and low mechanical robustness (J. Zhou et al., 2014).
Tailorability is another important parameter that governs the wearability of textile based TENGs.
Several studies have shown interest in addressing tailorability by using core-shell structured yarns
(Yu et al., 2017; Ye, Dong, et al., 2020) and sandwiched device structures (Guo et al., 2018).

Many textile based TENG developments so far have been limited to lab-scale, with significant
pragmatic concerns to be addressed before scaling up or commercialization. One of the main
concerns is the compatibility of conventional large-scale fibre/yarn manufacturing techniques with
the intricate designs of TENG designs developed so far, which will massively benefit the scaling up of
this technology. Therefore, it is important for TENG developers to be aware of the general
requirements and guidelines of the techniques and machinery used in the fibre/yarn spinning
industry. Almost all wearable developments based on triboelectric fibres/yarns are finally integrated
into garments via fabric manufacturing processes of weaving, knitting, or nonwoven, and, subjected
finally to sewing. Herein, the yarn diameter becomes a critical parameter. Considering weaving, the
diameter should be compatible with the weft insertion mechanism and machine type in the
commercial weaving processes. The yarn diameter is also an important factor in the knitting process
where the knitting ability depends on the insertion of triboelectric yarn into the knitting needles.
Furthermore, due consideration of the ‘gauge’ (the number of needles per unit length) of knitting
machines is of paramount importance for the compatibility of triboelectric yarns with the knitting
process. Other important parameters/requirements of both weaving and knitting processes are yarn
uniformity, flexibility, and high tensile strength (Adanur, 2000; Spencer, 2001; Ahmad et al., 2017).
As a guideline, a summary of the critical yarn requirements for common commercial fabric
manufacturing processes is provided in supplemental note 4. Tailorability of triboelectric yarns
requires meeting sewing requirement such as strength, abrasion resistance, low shrinkage etc.
Supplemental note 5 consists of a summary of such parameters (Ahmad et al., 2017).

Number of yarn processing techniques used in the textile industry can be applied for the fibre/yarn
type TENG developments and their output enhancement. Mechanical structural design (MSD) is a
prominent method that could potentially be used to enhance triboelectric charge density
(Dharmasena and Silva, 2019) by increasing the surface roughness and surface features of the fibres
and yarns. MSD can be applied for yarn processing techniques such as drawing, plying, twisting,
texturing, spinning, and covering, that can be adapted for TENGs (Lawrence, 2010; Zhang, 2014). For
instance, Air jet texturing is a method of creating bulky yarns (Sengupta, Kothari and Sensarma,
1995) from synthetic filaments, which significantly enhances their hand feel, comfort, and surface
features (Acar et al., 2006). Partially drawn yarn (PDY) can be used in the texturing process to
increase the bulkiness and the surface area by introducing extra length of loops and neps into the
yarn, which could enhance TENG output performances (Sengupta, Kothari and Sensarma, 1995;
Cayuela et al., 2012; Choi and Kim, 2015). Yarn covering is another process used in the textile
industry to wind a cover yarn around a stretchable or conductive core yarn, and, this process has the
potential to develop improved core-axial materials for TENGs (Yoshimura et al., 1969; Petrulis and
Petruiltye, 2009). For instance, hollow spindle covering is a well-known method to produce single and
double-covered yarns. Such processes would provide high yarn uniformity (Park, Kim and Kim, 2018),
higher surface area, (J. Wang et al., 2015; Asghar et al., 2019) better moisture management and air
permeability, (Lawrence, 2010; J. Wang et al., 2015) which will significantly enhance electrical and
wearable output performances of fibre/yarn-based TENGs.

5. Fabric related TENG Developments

Textile based TENG developments in which the major triboelectric functionalisation occurred in the
fabric stage (processes depicted in Fig. 3e-q) are categorized as fabric-related TENGs in this work.
Fabrics have been used as triboelectric layers, electrodes, and/or the substrates of TENGs
(Paosangthong, Torah and Beeby, 2019). Compared to fibre and yarn based TENGs, developing
wearable TENGs in the fabric stage facilitates convenience in handling, fabrication, and
functionalization. However, the construction of high performing fabric TENGs while retaining aesthetic and wearable properties has been challenging. Fabric-based TENGs are divided into three categories based on their structure and manufacturing method; woven, knitted and nonwoven based TENGs. Supplemental Note 6 summarizes some of the significant wearable TENG developments, based on common fabric structures.

### 5.1. Woven fabric related TENG

Woven fabric related TENGs are the most common type among fabric based TENGs (Pu, Li, *et al.*, 2016; Pu, Song, *et al.*, 2016; Shi *et al.*, 2017; Chen *et al.*, 2018, 2020; Ning *et al.*, 2018; L. Liu *et al.*, 2020; Lou *et al.*, 2020). This section discusses woven fabric related TENGs in which the major triboelectric functionalization took place during or after the weaving process. Such devices are analysed under two categories depending on the functionalization method, namely, surface modified, and, structurally modified woven fabric TENGs.

#### 5.1.1. Surface modified woven fabric based TENG

Woven fabrics can produce even and closely bound fabric surfaces for TENG fabrication. Therefore, they have been utilized as substrates or triboelectric interfaces, often in combination with nano/micro-structured surface modifications applied chemically or mechanically to improve contact area and frictional properties, targeting to enhance the triboelectric charge density (Ko, Nagaraju and Yu, 2015; Lee *et al.*, 2015; Pu *et al.*, 2015; Seung *et al.*, 2015; Xiong *et al.*, 2018).

