Supplementary Information (SI) for Nanoscale.

Supporting Information

Integration of Two-Dimensional WS_2 in Flexible Textile Triboelectric Nanogenerators via Electronic Dyeing for Self-Powered Sensing

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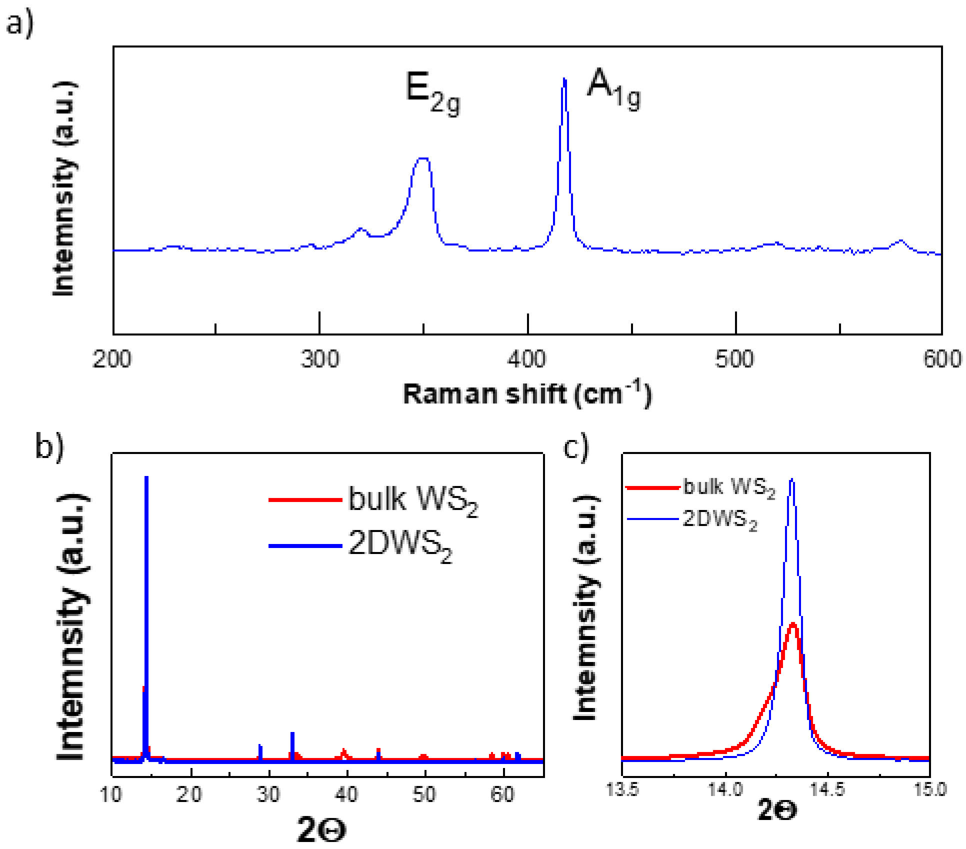

Figure S1. **Raman spectroscopy and X-ray diffraction (XRD) measurements to confirm the 2D nature of the exfoliated 2DWS_2.** a) Raman spectroscopy of exfoliated WS_2 showing characteristic peaks corresponding to the E2g and A1g modes at 349.5 and 417.2 cm^{-1} respectively. The E2g mode represents in-plane vibrations of tungsten (W) and sulphur (S) atoms, while the A1g mode corresponds to out-of-plane vibrations of sulphur atoms. The distinct separation between these peaks and their specific positions confirm that the material is in its 2D form, as these frequencies are characteristic of few-layer WS_2. b) XRD confirming that the exfoliated WS_2 has retained the 2H phase, i.e. indexed as hexagonal (P63/mmc space group) as expected for semiconducting WS_2. The characteristic (002) peak is observed at approximately 14.3°, consistent with the interlayer spacing of the 2H structure. Additional peaks, such as the (100) at ~33.5° and (110) at ~58.3°, further validate the hexagonal lattice. Importantly, no peaks associated with the 1T phase, such as a shifted (002) peak typically observed around 9°–13°, are present, indicating that the exfoliation process has not induced a phase transition. The additional peaks could arise from metallic tungsten (W) impurities or associated with the substrate. c) The XRD measurements of WS_2 reveal a prominent peak around 14.3°, corresponding to the (002) plane, which is characteristic of its layered structure. The intensity of this peak is higher in the 2D form compared to bulk WS_2. This enhancement is attributed to the alignment of layers and the preferred orientation of the 2D material on the substrate during preparation. In bulk WS_2, the layers are randomly oriented and stacked, resulting in broader reflections and lower intensity for specific planes. In contrast, the 2D form exhibits uniform layer alignment parallel to the substrate, amplifying the diffraction intensity from the (002) plane. This observation, coupled with the sharpness of the peak and the absence of secondary reflections associated with bulk stacking, confirms the successful preparation of WS_2 in its 2D form.

