

# Empowering Sustainability: Harnessing Textile Triboelectric Nanogenerators for Green Energy Harvesting

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**Abstract.** The triboelectric nanogenerators (TENGs) have shown the most significant potential in developing a sustainable power source for wearable technologies. Among the various TENGs devices, the textiles are the most suitable candidates for harvesting biomechanical energy due to their excellent flexibility, biocompatibility, conformability, and simple fabrication techniques. The advancement in the textile technologies enables a seamless integration of TENG into the clothing and accessories for efficient energy harvesting. Various approaches for developing textile-based TENGs are demonstrated mainly on weaving, knitting and combinations of different textile manufacturing processes. The potential of textile-based TENGs to provide sustainable energy for wearables makes them a promising avenue for future developments in the field of renewable energy technology. This paper provides a critical review of current developments in textile-based triboelectric nanogenerators as a sustainable power source, the effect of textile process parameters and the applications of TENGs for physiological monitoring.

## 1 Introduction

The rapid growth of wearable and portable electronics, including health monitoring sensors, has made these gadgets immensely popular. However, their reliance on conventional batteries raises concerns about power consumption. The energy requirements for wearables pose a unique challenge in terms of sustainability. As these devices become an integral part of our daily lives, sustainable power sources are essential to ensure their continuous and eco-friendly operation [1, 2]. Wearables need power solutions that are not only efficient but also renewable and environmentally friendly. Emphasizing low-carbon emission technologies, such as solar cells or energy harvesting from body movements, can help extend the battery life of wearables and reduce their reliance on disposable batteries. Integrating sustainable power sources into wearables not only enhances their usability and convenience but also contributes to a greener and more sustainable future for wearable technology [3].

Triboelectric Nanogenerators (TENG) are a promising sustainable power source that has garnered significant attention in recent years. TENGs harness mechanical energy from various sources, such as human motion, vibration, or wind, and convert it into electrical energy through triboelectric effects and electrostatic induction. Their sustainable nature stems from the fact that they do not require fuel or produce harmful emissions during operation, making them environmentally friendly [4]. TENGs offer several advantages as sustainable power sources for various applications. They can be integrated into wearable devices, where human movements can generate electricity to power small electronic components

like sensors and communication modules. When integrated into wearable textiles, TENG devices can capture and convert the mechanical energy produced during body movements into usable electrical power [5, 6]. The comparison of different sustainable energy harvesting technologies has compared in the Fig. 1, and among all the systems, TENGs exhibit a high power conversion efficiency and can be fabricated using low-cost, abundant materials, contributing to their scalability and cost-effectiveness.

Textiles offer an ideal platform for integrating TENG devices into wearable garments due to their soft, flexible, porous nature, and close proximity to the body [7, 8]. Specialized textile materials with high triboelectric properties can be used to enhance the charge generation efficiency during movement. The seamless integration of TENG devices within textile fabrics allows for unobtrusive energy harvesting as users go about their daily activities. The generated electricity can be used to power various small-scale electronic components embedded within the wearable, such as sensors, health monitoring devices, or even small communication modules [9].

The potential applications of human body movement energy harvesting using TENG and textile fabrics are vast. From wearable health monitors that continuously track vital signs to smart clothing that charges electronic devices on the go, this technology holds promise for improving energy efficiency and promoting sustainable practices in various industries. Moreover, it empowers individuals to contribute to their own energy needs and supports the transition towards a greener and more energy-conscious future. This paper explores different

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aspects of designing of textile based TENG and the current development status of TENG as a sustainable power source.

