

Upcycling Waste Toothpaste Packaging into a Flexible Triboelectric Sensor for Motion Recognition and Human–Machine Interaction

Shuping Xue ^{1,*}, Yuanyuan Wang ², Danyang He ³, Shuwei Zhang ³, Lei Jia ³ and Yun Yang ³

¹ Department of Architecture and Civil Engineering, Lyuliang University, Lvliang 033001, China

² Research Institute of Materials Science, Shanxi Normal University, Taiyuan 030032, China

³ Department of Resource and Mechanical Engineering, Lyuliang University, Lvliang 033001, China

* Correspondence: 20001026@llu.edu.cn

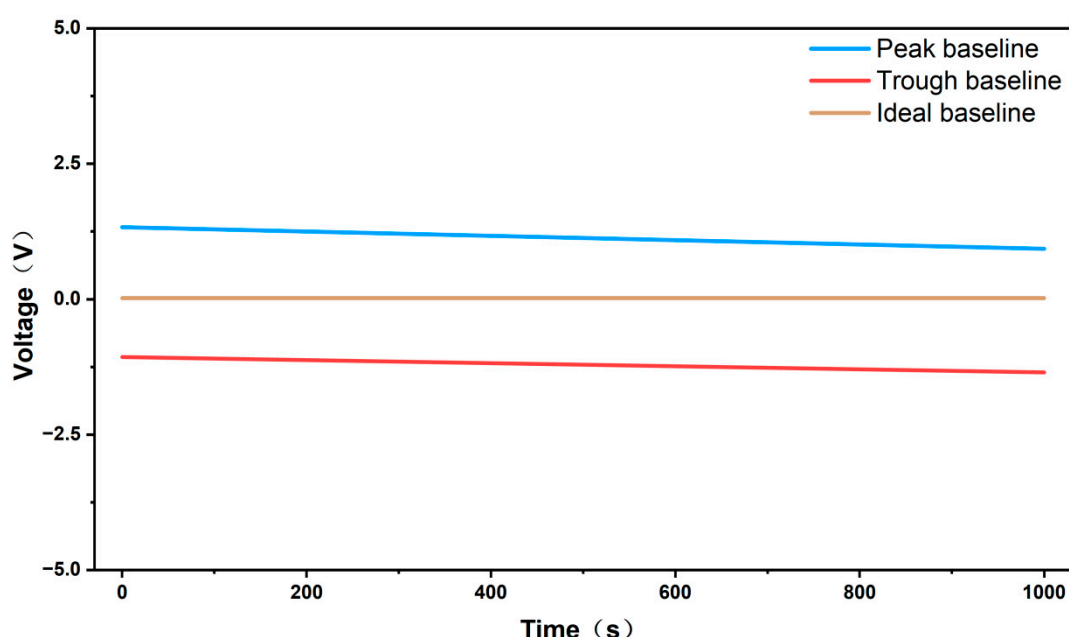


Figure S1. Baseline voltage drift test

To further evaluate the signal stability of the WTT sensor during prolonged operation, the temporal variations in the peak and trough baselines were analyzed. As shown in Figure Sx, both the peak and trough baselines exhibited only slight and gradual changes during the 1000 s continuous test, without any abrupt variation or pronounced continuous drift, while the ideal baseline remained at 0 V. These results indicate that the WTT sensor maintains relatively stable baseline characteristics during continuous operation, which helps minimize the influence of baseline drift on dynamic signal detection.

The slight baseline variation observed during the long-term measurement may be attributed to charge redistribution at the triboelectric interface, minor environmental fluctuations, and differences in the initial contact state, which are commonly observed in triboelectric sensing systems. Overall, the measured baseline remained close to the ideal zero-voltage reference, with no obvious persistent charge accumulation or irreversible zero-point shift. These results demonstrate that the WTT sensor exhibits good baseline stability and long-term electrical reliability, supporting its potential use in repeated mechanical sensing and human-motion

monitoring applications.