The Raman spectroscopy data was collected using a 514 nm CW diode laser (Coherent OBIS 514L) as a source. The laser was filtered with a laser line bandpass filter centred at 514 nm and focused on the sample through a ×50 magnification objective (laser spot diameter ≈ 500 nm). Reflected light from the sample was collected from the same objective, and once filtered with a 514 nm notch filter to remove the excitation line, was acquired with a Princeton Instruments PIXIS400 CCD camera coupled with a Princeton Instruments Acton SP2500 spectrometer. Raman measurements were carried out at ambient conditions employing 10 s integration time, and a laser power of 10 % for a single measurement, and using a 1 s integration time in static mode. The XRD data were collected at room temperature on a Bruker D8 powder diffractometer with parafocusing Bragg–Brentano geometry using CuKα radiation (λ = 0.15418 nm, U = 40 kV, I = 40 mA). The data was scanned over the angular range of 5–90° (2θ) with a step size of 0.02° (2θ).

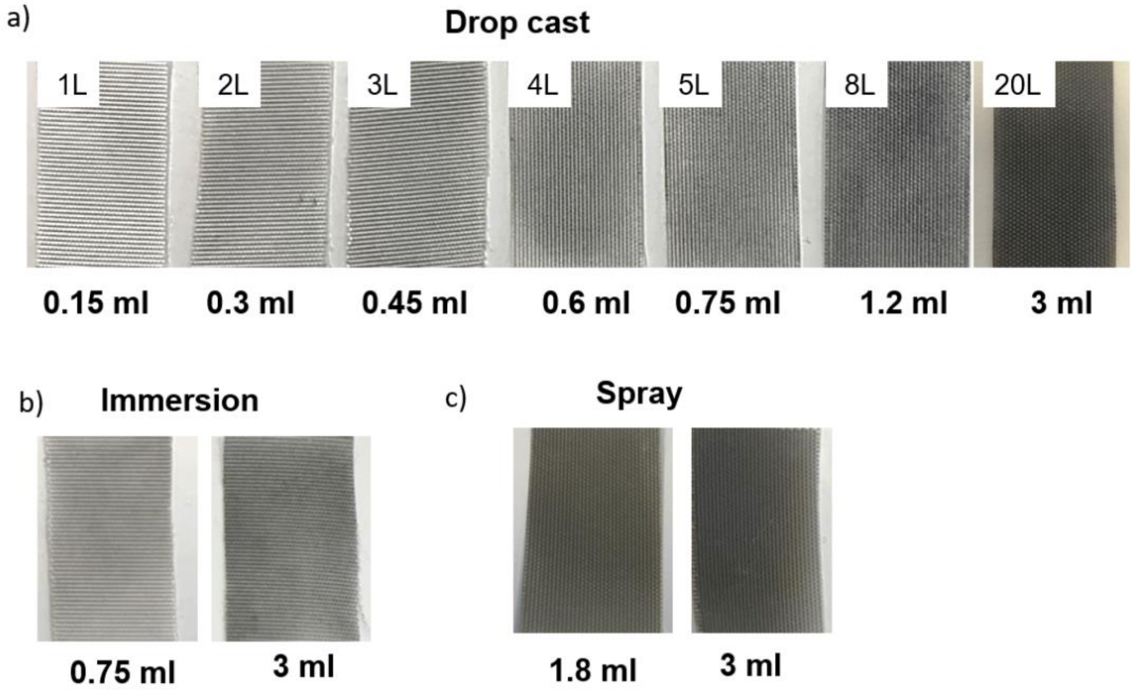

Figure S2. a) Photos of samples prepared by drop casting using different volumes of 2DWS_2 suspension. b) Photos of samples prepared by immersion using different volumes of 2DWS_2 suspension. c) Photos of samples prepared by spray coating using different volumes of 2DWS_2 suspension. The dimension of each sample is 1.5 cm × 2.5 cm.

