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Additive manufacturing-based recycling of laboratory waste into energy harvesting device for self-powered applications

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Abstract
The laboratory waste produced in several parts of the world has scaled up the pollution and adverse effect on human health in the present era. The “3 R” (reduce, reuse, and recycle) scheme is adopted by many communities for efficiently recovering waste products and utilizing them for the production of energy. In the present work, the laboratory waste is collected and directly utilized for fabricating a laboratory waste-based triboelectric nanogenerator (LW-TENG) operating in vertical contact-separation mode. The substrate, electrode, and triboelectric layer are randomly selected from lab waste. The waste plastic petri dishes were extruded into thin filament wires for 3D printing of the substrate for the LW-TENG. The effective electrical output is generated by LW-TENG having a triboelectric layer plastic-glass delivering voltage of 185 V, current of 1.25 μA, and power density of 8.1 μW/cm² across the load resistance of 500 MΩ. The positive and negative triboelectric layers are altered and the electrical output is systematically investigated. Additionally, the LW-TENG device is attached to various locations of the laboratory to demonstrate the energy harvesting from the mechanical motions. It is also utilized...
for demonstrating real-time applications that could be beneficial as a self-powered human tracking device (HSD) that tracks the location of the human during an emergency and self-powered exercise counter.

Graphical abstract

**Keywords:** Triboelectric, Recycling, 3D printing, Laboratory waste, Energy harvesting

**Introduction**

The laboratory wastes are produced in huge quantities daily and most of them are not recycled. This waste is piled up in landfills as non-biodegradable waste[1]. The laboratory waste comprises gloves, plastic dishes, plastic cups, tubes, glass slides, aluminium foil, tubes, cotton[2]. The plastic waste from packing (up to 7 %) that is recycled cannot be reused for the same purpose due to the presence of contaminants which limits the marketing and consumers for the recycled plastic wastes[3]. Plastic is the most durable non-biodegradable polymer and can be converted into micropellet as exposed to environmental change adding to the most dangerous
solid pollution[4]. Some of the laboratory waste is burned in an open-air environment and poses an additional threat to the environment and society. Several organizations such as US Energy Information Administration (EIA), Environmental Protection Agency (EPA) are more focused on implementing the concept of waste-to-energy for effectively using solid or laboratory waste effectively in energy generation and fuel production aiming towards a green and clean ecosystem[3, 5]. Recycling of laboratory waste for effective energy harvesting could promote the idea of circular economy and advantageous towards the building positive social benefits.

Three-dimensional (3D) printing has revolutionized the concept of an easy tool for any user to design, create, and fabricate[6]. In addition, 3D printing has allowed the tabletop production of complex structures over wide selections of materials. The fused filament fabrication (FFF) is a type of 3D printing technology that facilitates molding by melting a solid polymer by heat and extruding it under a certain pressure[7]. The FFF 3D printing technology can be utilized to print the filaments obtained from the waste laboratory plastics as they offer thermal stability, easy availability, and cost-effective processing. Such recycling of waste laboratory plastics as a substrate could lead to valorization, and thus promoting the effective utilization of waste. Several works have reported the conversion of plastics into suitable energy and fuel production[8, 9].

With the rapid growth of microelectronics industries, a continuous quest to designing a sustainable power source is in great demand. Green energy sources contribute as a backbone for the generation of micro/nanoscale energy, which is essential to promote a sustainable and eco-friendly ecosystem. Several research teams have focused on developing new structures and enhance the efficiency of photovoltaics, wind power generation, and biomechanical energy systems[10-13]. More specifically, the micro/nanoscale devices are shifting towards the utilization of the piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG) mechanisms for sustainable powering of low-power electronics[14-16]. Among them, the TENG devices gained a lot of attention in the scientific community for offering several advantages such as the wide material choice, device designs, high power generation, and easy fabrication routes[17, 18]. TENG follows the principle of triboelectrification and electrostatic induction. TENGs can be implemented in various self-power applications, implantable power sources, neuromodulation, and healthcare sensors while producing a high conversion efficiency [19-22].
TENGs have a great future towards commercialization and methods should be deployed to develop low-cost TENGs[23, 24].