Among examples in this category, Lee et al. (Lee *et al.*, 2015) developed a TENG using a gold (Au) coated woven textile (7 x 7 cm²), Aluminium (Al) nanoparticles, and PDMS (Fig. 7a). To create the top TENG layer, Al nanoparticles (triboelectric surface) were grown on the top of an Au-coated textile (electrode). Bottom TENG layer was produced by spin coating PDMS (triboelectric surface) over an Au-coated textile, followed by reactive ion etching which created a nanostructure with 150 nm diameter and 2.5 µm height. The device generated a maximum $V_{OC}$ of 368 V and $I_{SC}$ of 78 µA by bending at 100 mm/s and 3 cm bending length. A maximum power density of 33.6 mW/cm² was achieved through a 20 Ω load, under a 20 mm/s operation speed and 3 cm length. Attached onto an arm sleeve, the TENG was used to light up several LEDs using bending and releasing motion.

An oblique PDMS microrod array-based TENG was developed by Zhang et al. (Zhang *et al.*, 2019), for wearable energy harvesting (Fig. 7b). In this structure, the top TENG layer was prepared with a nylon woven fabric by printing carbon paste on one side (electrode), and, using reactive ion etching to create evenly distributed nanowires (diameter of 30-50 nm) (triboelectric surface) on the other side. PDMS microrods (25 µm diameter, 30 µm length, 30° inclined) (triboelectric surface) were structured over a spandex fabric (containing carbon paste as the electrode), using lithography and template transfer techniques (Fig. 7b(iii)), which was used as the bottom TENG layer. This device recorded a $V_{OC}$ of 1014.2 V, $I_{SC}$ of 3.24 µA/cm², and charge density of 10.28 nC/cm², under 5 Hz frequency and 10 mm amplitude movement (30% humidity, at 16°C). Furthermore, a maximum power density of 211.7 µW/cm² was reached through a 6 MΩ load, and, 48 commercial red LED bulbs connected in series were lit up simultaneously using continuous hand tapping.

Some recent woven fabric TENGs have focused on wearable properties such as air permeability, and washability alongside power enhancement. For example, Xiong et al. (Xiong *et al.*, 2018) developed a TENG by applying black phosphorus(BP) encapsulated hydrophobic cellulose oleoyl ester nanoparticles(HCOENP) on PET fabric (HPB fabric - triboelectric layer), along with a waterproof fabric and a fabric electrode (Fig. 7c). The static contact angle of 153° for the SETENG structure ensured superior hydrophobic properties over the fabric. This device also showed $1068±3$ L m⁻² s⁻¹ air permeability. Using skin as the secondary triboelectric layer, the TENG generated peak $V_{OC}$ of 880 V, $I_{SC}$ of 1.1 µA/cm² under hand touching which exerted a 5 N force at 6 Hz frequency. This device generated a power density of 0.52 mW/cm² through a 100 MΩ load, and, 150 LED bulbs were illuminated through hand tapping movements (<5 N, 4 Hz).

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Medeiros et al. (Sala de Medeiros et al., 2019) developed an omniphobic TENG by combining embroidery and spray deposition of conductive nanoflakes, PTFE, and fluoroalkylated organosilanes, in a twill woven fabric substrate. Herein, the top TENG layer was prepared (Fig. 7d(i)) by spraying fluoroalkylated organosilanes (to obtain omniphobic properties and act as a triboelectric surface) followed by Ag nanoflakes (electrode) on a laser-cut stencil to create the required design. This layer was protected by embroidering a shape matching design on the top of it. In the bottom layer (Fig. 7d(ii)) a spandex fabric was treated for omniphobic properties, then sprayed with Ag nanoflakes (electrode) followed by a PTFE layer (~8 µm) (triboelectric layer). The device demonstrated flexibility, lightweight, and air permeability of ~90.5 mm/s. When the two triboelectric layers were combined (device size 6.25 cm$^2$), peak $V_{OC}$ of 300 V, $I_{SC}$ of 80 µA was generated by two fingers tapping at 4 Hz frequency. The maximum power density of 600 µW/cm$^2$ was recorded from this device, through a 1 MΩ load. The device was attached into the collar of a shirt to the control volume, pause and resume functions of a music player integrated into the textile.

5.1.2. Structurally modified woven fabric based TENG

Some of the woven fabric based TENGs have been constructed using fabric structural modifications which include woven pattern variations, (Zhao et al., 2016; Zhao et al., 2016; Chen et al., 2018, 2020; Ning et al., 2018; Ma et al., 2020) grated fabric structures, (Pu, Song, et al., 2016; Paosangthong et al., 2019) corrugated structures, (Choi et al., 2017) and wrinkled structures (Liu et al., 2020) etc., which we discuss in this section. Such modifications are viable during weaving since two different yarn sets (warp and weft) are being interlaced.

For instance, Zhao et al. (Zhao et al., 2016) developed a machine washable TENG for human respiratory monitoring using shuttle weaving technology, which comprised of a Cu/PET yarn structure (~300 µm diameter) as warp yarns, and, polyamide coated Cu/PET yarn structure (~350 µm diameter) as weft yarns (Fig. 8a(i)). When subjected to tapping motion at 10 cm/s, the device produced a peak $V_{OC}$ of 4.98 V, $J_{SC}$ of 15.50 mA/m$^2$ and maximum power density of 33.16 mW/m$^2$ through 60 MΩ load. This device indicated air permeability of 0.17 ± 0.03 kPa s/m and good washability. The TENG was used to obtain respiratory rate and depth information, being used as a self-powered respiratory monitoring device. Additionally, a theoretical platform was constructed to relate woven fabric parameters with the electrical performances of the TENG (Fig. 8a(ii-v)), which will be further discussed in section 5.4.