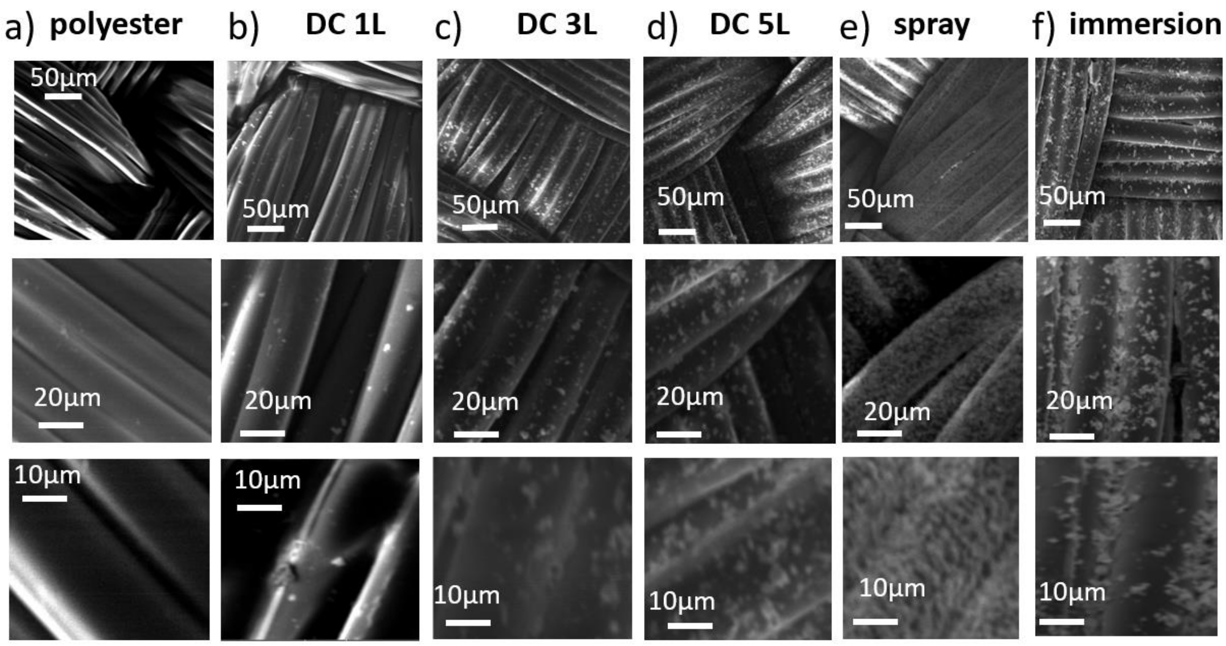

Figure S3: *SEM images at different magnifications showing (a) uncoated polyester and (b)–(d) polyester coated with 2D WS_2 using the drop casting method for layers 1, 3, and 5, respectively. Panels (e) and (f) display polyester coated via spray coating and immersion methods, respectively.*