In the present work, the recycling and utilization of the common laboratory waste, which are collected from the dustbins, towards the fabrication of robust and cost-effective TENGs. Laboratory waste is abundant and proper waste disposal has become a very serious challenge for many universities across the globe. Table S1 highlights the outstanding electrical output and competitive cost of our LW-TENG compared to the previously reported TENGs operating in the vertical contact-separation mode. The fabrication of the LW-TENG also showcases the right use of the laboratory waste, equipment and sheds light on the creation of a model for laboratory waste minimization. The TENG comprises two triboelectric layers having different work functions or polarities. The laboratory waste such as paper, aluminium, cotton, glass, and nitrile gloves bear a positive polarity while a waste plastic and PET sheet act as negative polarity. The waste plastic petri-dish was collected in few quantities and was washed with DI water and subsequently grinded into fine shredded particles utilizing a kitchen grinder. Then it was extruded as waste plastic petri dish transparent filaments that were 3D printed to form the substrate of the LW-TENG. The LW-TENG was measured systematically by alternating the triboelectric layers and the results elucidate the trends follow as per the triboelectric series. Figure S1 shows the table of the triboelectric layers according to the polarity [25, 26]. The LW-TENG was attached in several places in the laboratory and it was able to harvest the mechanical energy inside various activities of a laboratory into useful electrical energy. Further, a real-life application towards a self-powered human safety device has been demonstrated which could act as an alert to relatives or friends during an emergency.

**Processing and experimental techniques**

Laboratory waste materials like plastic, polyethylene terephthalate (PET), cotton, aluminium, paper, glass, and nitrile gloves were collected from a laboratory dustbin and directly employed as active materials for the fabrication of LW-TENG. The fabrication of the LW-TENG has an active area of 2.5 cm x 2.5 cm. The substrate was 3D printed from the filament of the waste plastic and the electrode is the aluminium. The spring is connected on four sides to create an air gap between two triboelectric layers. The plastic petri-dish is shredded and extruding of filament
with 2.38 mm diameter was fabricated using a single screw extruder (Wellzoom line II, China) at 240 °C. Here, the extrusion speed of 45 cm/min was set during the extrusion process.

The structural analysis of the waste material is carried out using a powder diffractometer Malvern PANalytical Empyrean, Netherlands employing a voltage of 30 mA and 40 V using CuKα radiation having a step size of 3°/min. The surface morphology of the different materials and filaments was captured by a scanning electron microscope (SU-8020, Hitachi, Japan). Raman spectra were recorded at room temperature by using a Nanobase XPERRAM Raman, Korea with an excitation laser of 532 nm. The Fourier transform infrared (FT-IR) spectra have been traced using Continuum, Thermo Fisher Scientific, USA at room temperature in attenuated total reflection (ATR) mode. The 3D printed substrate was printed using a dual nozzle FDM 3D printer (Ultimaker S3, Netherland). The thickness of all the used laboratory waste materials has been evaluated using a surface profiling measuring system (Bruker/Dektak XT, USA). The device measurements were performed using a linear motor (LinMot Inc., USA) inside a lab-designed Faraday cage. An electrometer, (Keithley 6514, USA) coupled with a LabVIEW program was used to measure current and voltage.