Energy Harvesting Technologies					
	Photovoltaic Effect	Thermoelectric Effect	Electromagnetic Effect	Piezoelectric Effect	Triboelectric Effect
<b>Voltage</b>	0.5-0.9 V	0.1-1 V	0.1-10 V	1-200 V	3-1500 V
<b>Current</b>	100-500 $\mu$ A	5-30 $\mu$ A	n/a	0.01-10 $\mu$ A	10-2000 $\mu$ A
<b>Power density</b>	5-30 mW/cm <sup>2</sup>	0.01-3 mW/cm <sup>2</sup>	n/a	0.001-30 mW/cm <sup>2</sup>	0.1-100 mW/cm <sup>2</sup>
<b>Efficiency %</b>	0.5-45	0.1-25	5-90	0.01-21	10-85
<b>Pros</b>	<ul style="list-style-type: none"> <li>High power output</li> <li>Continuous DC output</li> </ul>	<ul style="list-style-type: none"> <li>Easy scale down</li> <li>No moving component</li> </ul>	<ul style="list-style-type: none"> <li>Conversion efficiency high</li> <li>Large current at low voltage</li> </ul>	<ul style="list-style-type: none"> <li>High sensitivity to stimuli</li> <li>Easy integration</li> <li>Easy miniaturization (macro-nano scale)</li> </ul>	<ul style="list-style-type: none"> <li>High output power</li> <li>Conversion efficiency high</li> <li>No material constrain</li> <li>Cost-efficient</li> <li>Structural flexibility</li> </ul>
<b>Cons</b>	<ul style="list-style-type: none"> <li>Light presence inevitable</li> <li>Conversion efficiency low (organic photo-cells)</li> </ul>	<ul style="list-style-type: none"> <li>High temperature difference required</li> <li>Conversion efficiency low</li> <li>Low output performance</li> </ul>	<ul style="list-style-type: none"> <li>Heavy weight and size of magnet</li> <li>Short range (wireless) power transmission</li> <li>High structural complexity</li> </ul>	<ul style="list-style-type: none"> <li>High impedance</li> <li>Conversion efficiency low</li> <li>Pulse output</li> <li>Low output performance</li> </ul>	<ul style="list-style-type: none"> <li>High impedance</li> <li>High frictional damage</li> <li>Pulse output</li> </ul>

**Fig. 1.** Comparison of different sustainable energy harvesting technologies.

## 2 Principle working modes of TENG

The triboelectric effect is well known for almost thousand years through which material becomes electrically charged due to friction. It is observed that contact between two materials crates an electrochemical interaction formed between the surface molecules producing triboelectric charges on their surfaces. However, upon the separation, these triboelectric charges become the driving force for the electron to flow through the electrode to equalize the potential difference created. Based on this principle, four fundamental working modes are reported.

### 2.1 Vertical contact-separation mode

First reported in 2012 [10], contact separation mode work in relative perpendicular movement of two opposite triboelectric surfaces. The potential difference between triboelectric surfaces changes with vertical separation distance. Once the electrode of two layer connected with the load (Fig. 2a), free electrons travel from one layer to other. As the gap between the layers is closed, potential difference ceases and electrons drive back.

### 2.2 Lateral sliding mode

The sliding TENG composed of two opposite triboelectric material placed on a substrate. The resultant contact electrification and triboelectrification changes due to parallel sliding of one material over the other (Fig. 2b), reported in 2013 [11]. Linear periodic sliding is responsible to drive the electron back and forth among the electrodes. This type of TENG can be implemented in compact spaces as well as rotation induced sliding for power generation.

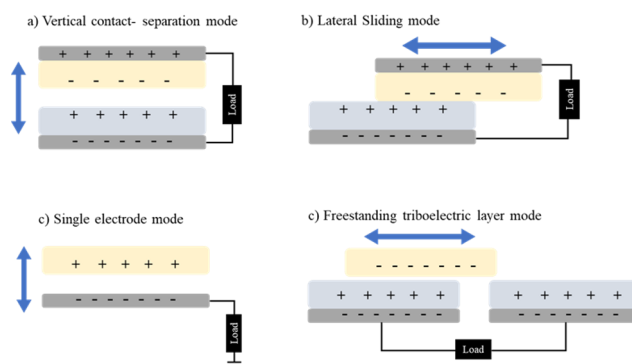
### 2.3 Single electrode mode

A TENG working on this principle does not need two electrodes as mentioned in previous two modes. This type of TENG is best suitable where the material cannot be

connected electrically to the load or circuit such as swinging of arms while walking or rotating object on the surface [12]. In order to harvest electrical energy, bottom electrode is grounded as shown in Fig. 2c. The moving top triboelectric layer changes the charge distribution and exchange of electrons takes place from ground to bottom electrode [13].

