Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

Supporting Information

Chicken Feather Fiber Based Bio-Piezoelectric Energy Harvester: An Efficient Green Energy Source for Flexible Electronics

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S1.Experimental:

The structural property was studied using X-ray diffractometer (Bruker-D8) with Cu-Kα radiation (wavelength 1.541 A) using Bragg-Brentano goniometer geometry and θ-2θ scanning mechanism. Vibrational spectra for the sample was recorded at 30°C by Fourier transform infrared spectroscope (Jasco FT/IR-460 PLUS) with a resolution of 1.0 cm^{-1}. The surface morphology of the sample was studied by scanning electron microscopy (SEM) (JEOL, USA). The piezoelectric coefficient of the chicken feather fiber (CFF) was measured using d33 meter (Piezotest, PM100). The response of biomechanical force (via a human finger touch) on the fabricated CFF based bio piezoelectric energy harvester (BPEH) was recorded in terms of output voltage from a digital oscilloscope (DSO-NVIS207C1T). Charging a capacitor response (with 2.2 μF of capacitance) and power up of LEDs were tested with the BPEH through a typical bridge rectifier circuit unit.

Cell culture. The human adult dermal fibroblasts (HADF) cells (NCCS, Pune) were cultured with high glucose DMEM supplemented with 10% fetal bovine serum (Gibco, USA) and 1% antibiotic-antimycotic solution (Gibco, Life Technologies, USA) in a 25 cm^2 flask with 5% CO_2 at 37 °C.

Cell viability assay. The cells were cultured on the pieces of a BPEH for 24 h and 72 h in a 96-well plate. MTT assay using EZcount™ MTT cell Assay Kit (HiMedia, Mumbai, India) was performed to evaluate the cellular proliferation of cultured HADF cells. 100 μL of MTT dye (5 mg/ml) was added into each well, and the cells were incubated for 4 h at 37 °C. After removing the supernatant, 100 μL of solubilization buffer was used to dissolve the form azan crystals for 10 mins at room temperature on a shaker. Absorbance values were obtained at 570 nm using a spectrophotometer (MultiSkan GO Microplate Spectrophotometer, Thermo Fischer Scientific, Ratastie 2, FI-01620 Vantaa, Finland).The experiment was performed in triplicates. Percentage of cell viability was calculated by the following formula,

$\%\ \text{cell viability} = [(Abs_{test} - Abs_{blank}) / Abs_{control} - Abs_{blank}] \times 100$

where, Abs_{test}, $Abs_{blank}$and $Abs_{control}$signify absorbance of the sample, blank and control at 570 nm.

Cell morphology visualization by fluorescence staining. After culturing for 1 day and 3 days, the sample was washed in 1X PBS (pH 7.4) and fixed in 4% paraformaldehyde for 15 min. After washing with PBS, the sample was incubated with 50 μg/ml rhodamine-conjugated phalloidin (Invitrogen, CA, USA) for 90 min to stain the cellular F-actin cytoskeleton and counterstained with 1 μg/mL of DAPI for 1 min to stain the nucleus. Finally, the stained cells were characterized using aninverted fluorescence microscope (Nikon eclipse Tí U, Japan) equipped with 20x objective. Two different fluorescence filters (λ_{ex}340-380 nm and λ_{ex}512-552 nm and λ_{em}435-485 nm and λ_{em}565-615 nm for blue and red emission respectively) were used for imaging.

S2: Supplementary results and discussion:

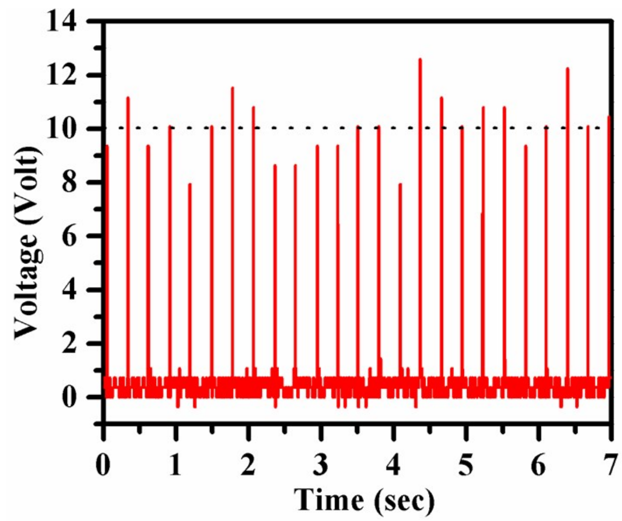

Fig.S1: Rectified output voltage of the BPEH induced by periodical vertical compression.