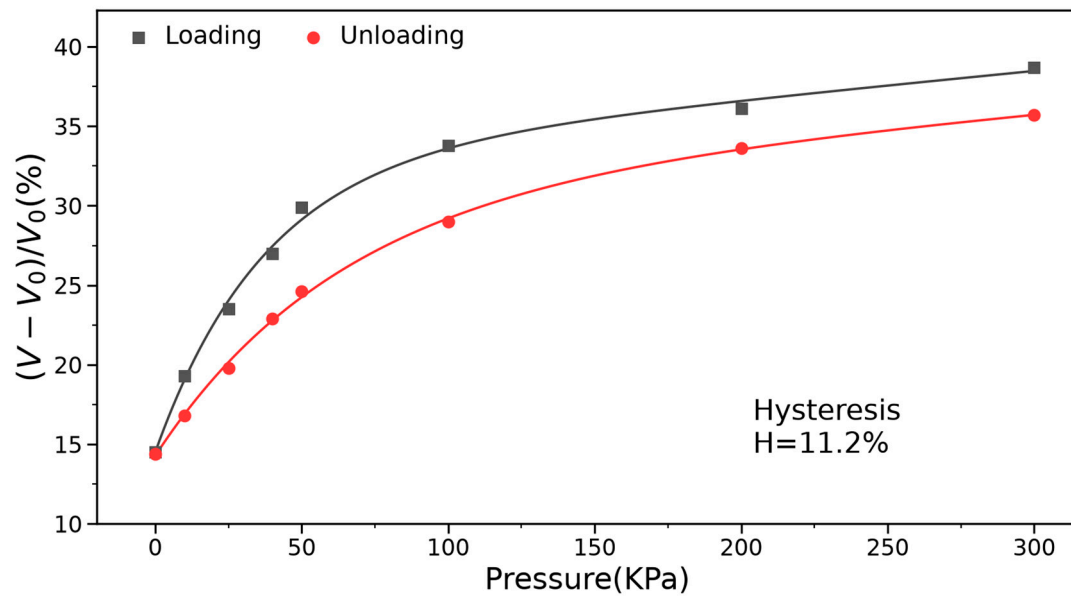


Figure S2: Hysteresis characteristics of the pressure response of the sensor

To further evaluate the stability and reliability of the WTT sensor during dynamic pressure detection, cyclic pressure loading – unloading tests were conducted. As shown in Figure X, with the gradual increase of external pressure from low to high levels, the output signal of the sensor increased accordingly, exhibiting an obvious pressure-responsive characteristic. When the applied pressure was gradually released, the output signal changed in the opposite direction while maintaining a similar variation trend to that during the loading process.

A certain difference between the loading and unloading curves was observed, which can be attributed to the intrinsic hysteresis behavior caused by elastic deformation recovery, charge redistribution, and variations in the interfacial contact state within the sensor structure. Based on the maximum output deviation between the loading and unloading processes, the pressure hysteresis of the sensor was calculated to be 11.2%.

The relatively low hysteresis value indicates that the WTT sensor possesses good response consistency during both pressure application and release, effectively reducing measurement errors induced by mechanical recovery delays. Furthermore, both the loading and unloading curves maintained similar fitting trends, demonstrating the stable pressure response behavior of the sensor. These results confirm that the WTT sensor is capable of meeting the requirements of dynamic applications, such as human motion detection and interactive control.