### 2.4 Freestanding triboelectric layer mode

This mode is first appeared in 2014 [14], in which instead of using one ground reference electrode, it uses pair of similar electrodes connected by the load shown in Fig. 2d. Most of the triboelectric material remain charged for many hours after charging. This type of TENG can be operated without frequent contact after initial contact electrification. When such charge material approach to and departed from the electrode, it changes charge distribution which causes flow of electron from one layer to another. Without direct mechanical contact between the layers, friction and wear is drastically reduce which enhance the durability of TENG.



**Fig. 2.** The four principle working mode of TENG.

## 3 Structural designs and working mechanism

The first flexible triboelectric generator was invented by Fan et al. [15] in 2012 for scavenging electrical energy from mechanical motion. A schematic of structural arrangement and power generation mechanism is shown in Fig. 3. There are two different triboelectric layers formed by two material which has different electron affinity towards each other. In order to transfer the generated electrons, each layer is combined with the conductive electrode material on the back of the triboelectric material. The contacting face has nano or micro scale roughness to create friction while two material contact each other. When an external force pressed one layer over the other, opposite charges are generated and distributed over the two triboelectric layers due to contact electrification. In this situation, material surface with strong electron affinity will produce negative charge and other will become positive. A dipole layer is formed at the interface which create potential difference across the two electrodes called electrostatic induction. As the distance between two layers reduces (from D to d),

electrostatically induced free electrons flow across the external circuit. If  $C$  is the capacitance and  $V$  is the voltage across the two layers, the current generated in the system is defined as

$$I = C \frac{\partial V}{\partial t} + V \frac{\partial C}{\partial t} \quad (1)$$

$C \frac{\partial V}{\partial t}$  = Potential difference due to contact electrification.

$V \frac{\partial C}{\partial t}$  = Change in capacitance of the system due to reduction in interplanar distance ( $D$  to  $d$ )

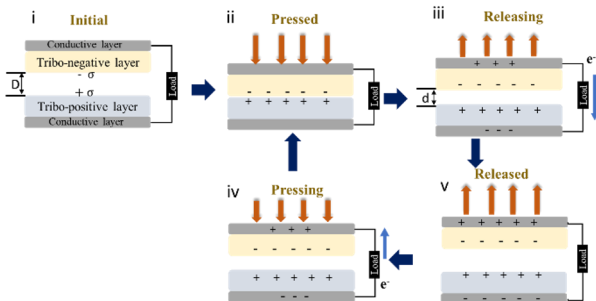
Once the applied force is released, system begin to come original position, electrostatic charges neutralize, and electrostatically induced free electrons returns to electrode through external circuit forming current signal in opposite direction. The open circuit voltage generated during the separation is expressed as [16].

$$V_{OC} = \frac{\sigma d}{\epsilon_0}$$

Where,  $\sigma$  = charge density

$\epsilon_0$  = vacuum permittivity

$d$  = separation distance at any instanced.