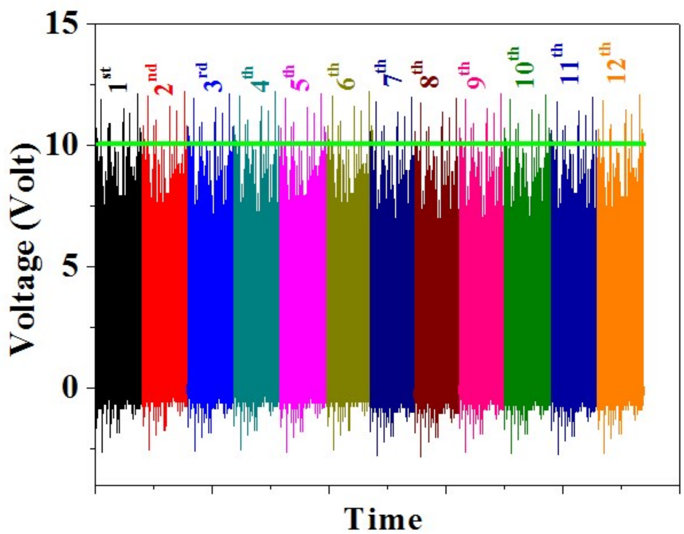

Fig.S2: Output of the BPEH over 12 weeks ensuring the durability of the device.

S2.1. Calculation of pressure applied to the fabricated BPEH

Calculation of the imparting pressure on the BPEH due a falling object is very important for evaluating the efficiency of the nanogenerator. The imparting pressure due to the finger imparting is calculated by a physical model combining the gravity and pulse term [S1]. Based on the momentum and kinetic energy theorem following equation can be written [S1],

$$m \times g \times \mathrm{h} = \frac{1}{2} \times m \times v^2 (S1)$$

$$(F - mg).\Delta t = mv \qquad (S2)$$

$$P = \frac{F}{A} (S3)$$

Where, *m* is the mass of the object, *h* is the height, *P* is the applied mechanical pressure, *v* is the maximum falling velocity, *A* is the electrode area or active area, *F* is the contact force, and *Δt* is the time span. Here *m*=90-220 gm is measured by a laboratory load cell, average Δ*t* is 0.001 sec, *h*=15 cm is the approximate height, g= 9.81 cm/S^2 and A=(2.0 x 6.0 cm^2) is the electrode area. Therefore the calculated value of applied pressure P is 0.13-0.31 MPa.

S2.2. Calculation of internal resistance and capacitance of the fabricated BPEH

As seen from the Fig.5e of the main article, the voltage drop across the applied load increases with the increasing amount of load resistance. Now the voltage drop across the load resistance can be written as,

$$V_L = \frac{V_0 R_L}{R_L + R_i}, \qquad \text{(S1)}$$

Where, V_0 is the open circuit voltage of the BPEH, R_i is its internal resistance of BPEH, and R_L is the resistance of the load resistor. Thus it can be obtained from the previous relation that

$$\frac{1}{V_L} = \frac{R_i}{V_0} . \frac{1}{R_L} + \frac{1}{V_0} \qquad \text{(S2)}$$

Now from the linear fit of the plot $\frac{1}{V_L}$ vs. $\frac{1}{R_L}$ (as shown in Fig.S3) the obtained value of the open circuit voltage V_0 is 12.5 V. Hence theoretical open circuit voltage is in well agreement with the experimentally obtained maximum output voltage (10 V). The corresponding internal resistance R_i is 1 MΩ. Thus it can be infer that such significant low value of internal resistance enables the BPEH as an efficient high voltage power source.