Utilizing more advanced weaving techniques, Dong et al. (Dong, Deng, et al., 2017) developed a 3D orthogonal woven structure, consisting of 2D plain fabrics (stainless steel warp/PDMS coated stainless steel weft) connected by non-conductive binding yarns (z-yarn) (Fig. 8b(i,ii)). Compared to a 2D plain-woven fabric, the 3D structure provided enhanced surface area, allowing the generation of high surface charges along with improved breathability, flexibility, and comfort. This device (area 45 x 40 mm$^2$) generated a peak $V_{OC}$~45 V, $I_{SC}$~1.8 µA, and charge~18 nC under 5 Hz frequency and 25 mm amplitude tapping movement. A power density of 263.36 mW/m$^2$ was achieved through a 132 MΩ load when the device was subjected to 3 HZ movement, and, a 0.68 µF commercial capacitor was charged to 2.5 V within 7 seconds by hand tapping.

The structural modification capability of woven TENGs has been demonstrated to address inherent performance issues of TENG technology such as their power management. For example, Chen et al. developed an energy harvesting and storage integrated woven textile (Fig. 8c(i)) (Chen et al., 2018) using shuttle weaving. In this FSTENG based energy harvester, the dielectric woven fabric was constructed using cotton in the warp direction, with cotton and PTFE yarns inserted selectively as the weft. The electrode of this device was woven by using cotton in the warp direction, while cotton and carbon fibre yarns were inserted selectively as the weft). Different carbon fibre electrode segments were connected through loads to harvest output energy, generated through relative movement between the dielectric fabric layer and the electrode fabric layer. A supercapacitor woven fabric was constructed using cotton yarns in the warp direction, and, the weft consisting of
carbon fibre yarn electrodes, RuO$_2$ coated carbon fibre yarns (separated by cotton threads), and PVA/H$_3$PO$_4$ gel electrolyte coated carbon fibre yarns. The TENG device, subjected to 20 cm/s sliding speed, generated a peak $V_{OC}$~118 V, $I_{SC}$~1.5 µA, and, charge of 48 nC. The output characterization indicated improved performance at low yarn diameters (Fig. 8c(iii)) and low weft yarn gaps (Fig. 8c(iii)), potentially due to increased cover factor of the fabric. This device was stitched on to a hand glove and the rubbing and patting movements were used to illuminate 18 LEDs.

Similarly, Chen et al. (Chen et al., 2020) developed direct current (DC) woven fabric TENG to address discontinuity of electrical outputs of a textile-based TENG, along with improved wearable properties. In this woven structure, three plied twisted nylon 6,6 was used as warp yarns. The weft consisted of two types of yarns, nylon nonconductive yarns, and, nylon conductive yarns with an Ag coating which were separated as two electrodes (electrostatic breakdown yarns (0.4 mm diameter) and frictional yarns (0.52 mm diameter)) (Fig. 8d(i)). The area density of the fabric was 326 g/m$^2$. With the combined effect of electrostatic induction and electrostatic breakdown effects, this device produced DC outputs for voltage (Fig. 8d(ii)), current (Fig. 8d(iii)), and charge (Fig. 8d(iv)). The device (6.8 x 7 cm$^2$) generated a peak $V_{OC}$ of 4500 V, $I_{SC}$ of 40 µA, and, short circuit charge ($Q_{sc}$) of 4.47 µC, by moving a PTFE film over the device at 0.01 m/s for a moving distance of 20 mm, with a weight of 1 kg. A yarn-based supercapacitor was constructed using two sets of carbon fibres (electrodes) coated with Nafion, PEDOT: PSS, and solid-state H$_3$PO$_4$/PVA gel electrolyte along with this TENG device. The outputs from the small size TENG (1.5 cm x 3.5 cm) was used to light up 416 LEDs (serially connected).

### 5.2. Knitted fabric related TENG

Knitted fabrics are gaining increasing popularity in constructing fabric type TENGs, due to its improved wearable and comfort characteristics such as high stretchability and breathability. (Spencer, 2001) Using three main stitch types; knit stitch, tuck stitch and miss stitch (Fig. 9a), and, combining different inter looping patterns, a wide variety of knitted fabric types are constructed at present. (Spencer, 2001) Majority of knitted fabric TENGs developed so far, focussed on weft knitted structures (Fig. 4e) which include 2D fabrics as well as 3D knitted structures. (Dong, Wang, et al., 2017; Kwak et al., 2017; Huang et al., 2019)

Considering 2D knitted examples, Huang et al. (Huang et al., 2019) developed a FSTENG (Fig. 9b(i)) using a simple plain knit. One of the triboelectric layers (9x10 cm$^2$) consisted Ag coated nylon yarns (positive triboelectric surface and electrodes) and cotton yarns (separating the electrodes). The counter triboelectric layer (9x5 cm$^2$) was constructed using a PTFE membrane (triboelectric surface) attached to a polyester fabric. The sliding movement between the two TENG layers was used to generate power (Fig. 9b(ii)), exhibiting acceptable air permeability (884.78 mm/s), washability, and flexibility for wearable applications. Different fabric textures of the knitted fabric (technical front and back sides) were investigated with regards to output performances, with the highest performance of the TENG being a peak $V_{OC}$ of 900 V, $I_{SC}$ of 19 µA, and, a peak power density of 203 mW/m$^2$ (through a 80 MΩ resistor), obtained using a simple swinging motion. The applicability of this device for powering electronics was demonstrated by lighting up 51 LEDs using arm swinging motion.

