Electronic Supplementary Material (ESI) for Environmental Science: Advances.

Supplementary Information

Medical Waste X-ray Film Based Triboelectric Nanogenerator for Self-Powered Devices, Sensors, and Smart Buildings

M Navaneeth[1], Supraja Potu[1], Anjaly Babu[1], Rakesh Kumar Rajaboina[1], Uday Kumar K[1], Haranath Divi[1], Prakash Kodali[2], Balaji K[3]*

S1: Fabrication steps of X-ray film-based triboelectric nanogenerator

Figure S1 (a)-(c) shows the different steps involved in the fabrication of TENG. Initially, two acrylic sheets (7x7 cm^2) were taken. In the next step, two hard cardboard sheets (5x 5 cm^2) and aluminium sheets (5 x 5 cm^2) were attached to the acrylic sheets, as shown in Figure S1 (a). X-ray film and silicone films were attached to both aluminium electrodes, as shown in figure S1 (b). in the last step, with the help of flexible sponge spacers, both frames (figure s1(b)) were placed one over the other with a gap of 1 cm between them. Figure S1(d)-(e) shows the photographs of the triboelectric layers and final TENG device.

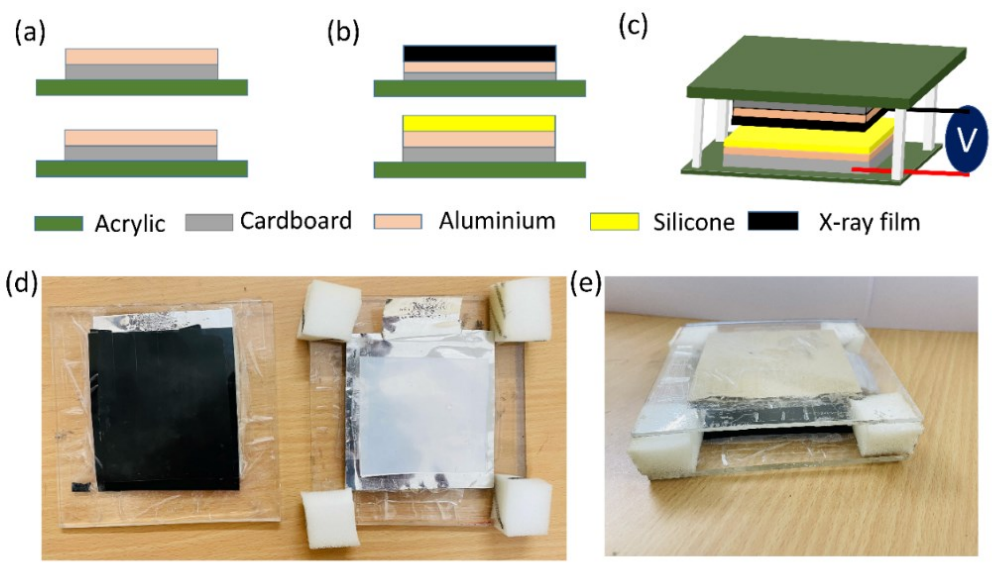

Figure S1. (a)-(c) Schematic of the TENG fabrication steps, (d) photographs of the triboelectric layers attached to electrode and base support, (e) Final TENG device.

S2: Fabrication of switched-capacitor-convertors circuit.

