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Eco-friendly PVA-Walnut shell-based triboelectric nanogenerator for biomechanical energy harvesting and self-powered touch sensing

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Abstract

The growing demand for sustainable power in wearable electronics necessitates eco-friendly energy harvesting alternatives. Herein, a polyvinyl alcohol-walnut shell (PVA-WS) composite was developed as a biodegradable triboelectric active layer for a single-electrode triboelectric nanogenerator (TENG). Walnut shell powder, a lignocellulosic agricultural byproduct, was incorporated into PVA at an optimised 3 wt%, enhancing surface micro-roughness and charge trapping capability as confirmed by SEM and XRD analyses. The fabricated device yielded a peak output voltage of 130 V, short-circuit current of 390 nA, and maximum power of 20 µW at 500 MΩ under 1 Hz excitation, while also successfully harvesting biomechanical energy from human motion and functioning as a self-powered material-discriminating touch sensor, positioning PVA-WS composites as promising candidates for next-generation sustainable electronics.

1. Introduction

The rapid expansion of portable electronics, wearable electronics, and networked sensors has raised a pressing, urgent need for sustainable and autonomous power supplies [1-3]. Traditionally, batteries were found to restrict themselves in terms of life, environmental issues, and maintenance needs. In turn, a new form of mechanical energy harvesting technique, in the form of triboelectric nanogenerators (TENGs), which can harness ambient mechanical energies and convert them into useful electrical energies using techniques like contact electrification and electrostatic induction, has been found to gain much interest [4-6]. TENGs can harness low-frequency mechanical energies like human motions, vibrations, wind, and water currents in an efficient manner [7,8]. Among the various operating modes of triboelectric nano-generators, the single electrode based TENG has attracted significant attention due to its simple structure and ease of fabrication compared to the conventional contact-separation and sliding mode TENGs. In the single electrode configuration, only one triboelectric layer is required, eliminating the need for a back electrode on the moving part, which greatly simplifies the device design and broadens its practical applications.

In addition, the role of materials in output performance, long-term stability, and environmental aspects of TENGs is critical. While several reports on high-performance TENGs utilize man-made polymers and fluorinated materials, issues concerning environmental sustainability, cost, and production have encouraged researchers to find eco-friendly alternatives [9-11]. Among the alternatives, PVA emerges as a promising matrix material for its solubility in water, film-formation ability, mechanical flexibility, non-toxicity, and water solubility [12-14]. Furthermore, the presence of hydroxyl groups in PVA ensures strong intermolecular interactions and generates a surface charge, which is useful for triboelectric devices [15-17]. Further enhancement of the electrical and mechanical properties of polymer-based TENG devices can be obtained by incorporating natural fillers into the polymers.

Walnut shell powder, an abundant agricultural byproduct, is rich in lignocellulosic components, including cellulose, hemicellulose, and lignin [18]. These constituents possess intrinsic dielectric properties and surface functional groups that may contribute to improved charge generation and storage in triboelectric systems [19]. Its rigid particulate morphology promotes surface micro-roughness when embedded in a polymer matrix, effectively enlarging the contact area during triboelectric interaction. Moreover, walnut shell powder is naturally abundant, biodegradable, and cost-effective, making it an environmentally sustainable alternative to synthetic fillers. Its rich surface chemistry, including hydroxyl and cellulosic functional groups, further enhances charge generation and retention capacity, positioning it as a highly promising filler material for PVA-based TENG applications. In 2025, Jeong *et al.* developed a TENG using biodegrade materials and achieved an output of 62 V, 170 nA respectively. The device is used as a fire alarm system for public safety during fire accidents [20]. In another study, Zhang and team prepared a eco friendly TENG by taking peanut shell powder and reaches a performance of 248.9 V and 39.4 µA respectively. The device was used to charge the various capacitors, small electronics and is used as anti-corrosion tool for ships and marine pipelines [21]. Recently, Panda *et al.* developed a sustainable TENG and operated in single electrode mode. The device recorded an electrical performance of 220 V and 25 µA respectively. The device is able to harvest the various human motions and exercises [22].

In the present research work, a novel sustainable composite material using PVA and walnut shell powder is developed. The optimization of the composite material has been performed for the filler concentration of the composite. In the present research work, the morphological performance of the developed material has been investigated using characterization. Finally, the TENG devices are used for the assessment of the electrical performance of the developed materials and paper as a triboelectric layer. To evaluate practical applicability the single electrode-based TENG was fabricated, and it generates the peak output voltage of 130 V and 390 nA short circuit current under an operating frequency of 1 Hz. Furthermore, TENG demonstrated effective energy harvesting from human body movements, producing sufficient electrical energy for operating small-scale electronic devices such as a calculator.