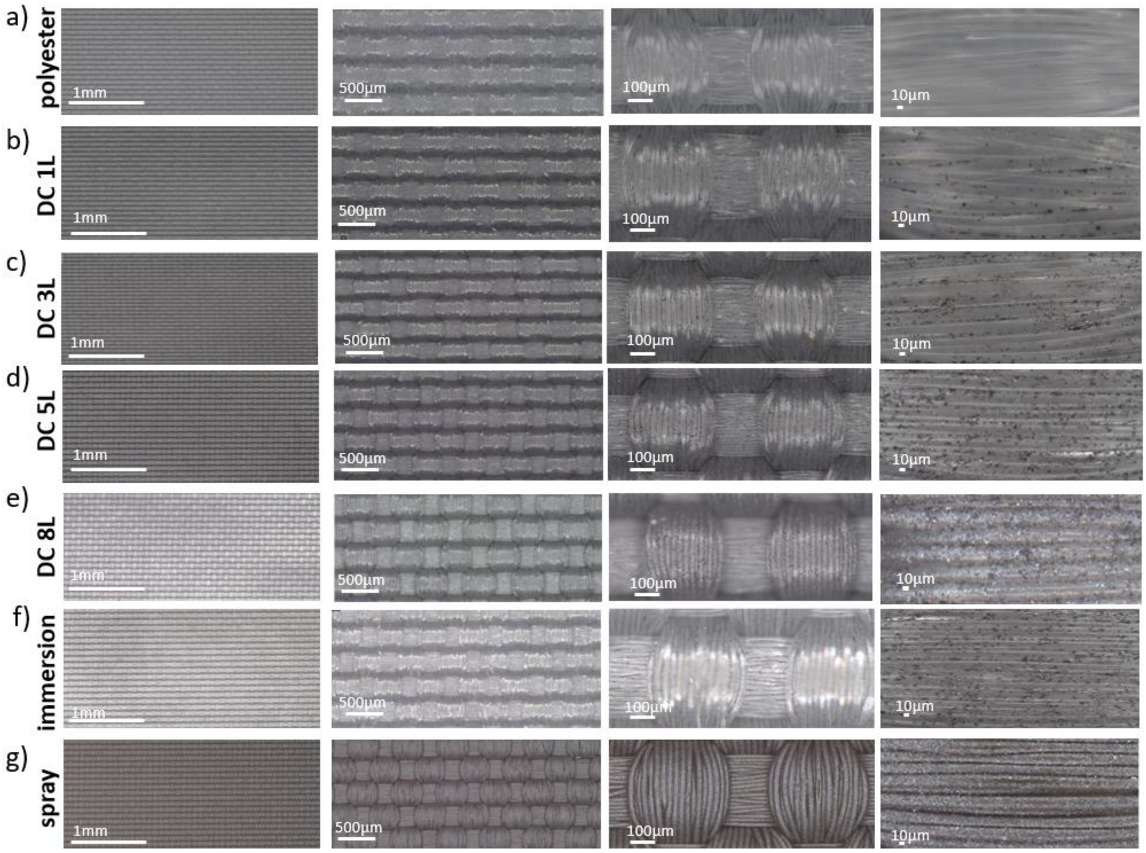

***Figure S4**: Light microscope images at different magnifications illustrating the morphological characteristics of (a) uncoated polyester and (b)–(e) polyester coated with 2DWS$_2$ using the drop casting method for layers 1, 3, 5, and 8, respectively. Panels (f) and (g) show polyester coated via immersion and spray coating methods, respectively.*

