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Low-cost high performance sustainable triboelectric nanogenerator based on laboratory waste

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Abstract

The production of waste materials in laboratories is an unavoidable consequence of diverse experiments and activities. These materials can range from chemicals, solvents, and biological samples to electronic components, glassware, and plastics. Typically, this waste is classified into hazardous and non-hazardous categories, requiring careful disposal to avoid environmental and health risks. These can be repurposed for energy harvesting methods, such as using polymers in triboelectric nanogenerators (TENGs) or recycling metallic waste for electrodes. This approach reduces waste while advancing sustainable energy solutions. This technique demonstrates remarkable efficiency in utilizing diverse waste materials to transform various forms of mechanical energy into electricity for multiple smart applications. Herein, we have collected several laboratory wastes including used waste latex gloves, aluminium tape, and glass slides, and fabricated a single-electrode TENG which produced electrical outputs of 220 V voltage, 25 µA current, and power of 72 µW at 500 MΩ resistance. The TENG device was also used to charge various capacitors and power LED light. Finally, the TENG was used to harvest various mechanical energies from natural source like wind energy, droplet energy, various exercise activities, and body movement like speaking and drinking water. This kind of sustainable, low-cost, easy to fabricate TENG device can be very useful in various applications like sensing, and biomedical sectors.

1. Introduction

Plastic waste from laboratories significantly contributes to the broader issue of global plastic pollution, as research institutions, educational laboratories, and diagnostic centers generate considerable amounts of disposable plastic waste [1,2]. This waste primarily includes single-use items such as pipette tips, Petri dishes, microcentrifuge tubes, gloves, storage containers, and other consumables essential for ensuring sterility and precision in experimental procedures [3,4]. The reliance on these materials is primarily driven by safety protocols and the need to prevent cross-contamination in sensitive experiments [5,6]. However, the heavy dependence on such non-biodegradable materials has resulted in the accumulation of plastic waste, posing severe environmental challenges [7-9]. Furthermore, this waste is often contaminated with hazardous chemicals or biological agents, making its disposal not only challenging but also risky.

Efforts to address this problem have led to increasing interest in transforming laboratory plastic waste into more sustainable forms [10-14]. Such transformations can reduce environmental pollution and, in some cases, contribute to energy generation. Among the innovative approaches in this domain, TENGs have emerged as a promising technology. TENGs can convert mechanical energy into electrical energy by the contact and separation of two dissimilar materials, a process based on the triboelectric effect. These devices have been developed in various operational modes, including vertical contact-separation (VCS), lateral sliding (LS), single-electrode (SE), and freestanding (FT), each catering to specific applications [15-19]. Among these modes, the single-electrode TENG stands out due to its simple design, ease of fabrication, and adaptability for diverse applications [20-23]. This mode has shown great potential for wearable electronics, as it can seamlessly integrate into fabrics to harvest energy from natural body movements [24-28]. By recycling waste materials and turning them into useful energy sources, TENGs also provide an ecologically friendly solution [29-31]. Sahu *et al.* collected waste fabric and fabricated 4 fingers knitted single-electrode mode device which was then utilized for smart sports monitoring system [32]. Navaneeth *et al.* demonstrated a TENG fabricated using medical waste, achieving an impressive output of 508 V and 105 µA. Similarly, Panda *et al.* utilized biowaste materials to develop a TENG that generated an electrical response of 20 V and 200 nA. This device also served as a biocompatible sensor for monitoring oral health, showcasing the versatility of TENGs in real-world applications [33]. Sahu *et al,* recently utilized lab waste plastics, recycled them by extruder process, and prepared a TENG by using 3D printed substrate. It produced a voltage and current of 185 V, 1.25 µA respectively, and was used for smart laboratory applications [34].

In this study, we developed a TENG utilizing laboratory waste, specifically gloves, and glass slides as triboelectric layers. The device operates in the SE mode and achieves a voltage of 220 V and a current of 25 µA. To explore its practical applications, the TENG was tested in various scenarios. It was connected to the human body to capture energy from different body movements. Additionally, the device demonstrated its ability to harvest energy from natural sources like water and wind, further establishing its feasibility for diverse real-world applications. These findings demonstrate that TENG technology can both solve the problem of plastic waste and support the production of renewable energy.