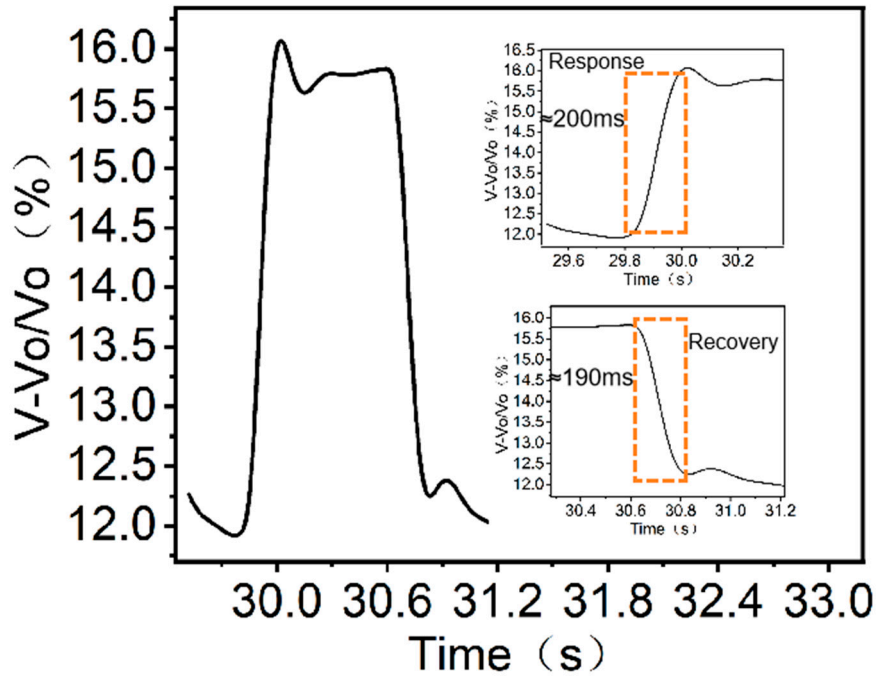
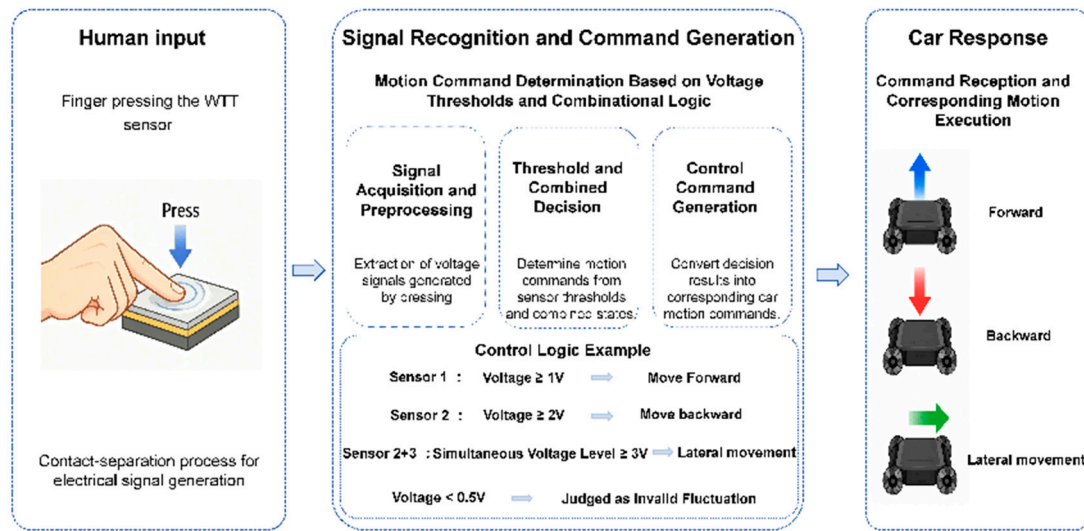


Figure S3: Response/recovery time test

To further evaluate the dynamic response performance of the WTT sensor, the output variation process of the sensor under the application and removal of external stimuli was analyzed. As shown in Figure X, when an external mechanical stimulus was applied to the sensor, the output signal rapidly changed and reached a stable response state within approximately 200 ms, which was defined as the response time of the sensor. After the removal of the external stimulus, the output signal gradually returned to the initial baseline level, with the recovery process lasting approximately 190 ms, corresponding to the recovery time.

The response time and recovery time reflect the sensing speed toward external stimuli and the capability of charge dissipation and interfacial state restoration, respectively. The short response/recovery times indicate that the WTT sensor can rapidly complete the processes of triboelectric charge generation, transfer, and charge equilibrium, enabling real-time detection of dynamic mechanical stimuli.

It is worth noting that the response and recovery processes exhibited distinct and highly reproducible voltage variation characteristics, without obvious signal delays or abnormal fluctuations during stimulus loading and release. These results demonstrate the excellent dynamic response capability of the WTT sensor, indicating its potential for real-time triggering applications, including human motion monitoring and wireless human – machine interaction.