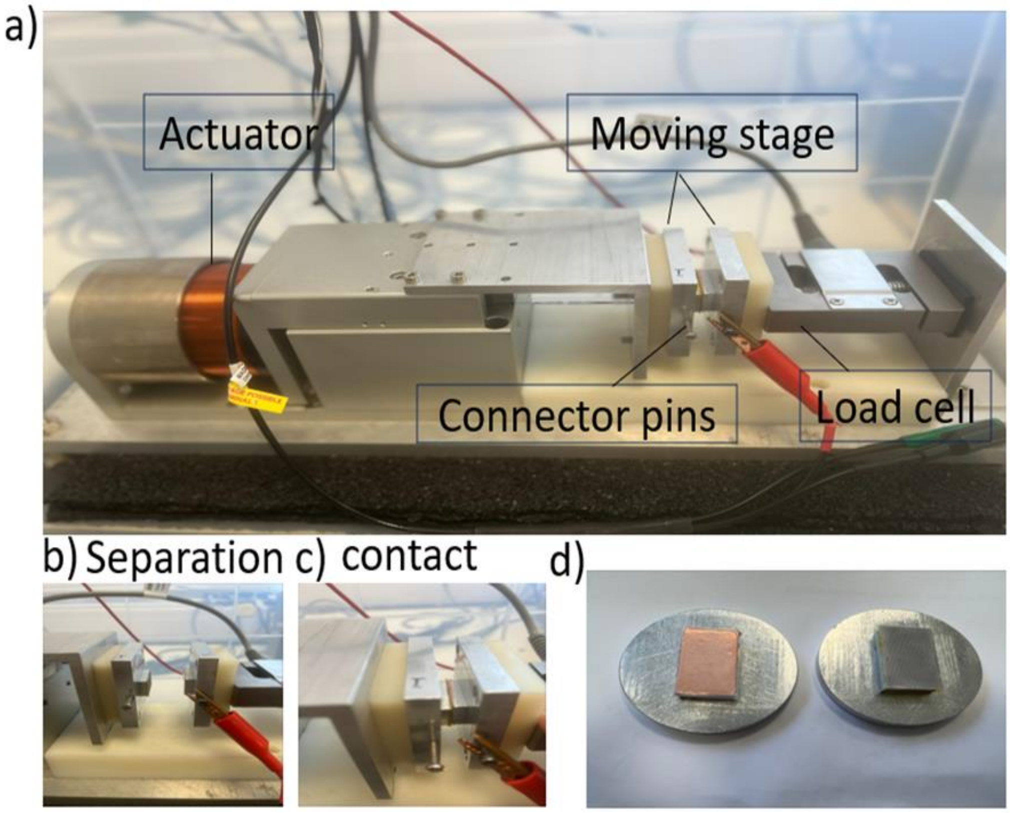

Figure S5: *(a) Configuration of the triboelectric nanogenerator (TENG) system, illustrating a horizontally operating TENG device. The setup includes a linear motor with a voice coil actuator connected to an aluminium moving stage. The sample stage features TENG mounting plates, insulated from the moving stage and the load cell using a polymer sheet. The load cell measures and calculates the force applied to the TENG device, while a spirit level ensures proper alignment. (b, c) Illustration of the TENG process: during the separation and the contact phases. (d) Sample holders for 2DWS$_2$-coated polyester and copper-nylon configurations.*

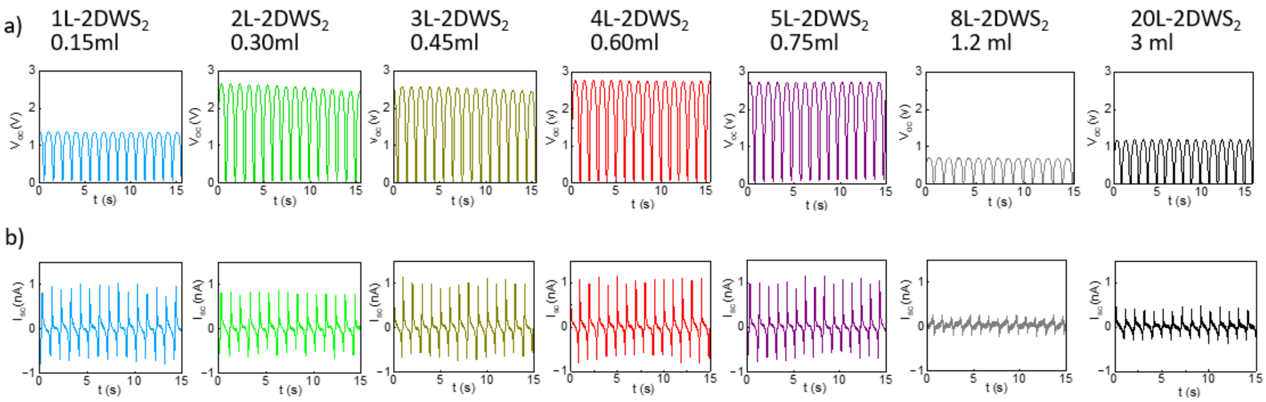

Figure S6: *Open-circuit voltage (Voc) and short-circuit current (Isc) measurements for TENG devices using 2DWS$_2$-coated polyester with PVC as the counter material. The 2DWS$_2$ coatings were prepared by drop casting with varying volumes, ranging from 0.15 mL to 3 mL, corresponding to varying layer numbers, where each layer is obtained using 0.15mL of drop casted 2DWS$_2$ suspension. The results highlight the performance characteristics of the devices as a function of the deposited WS$_2$ volume.*