2. Materials and methods

2.1 Materials

PVA was purchased from Sigma-Aldrich, Walnut shell powder was purchased from Amazon, aluminium tape, copper wire and PET substrate were utilised to create the single electrode-based TENG.

2.2 TENG fabrication method

A single-electrode TENG was fabricated by employing a PVA-WS composite film as the active triboelectric layer, with paper serving as the freely movable counterpart. The device assembly began by cutting a PET substrate into 4 cm × 4 cm sections, followed by attaching a 3 cm × 3 cm aluminum tape electrode to the PET surface using double-sided adhesive tape to ensure robust fixation and uniform contact. Finally, the copper wire, which served as the connection, was connected to the aluminium electrode, and the PVA-WS composite film, which accounted for the active material, was laminated onto the aluminium electrode.

2.3 Characterization techniques

The electrical output signals of the fabricated TENG were recorded using a Keithley 6514 electrometer controlled via LabVIEW software. Periodic mechanical excitation was applied to the device using a LINMOT linear motor (USA). The structural properties of the active layer were characterised by X-ray diffraction (Rigaku Miniflex, Japan), and its surface morphology was examined using a scanning electron microscope (FESEM, ZEISS).

3. Result and discussion

The schematic representation of the preparation of the PVA-WS composite is shown in Figure 1(a). Initially, the 1 g PVA powder was added to the 10 mL of double-distilled water and stirred using magnetic stirrer for 2 h at 60°C to achieve a transparent solution. Then, with continuous stirring, the different wt% of the WS powder was added to the formed solution and stirred for 1 h. After that, the obtained solution is cast by pouring in petri dish, and it is kept drying for 2 days at room temperature. The dried film is then carefully peeled off and used for subsequent characterisation and application. Figure 1(b) illustrates the fabrication process of TENG. The proposed device was developed by using PET as a substrate and adhesive aluminium tape as an electrode. The prepared PVA-WS composite films were attached to the adhesive aluminium tape for fabricating a single electrode TENG. Figure 1(c) shows the operating principle of the single-electrode TENG. In a full contact state between the triboelectric surfaces, first induces charge separation according to their polarity differences. Force release then drives electrons from ground to electrode through the resulting potential gradient, creating a positive output spike. Complete layer separation restores equilibrium with zero current. As the counterpart layer nears the PVA-WS surface once more, reverse electron flow from electrode to ground produces the negative peak. Repetitive contact-separation generates alternating electrical signals across the device.

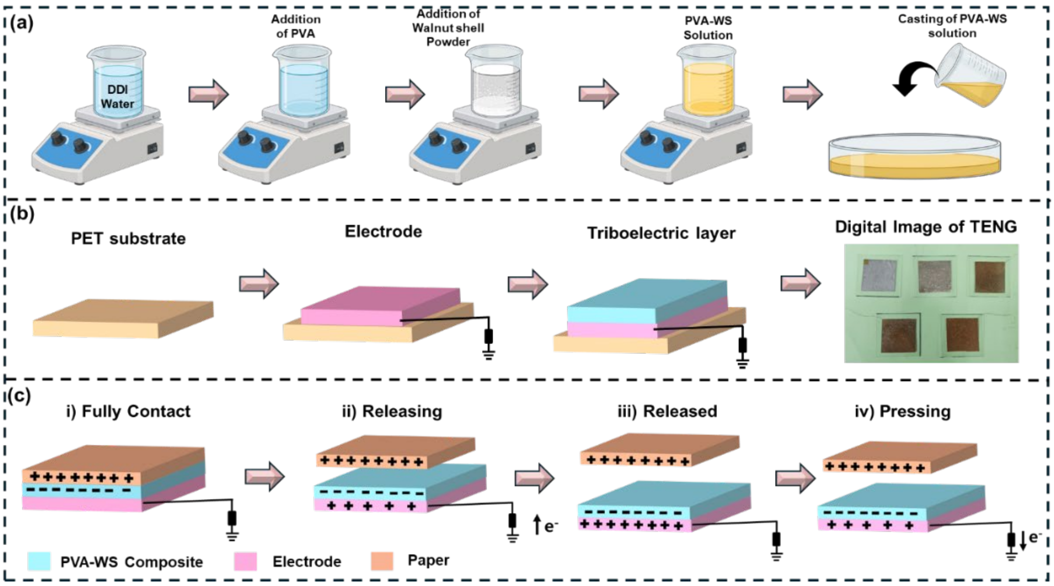

Figure 1. (a) Schematic representation of synthesis process of PVA-WS composite films, (b) Device fabrication process of PVA-WS TENG, and (c) Working mechanism of proposed single electrode PVA-WS TENG.