In a relatively complicated design, Fan et al. (Fan et al., 2020) constructed a knitted TENG sensor array using a stainless steel/terylene twisted yarn (electrode and negative triboelectric layer) and a nylon yarn (positive triboelectric layer) plated together, in a full cardigan knit (Fig. 9c(i)). The device was fabricated using a double bed flat knitting machine, where the conductive yarn and nylon yarn were tucked alternatively in front and back needle beds, obtaining a complete plating rather than a point contact. The capability of this architecture in pressure sensing was investigated while varying the yarn parameters. Among different yarn parameters, 210D/3 (3 plied, 210 deniers) conductive yarn along with 210D/6 (6 plied, 210 deniers) nylon yarn provided the best output performances, demonstrating pressure sensitivity of 7.84 mV/Pa up to 4 kPa, and, sensitivity of 0.31 mV/Pa thereafter. The device demonstrated fast response time (20 ms) in 1-5 Hz frequency range, under 1
kPa pressure. Applicability of this device in self-powered epidermal physiological monitoring was demonstrated by sensing pulses from the neck, wrist, fingertip, and ankle (Fig. 9c (ii,iii)).

Several 3D knitted TENG fabrics have been reported for energy harvesting and sensing purposes. For example, Gong et al. (J. Gong et al., 2019) developed a wearable TENG based on 3D knitting (spacer fabric) techniques, which operated in the SETENG working mode (Fig. 9d). Herein, Ag coated nylon yarns were used to knit the top fabric, which acted as electrode as well as the positive triboelectric surface. A PAN based yarn was used to construct the bottom fabric, acting as the negative triboelectric surface. Cotton was used as the spacer yarn, which connected the top and bottom fabrics, creating a 1 mm spacer gap. In terms of comfort properties, the device indicated an improved thermal conductivity of 8.35 x 10^{-2} Wm^{-1} K^{-1} (higher than cotton) and high air permeability of 0.834 kPa s/m. During performance characterization, a PDMS film was used as a triboelectric element to contact and separate with respect to the conductive layer, and, under a contact force of 1200 N, the device generated a maximum power density of 1768.2 mW/m^2 through a 50 MΩ load. This device was used to illuminate up to 320 commercial LEDs, and, to charge a 200 µF commercial capacitor at a rate of 11.3 mV/s.

5.3. Nonwoven fabric related TENG

Being a relatively innovative manufacturing method, nonwoven fabrics provide advantages such as ease of fabrication and scaling up, fast production rates, and, compatibility with a large variety of fibre types. While not being as popular as woven or knitted developments, limited number of nonwoven related TENG designs have been presented in the literature (G. Liu et al., 2018; Peng et al., 2019; Wang et al., 2019), which used the nonwovens as the substrate of the TENG architecture. We note that, in our categorisation, these particular examples fall under sandwiched fibre structured TENG category (section 4.2), since the main triboelectric modification took place at the fibre stage of the active materials. However, looking at the origin and the fast growth of nonwovens in the mainstream textiles industry, it is highly likely that non-woven based standalone TENG developments will be available in near future.

5.4. Optimization methods for fabric based TENG devices

Analysing fabric based TENGs discussed in sections 5.1 – 5.3, several key optimization techniques can be identified. Among theoretical developments, Zhao et al. (Zhizhen Zhao et al., 2016) presented a set of equations to approximate voltage and current outputs of a woven fabric (Fig. 8c (ii)-(v)). According to this model, increasing the triboelectric charge density, separation velocity, and, reduction of dielectric constant of the fabrics result in higher TENG outputs, agreeing with the DDEF model predictions (Fig. 2). On the other hand, experimentally demonstrated optimizations for fabric based TENGs can be related to triboelectric charge density improvements, and, electrostatic induction enhancements. Considering charge density improvements, selecting triboelectric materials further apart in the triboelectric series has been a major focus. (Pu, Li, et al., 2016; Pu, Song, et al., 2016; Shi et al., 2017; Chen et al., 2018, 2020; Ning et al., 2018; L. Liu et al., 2020; Lou et al., 2020) Furthermore, physical and chemical modifications of triboelectric materials and contact surfaces have also been successfully implemented in this regard. For instance, composite material structures have been used for fabric based TENG developments, obtaining higher triboelectric charging. (Bai et al., 2019; Guo et al., 2020; H. Liu et al., 2020) Similarly, constructing surface patterning on fabrics (Choi et al., 2017; Huang et al., 2019; Paosangthong et al., 2019; Zhang et al., 2019) (e.g.: grated or corrugated structures, reactive ion etching), and, the use of nanomaterials and nanopatterning techniques to enhance triboelectric contact area (Lee et al., 2015; Xiong et al., 2018), were successfully implemented to improve triboelectric charge density, thus, enhancing TENG outputs. Furthermore, charge density enhancements have also been achieved by increasing triboelectric contact area via improvements in fabric structure. Some of such methods include designing fabrics using rough fibres with surface features (e.g.: natural fibres), (Zhang et al., 2016) stretchable fabrics (e.g.: 2x2 rib knit),
Early fabric based TENG developments mainly used woven fabrics, relying on surface modifications via triboelectric coatings (Ko, Nagaraju and Yu, 2015; Lee et al., 2015) and nanostructures (Lee et al., 2015; Seung et al., 2015) to increase electrical outputs, with less attention given to wearable properties. However, with the progress of the technology, it has become increasingly clear that the success of fabric based TENGs depends on obtaining an acceptable balance between the electrical outputs and wearable properties. More recently, a range of fabric manufacturing methods (knitting, nonwoven, braiding), and, surface modification techniques (printing, nanoparticle deposition, fabric pattern variation, grated structures) have been used, obtaining enhanced wearable properties (air permeability~1068 L/m² (Xiong et al., 2018), thermal conductivity~8.35 x 10⁻² W/m K, (J. Gong et al., 2019) less bulk (<0.08 g/cm² (J. Gong et al., 2019)), washability, tactile properties), in addition to improved electrical performances.