**Fig. 3.** Schematic and working principle of triboelectric generator.

## 4 Material selection

The selection of material carries a crucial role in deciding the output performance of the TENG device which depends on the polarity, electron affinity and charge density of individual material. A material selection guideline known as triboelectric series were proposed containing series of material sorted according to their electron affinity [17]. Further apart the two materials are on the list, greater will be the propensity for electron transfer. According to the positioning of material in triboelectric series metal such as copper (Cu), aluminium (Al), silver (Ag) and textile substances such as nylon, silk, wool preferred as a positive material [18]. Materials such as polytetrafluorethylene (PTFE), polypropylene (PP) [19], polydimethylsiloxane (PDMS) [20], exhibit negative triboelectric characteristics are explored due to their flexibility, chemically inert structure and possibility to modify surface properties physically or chemically to enhance interaction area. Many studies show application

of polymer film based TENG unit attached directly to human skin or Textiles for biomonitoring as well as energy harvesting. Bai et. Al developed PDMS micro-pyramid polymer film based TENG motion sensor for human machine interaction [21]. Zhu et al. used PTFE as a negative triboelectric material to develop a thin film based micro grated TENG [22]. The film based TENG devices suffered from several drawbacks such as toxicity to skin [23], impermeable to sweat and moisture [21], complex and expensive manufacturing. These limitations of film based TENG demand for more skin friendly and manufacturing viable product.

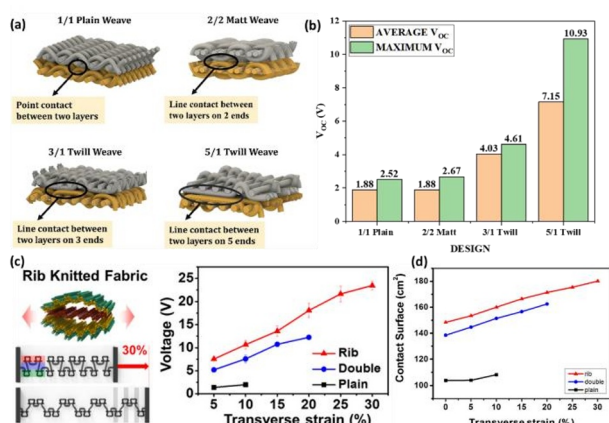
## 5 Textile based TENG

Recently textile based TENG devices has gain lot of attention from the researcher due to its intrinsic flexible, soft, and breathable properties as well as efficient production techniques. To enhance the performance of textile based TENG, these polymers are often coated on textiles [24]. Among those core spun hybrid yarns [25] and their integration in fabric using weaving [26], knitting [27], embroidery processes [28] are mainly found in literatures. The integration of triboelectricity phenomenon into the textile is becoming more promising due to constant source of friction, high roughness and large surface area thus producing higher output. Moreover, different structural combination provides varied level of effective contact and the number of contact combinations is almost endless, particularly in the case of textile fabrics with almost infinite patterns [29].

### 5.1 Woven structure based TENG

Woven fabrics in any integrated E-textile is preferred due to durable and stable structure, which enhances the signal quality in terms of low displacement of components. Stability of woven fabric allow more accurate placement of electrode and dense integration of key components of electronics circuit [30]. Various approaches have been devised by the researchers for designing different woven structured TENG including integration of triboelectric yarns, multilayer triboelectric fabric assembly, coating of fabric with triboelectric, and conductive polymers [31]. Zhou et al. reported the first TENG utilizing plain woven structure interlacing nylon and polyester in warp and weft, and skin as the triboelectric material [32]. The silver (Ag) coated woven fabric is selected as electrode material. An open circuit voltage of 20V and short circuit current of 1  $\mu$ A generated working with 40 mm lateral displacement in freestanding mode. However, the adhesive bonded electrode material poses a disadvantage of layer separation after several cycles. Zhao et al. reported a single layer integrated TENG device produced by direct weaving of triboelectric yarns coated with conductive metal substance. Copper coated polyethylene (Cu-PET) yarn used in warp and polyamide coated Cu-PET (PI-Cu-PET) weft yarn was incorporated in plain woven configuration to produce an integrated TENG fabric. Unlike the other conventional triboelectric device where minimum of two layers required for charge generation,