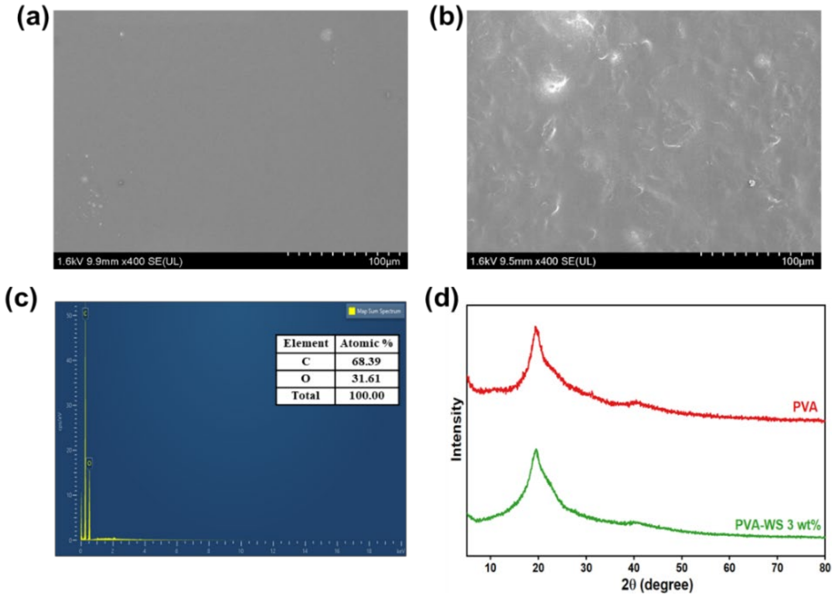

Figure 2. (a-b) Surface morphology of PVA and PVA-WS 3 wt% films, (c) EDS spectra of the PVA-WS 3 wt% film, and (d) XRD pattern of pristine PVA and PVA-WS 3wt% composite film.

The surface morphology of the pristine PVA and PVA-WS 3 wt% composite films was investigated by using SEM. Figure 2(a) shows the SEM image of the pristine PVA film shows a smooth plane and a homogeneous polymer matrix. However, the PVA-WS composite shows noticeably rougher surface and dispersed bright domains, which can be attributed to the incorporation of walnut shell powder particles within the PVA matrix shown in Figure 2(b). The EDS analysis confirmed the presence of carbon and oxygen as constituent elements, with atomic percentages of 68.39% and 31.61% respectively, as shown in Figure 2(c). This increased surface roughness and micro-structural heterogeneity are beneficial for TENG application, as they enlarge the effective contact area, promoting the enhancement of the triboelectric charge generation and output performance. Figure 2(d) presents the XRD pattern of pristine PVA and PVA-WS 3wt% composite films, which reveal that both materials exhibit a characteristic broad diffraction peak centered at 19.46° corresponding to the (101) planes of PVA's semi-crystalline structure. The XRD analysis was conducted at a scan rate of 2° min^{-1}, and SEM imaging was performed at a voltage of 1.6 kV.

The electrical performance of the fabricated TENG was investigated using a linear motor to apply periodic mechanical pressure. To address the relatively low triboelectric output of pristine PVA films, WS powder was introduced as an eco-friendly filler at different weight percentages (1 wt%, 3 wt%, 5 wt%, and 10 wt%). Figure 3(a-b) compare the output voltage and current of pristine PVA and PVA–WS composite films. Among them, the PVA film containing 3 wt% WS exhibits the highest output, delivering a peak voltage of 130 V and a current of 390 nA. This enhancement can be attributed to increased surface roughness, a higher dielectric constant, and the presence of additional functional groups that promote effective charge trapping in the PVA-WS composite. However, at higher filler concentrations of 5 wt% and 10 wt%, the performance of the device was observed to decline. This decline in the performance attributed due to the agglomeration of walnut shell powder particles at higher concentrations, which leads to the formation of defect sites and non-uniform stress distribution within the polymer matrix. Additionally, the increased particle aggregation at higher loadings reduces the effective contact area between the active layers, thereby minimizing the surface charge generation and overall device performance. The charge generated by PVA-WS 3 wt% composite film based TENG was 13 nC as shown Figure 3(c) The frequency-dependent performance of the TENG was further examined, as shown in Figure 3(d-e). The output voltage remains nearly unchanged with increasing frequency, indicating that the amount of generated surface charge per cycle is constant. In contrast, the output current increases with frequency due to the faster transfer of charges through the external load. The long-term operational stability of the fabricated PVA-WS TENG was systematically evaluated under a consistent applied force of 5 N and a frequency of 1 Hz, as demonstrated in Figure 3(f). The device exhibited a stable and consistent output performance over the entire test duration, confirming its mechanical robustness and reliability for continuous operation.