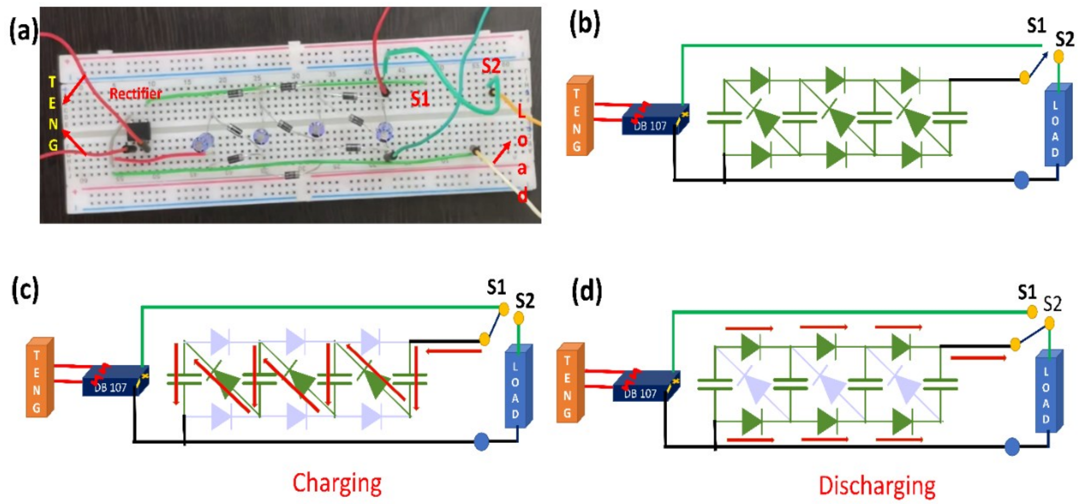

Figure S2. (a) photograph of the circuit developed on the breadboard, (b) schematic of the circuit, (c) During charging of the capacitors with X-TENG connected to the circuit, (c) During discharging of the capacitors with the load connected to the circuit.

S3: Efficiency calculation

The energy conversion efficiency was calculated using the below formula and the procedure adopted from the reported literature on efficiency calculation of TENG[1][2][3][4].

$$\text{Efficiency}(\eta) = \frac{\text{Output electrical energy}}{\text{Input mechanical energy}}$$

The maximum electric energy generated by a TENG within a cycle of current at the frequency of 4 Hz can be estimated using the data of the TENG's output measured at 5 MΩ. The heat energy (H) dissipated by the resistor in one cycle is calculated from integration of current curves, as shown in figure S3.

$$\text{Electrical energy (H)} = \int_{t1}^{t2} I^2 . R\, dt + \int_{t3}^{t4} I^2 . R\, dt$$

$$= 5.96\ \mu J$$

where I is the instantaneous current, and R is load resistance, and t_1,t_2 are the time period of the cycle [1].

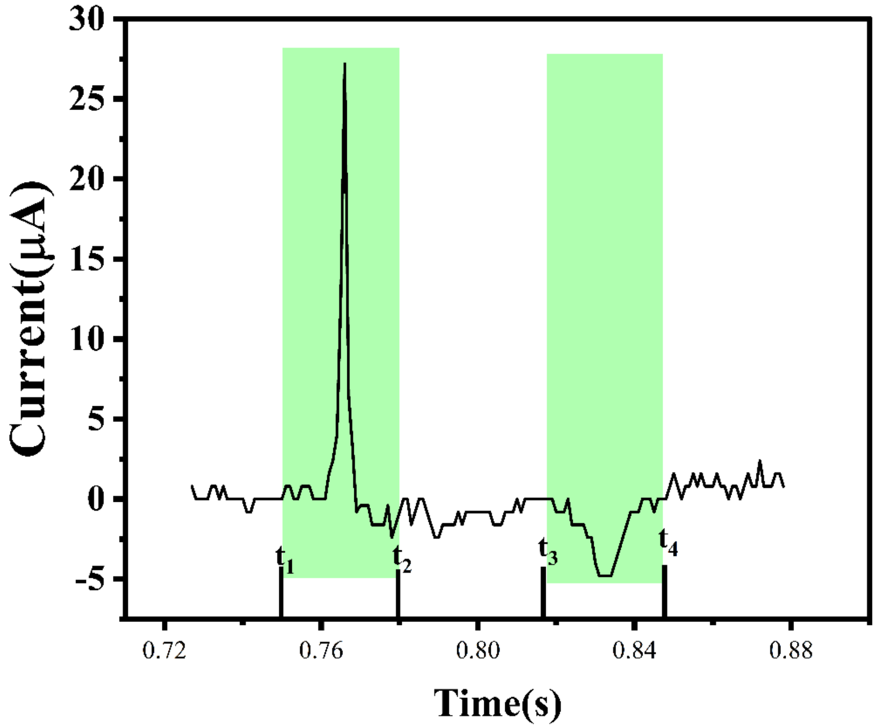

Figure S3. A current pulse output produced by hand tapping at load resistance of 5 MΩ when a contact is made (in one cycle).