**Results and Discussion**

Laboratory waste disposal and its management have been a challenging part of the world. It is sometimes toxic, non-biodegradable, and ends up in landfills producing immense pollution affecting human and aquatic life. The US environmental protection agency has put forward strict propaganda towards the regulation of small waste generations such as pavement services, universities, museums, airplanes, and analysis laboratories which churn out 200 to 1000 kilogram waste and at least 2 kilograms of hazardous waste in a month[27]. The laboratory waste varieties and quantities should be properly identified to utilize the reduce, recycle and reuse (3R) methodology to a greater extent. Figure 1 a shows the type of plastic waste dustbin utilized in the laboratory of Nanomaterials and Devices Laboratory, DGIST in South Korea. This approach has been undertaken to take a step towards converting trash into useful energy devices. The four dustbin colors were chosen as green, white, blue, and red. The disposed waste in the green dustbin is office stationery, disposable paper cups, and tissue paper, for the red dustbin the waste contents are cut plastic, latex gloves, and rubber tubes, for the white dustbin the contents are packing material, metal objects, paper and finally for blue dustbin comprises of the broken glass bottles, glass slides, and glass Petri dish. Figure 1 b shows the recycling of plastic petri-dish
waste into 3D printing compatible filaments, which is later used for the printing of device substrate. The used plastic petri dish collected from the red dustbin is washed with DI water to eliminate any dust or residue upon it. Then it is transferred to an electrical oven at 60 °C for 2 hours. The plastic petri plates were shredded into small particles utilizing a kitchen grinder. Further, the particles were transferred to the inlet of the single filament extruder equipment and the filament wire was obtained which was 3D printed into the substrate for TENG. Video 1 and 2 shows the processing of the filament wires and the 3D printed substrate, respectively. Figure 1 c shows the layer-by-layer fabrication of the LW-TENG. First, the 3D printed substrate was taken and the aluminum electrode was pasted. The copper wires were attached to the electrode and further, the positive/negative triboelectric layer attachment complete the contact-separation mode based LW-TENG. The digital image of the LW-TENG device is shown in Figure 1c. Figure S2 a shows the cross-section image of the fabricated 3D printing filament obtained from the waste plastic petri-dish and the natural surface morphology of the filament. The substrate of the LW-TENG was investigated by Raman spectroscopy and the vibrational modes were recorded as shown in Figure S2 b. The peak positions at 1004 cm⁻¹ represent the ring breathing, 1032 cm⁻¹ corresponds to in-plane CH deformation, 1352 cm⁻¹ corresponds to CH deformation, 1527 cm⁻¹ corresponds to ring stretching, 2915 cm⁻¹ corresponds to antisymmetric CH₂ stretching, and 3060 cm⁻¹ corresponds to aromatic CH stretch. These results are consistent with the reported polystyrene data[28]. Figure S2 c presents the FT-IR spectrum of the substrate filament. The 2916 cm⁻¹ corresponds to stretching vibrations of C-H and around 1700 cm⁻¹, it represents C=O stretching of carboxyl[29]. Figure S3 a and b shows the surface morphology of the negative triboelectric layers (PET, Plastic). Figure S3 c shows the Raman data for the PET triboelectric layer. In this 1060 and 1116 cm⁻¹ corresponds to C-C stretching, 1290 cm⁻¹ corresponds to C(O)-O stretching, 1615 cm⁻¹ corresponds to ring mode 8a, 2960 cm⁻¹ corresponds to symmetric CH₂ vibrations and 3080 cm⁻¹ corresponds to aromatic C-H bonds. It shows the presence of mixed polystyrene and polyethylene[30]. Figure S3 d shows the Raman spectra of the plastic triboelectric layer. It shows the presence of polyethylene. The C-C stretching linked to 1060 and 1127 cm⁻¹, 1375 cm⁻¹ corresponds to CH₂ wagging, 1434 cm⁻¹ corresponds to CH₂ bending while C-H stretching is linked to 2850 and 2880 cm⁻¹[31]. Figure S3 e and f show the structural analysis of the PET and plastic triboelectric layer respectively. The PET sample detected a single-crystalline peak at 2 theta=26° showing a (100) plane [32]. The crystalline nature of the plastic
sheet is also depicted from the sharp peak arising at $2\theta = 21.7$° and $24.1$°[33]. Figure S4 shows the SEM micrograph of the various positive triboelectric layers such as aluminium, cotton, gloves, tissue paper, and glass. Table S2 shows the thickness of the negative and positive triboelectric layers utilized to construct the LW-TENG. Figure S5 shows the XRD pattern of the positive triboelectric layers such as aluminium, cotton, gloves, tissue paper, and glass. In the case of the glass, only a board diffraction peak with no peaks related to the crystalline phase is observed confirming the amorphous nature of the glass. In the case of the paper, the peak around $2\theta = 18$° has two peaks (110) and (200) planes corresponding to the low ordered cellulose while the highest intensity peak between $2\theta = 22$° - $24$° having (200) plane corresponds to both crystalline and low ordered cellulose [34]. In the case of the gloves, its XRD pattern matches with the acrylonitrile-butadiene-styrene (ABS) in which the peak at $19.9$° is characteristic of an amorphous structure and peaks at $27.4$° corresponds to additional subcomponents of the polymer [35]. The cotton XRD pattern comprises of three characteristic peaks at $2\theta = 14.7$° (101), $2\theta = 16.3$° (101), and $2\theta = 22.5$° (002), respectively [36]. In the case of aluminum foil, it can be seen that a high-intensity peak at $2\theta = 44.7$° corresponds to the pure Al phase [37]. Figure S6 presents the Raman spectra of the positive triboelectric layers such as aluminium, cotton, gloves, tissue paper, and glass at room temperature. The glass shows Raman peaks around 950 cm$^{-1}$ and 1090 cm$^{-1}$. These peaks correspond to the Si-O stretching vibration modes [38]. In the case of the paper, the Raman peaks are observed at 2896 cm$^{-1}$, 1476 cm$^{-1}$, 1121 cm$^{-1}$. The peak 2896 cm$^{-1}$ and 1121 cm$^{-1}$ are related to cellulose [39]. In the case of the gloves, a board peak was observed, which matches with ABS polymer [40]. The pristine cotton showed peaks corresponding to $\nu$(C–O–C) bending at 1116 and 1331 cm$^{-1}$ while 2906 cm$^{-1}$ corresponds to CH, CH$_2$ stretch [41]. The characteristic Raman peak of the aluminium foil matches the reported data [42].