2. Materials and methods

2.1 Materials

Several laboratory waste such as glass slides, waste and used latex gloves, aluminium tape was collected and washed thoroughly to remove any contaminants. The washed materials were then dried at room temperature for 24 h before use. Waste latex gloves and aluminium tape were cut into the required size and stored.

2.2 TENG fabrication method

A SE mode TENG was fabricated using aluminium tape as the electrode, and the waste latex gloves were used as the active material of the TENG. The glass slide was used as the opposite free-moving layer. The device size was kept 4 cm × 4 cm as the active area. One copper wire was drawn from the electrode area, and the glove was fixed to the electrode properly to achieve a stable device.

2.3 Characterisation techniques

The micrographs of the glove and glass were analyzed using a FESEM (ZEISS) to acquire energy-dispersive X-ray (EDX) spectra and scanning electron microscopy (SEM) images. The TENG electrical signals were recorded utilizing a Keithley Electrometer 6514 and a custom LabVIEW software. The force exerted on the device was applied by a linear motor (LINMOT, USA).

3. Results and discussion

The digital image of the collected waste such as waste glass, latex gloves from the laboratory is shown in Figure 1(a) These collected wastes were washed properly and dried in room temperature for 24 h before use. Figure 1(b) shows the schematic diagram and layers of the single-electrode mode-based TENG (G-TENG) where the aluminium tape was used as the electrode and the waste latex glove was used as the active area. Figure 1(c) shows the digital image of G-TENG. The morphology of the waste glove and the glass was tested using scanning SEM. The SEM image of glove and glass are shown in Figure 2(a-b), the color maping and EDS spectra, element percentage of glove and glass are presented in supplementary section.

The working mechanism of SE of G-TENG is shown in Figure 3. At the initial state (Figure 3(a)) the triboelectric layer and the free-moving triboelectric layer (in our case glass slide) are in contact, so there are no charge generations. When the two layers start to separate (Figure 3(b)), there will be positive charges induced at the end of the electrode due to the electrostatic induction. The electrons will flow from the ground electrode to the active electrode due to potential differences, resulting in an electrical current. When the two layers are fully separated, the device reaches its equilibrium state, and there is no electron flow occurs (Figure 3(c)). Again, while the two layers are contacting again, the electrons will flow from the active electrode to the ground electrode making charge balance. This periodic process leads to the generation of peak-to-peak electrical output generations. As compared to dual-electrode, the single-electrode mode TENG is simpler in design, requiring only one active electrode and relying on the ground as a reference. It offers greater flexibility, compactness, and adaptability for dynamic or irregular surfaces, making it ideal for wearable and portable applications.

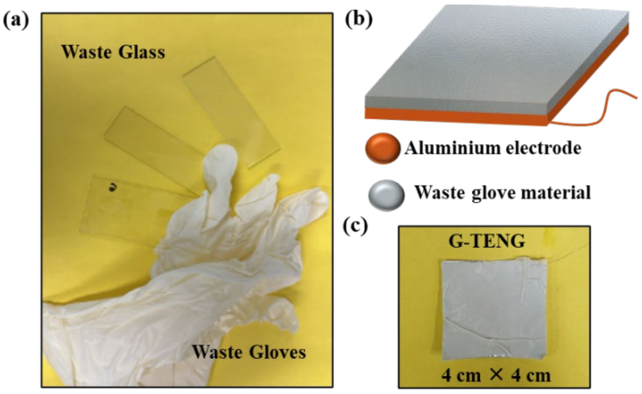

Figure 1. (a) Collection of laboratory waste, (b) schematic diagram of the G-TENG device, and its layer, (c) digital image of the G-TENG device.