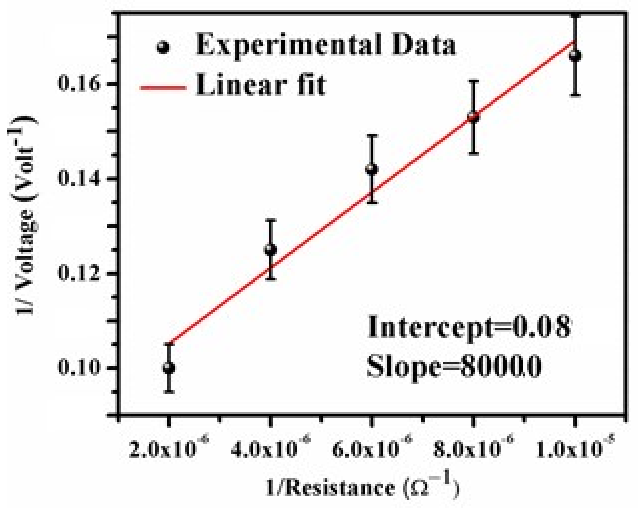

Fig.S3: Calculation of the open circuit voltage and internal resistance of BPEH using linear circuit theory [S1].

S2.3. Calculation of equivalent d_{33} of CFF

Equivalent piezoelectric constant (d_{33}) of the CFF can be calculated by [S2-S3] $d_{33} = \frac{C \times V_o}{F}$, where F is applied force (~400 N), C is the capacitance, V_o is the output voltage of BPEH. Using the values of the capacitance of the device (120 pF at 20 Hz) and average output voltage generated by the BPEH (10 V), the value of d_{33} is found out to be ~3 pC/N.

S2.4 .Energy conversion efficiency of BPEH

The energy conversion efficiency of a piezoelectric energy harvester is estimated as the ratio [S1, S4]

$$\eta = \left(\frac{Wout}{Win}\right) \text{ x } 100\% = \frac{Ee}{(Es)n_{cy}} \times 100\% \qquad (S3)$$

where E_e is the total output electrical energy stored in capacitor for 720 cycles during 180 seconds by mechanical compression, E_s is the mechanical strain energy during a single cycle [S1, S4] and n_{cy}=720 cycles. The mechanical strain energy E_s is expressed as [S1, S4]

$$E_s = \frac{1}{2} YAL\sigma^2 \qquad (S4)$$

where A is the active area of the BPEH, L is the thickness of EPE stack (50 μm), Y~ 3.6 GPa [S5] is the Young's modulus of the material and σ is the strain. σ is calculated according to the equation $\sigma = \frac{P}{Y}$ where P is the imparting pressure (0.31 MPa). Calculation of the imparting pressure is shown in section S2.1. The electrical energy storage in the capacitor of 2.2 μF is calculated by $E_e = \frac{1}{2}CV^2$, which is 4.4 μJ (as V=2 volt) for the charging time of 720 cycles during 180 seconds. Therefore, $\eta = (\frac{Wout}{Win})$ x 100% =(4.4 μJ/568 μJ) x 100 ≈ 0.8%.

S2.5 Current-time plot:

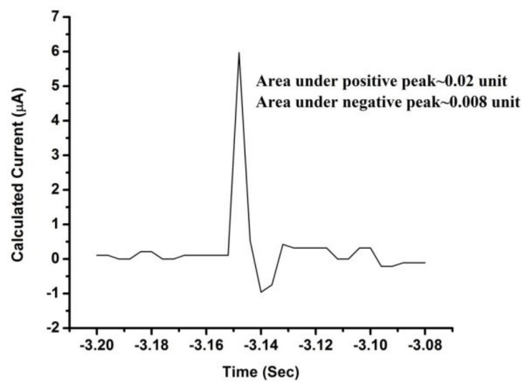

Figure S4: Calculated current- time plot for 1.5 MΩ load.

The Figure S4 shows that the ratio of area under the negative peak and positive peak is 40 %. The neutralization/loss of piezoelectric charges during the comparatively slow relaxation process may be responsible for this inequality. Previously similar kind of inequality was shown in piezoelectric energy harvesters for biomechanical energy harvesting [S6, S7].

Supplementary video:

Video S1: Lightning of LEDs by BPEH under the periodical force applied by gentle finger imparting.

Video S2: Measurement of d_{33} of CFF by using d_{33} meter.

References:

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