The voltage and power characteristics of the device were examined under different load resistances, and the results are illustrated in Figure 4(a). The output voltage increased gradually with higher resistance values, follows by Ohm's law (V = IR). As shown in Figure 4(b), the peak instantaneous power reached approximately 20 μW at an optimal load resistance of 500 MΩ. Since the electrical signal generated by the TENG is alternating current (AC), it is not directly compatible with low-power electronic devices. Therefore, the AC output was converted into direct current (DC) using a bridge rectifier. The rectified output was subsequently employed to charge capacitors. The charging behaviour of capacitors with different capacitances was evaluated over a charging duration of 60 s, as presented in Figure 4(c). In addition, the amount of charge stored in each capacitor was calculated and displayed in Figure 4(d). Furthermore, the output voltage of TENG device was measured for harvesting biomechanical energy from various human motions, including finger tapping and hand tapping, as depicted in Figure 4(e-f). The measured output voltages were approximately 11 V for finger tapping and 38 V for hand tapping.

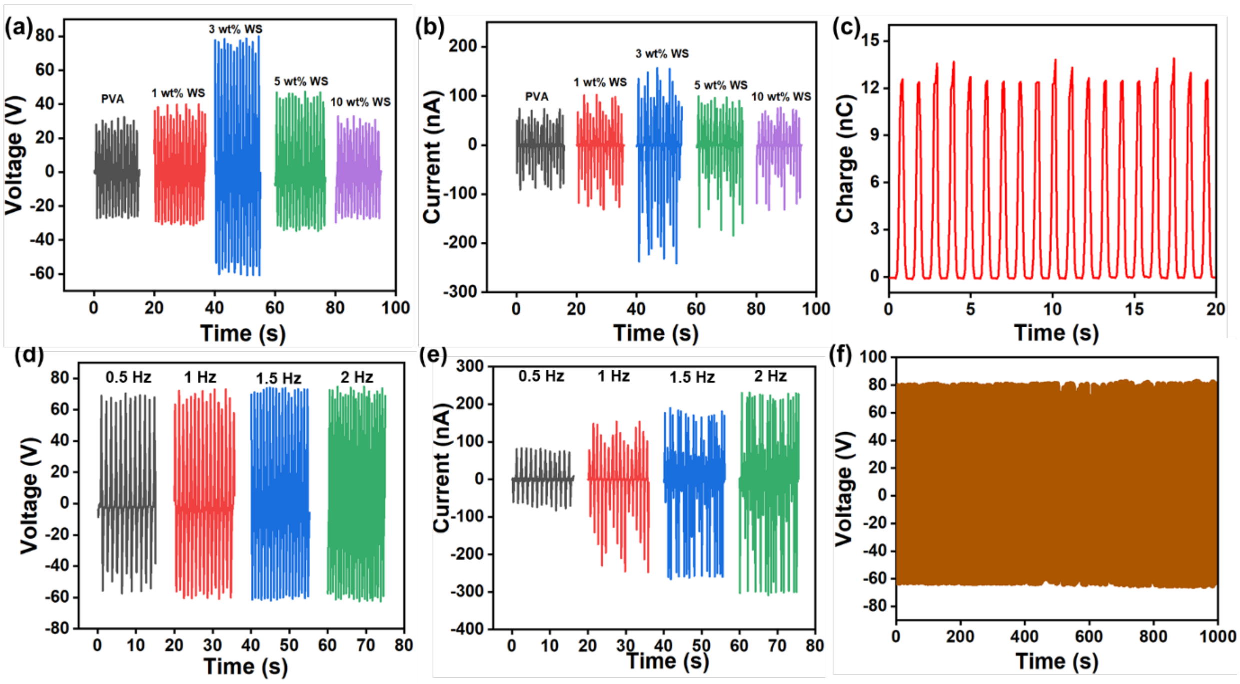

Figure 3. (a-b) Comparison of output of the pristine PVA and various PVA-WS composite films, (c) Charge response of the PVA-WS 3 wt% film based TENG, (d-e) The voltage and current output of the TENG under varying of frequencies, and (f) Long term stability of the device.