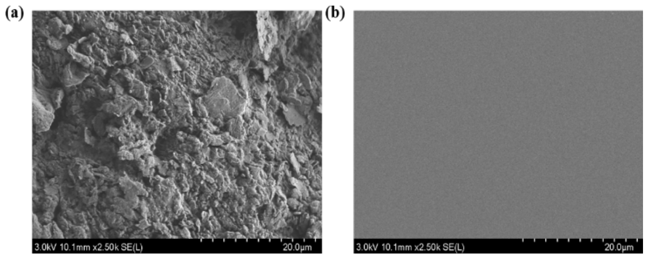

Figure 2. SEM image of (a) latex glove, (b) glass slide.

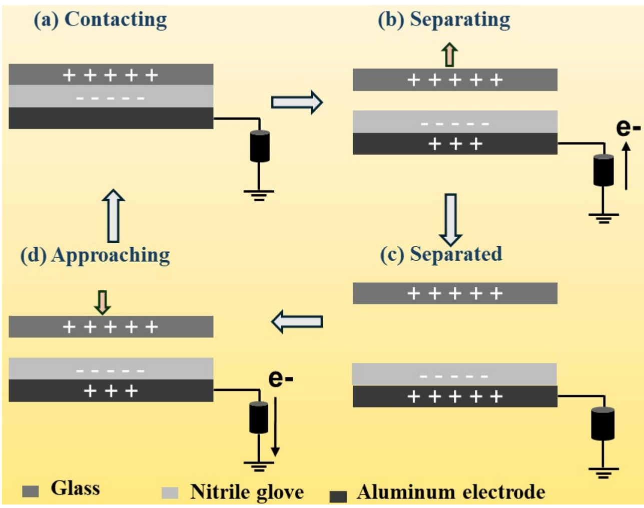

Figure 3. Working mechanism of SE G-TENG.

The electrical response from the G-TENG is shown in Figure 4. The voltage and current output from the G-TENG were 220 V and 25 µA, respectively (Figure 4(a-b)). The stability of the G-TENG was tested for 1500 sec as shown in Figure 4(c). The voltage output of the G-TENG using various load resistance was also demonstrated in Figure 4(d), which follows Ohmic condition (V = IR, where V = voltage, I = current, R = resistance). The highest power of the G-TENG device was determined using the formula $P = (V^2/R)$ which is found to be 72 µW at 500 MΩ resistance (Figure 4(e). Various capacitors (1 µF, 2.2 µF, 10 µF) were charged using the G-TENG (which proves that the G-TENG can successfully power any low-power electronics by harvesting mechanical energy as shown in Figure 4(f). The charge stored in each capacitor was computed using the formula Q = CV, where Q = charge, C = capacitance, and V = voltage as shown in Figure 4(g). The charging-discharging behavior of the capacitor value 0.1 µF was used as shown in Figure 4(h). Finally, an LED light was powered using the G-TENG by converting the AC signal to DC through a bridge rectifier. The overall electrical experiment proves the G-TENG is not only capable of transforming mechanical energy into electrical energy but also a sustainable, cost-effective, easy-to-fabricate, battery-free device. Exploring design variations, such as different electrode materials or surface treatments, could lead to improvements in the device performance or longevity. By increasing the device size also can improve the device performance.

The G-TENG was used to harvest various types of mechanical energy from the surrounding environment. As shown in Figure 5. G-TENG was used to harvest energy available from natural sources such as wind energy and droplet-based energy harvesting. Figure 6. shows the energy harvesting using exercise activity which is also biomechanical energy harvesting using the G-TENG. Figure 6(a-b) shows energy harvesting from pressing the tennis ball using hand and the G-TENG was attached to the ball surface. Due to its flexibility nature, it can easily adhere to any kind of flat of curvature surface. Figure 6(c-d) shows the energy harvesting by attaching the G-TENG to the upside of arm and touching it with the dumbbel lifting exercise. The G-TENG was then attached to the throat region of the body followed by saying hello and drinking water as an activity. As can be seen from Figure 7(a-d), the G-TENG can successfully produce electrical output from this low-frequency output making it a potential device for any sensing and biomedical applications.