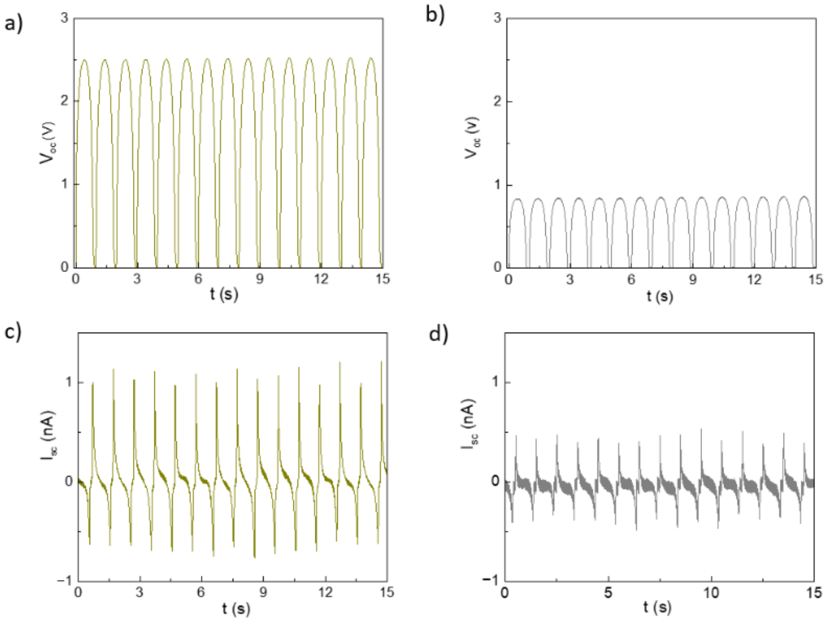

Figure S7*: Comparison of TENG performance for different amounts of 2DWS$_2$ applied via immersion with PVC as the counter material. (a) Open-circuit voltage (Voc) for 2DWS$_2$ volumes of 0.75mL, (b) Voc for 3 mL of 2DWS$_2$, (c) Short-circuit current (Isc) for 2DWS$_2$ volumes of 0.75 mL, and (d) Isc for 3 mL of 2DWS$_2$.*

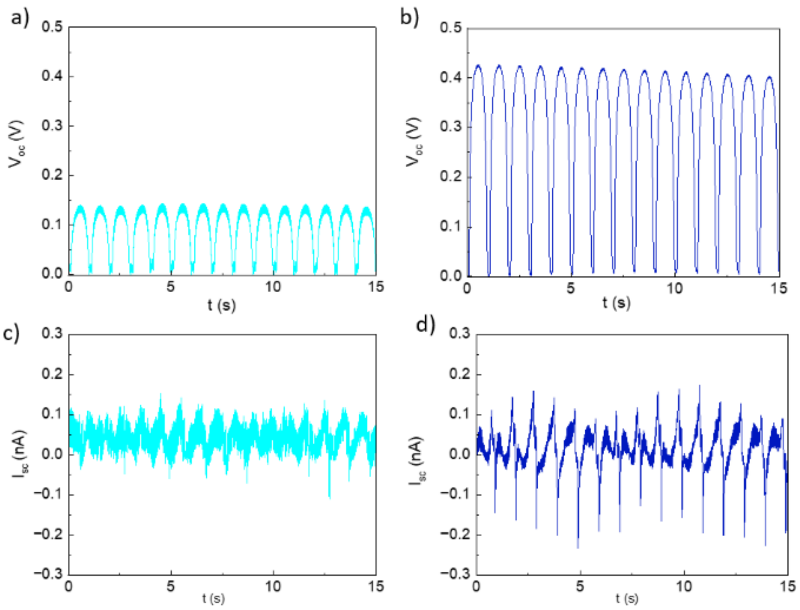

Figure S8: *Comparison of TENG performance with different amounts of 2DWS$_2$ applied via spray coating, with PVC as the counter material. (a) Open-circuit voltage (Voc) for 1.8 mL of 2DWS$_2$, (b) Voc for 3 mL of 2DWS$_2$, (c) Short-circuit current (Isc) for 1.8 mL of 2DWS$_2$, and (d) Isc for 3 mL of 2DWS$_2$.*

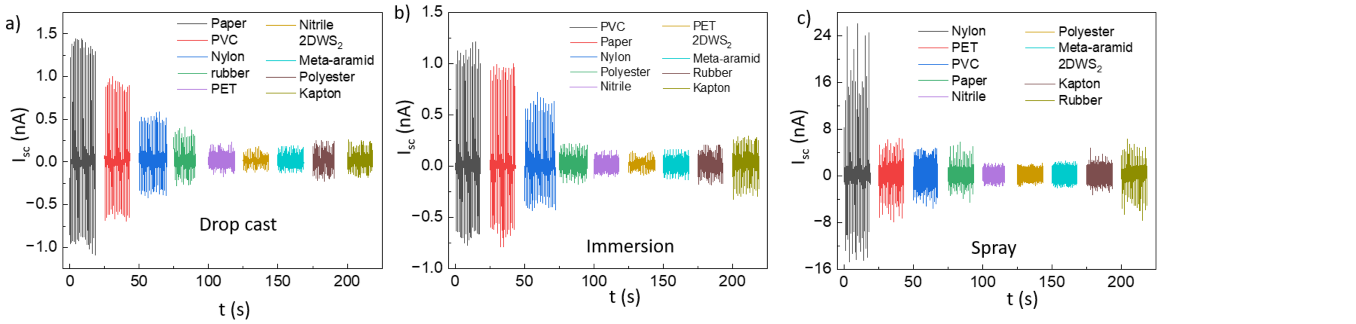

***Figure S9**: Triboelectric series based on short-circuit current measurements over time, for different triboelectric layers of TENGs tested with polyester coated with 2DWS₂ via drop casting (a), immersion (b), and spray.*