the single layer TENG produces individual TENG unit at each crossover in plain woven structure which upon even very slight deformation of the unit by tapping or bending, the contact area at each yarn intersection changes to result in an efficient generation of triboelectric charges. Results shows maximum power density reached up to 33.16 mW/m<sup>2</sup> at a resistance of 60 MΩ during tapping at a rate of 10 cm/second and 23.86 mW/m<sup>2</sup> at a resistance of 80 MΩ when bending force is applied under a radius of curvature of 4.0 to 1.8 cm at a rate of 15 cm/second [33]. Although chemical and metallic coating provides better output performance, the weak interfacial bonding between textile and coating substrate, brittleness and cracking/delamination of functional material makes these methods vulnerable to damage in practical use. Apart from plain woven fabric, commonly used structure such as twill, matt and satin show a significant improvement in performance of the TENG. Somkuwar et al. reported that change of weave design creates different effective contact area which directly affects the output performance of the TENG. The comparison of 1/1 plain, 2/2 matt and 5/1 twill structure shows an improvement in output power from 1.56 μW/cm<sup>2</sup> for 1/1 plain weave to 12.84 μW/cm<sup>2</sup> [34].



**Fig. 4.** Effect of weave structure on (a) contact area, (b) voltage and change in (d) voltage and (e) contact surface of different knitted structure in response to transverse strain.

## 5.2 Knitted structure based TENG

Knitted textile structures are more popular among the E-textile area is not only due to material processability but also their physical characteristics such as high elasticity, flexibility, and confirmability. The 3D configuration of interconnected loops in knitted fabric are the main reason behind its flexible and deformable structure. Woven structure lacks in these properties due to straight horizontal and vertical interlacement of yarns, which limits yarn mobility into the structure [35]. The effect of knitted structure on the efficiency of TENG was demonstrated by Kwak et. Al. the polytetrafluoroethylene (PTFE) yarns and silver (Ag) yarns were used to produce plain, double and rib weft knitted structure. A three-layer structure composed of top and bottom negative triboelectric layer while middle layer composed of Ag coated yarn. The outer triboelectric layer also stitched

with Ag knitted fabric to provide conductive surface for charge transfer. The charge generation process involves lateral stretching which initiate contact electrification and as soon as fabric released, the separation cause change in electric potential to drive electron through the circuit. Results shows 30 % extension of rib structure produced 23.5 V. The current at load of 100Ω found 0.09 μA for plain knit and 0.53 μA for rib knitted structure. The enhancement in contact area during stretching reached to 108 and 180 cm<sup>2</sup> for plain knit and rib structure, respectively [43]. The multilayer stitching approach are complicated to obtain and increases rigidity of the knitted TENG. Chen et al. reported an 3D interlock knitted fabric consisting two types of yarn producing an integrated TENG structure. A nylon composite yarn was produced by coating of silicon rubber and silver (Ag) which is knitted along with a cotton yarn on a double bed weft knitting system to produce an integrated interlock fabric. The peak power density of 3.4 mW/m<sup>2</sup> was obtained with applied pressure of 4Kpa at an external load of 200 MΩ [36]. Zhu et. Al. demonstrated a spacer fabric produced by graphene coated Nylon top layer and PTFE coated bottom layer with an intermediate polyethylene spacer layer. The intermittent contact and separation between nylon fabric and PTFE coated fabric leads to charge induction producing a power density of 53.3 mW/m<sup>2</sup> with an applied load of 0.6 MΩ [37]. Although the coating of substances on textile shows a considerable improvement in efficiency of TENG, the fabrication techniques, breathability and durability of coating limits its applications in fabric based TENG. This challenges demands a completely integrated textile based TENG where textile fabric will not be use just as a substrate for triboelectric material deposition.