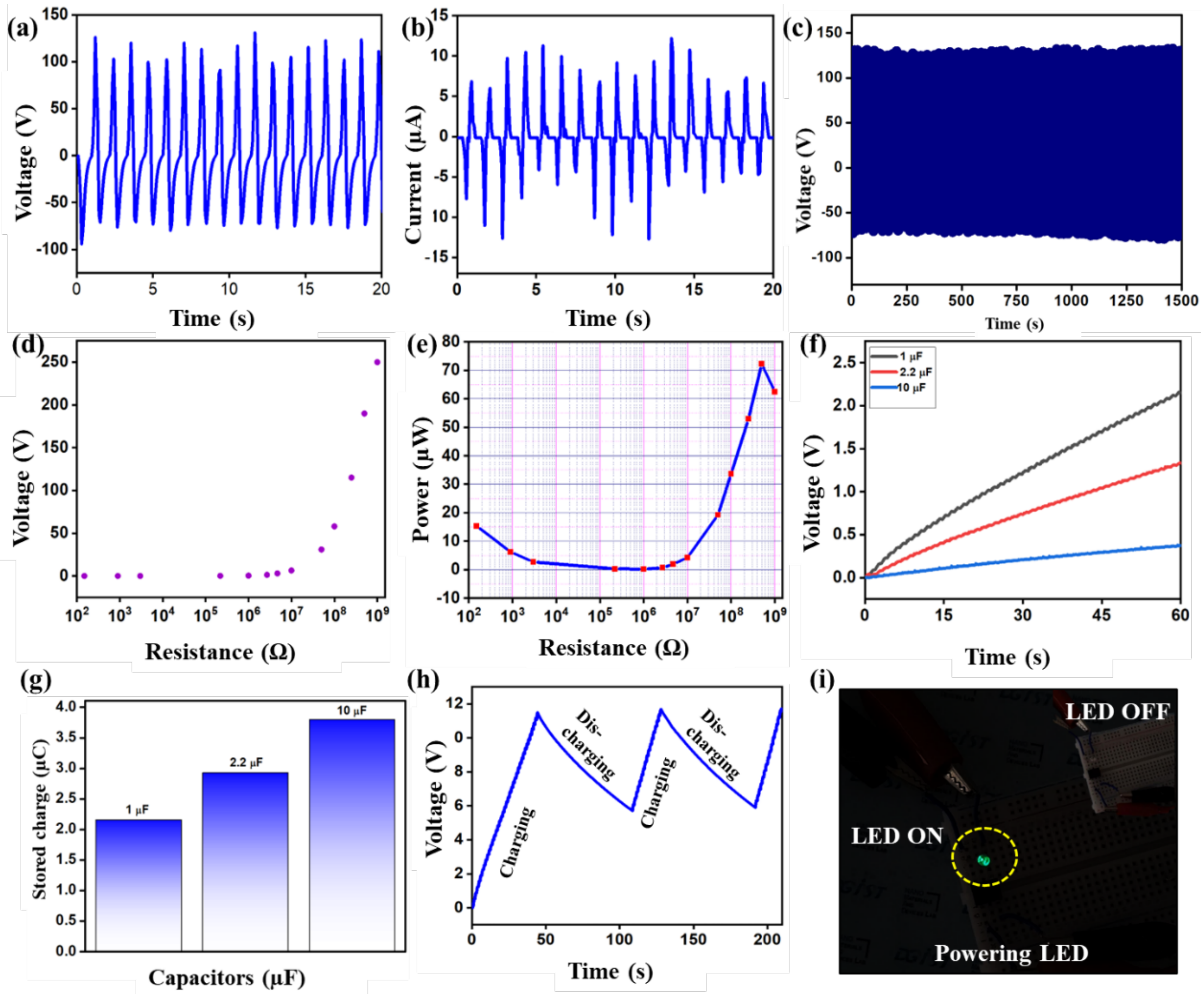

Figure 4. (a-b) Voltage and current output of G-TENG, (c) long-term stability test, (d-e) voltage and power output across various load resistance, (f) charging of various capacitors, (g) calculated stored charge in various capacitors, (h) charging-discharging curve, (i) powering LED light using the G-TENG.