The total of elastic (stored in the sponge) and kinetic energy (due to movement of the top layer) can be used to calculate the mechanical energy delivered to TENG. The well-known elastic and kinetic energy formula was used to determine these two mechanical energies. Sponge potential energy was computed as,

$$E_{spring} = \frac{1}{2}kx^2$$

The spring constant of the sponge was found to be **160 N/m**. Four such sponges were used for the TENG fabrication. The spacer distance of the TENG was 1cm. So the total elastic energy will be

$$E_{spring} = \mathbf{(4\,(\tfrac{1}{2}\;k\;x^2) = 32}\ \mathrm{mJ}$$

The total kinetic energy of the movable substrate

$$E_{Kinetic} = \frac{1}{2} m v^2 \quad .$$

Mass of the movable electrode with triboelectric layer (m) = 4.76 g

Velocity of the moving section can be calculated from the applying frequency (4Hz).

Velocity, V= 8cm/s.

The total kinetic energy of the top moving layer will be

$$E_{Kinetic} = \frac{1}{2} m v^2 = 15\ \mu J$$

So the efficiency (η) can we calculated as

$$\eta = \frac{E_{Electric}}{E_{Mechanical}} = \frac{E_{Electric}}{E_{Kinetic} + E_{Eleastic}} \times 100$$

$$\eta = \frac{15\mu J + 32 mJ}{5.96\ \mu J} \times 100 = 0.018\ \%$$

It should be noted that the number mentioned above shows overall device efficiency. The elastic energy held in the springs, on the other hand, does not contribute to energy conversion at the conversion process level. As a result, if we only consider the kinetic energy that is partially converted to electric energy, the conversion process' direct efficiency,

$$\eta_{Actual} = \frac{E_{Electric}}{E_{Kinetic}} \times 100 = 39.73\%$$

S4: COMSOL simulation details of X-TENG

Table 1. Parameters applied in COMSOL software

Parameters	Value
Tribo-charge surface density σ	11 μC m^{-2}
X-ray thickness d_1	0.25 mm
Silicone rubber thickness d_2	1 mm
Electrodes (Al) thickness d_3	1mm
Dielectric constant of X ray ε_1	3.8
Dielectric constant of silicone rubber ε_2	3.2
Maximum separation distance x_{max}	0.01m
Area of the device	5x5 cm^2