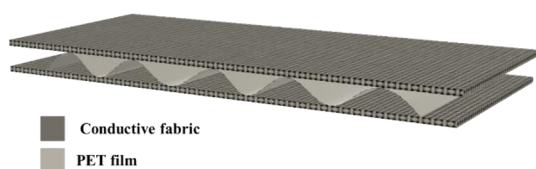
## 6 Optimization of textile TENG

The different processing parameters have been addressed to optimised the performace of the TENG devices. For the quantitative characterization of TENG device, effect of different excitation frequency, and applied pressure needs a fair investigation. The recurrence and the intensity of each triboelectric cycle defines the output performance of the TENG device. Hui et al. analyze the effect of frequency on output performance of PTFE and nylon (PA6) TENG device. A frequency controlled linear motor setup was used to provide controlled excitation. Results shows a constant open circuit voltage (Voc) and an increasing trend of short circuit current (Isc) with increasing frequency. Another analysis by Chen et al. on a PTFE woven TENG in sliding excitation mode revealed the output signals of Isc shows first increased and then decreased trend with increasing the speed of sliding. However, the sliding speed does not show any impact on the maximum Voc [38]. The impact of different pressure intensity was also analyzed in vertical contact separation mode to optimize the output of the TENG. Chen et al. analyzed the effect of different pressure intensity on an interlock knitted TENG unit consisting silicon rubber coated PA composite yarn when press against a polyester fabric. The results depicted a linear increasing trend of

Voc and Ioc with increasing pressure from 0.4 kPa to 4kPa [36]. An enhancement in output is due to a larger applied force results in a larger contacting area, suggesting the formation of higher charge density triboelectric material.

## 7 Self powered applications of textile based teng device

Textile based TENG devices utilizes to monitor vital body parameters using indirect method of analysis. As we understand, TENG converts mechanical energy from different stimuli into electricity, and this electrical signal are proportional to the mechanical stimulus feed to the TENG device. This approach of realization of electrical signal in response to bio-mechanical movement makes them a self-powered sensor. Muscle/body motion monitoring, such as joint motion, bicep Exercises and abdominal breathing have wide applications in the Postoperative recovery, supervision of sport and fitness. There is relatively significant displacement in the motion of the muscle or body, and it is therefore relatively simple for TENGs to detect. Yu et al. reported a polyaniline (PANI) based flexible single electrode TENG device works in contact with various material worn in daily life to scavenge mechanical energy as well as track human limb movement. The TENG unit consist of a conductive polymer PANI was deposited on a cotton textile by in-situ polymerization, which is used as a positive triboelectric material and produces electric potential when slide over PTFE film. To realize TENG application as a movement sensor, it is mounted on back and under the arm of a T-shirt to detect the frequency and amplitude of a movement[39]. Lin et al. developed a pressure sensitive washable textile based TENG array to monitor sleep pattern and warnings for abnormalities. The TENG array consist of a wavy structure of polyethylene terephthalate (PET) films sandwiched between conductive top and bottom fabric (Fig. 5).



**Fig. 5.** A schematic arrangement of sandwiched structure TENG developed for sleep monitoring.

The TENG unit has shown the pressure sensitivity of 0.77 V/Pa with response time of less than 80 ms. The self-powered sensor array was developed using the  $4 \times 4$  TENG units which generate voltage response to every TENG pixel, and the 2D pressure distribution was demonstrated using the voltage values. The pressure distribution system was employed for a real time sleep behaviour monitoring including the body's posture, position, sleep timing and pressure distribution. These stored information can be analyzed to provide a diagnosis against sleeping disorders such as sleep apnea. The pressure distribution mapping system could also adopted for motion tracking, activity recognition as well as tactile