Realization of Wireless Human-Machine Interaction Control from Human Pressing to Car Motion

Figure S4:Schematic diagram of wireless human-machine interaction control from finger pressing to vehicle motion

The proposed human – machine interaction system employs the WTT flexible triboelectric sensor as a self-powered input unit. When a finger presses the sensor, transient triboelectric signals are generated through the contact – separation process. These signals are converted into detectable voltage signals by the signal acquisition module and subsequently transmitted to an Arduino UNO microcontroller. The microcontroller performs logical analysis based on the voltage thresholds and combined triggering states of different sensing channels, generates corresponding motion commands, and wirelessly transmits them to the vehicle control unit through a Bluetooth module. Finally, the Mecanum-wheel-based mobile robot is driven to perform various motions, including forward movement, backward movement, and lateral rightward displacement.

Specifically, a voltage signal of approximately 1 V from sensor No. 1 triggers forward movement; a signal of approximately 2 V from sensor No. 2 triggers backward movement; and the simultaneous activation of sensors No. 2 and No. 3 with output voltages of approximately 3 V triggers rightward lateral movement. Signals below 0.5 V are considered invalid fluctuations and are excluded from the control logic.

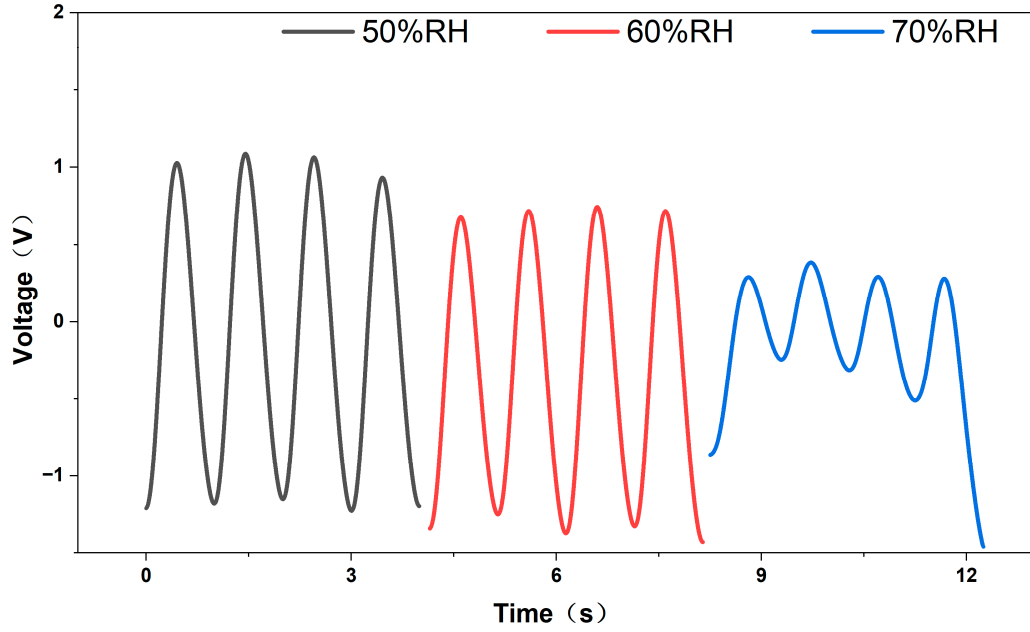


Figure S5. Voltage response of the WTT sensor under different relative humidity conditions.

To further evaluate the influence of environmental humidity on the output performance of the WTT sensor, voltage-response measurements were conducted at relative humidity (RH) levels of 50%, 60%, and 70%. As shown in Figure S8, the WTT sensor generated clear periodic voltage signals under all tested humidity conditions, indicating that the device maintained stable mechanical responsiveness across different humidity environments. As the relative humidity increased from 50% to 70%, the output-voltage amplitude exhibited an overall decreasing trend, with a more pronounced reduction observed at 70% RH compared with those at 50% and 60% RH. These results indicate that ambient humidity has a certain influence on the triboelectric output of the WTT sensor. Nevertheless, the sensor retained distinguishable periodic responses throughout the investigated humidity range, demonstrating a certain degree of environmental adaptability.