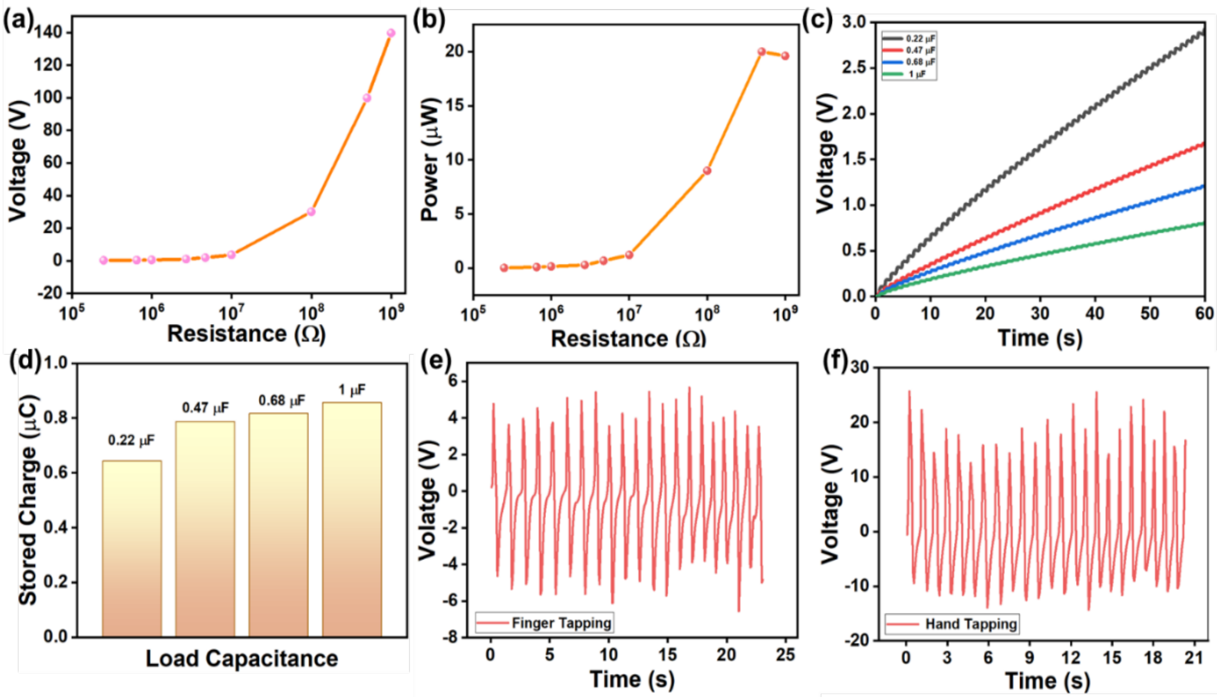

Figure 4. (a-b) Output voltage and instantaneous power density of the PVA-WS TENG as a function of external load resistance, (c) Charging of various capacitor by using PVA-WS TENG, (d) Stored charged in capacitors charged by rectified output of the PVA-WS TENG, (e-f) Voltage output generated by PVA-WS TENG during biomechanical energy harvesting from human motions.

Table 1. Comparison of output performance of recently reported TENGs with present work.

Triboelectric layer 1	Triboelectric layer 2	Voltage	Current	Reference
CH-PA fabric	Kapton	62 V	170 nA	[20]
Peanut shell powder	PTFE	248.9 V	39.4 μA	[21]
Nitrile glove	Glass	220 V	25 μA	[22]
PVA-WS 3wt%	Paper	130 V	390 nA	This work