Expanding beyond lab scale towards mass scale production and commercialization, fabric based TENGs need to be examined in different viewpoints. Firstly, wearable properties of fabric TENGs need to be improved to make them more attractive to the users. Triboelectric modifications typically tend to degrade fabric wearability. Ideally, if textile based TENG designs can be engineered to comply with the standard performance requirements of commercial textiles, they can be readily integrated into garments without compromising wearable properties. In this regard, fabric weight, fabric strength, air permeability and thermal conductivity etc. need to be considered. Fabrics are divided into several of weight categories; very lightweight (<1 ounce per square yard (oz Yrd²)), light weight (2 – 3 oz yrd²), medium weight (5 – 7 oz yrd²) and heavy weight (>7 oz yrd²) (Li and Dai, 2006), and, their applications depend heavily on this categorisation (supplemental note 7). Obtaining the desired weight range for a given wearable TENG application is therefore a critical design factor. Fabric strength need to comply with the requirements for specified applications, however, the exact strength specifications vary depending on the apparel manufacturers. Air permeability greatly affects the comfort of a garment, and, for a typical textile product, this should be kept between 0.05–0.5 m/s to be comfortable for a wearer (Bartels, 2011). The thermal comfort of a fabric depends on its thermal conductivity, which again varies with the end application of the textiles, as summarised in supplemental note 7 (Bartels, 2011). Secondly, ensuring processability of TENG fabrics using existing textile technologies for dyeing and finishing etc., will allow their streamlined scaling up. The main parameters affecting this processability includes fabric weight and strength, and the TENG fabrics should be designed to comply with these requirements (Hu, 2008). Therefore, in our view, wearability and scalability factors are pivotal in the future success of textile based TENG technology, and, should be given careful consideration when designing TENGs.
In a textile engineering perspective, several common fabric manufacturing techniques can potentially be used to develop fabric based TENGs with enhanced power generation and wearable properties. One of the interesting aspects to consider is the fabric formation methods which allow precise control of the position, movement, and timing of individual yarns (both width wise and lengthwise directions). Such technologies will allow the construction of carefully engineered fabric structures with desired surface textures, porosity, flexible and stretch characteristics etc., enabling improved electrical and wearable properties for TENGs. Jacquard weaving is one such fabric formation method, which facilitates the individual control over each warp and weft yarn of a fabric (Adanur, 2000). Jacquard knitting allows the precise control of each knitted loop by controlling the needle movements and yarn insertion (Spencer, 2001). These Jacquard methods provide the potential of constructing TENG architectures with different fabric structures, triboelectric materials, and surface textures, which would enhance triboelectric properties as well as wearable characteristics. Secondly, the manufacturing techniques which facilitate the construction of multiple fabrics with different materials combined onto a single fabric structure is another useful prospect. These methods include computerised flatbed knitting, 3D knitting, (Munden, 1959; Spencer, 2001; Maziz et al., 2017) 3D weaving, and multiphase weaving (Gandhi and Sondhelm, 2016) techniques, that could allow stand-alone compact TENG architectures with desirable motion characteristics. Conventionally, TENGs have been incorporated into specified regions of garments, for example the underarm area (Ning et al., 2018) and the sleeves, (Haque, Farine and Briand, 2018) considering the availability of high mechanical power. Instead of traditional integration techniques such as sewing, fabric development methods such as the Intarsia knitting technique can be used to incorporate triboelectrically active TENG regions into selected parts of a garment panel with high integrity and seamless finishes, (Spencer, 2001) providing the potential to significantly enhance their wearable characteristics.

6. Testing of Textile based TENGs

Within the brief history of textile based TENGs, standard techniques to measure their wearable or electrical performances have not yet been established. Herein, we summarise standard test methods used for generic textiles (supplemental note 8) as a guideline for testing wearable properties of textile based TENGs, along with a summary of electrical characterisation methods commonly used for TENGs. While the type of testing and the threshold evaluation values may vary depending on their end use, examining these test methods could guide the development of future standards for textile based TENGs.

Considering the wearable characteristics of generic textiles, several test categories including structural, durability, comfort and aesthetics, and safety testing can be identified. In addition, a test category termed intelligent testing is being developed to evaluate the performance of smart textiles. These test standards are presented by Internationally recognised bodies such as ISO (International Standard organization), BSI (British Standard Institution), ASTM (American Society for Testing and Materials), and AATCC (American Association of Textile Chemists and Colourists) (Hu, 2008). The basic test parameters and the test methods of each of the above test categories are summarised in supplemental note 8. Designing future textile based TENGs adhering to these specifications and using the standards as guidelines will ensure that the TENGs contain required wearable properties, which is massively beneficial for their end users.

Textiles should not contain any substances which are harmful to human health such as cytotoxic, irritating or carcinogenic matter etc., since they contact human skin and the body. According to REACH (the governing body for European chemical registration, evolution, authorization, and restrictions) there are strict regulations against hazardous substances in textiles, some of which are summarised in supplemental note 9 (Das, 2013). In our view, wearable TENGs should be designed within these guidelines to ensure the safety of the wearers.
Electrical characterisation of textile based TENGs is conducted by different research groups using different methods. These methods include the measurement of current, voltage, charge and power outputs, using oscilloscopes or electrometers, (Dudem et al., 2019; Paosangthong et al., 2019; Sala de Medeiros et al., 2019; Wang et al., 2020) when the TENG is subjected to mechanical excitation. Mechanical excitation could be provided manually (hand tapping, (Lai et al., 2017; G. Liu et al., 2018; Mallineni et al., 2018; Yang, Sun, et al., 2018) bending (J. Zhou et al., 2014; Zhang et al., 2016, 2019; Dong, Deng, et al., 2017)) or mechanically (linear motor (Dong, Wang, et al., 2017; Zhao et al., 2020), shaker (Dudem et al., 2019, 2020)), with a specified amplitude and speed. In addition, unique analysis techniques such as TENG impedance plots, TENG power transfer equation, and voltage-charge (V-Q) plots are used to investigate TENG outputs. However, the TENG outputs are highly sensitive to number of material, structural, motion, and environmental parameters, as well as to the electrical measurement methods (Dharmasena et al., 2017, 2018; Dharmasena, Deane and Silva, 2018; Dharmasena and Silva, 2019). Therefore, output characterisation and reporting for textile based TENGs have often been non-standard, and, performance comparison between different devices has not been feasible. This calls for the urgent need to develop standard output characterisation methods for TENG devices.