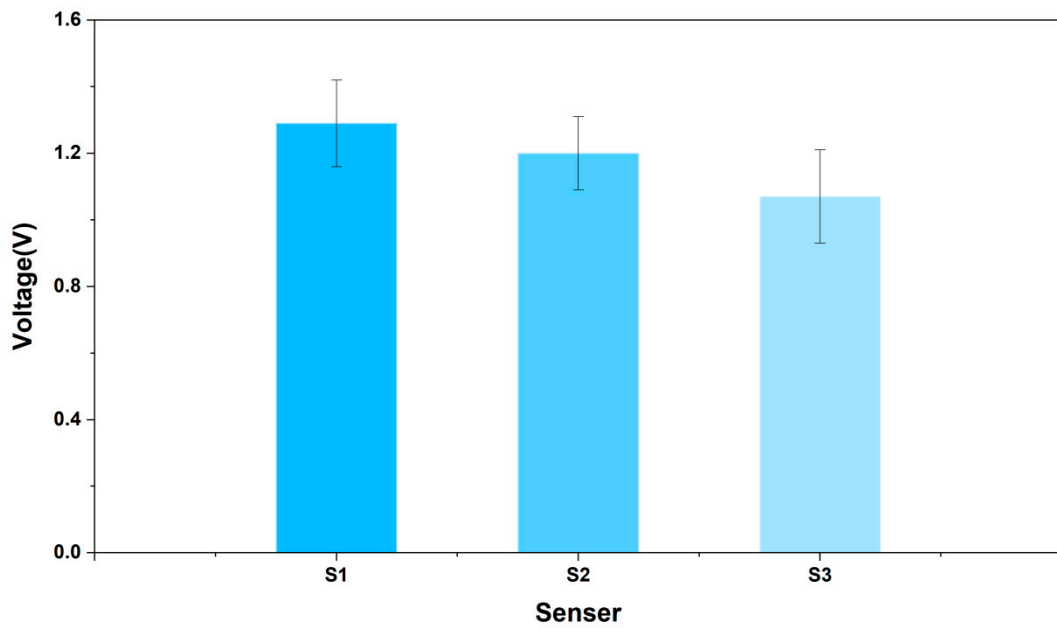


Figure S6.Descriptive Statistics of Output Performance for Three Identical-Type Sensors Fabricated from Toothpaste Waste

To further evaluate the stability of the output signals generated by the fabricated WTT sensors, repeated measurements were performed using different sensor samples, followed by statistical analysis of the experimentally recorded output-voltage waveforms. Three sets of sensor response signals were randomly selected, and their peak voltages were statistically analyzed. The mean, standard deviation (SD), coefficient of variation (CV), and 95% confidence interval (CI) were calculated, with the results summarized in Figure S6. .

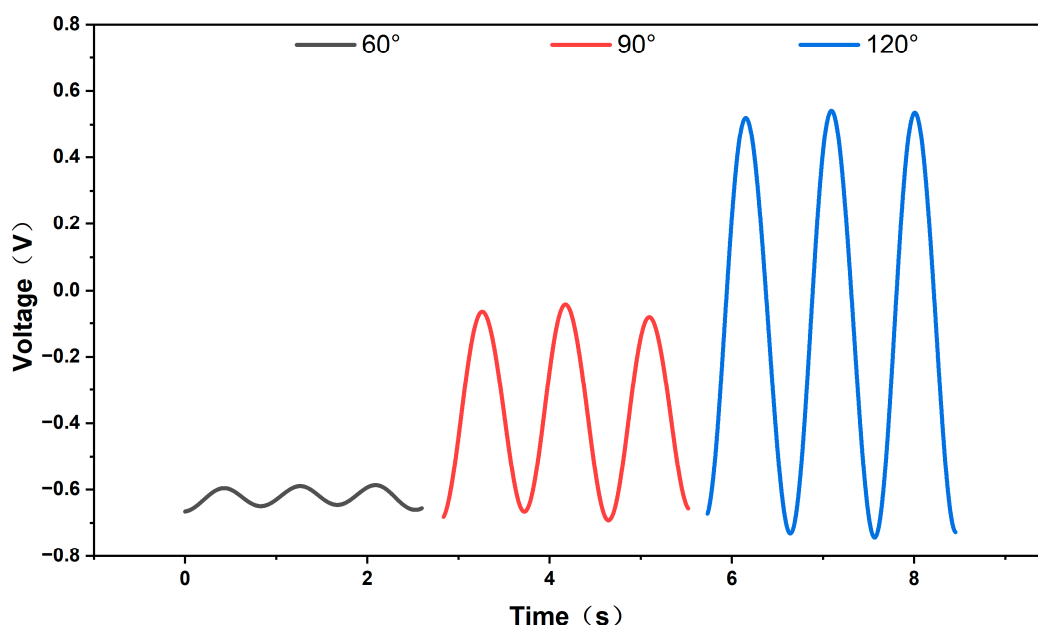


Figure S7.Voltage responses of the sensor attached to the elbow joint at different bending angles of 60° , 90° , and 120°