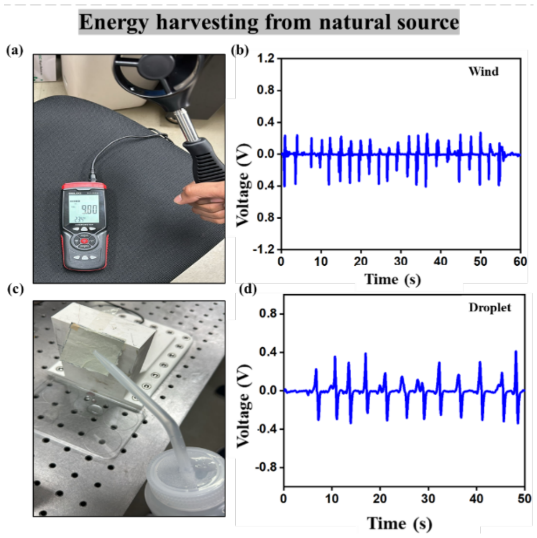

Figure 5. Energy harvesting from natural sources: (a) wind energy harvesting, (b) droplet energy harvesting using G-TENG.

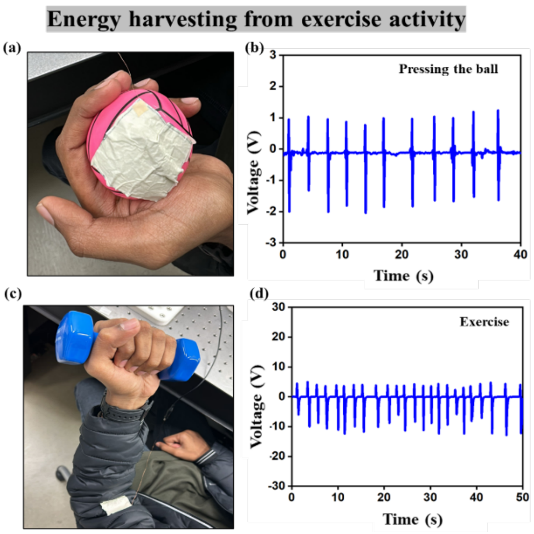

Figure 6. Energy harvesting from exercise activities: (a) pressing the ball, (b) dumbbel lifting exercise.

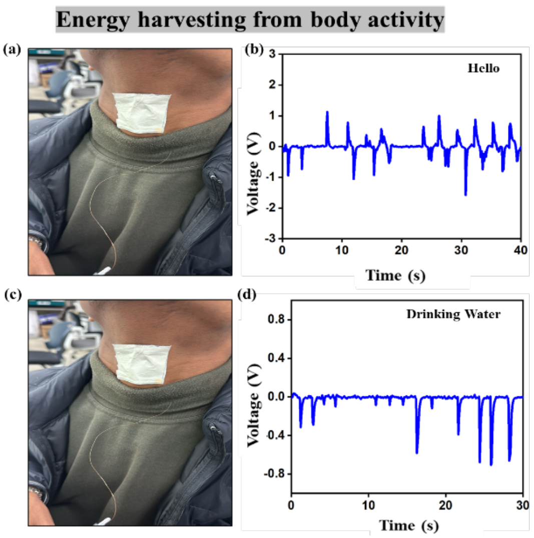

Figure 7. Energy harvesting from body activities: (a) speaking a word "hello", (b) drinking water by attaching the G-TENG to the throat region.

4. Conclusions

In this paper, we have developed a waste material derived from laboratory and successfully fabricated a single-electrode mode TENG using waste latex glove, aluminium tape, and glass slide. The fabricated G-TENG offers an electrical output of 220 V and 25 µA of voltage and current respectively. Also, the G-TENG demonstrates highest output power of 72 µW at 500 MΩ resistance. Then G-TENG was also used to charge various capacitors and glow LED and then finally many mechanical energies from natural source like wind energy, droplet energy, exercise activity and energy for body activity such as speaking and drinking water were also harvested and successfully converted into electrical energy. This sustainable TENG device is sustainable, low-cost, easy to fabricate and can provide lot of future directions in sensing and biomedical applications. The study effectively addresses the growing concern of plastic waste in laboratories, offering a creative solution.

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