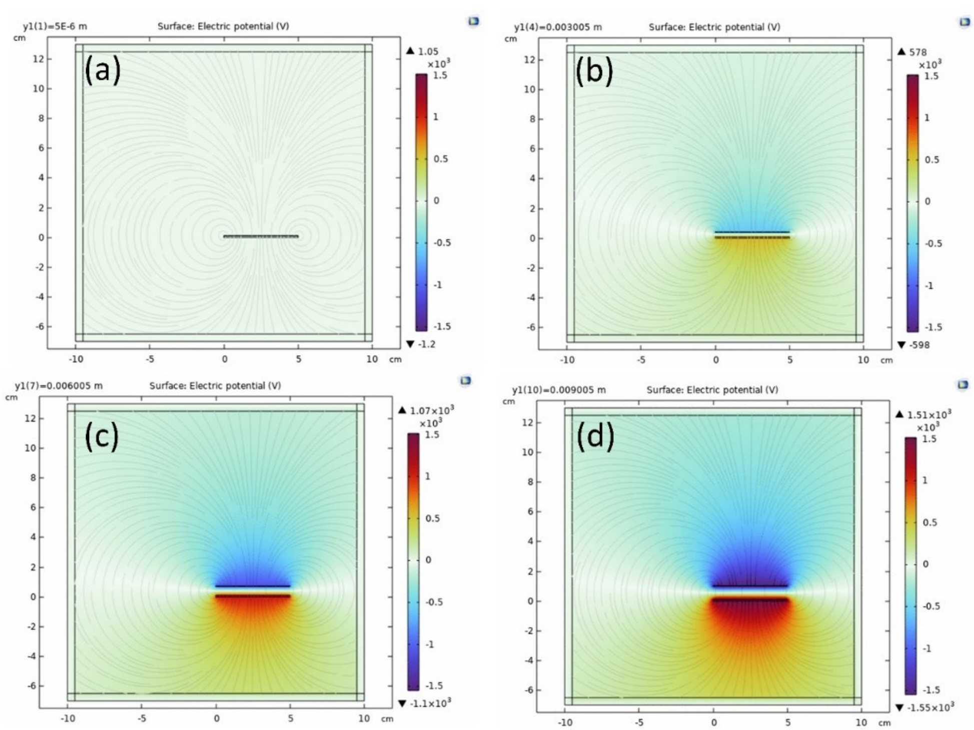

Figure S4 Finite element simulation of the vertical contact-separation mode of TENGs at different separation distances between X-ray and Silicone using COMSOL Multiphysics software.

S5: Stability of TENG using modified linear motor.

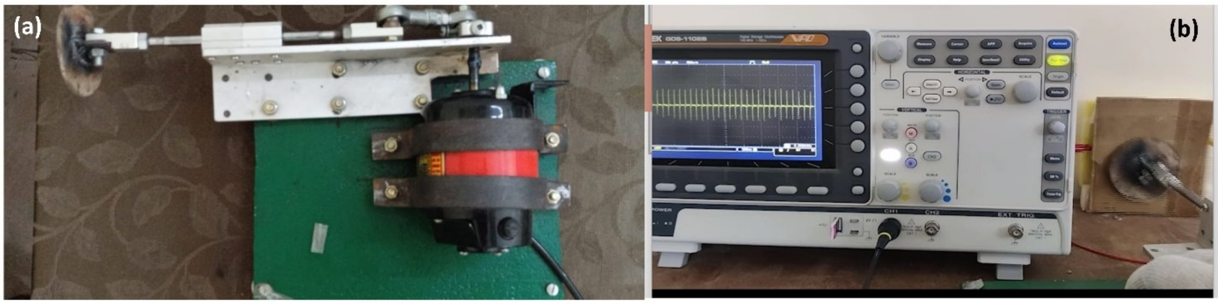

Figure. S5. Photographs of the (a) modified linear motor, (b)TENG response in DSO.

S6: Photographs of the LEDs connected in EXIT text and arrow symbol.

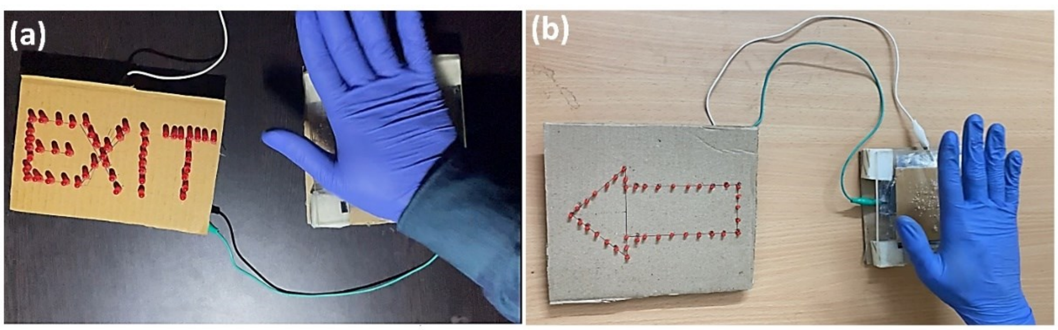

Figure. S6 Photographs of the designed EXIT and arrow indicator displays connected to the TENG.

S7: Force calculation

We have used kinetic energy and momentum theorem to find the approximate hand tapping force, asorted in the literature[5][6] The calculation of the contact pressure induced by a falling object (a droplet of water and a falling feather or finger/hand tapping) was based on a simple physical model, combining the gravity term and the pulse term. When the object falls/hand tapping on the surface of the TENG device, it encounters two processes: (1) falls through the air and touches the surface of the device, (2) completely falls on the device. The descending velocity of the object increases to a maximum value in the first process and decreases to zero in the second one.