Figure 2 a shows the digital image of the collected waste materials, which were directly utilized in the fabrication of an LW-TENG. Figure 2 b presents the illustration of the device design of the LW-TENG constructed with help of waste materials. The LW-TENG operates with the help of the triboelectric mechanism as shown in Figure 2 c. In the initial state, no potential difference persists in the absence of force, which hinders the generation of charges. Step (i) shows that the LW- TENG is fully in contact leading to the generation of equal and opposite charges on the triboelectric layers. The positive triboelectric layer (aluminium, cotton, glass, nitrile gloves, and tissue paper) behaves as a positive triboelectric layer, and PET/ plastic behaves as a negative
triboelectric layer, thus generating a positive charge and negative charge as per their polarity. Step (ii) shows that as the applied force is detached, the regain in the top triboelectric layer forms a potential difference, leading to electron flow from top to bottom electrode. Step (iii) shows an equilibrium position has reached and the flow of electrons stops as the device reaches full separation. Step (iv) shows as the force is again subjected upon the device, the top layer starts moving towards the bottom layer and leads to the reverse flow of electrons. The periodic contact-separation between the triboelectric layers of LW-TENG generates the device output response\[43\].

The voltage and current response of the triboelectric device shed light upon the design of suitable applications. Figure 3 a and b shows the voltage and current of the LW-TENG comprising of PET as a negative triboelectric layer and the positive triboelectric layer is varied with laboratory waste having a positive polarity. The voltage and current outputs follow the trend of the materials as listed in the triboelectric series, which is summarized in Figure S1. The highest electrical output was fetched from the PET/Glass LW-TENG giving a voltage of 115 V and a current of 0.74 μA. Figure 3 c and d presents the voltage and current output of the LW-TENG comprising of the fixed negative triboelectric layer plastic and varying the different laboratory waste having positive affinity. The highest output was obtained from Plastic/Glass LW-TENG showing a voltage of 185 V and a current of 1.25 μA. The LW-TENG based on plastic/ (aluminum, cotton, gloves, paper, glass) follows the working principle of contact electrification and electrostatic induction. The performance of the LW-TENG is highly dependent on the tendency of losing or gaining electrons from the triboelectric layers. The surface charge output can be improved by several chemical functionalization of the triboelectric layer by fluorinating surfaces, ion injection, and molecular docking \[44-46\]. Such methods are complex time-consuming routes and limited to a specific group of materials or polymers. In the present study, the SEM micrographs of the positive triboelectric layers in Figure S4 show that the laboratory waste materials themselves comprise the surface roughness which is responsible to generate a large amount of charge when coming into contact with the negative triboelectric layer (i.e. Plastic). Figure S7 shows the output charge of the different laboratory waste materials and plastic (the device dimensions remained constant for all the materials). The charge generated follows the trend similar to voltage and current output depicting that the glass-plastic LW-TENG generates higher electrical output performance due to more generation of output charge. Figure 3 e and f
show the power density of optimized LW-TENG (PET/Glass and Plastic/Glass) respectively as a resistance function (1 kΩ to 1 GΩ). The power density of 2.5 μW/cm² is seen in the case of PET-glass-based LW-TENG while it enhances to 8.1 μW/cm² for plastic-glass-based LW-TENG across a load of 500 MΩ. The robustness of any triboelectric device can be depicted from the long-time stability of the device. Figure 3 g-i shows the charge, voltage, and current output of the LW-TENG by altering different frequencies (0.5 Hz, 0.9 Hz, 1.6 Hz, 2.0 Hz). More specifically, there is no change in the maximum amplitude of the movement during a change in the frequencies. Thus, the LW-TENG follows relatively the same contact and separation path. Hence, the maximum voltage and charge are almost the same for all frequencies as it depends on the position of the TENG surface, which does not alter with the change in frequencies. However, increasing the frequencies of the linear motor movement can induce a rise in the rate of charge exchange, producing higher current output. The electrical current output of the LW-TENG (plastic-glass) increases with an increment in the frequency of the movement. These results are consistent with the previous works [47, 48].