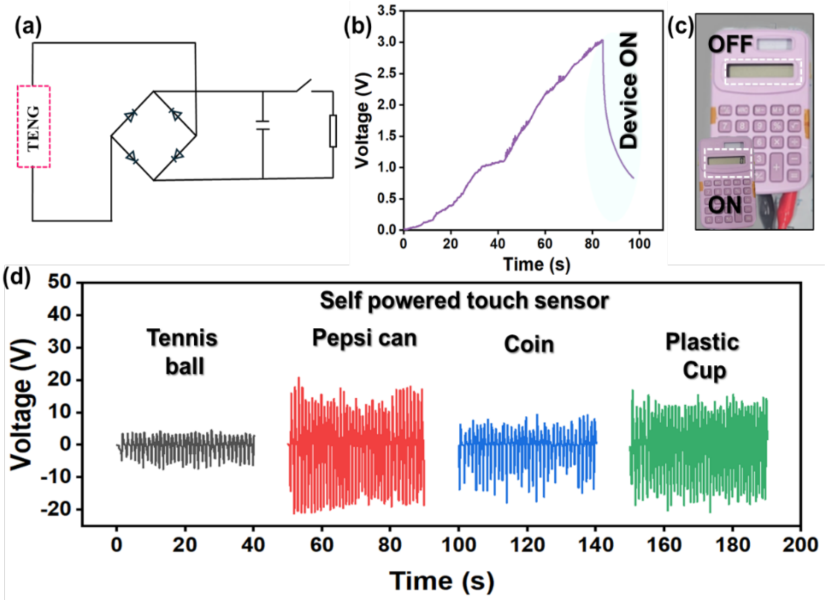

Figure 5. (a) Illustration of circuit diagram used for the charging of capacitors, (b) Capacitor charging by hand tapping for powering calculator, (c) Digital image of the fabricated PVA-WS TENG device successfully powering commercial calculator using harvested biomechanical energy, (d) Output voltage responses of the PVA-WS TENG to contact with various object, demonstrating distinct signal foe self-powered touch sensor.

Figure 5(a) presents the schematic representation of the TENG-based circuit employed for charging capacitors to operate a calculator. As shown in Figure 5(b), a 4.7 µF capacitor was charged up to 3 V through hand-tapping motions, demonstrating the capability of the TENG device to effectively charge the capacitor. The energy accumulated in the capacitor was subsequently utilized to power the calculator. Figure 5(c) displays digital photographs of the calculator in its ON and OFF states, confirming the successful operation of the device using the harvested energy.

In recent years, touch sensors have gained significant attention for applications in human–machine interfaces, wearable electronics, and intelligent monitoring systems. Nevertheless, most conventional touch-sensing technologies depend on an external power source for operation, which increases system complexity and limits their applicability in autonomous platforms. To address this limitation, the development of self-powered touch sensors has become highly desirable. So, we demonstrate a self-powered touch-sensing system based on a PVA-WS TENG. The sensing performance was evaluated by bringing the device into contact with various objects, including a tennis ball, a Pepsi can, a coin, and a plastic cup. Upon contact, the triboelectric interaction between the PVA-WS active layer and each object generated distinct voltage signals. The variation in output voltage can be attributed to differences in triboelectric polarity, surface texture, and effective contact area of the tested materials. These results confirm that the TENG device can not only harvest mechanical energy but also function as an effective self-powered touch sensor capable of distinguishing different materials. The corresponding output voltages for each object are presented in Figure 5(d). Such a self-powered touch sensing platform shows great promise in developing next-generation intelligent interfaces, electronic skin, and interactive systems, wherein sustainable, battery-free, and maintenance-free operation is critically important. The PVA-WS TENG device under development integrates both harvesting and sensing concepts, which could be an important towards developing intelligent, adaptive, and sustainable human-machine interaction technologies. Table S1 presents a comparative overview of recently reported TENGs, highlighting the output voltage and current performance of various material combinations relative to the present work.

4. Conclusion

In conclusion, our present research successfully developed the sustainable PVA-WS composite as an active triboelectric material for constructing the triboelectric layer of single-electrode based TENG with efficient filler concentration for enhancing surface roughness while maintaining the inherent semi-crystalline characteristics of the embedded PVA material. Notably, the proposed fabricated TENG generated promising output of 130 V and 390 nA at 1 Hz, with the obtained power output of 20 µW at 500 MΩ. Also, PVA-WS TENG efficiently harnessed the biomechanical energy harvested by the finger tapping and hand tapping. Most notably, the obtained output voltage trace for the distinctive touches of the objects validates the functionality of the purposed TENG as a touch sensor. This eco-friendly approach positions PVA-WS composite as viable alternatives to synthetics materials, paving the way for wearable and sustainable electronics.

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