sensing applications [40]. For clinical biomotion assessment, gait monitoring is important, which can provide valuable information for different health-related Applications like mitigating falls. Zhu et al. reported a self-functional sock to realize multiple functions such as energy harvesting, monitoring physiological signals such as gait, contact force, sweat level etc. The sock uses a hybrid nanogenerator consists of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)-coated fabric TENG and lead zirconate titanate (PZT) piezoelectric nanogenerator (PNG). The pressure exerted by the foot on the PNG produces a proportionate voltage signal whereas contact with the fabric inside the shoes or on the ground produces contact electrification for charge generation through TENG. The smart sock shows an excellent sensitivity of 0.06V/N to produce more accurate result of impact force generated by the sensor. Arrangement of PNG and TENG unit inside the socks helps in identification of different foot location and contact force produced by heel, toe, side touch which can be used to identify the person walking in the room. Besides the identification, the smart sock can produce a waveforms which recognize walking pattern and motion tracking of individual for gait analysis as well as for the treatment of Parkinson's disease [41].

## 8 Development challenges

Although the technology looks very promising in the development of sustainable power generation for wearable sensors, the following issues needs to be addressed as the technology associated with the human clothing and biomovement which is itself very irradicate and inconsistent. Hence, the development must consider the follwing issues for making the technology feasible for the commercialisation.\

### 8.1 Washing and durability

Washability and durability are one of the most significant factors in assessing the viability of TENGs in textile type in real-world applications. Various approaches were observed to demonstrate washing and durability of the fabric over the period of time [42-45]. For instance, Ning et al. shows stability of a PTFE film coated TENG device to washing in water, oil, ink, and similar liquids by a simple shaking in beaker. The results show retaining the peak voltage at 91% after 5 washing cycles [46]. In real life application washing of a fabric is performed in a standard washing machine along with other fabrics which is required to be simulated to analyze the performance of the TENG device. zhao et al. reported a washing durability of Cu coated PET yarn when subjected to 20 cycles of machine wash according to test method AATCC 135. The results show under a fixed tapping frequency, the output current reduced from 13.78 mA/m<sup>2</sup> to 3.52 mA/m<sup>2</sup> after 3rd wash only. This results attributes to the unstable coating characteristics of the fabric [33]. The robustness and durability of the TENG was also investigated by subjecting the sample to series of bending and squeezing cycles. Bhaskar et al. demonstrated effect

of bending, squeezing, and rolling action on a polyaniline (PANI) coated cotton fabric used in development of TENG device. The fabric samples were manually folded, squeezed, and rolled with different angle and the relative change in resistance were noted. Results shows a small incremental change in resistance of less than 26  $\Omega$ /sq.m observed after 2000 cycles [39]. However, the method of analyzing the stiffness of fabric by hand is very subjective testing and cannot define the accurate stiffness induced into the fabric due to incorporation of conductive electrode or coating of triboelectric substances. The standard method to measure force needed to bend the sample to a certain angle needs to be addressed to determine the bending properties of the TENG unit.

## 8.2 Scalability and mass production

For textile-based TENGs to become commercially viable, they must be scalable and compatible to mass production. Developing manufacturing processes that can efficiently produce TENG-integrated textiles at a reasonable cost is a significant challenge. Techniques such as roll-to-roll printing and scalable nanofabrication methods need to be explored to achieve large-scale production. The manufacturing technique also needs to cost efficient as the cost will directly affects the consumer and also affects the sustainability.

## 9 Conclusion

The development of textile based TENGs holds tremendous promise for the future of wearable electronics and smart textiles. The power generation mechanism offers a promising avenue to create an environmentally sustainable energy source, capable of powering a multitude of wearable devices integrated into human life. The different textile structural features allows the researcher to explore the various possibilities to develop an efficient textile based TENG to harvest human biomechanical energy. However, the major challenges in terms of its wearability properties such as washing, durability needs further exploration and critical evaluation. The mass production becomes the major concern as the integration of electronics within the soft flexible textile material demands specialised equipments and expertise. Through our collective efforts, we envision smart textile TENGs becoming an integral part of people's daily lives over the next decade. These innovative technologies will offer sustainable, all-in-one power supply systems and serve as crucial interactive tool support in the era of the Internet of Things and artificial intelligence.

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