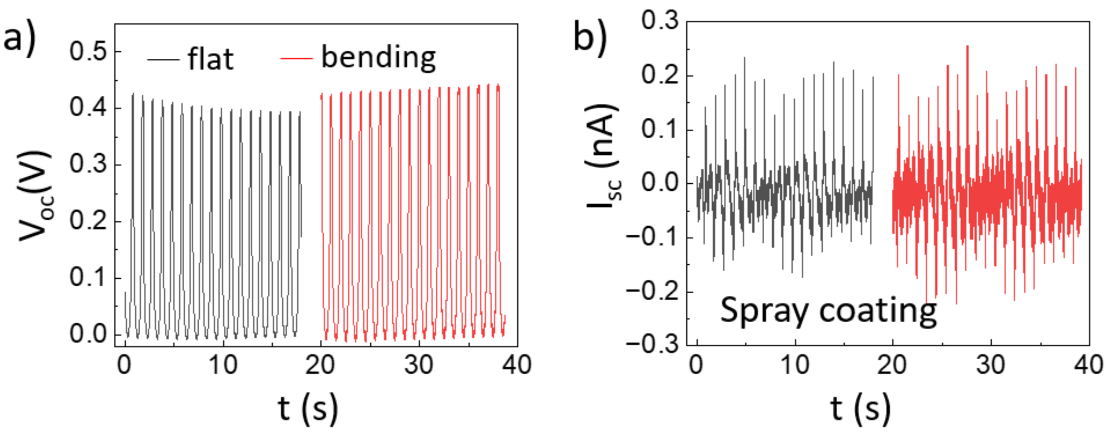

***Figure 10**: The open circuit voltage (a) and short-circuit current (b) of TENG devices in the flat position and after bending 5mm with $2DWS_2$ device prepared by spray. The counter triboelectric layer is PVC.*

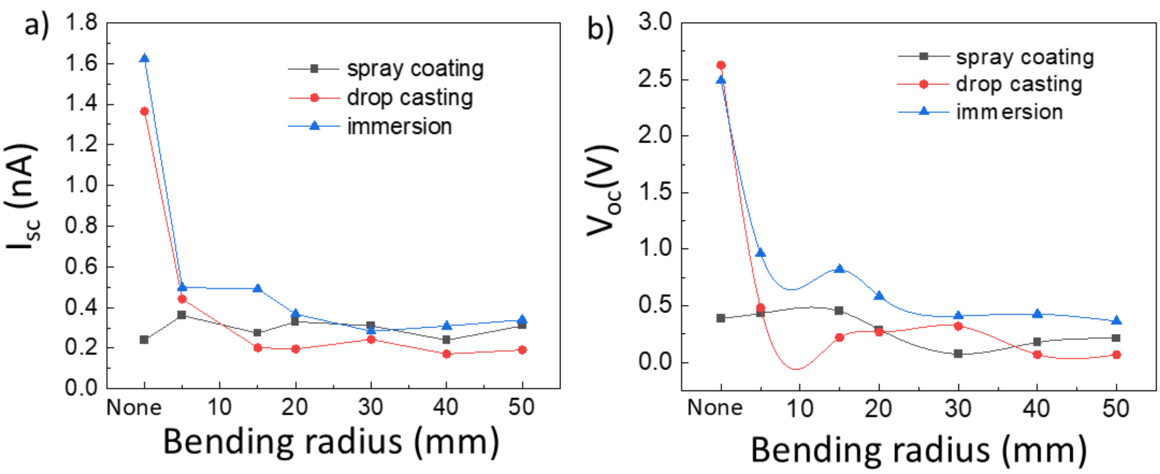

Figure 11: Summary of measurements after bending tests with varying bending radii, ranging from no bending to 50 mm, for samples produced by the three different deposition methods. The counter triboelectric layer is PVC