7. Summary and Outlook

Triboelectric Nanogenerators are widely regarded as one of the most promising candidates to power the next generation of low-power electronics for mobile, portable and wearable applications. More recently, significant efforts have been directed towards constructing wearable TENGs to harvest mechanical energy generated through human body movements to power smart textiles and health sensors etc. To this end, textile technologies provide a wide range of possibilities in constructing highly efficient wearable TENG architectures. In this work, we presented a comprehensive analysis on the textile based TENG technology with device optimisation and textile engineering perspectives. Following a brief introduction to TENGs, we created a broad platform on TENG output optimization based on our previous theoretical and experimental studies. The technological landscape of textile based TENGs was discussed in relation to the textile manufacturing process, bridging these apparently distant but closely interrelated technical disciplines. Textile based TENGs were classified under fibre/yarn or fabric based developments, considering the stage at which the triboelectric functionalisation takes place in relation to the textile manufacturing process. State-of-the-art developments of each of these TENG categories were highlighted. Subsequently, the progress and optimisation techniques used in recent textile based TENG developments were thoroughly examined. Within the device optimisation criteria, we discussed textile manufacturing methods and processes applicable for the fabrication of TENGs, which contain the potential of enhancing their performances. The success of TENGs in wearable applications depends on the ability to obtain an appropriate balance between their electrical and wearable properties. Herein, we provided insights on the improvement of key textile parameters affecting TENG wearable aspects as well as electrical performances. Scaling up of textile based TENG technology was a major focus point in this work, and, the compatibility of TENG designs with existing textile machinery and processes was highlighted as a main strategy of achieving this target. To this end, a set of specifications for TENG design parameters were presented as a guideline to ensure this compatibility. Finally, the testing standards potentially applicable for evaluating wearable and electrical properties of textile based TENGs were summarized. In our view, complying with these test standards and guidelines will be pivotal for successfully fabricating textile based TENGs, and, their scaling up using well established textile related technological resources.

Exploring the outlook and prospects of this technology, number of exciting contemporary trends can be observed. Recent textile based TENG architectures have produced significantly high electrical output performances (J. Gong et al., 2019; Sala de Medeiros et al., 2019; Chen et al., 2020) and
improved wearable characteristics (Xiong et al., 2018; J. Gong et al., 2019) which can be attributed
to several factors. There were wide expansions in the range of materials used in textile based TENGs,
including conventional and modified textile related materials (Shi et al., 2016; Choi et al., 2017; Gong
et al., 2017; Song et al., 2017; Yao et al., 2017; Chen et al., 2018; Ning et al., 2018; He et al., 2020;
Ye, Dong, et al., 2020) and conductive polymers (Li et al., 2016; Dudem et al., 2019) etc. along with
improved application techniques such as enhanced coating methods (J. Zhou et al., 2014; Sala de
Medeiros et al., 2019) and deposition techniques, (J. Zhou et al., 2014; Choi et al., 2017; Huang et al.,
2019; Paosangthong et al., 2019; Zhang et al., 2019) resulting in improved TENG performances. The
structural developments of TENGs have also boosted TENG performances, which were obtained
through various micro-fabrication techniques and textile manufacturing methods (e.g.: weaving, (Pu,
Li, et al., 2016; Pu, Song, et al., 2016; Shi et al., 2017; Chen et al., 2018, 2020; Ning et al., 2018; L. Liu
et al., 2020; Lou et al., 2020) knitting, (Dong, Wang, et al., 2017; Kwak et al., 2017; Huang et al.,
2019) nonwoven (G. Liu et al., 2018; Peng et al., 2019) etc.). More recently, some TENG designs
utilized cleverly designed hybridisation of several textile manufacturing techniques, which include
hybrid knitted/woven (Yi et al., 2019) fabric structures, and, hybrid yarn/fabric based structural
modifications, (Liu et al., 2016) providing enhanced wearable and electrical functionalities compared
to conventional devices. Furthermore, textiles have been increasingly used as triboelectric
components and active structural elements, providing an escalated degree of device integration.

Developing multi-functional energy harvesting textiles is another notable trend, achieved by
hybridizing different technologies. A number of textile based TENGs were presented, integrating
triboelectric energy harvesting and wearable energy storage components, attempting to minimize
this issue (J. Wang et al., 2015; Pu et al., 2015; Pu, Li, et al., 2016; Wen et al., 2016; Dong, Wang, et
al., 2017; Song et al., 2017; Yang, Xie, et al., 2018). Furthermore, harvesting energy from multiple
sources through hybrid triboelectric/piezoelectric, (Kim et al., 2017; Guo et al., 2018) triboelectric/solar cell, (Chen et al., 2016; Wen et al., 2016) triboelectric/thermoelectric, and, triboelectric/solar cell/energy storage *(Wen et al., 2016)* structures was demonstrated which would enable self-powered wearable energy systems that efficiently utilize multiple ambient energy
sources with a high degree of autonomy. There have been significant improvements in theoretical
modelling and optimisation methods supported by the DDEF model, TENG impedance plot, V-Q plots
eq etc., which can be effectively used to further improve the textile based TENG performances.

Furthermore, recent investigations into TENGs have uncovered underlying reasons behind their
inherent drawbacks such as the discontinuous and irregular output generation, (Dharmasena, 2020)
and, several innovative methods have been presented such as the development of direct current
TENG (DC TENG) (D. Liu et al., 2019; Dharmasena et al., 2020) to overcome such issues. These
prospects would potentially pave the way towards highly efficient energy harvesting textiles with
wearable and durable properties comparable to typical garments in the future.