We set m as the mass of the object, h as the falling height (spacing between the triboelectric layers), v as the maximum falling velocity, F as the contact force, p as the contact pressure, Δt as the time span during the second process, and A as the effective area of the device. Based on the kinetic energy theorem and momentum theorem, we have

$$m.g.h = \frac{1}{2}mv^2 \cdots (1)$$

$$(F - m.g).\Delta t = m.v \cdots (2)$$

Where m is measured by weighing balance (m=0.9kg), h =1 cm, g =9.8 N/kg, Δt could be estimated as the time variation between the two consecutive voltage peaks induced by hand tapping

From eqn. 1,

$$v = \sqrt{2gh}$$

Where, g= 9.8 N/kg, h= 0.01m, Δt=1/4=0.25s

So, $v = 0.44\frac{m}{s}$

From eqn. 2,

$$F = \frac{m.v}{\Delta t} + m.g$$

Where m= 0.9 kg

So, F=10.4 N

S8: Demonstration of hotel services with TENG.

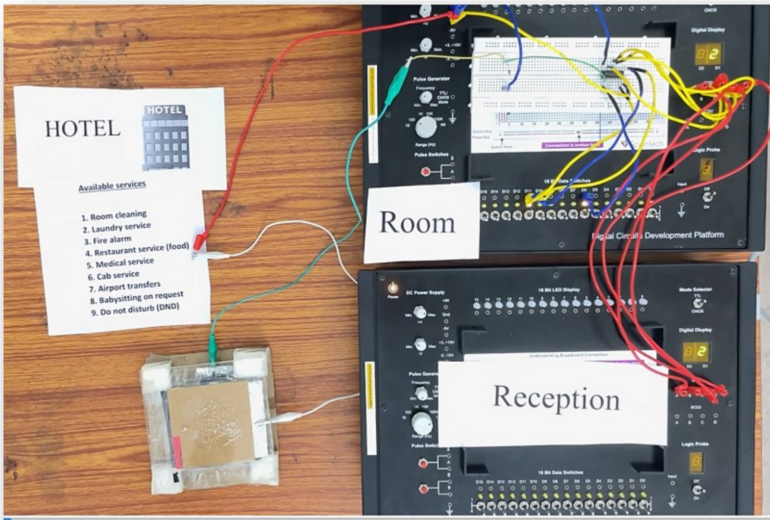

Figure. S7 Different hotel room services enabled by TENG (ex: Laundry service requested).

References

[1] G. Zhu, Z.H. Lin, Q. Jing, P. Bai, C. Pan, Y. Yang, Y. Zhou, Z.L. Wang, Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator, Nano Lett. 13 (2013) 847–853. https://doi.org/10.1021/nl4001053.

[2] C.K. Jeong, K.M. Baek, S. Niu, T.W. Nam, Y.H. Hur, D.Y. Park, G.T. Hwang, M. Byun, Z.L. Wang, Y.S. Jung, K.J. Lee, Topographically-designed triboelectric nanogenerator via block copolymer self-assembly, Nano Lett. 14 (2014) 7031–7038. https://doi.org/10.1021/nl503402c.

[3] S. Mishra, P. Supraja, D. Haranath, R.R. Kumar, S. Pola, Effect of surface and contact points modification on the output performance of triboelectric nanogenerator, Nano Energy. 104 (2022). https://doi.org/10.1016/j.nanoen.2022.107964.

[4] A. You, X. Zhang, X. Peng, K. Dong, Y. Lu, Q. Zhang, A Skin-Inspired Triboelectric Nanogenerator with an Interpenetrating Structure for Motion Sensing and Energy Harvesting, Macromol Mater Eng. 306 (2021). https://doi.org/10.1002/mame.202100147.

[5] F.R. Fan, L. Lin, G. Zhu, W. Wu, R. Zhang, Z.L. Wang, Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films, Nano Lett. 12 (2012) 3109–3114. https://doi.org/10.1021/nl300988z.

[6] A. Sultana, M.M. Alam, S. Garain, T.K. Sinha, T.R. Middya, D. Mandal, An Effective Electrical Throughput from PANI Supplement ZnS Nanorods and PDMS-Based Flexible Piezoelectric Nanogenerator for Power up Portable Electronic Devices: An Alternative of MWCNT Filler, ACS Appl Mater Interfaces. 7 (2015) 19091–19097. https://doi.org/10.1021/acsami.5b04669.