Figure 4 a shows the stability of the plastic-glass-based LW-TENG for 2300 seconds. The output from any TENG device is generally AC output so it needs to convert into the DC output to be utilized in power electronics. Thus, the AC to DC output conversion could be done employing a bridge rectifier circuit. Figure 4 b shows the charging and discharging curve of a 1 μF capacitor showing the continuous stable electrical output of the plastic-glass-based LW-TENG for a long time. Figure 4 c shows the charging of various capacitors (1, 4.7, 10, and 47 μF) shows that the energy obtained from the plastic-glass-based LW-TENG successfully charges various capacitors. Figure 4 d shows the stability test for the device LW-TENG based on PET-glass up to 2300 seconds showing stable output. Figure 4 e shows the charging and discharging curve of a 1 μF capacitor, shedding light upon the stable electrical output of the PET-glass-based LW-TENG for a long time. Figure 4 f shows the charging of various capacitors using the PET-glass-based LW-TENG. Figure 4 g and h shows the amount of charge and energy stored in a capacitor which is derived by using the following equation: \( Q = C \times V \) and \( E = \frac{1}{2} C V^2 \). The voltage accumulated across the 1 μF capacitor by human activity stomping is shown in Figure 4 i. It can be depicted that the LW-TENG (Plastic-glass) charges the capacitor up to 1 V in 70 secs while the LW-TENG (PET-glass) charges the capacitor up to 1 V in 210 secs during stomping upon the device by feet.
The relative motion of the human body and several activities occurring in an academic laboratory is an excellent source of mechanical energy. The biomechanical energy is abundantly available and can be altered to electrical energy using TENG. The LW-TENG based on plastic glass was chosen due to its higher electrical output for practical application and finally altering the mechanical energy in the laboratory into useful electric energy. Figure 5 a and b shows the voltage of the plastic-glass-based LW-TENG which was attached in various locations like a chair, floor, door, fume hood, and drawer. The output voltage obtained from plastic-glass-based LW-TENG by leaning in the chair is 15 V, sitting on the chair is 55 V, leg tapping delivers 30 V, open and closing of door delivers 5 V, opening and closing of the drawer generates 2 V and opening and closing of fume hood delivers 13 V. Figure 5 c shows the digital images of the plastic-glass-based LW-TENG when placed in several locations of the laboratory delivering the mechanical energy to the device during everyday laboratory activities. Figure 5 d and e show the current generated by the plastic-glass-based LW-TENG which is seen to be 100 nA during leaning in the chair, 300 nA sitting on the chair, 70 nA for leg tapping, 38 nA opening and closing of the door, 5 nA opening and closing of the drawer and 45 nA for opening and closing of the fume hood.

The developed LW-TENG device based on plastic/glass could be utilized in solving some real-life mishaps. Figure 6 a shows the digital image of the front and backside of the human safety device (HSD) where the backside was wired with thin copper wires. This type of approach of powering the low-power electronics by the LW-TENG could also be helpful to reduce the usage of batteries. Figure 6 b shows the switch-off and switch-on conditions. The capacitor of 750 μF was charged up to 3 volts using the LW-TENG device based on plastic/glass as shown in Figure 6 c. As the switch is on, the capacitor gets discharged and the mobile app could easily recognize the signal strength coming from the tag. The public outcry about crimes like murder, rape, violence, kidnapping has become a serious issue in many parts across the world [49]. The approach of legal response in many countries takes several years to seek justice and the victim has to suffer discrimination and inequality in society. Therefore, the present study is aimed at powering the low-power HSD device to track the user through a commercially available app providing safety during some violent attack. Video 3 shows the demonstration of detecting the HSD signal by mobile phone app. Figure 6 d shows the crime index of many countries over past years. Figure 6 (e) shows the user wearing the HSD device as a pendant and while the switch is
ON the capacitor starts to discharge. During an attack, the user can quickly press the button and the location of the user will be saved in the mobile phone of the relatives. This approach can be improved in the future using a power management circuit and combining other services like cameras, calling facilities.