Several challenges need to be overcome in this technology, to enable sustainable device structures
and their scaling up. The electrical output performances of textile based TENGs still fall behind
conventional plastic based TENG architectures, (Dharmasena and Silva, 2019) which need to be
improved. This could potentially be achieved via developing triboelectric polymers with stable and
high triboelectric charge densities, high conductivity electrodes with wearable and safety
characteristics, and, highly efficient textile structures which provide improved friction properties and
high-speed movements. Similar strategies could be used to improve wearable characteristics such as
comfort properties, durability against the harsh usage conditions of textiles, and safety, which are of
equal importance as the electrical properties in a wearable TENG context. Scalability of textile based
TENGs need to be carefully considered in order to make them commercially viable. Selecting low-
cost, widely available and recyclable materials and scalable production methods is important in this
regard. Designing TENGs to be compatible with existing textile technologies and standards would
also be a critical strategy in overcoming this challenge.
There has not been a standard output characterisation for TENGs making it difficult to evaluate and compare their performances. Due to their high sensitivity to device, motion and environmental parameters, non-linear output generation, and, specific measurement requirements, a carefully designed test method needs to be developed for TENGs to obtain reliable and comparable performance data. Moreover, present theoretical methods and optimisation techniques which are limited to planar architectures need to be improved to accommodate complex structures and motion characteristics of textile surfaces. In addition, overall improvements are necessary against generic drawbacks of TENG technology such as high impedance and discontinuous outputs, in constructing efficient textile based TENGs.

In summary, textile based TENGs have demonstrated remarkable progress, emerging as a prime candidate for powering the next generation of wearable electronics. Developing textile based TENGs with detailed attention to electrical output performances as well as wearable properties, in synergy with the optimisation methods, textile engineering concepts and manufacturing techniques, will pave the way towards highly efficient sustainable self-powered wearable energy systems.

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, R.D. Ishara G. Dharmasena (r.i.dharmasena@lboro.ac.uk)

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Author Contributions

R.D.I.G.D and K.R.S.D.G. conceived the idea designed the structure. R.D.I.G.D. and N.D.W. Supervised the project. K.R.S.D.G. and N.D.W. wrote the first draft of the manuscript. All authors commented, edited and revised the final manuscript.

Declaration of Interest

The authors declare no competing interests.

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Figure 1: Power requirements of various portable electronics. Adopted from ref (Byun et al., 2017) (B)
Average energy generation in different regions of the body during mild physical activities (walking movement of an average person). Adopted from ref (Riemer and Shapiro, 2011; Invernizzi et al., 2016; Dharmasena and Silva, 2019).

Figure 2: (A) Schematic of basic TENG working modes. Adopted from ref (Dharmasena and Silva, 2019). (B) Several common textile materials included in the triboelectric series. Adopted from ref (S. Liu et al., 2018).

Figure 3: Textile manufacturing process depicting fibre, yarn, fabric, and garment stages. (A) Fibre stage showing: (i) Synthetic fibres, (ii) Regenerated fibres, (iii) Wool fibres, and, (iv) Cotton fibres. (B) Synthetic yarn manufacturing process (melt spinning) Reprinted from ref, (George, 1982) with permission, Copyright©1982 Society of Plastics Engineers Inc. (C) Cotton yarn manufacturing process: (1) Bale preparation, (2) Blow room operation, and, (3) Carding operation. Reprinted from ref, (Lee and Ockendon, 2006) With permission, Copyright©2006 Springer Nature. (4) Draw frame operation, (5) Roving frame operation, (6) Ring frame operation. (D) Final yarn packaging. (E) Non-woven fabric manufacturing (polymer laid method). (F) schematic of weaving. Reprinted from ref, (De Pauw et al., 2020) with permission, Copyright©2019 SAGE Publications (weaving operations; shuttle, air jet, water jet, rapier). (G) Schematic of knitted fabric manufacturing. Reprinted from ref, (M. Zhu et al., 2016) with Permission, Copyright©2016 Elsevier Ltd. (knitting operations; flatbed, circular). Dyeing and finishing operations, depicting (H) Jet dyeing (I) Jigger dyeing (J) Multi-flow dyeing (K) Beam dyeing (L) Reprinted from ref, (Nair, 2011) with permission, Copyright©2011 Elsevier). (L) Stenter process for fabric finishing. Garment manufacturing process, showing (M) Marker making, (N) Cut and sawing, (O) Screen printing, (P) Die printing, and, (Q) Embroidery processes.

Figure 4: Schematics of basic woven and knitted fabric structures. Weave patterns depicting (A) Plain weave (B) Twill weave (C) Sateen weave, and, (D) Satin weave. Adopted from ref (Adanur, 2000). A generic schematic representation of (E) A weft-knitted, and, (F) A warp knitted fabric. Photographs of weft-knitted designs, depicting (G) Plain knit (H) Rib knit (I) Interlock knit, and, (J) Purl knit. Adopted from ref (Spencer, 2001)