Figure 7 a shows the charging and discharging profile of the 10 μF capacitor using a bridge rectifier and the LW-TENG (plastic-glass). Figure 7 b and c show the digital picture of a calculator and a wristwatch in the switch ON and switch OFF condition. Human life is full of stress, which is causing depression and mental health problems in the younger generation. To overcome this problem physical activities like exercises and yoga are recommended by several medical specialists to maintain healthy body weight and avoid mental illness. The exercise counter acts to count each activity for properly carrying out each exercise. Sometimes unknowingly excess number of pushups of hand exercise may lead to moderate or severe muscle strain and fatigue. Hence, an exercise counter may be beneficial to track the exercise time and repetitions maintaining the proper fitness of the user. Figure 7 d shows the various exercises performed by the user and the location of the LW-TENG (plastic-glass). Figure e-g shows the real-time voltage output during the activity like lower back exercise, hand-gripping exercise, and stretching exercise. The number of peaks can be used to count the number of times each exercise is being performed. Hence, the LW-TENG could effectively count the repeats performed during the exercise period and can serve as a self-powered exercise counter.

Conclusion

In summary, the concept of recycling, reduce, and reuse (3R) of laboratory waste materials were employed to construct a cheap, robust, and cost-effective TENG device operating in vertical contact mode. This approach promotes the reduction of pollution and a move towards sustainable development. The innovative 3D printing approach was undertaken to print the substrate from the waste Petri dish filament. The enhancement of LW-TENG output is consistent with the materials in the triboelectric series. The plastic-glass-based LW-TENG produced the highest output voltage of 185 V and a current of 1.25 μA among all the compositions. Moreover, a plastic-glass-based LW-TENG is demonstrated for harvesting the mechanical energy of a laboratory in various locations such as doors, fume hood, drawer, floor, and chair. Finally, a plastic-glass-based LW-TENG could help to power up an HSD via a charging capacitor, which can be a beneficial and cost-effective approach towards providing human safety. The powering
of a wrist-watch, a calculator, and a self-powered exercise counter was demonstrated using the LW-TENG. The obtained results demonstrate that the TENG device could be very helpful in converting the abundant amount of biomechanical energy into electrical energy and also extend various self-powered applications.

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**Authors Contributions**

**Manisha Sahu:** Conceptualization, Formal analysis, Investigation, Writing - Original Draft;  
**Sugato Hajra:** Writing – Editing, Methodology, Formal analysis;  
**Hang-Gyeom Kim:** Data Curation;  
**Horst-Günter Rubahn:** Writing – Editing;  
**Yogendra Kumar Mishra:** Methodology, Writing- Review;  
**Hoe Joon Kim:** Funding acquisition, Writing - Review & Editing, Supervision.

**References**

Figure Captions

**Figure 1:** (a) Type of dustbin in a laboratory and the possible obtained waste from each dustbin. (b) plastic petri dish extruded to 3D printer filaments along with a digital picture of 3D printing substrates and (c) Layer by layer arrangement of the LW-TENG and digital image.

**Figure 2:** (a) Digital image of the collected laboratory waste; (b) Three-dimensional schematic illustration of the LW-TENG and (c) working mechanism of the LW-TENG in vertical contact separation mode.

**Figure 3:** (a-b) Voltage and current of the LW-TENG with negative triboelectric layer as PET and different laboratory waste positive triboelectric layer; (c-d) voltage and current of LW-TENG with plastic as a negative triboelectric layer and positive layer is taken as different laboratory waste; (e) power density of the LW-TENG (PET-glass) for external load matching, (f) power density of the LW-TENG (plastic-glass) for external load matching, (g-i) charge, voltage and current output of the LW-TENG (plastic-glass) concerning to different frequencies.

**Figure 4:** (a-c) Long term stability test by applying constant force for 2200 secs, charging-discharging of 1μF capacitor, charging of various capacitors using the plastic-glass based LW-TENG and (d-f) Long term stability test by applying constant force for 2200 secs, charging-discharging of 1μF capacitor, charging of various capacitors using the PET-glass based LW-TENG; (g) charge and energy stored by various capacitors via LW-TENG (plastic-glass); (h) charge and energy stored by various capacitors via LW-TENG (PET-glass) and (i) charging profile of the 1μF capacitor using a human activity (stomping).

**Figure 5:** Biomechanical energy harvesting (a-b) voltage output by attaching the plastic-glass based LW-TENG in different areas in a laboratory; (c) digital image of the location of the LW-TENG in several areas of a laboratory where contact and separation of the device can occur; (e-f) current output by attaching the plastic-glass based LW-TENG in different areas in a laboratory.

**Figure 6:** Demonstration of Self-powered human-safety tracking device (a) digital image of the women safety device front and back view; (b-c) digital image of the HSD device and phone during the switch ON and OFF conditions; (d) Charging of a 750 μF capacitor by using plastic-glass based LW-TENG; (e) graph showing the increase in the crime rate across the world and (f) Location tracking by the commercial android app when the HSD is pressed as the switch is ON.
Figure 7: (a) Charging and discharging profile of a 10 μF capacitor and powering up of (b) calculator and (c) a wrist-watch; (d) digital images of the LW-TENG acting as an exercise counter and (e-g) voltage response of the LW-TENG (plastic-glass) showing each peak as a counter for repetition of the exercise performed.
**Figure 1:** (a) Type of dustbin in a laboratory and the possible obtained waste from each dustbin. (b) plastic petri dish extruded to 3D printer filaments along with a digital picture of 3D printing substrates and (c) Layer by layer arrangement of the fabricated LW-TENG and digital image.
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Figure 3: (a-b) Voltage and current of the LW-TENG with negative triboelectric layer as PET and different laboratory waste positive triboelectric layer; (c-d) voltage and current of LW-TENG with plastic as a negative triboelectric layer and positive layer is taken as different laboratory waste; (e) power density of the LW-TENG (PET-glass) for external load matching, (f) power density of the LW-TENG (plastic-glass) for external load matching, (g-i) charge, voltage and current output of the LW-TENG (plastic-glass) concerning to different frequencies.
Figure 4: (a-c) Long term stability test by applying constant force for 2200 secs, charging-discharging of 1μF capacitor, charging of various capacitors using the plastic-glass based LW-TENG and (d-f) Long term stability test by applying constant force for 2200 secs, charging-discharging of 1μF capacitor, charging of various capacitors using the PET-glass based LW-TENG; (g) charge and energy stored by various capacitors via LW-TENG (plastic-glass); (h) charge and energy stored by various capacitors via LW-TENG (PET-glass) and (i) charging profile of the 1μF capacitor using a human activity (stomping).
Figure 5: Biomechanical energy harvesting (a-b) voltage output by attaching the plastic-glass based LW-TENG in different areas in a laboratory; (c) digital image of the location of the LW-TENG in several areas of a laboratory where contact and separation of the device can occur; (e-f) current output by attaching the plastic-glass based LW-TENG in different areas in a laboratory.
Figure 6: Demonstration of Self-powered human-safety tracking device (a) digital image of the women safety device front and back view; (b-c) digital image of the HSD device and phone during the switch ON and OFF conditions; (d) Charging of a 750 μF capacitor by using plastic-glass based LW-TENG; (e) graph showing the increase in the crime rate across the world and (f) Location tracking by the commercial android app when the HSD is pressed as the switch is ON.
Figure 7: (a) Charging and discharging profile of a 10 μF capacitor and powering up of (b) calculator and (c) a wrist-watch; (d) digital images of the LW-TENG acting as an exercise counter and (e-g) voltage response of the LW-TENG (plastic-glass) showing each peak as a counter for repetition of the exercise performed.
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**Manisha Sahu**: Conceptualization, Formal analysis, Investigation, Writing - Original Draft;

**Sugato Hajra**: Writing – Editing, Methodology, Formal analysis; **Hang-Gyeom Kim**: Data Curation; **Horst-Günter Rubahn**: Writing – Editing; **Yogendra Kumar Mishra**: Methodology, Writing- Review; **Hoe Joon Kim**: Funding acquisition, Writing - Review & Editing, Supervision.
Declaration of Competing Interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
Research Highlights

- Circular economy-Circumvention of laboratory waste to sustainable energy
- Straightforward and cost-effective 3D printing of plastics into devices.
- Recycling of plastic wastes to develop LW-TENG device.
- Demonstration of self-powered biomechanical energy harvesting applications.