Figure 5: (A)Schematic of silk/stainless steel fibre (SF/SSF), and, PTFE/stainless steel fibre (PTFE/SSF) based TENG. Corresponding SEM images for (ii) SF/SSF, and, (iii) PTFE/SSF. Reprinted from ref (Ye, Dong, et al., 2020) with permission, Copyright©2019 Springer Nature. (B) (i) Schematic of a TENG based on a coiled electrode, consisting of silicone rubber, CNT, and copper. Variation of outputs against increasing number of coils per cm (at 50% strain and 2 Hz frequency) demonstrating (ii) Isc, and, (iii) Voc, and, variation of outputs against increasing frequency of movement (22 coils/cm, 50% strain) demonstrating (iv) Isc, and, (v) Voc. Reprinted from ref (He et al., 2017) with permission, copyright©2016 WILEY-VCH Verlag GmbH & Co. (C) Development of a SETENG with silver yarn as the core and PVDF, PAN hybrid nanofibers as the shell, using electrospinning. Reprinted from ref (Ma et al., 2020) with permission, Copyright©2020 American Chemical Society. (D) Schematic of silver-coated nylon yarn-wrapped PU fibre TENG. Reprinted from ref (Sim et al., 2016) with permission, Copyright©2016 Springer Nature. (E) Schematic of the fabrication process of wavy structured covering yarn based TENG. Reprinted from ref (Gong et al., 2017) with permission, Copyright©2017 Elsevier. (F) Schematic of the fabrication process of the twisted fiber based TENG constructed using cotton yarns with CNT, and, PTFE. Reprinted from ref (J. Zhou et al., 2014) with permission, Copyright©2014 American Chemical Society.
Figure 6: (A) Schematic of a TENG fabrication flowchart for a nanostructured surface geometry. Reprinted from (Lee et al., 2015) with permission, Copyright©2015 Elsevier Ltd. (B) (i) Design of TENG to harvest energy from human motion, (ii) Schematic diagram of the TENG structure, and, (iii) PDMS microrod array fabrication process on a spandex fabric. Reprinted from (Zhang et al., 2019) with permission, Copyright©2019 American Chemical Society. (C) (i) The fabrication process of TENG consisting of a PET fabric with BP, Ag flakes, PDMS and HCOENP, and, (ii) A schematic of the TENG device. Reprinted from (Xiong et al., 2018) with permission, Copyright©2018 Springer Nature. (D) (i) Flowchart for top TENG layer, and, (ii) Bottom TENG layer for an omniphobic TENG. Reprinted from ref (Sala de Medeiros et al., 2019) with permission, Copyright©2019 Wiley-VCH Verlag GmbH & Co.

Figure 7: (A) Schematic of a TENG fabrication flowchart for a nanostructured surface geometry. Reprinted from ref (Lee et al., 2015) with permission, Copyright©2015 Elsevier Ltd. (B) (i) Design of TENG to harvest energy from human motion, (ii) Schematic diagram of the TENG structure, and, (iii) PDMS microrod array fabrication process on a spandex fabric. Reprinted from (Zhang et al., 2019) with permission, Copyright©2019 American Chemical Society. (C) (i) The fabrication process of TENG consisting of a PET fabric with BP, Ag flakes, PDMS and HCOENP, and, (ii) A schematic of the TENG device. Reprinted from (Xiong et al., 2018) with permission, Copyright©2018 Springer Nature. (D) (i) Flowchart for top TENG layer, and, (ii) Bottom TENG layer for an omniphobic TENG. Reprinted from ref (Sala de Medeiros et al., 2019) with permission, Copyright©2019 Wiley-VCH Verlag GmbH & Co.

Figure 8: (A) (i) Schematic of Cu-PET yarn based woven TENG structure, and, illustration related to the woven TENG theoretical model development, showing (ii) The side and top view of yarn interlacing (iii) Morphology of the contacting interlacing (iv) Cross-sectional view of the yarn interlacing point when pressure is applied (top) and released (bottom) (v) Charge distribution at yarn interlacing point when contacting area changes. Reprinted from ref (Zhizhen Zhao et al., 2016) with permission, Copyright©2016 Wiley-VCH Verlag GmbH & Co. (B) Fabrication process of the 3D orthogonally woven TENG, depicting (i) Conductive, and, (ii) Nonconductive z-direction yarn binding. (iii) Photograph of 3D woven TENG, Reprinted from ref (Dong, Deng, et al., 2017) with permission, Copyright©2017 Wiley-VCH Verlag GmbH & Co. (C) (i) Schematic of a woven TENG, demonstrating the dielectric component, electrode component, and energy storage unit. The output variation of the TENG against (ii) Increasing PTFE yarn diameter, and, (iii) The interval distance between the yarns. Reprinted from ref (Chen et al., 2018) with permission, Copyright©2018 Elsevier Ltd. (D) (i) Schematic of the woven DC TENG, and, the corresponding electrical outputs depicting (ii) $V_{oc}$ (iii) $I_{sc}$, (iii) $Q_{sc}$. Reprinted from ref (Chen et al., 2020) with permission, Copyright©2020 American Chemical Society.

Figure 9: (A) Schematic of knitting stitch types of a weft knitted fabric on the (i) Technical front, and, (ii) Technical backsides, adopted from ref (Spencer, 2001). (B) (i) Schematic of the structure of a 2D knitted TENG, and, (ii) A photograph of the TENG attached to a lab coat. The output characterization of the 2D knitted TENG, demonstrating (iii) Voltage, and, (iv) Current against time, for several knitting variations. Reprinted from ref (Huang et al., 2019) with permission, Copyright©2019 Elsevier Ltd. (C) Schematic of the cardigan structure based knitted TENG. Outputs from the knitted TENG demonstrating (ii) Pulse of the neck of a person, and, (iii) Comparison of pulse waveforms of persons at different ages. Reprinted from ref (Fan et al., 2020) with permission, Copyright©2020 The Authors. (D) Schematic of the structure of a 3D knitted fabric based TENG (top), and, a photograph of the device (bottom). Reprinted from ref (J. Gong et al., 2019) with permission, Copyright©2019 Elsevier Ltd.
Research Highlights

- A review on textile based TENG is presented, examining their evolution and progress
- Manufacturing methods and optimising techniques of wearable TENG are analysed
- Potential scaling up of TENG with existing textile processing techniques is studied
- Guidelines are given to improve performance & compatibility of textile based TENG