To further evaluate the feasibility of the WTT sensor for motion monitoring at different body locations, the sensor was attached to the elbow region, and its voltage responses were investigated at elbow bending angles of 60° , 90° , and 120° . As shown in Figure 7, the sensor generated stable and distinguishable periodic voltage signals at different bending angles, with the overall output amplitude increasing as the elbow flexion angle increased. These results demonstrate that the WTT sensor can effectively respond to the mechanical deformation induced by elbow bending and distinguish different amplitudes of joint motion. This finding further indicates that, beyond heel-mounted motion monitoring, the WTT sensor also shows promising potential for multi-site wearable motion sensing.

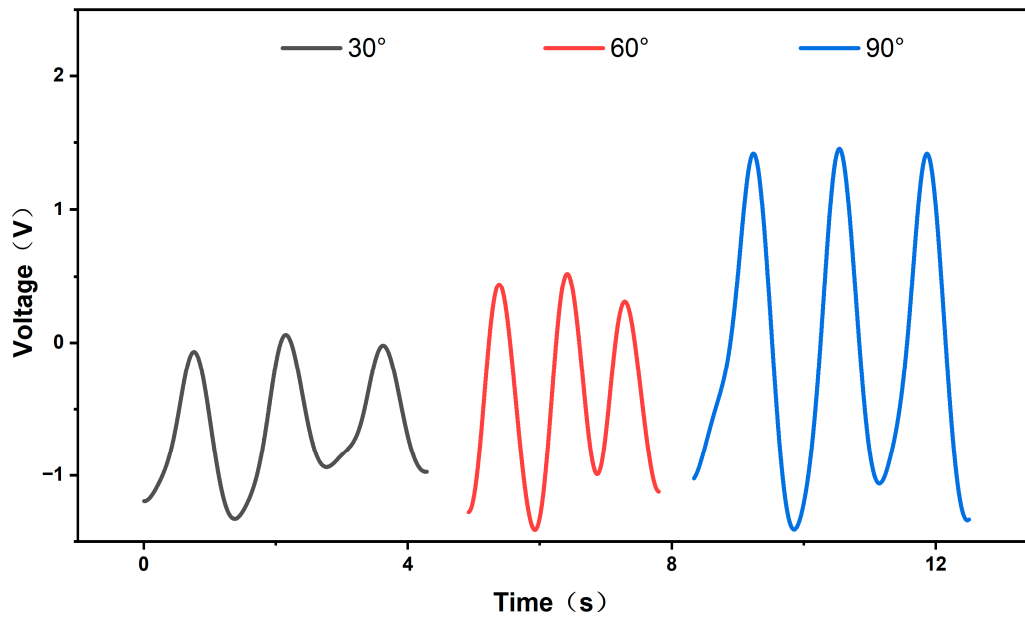


Figure S8.Voltage response of the WTT sensor at different wrist bending angles.

To further evaluate the feasibility of the WTT sensor for motion monitoring at different body locations, the sensor was attached to the wrist region and tested at bending angles of 30° , 60° , and 90° . As shown in Figure S8, the WTT sensor generated clear and distinguishable periodic voltage signals at different wrist bending angles. The overall output amplitude increased as the bending angle increased from 30° to 90° , indicating that different degrees of wrist flexion induced different levels of mechanical deformation and consequently distinct electrical responses. These results demonstrate that the WTT sensor can effectively detect wrist-joint motion and distinguish different bending amplitudes, further highlighting its potential for multi-site wearable human-motion monitoring.

Table S1.Descriptive statistics of the output voltage of the waste toothpaste packaging-based sensor and the pure aluminum foil control sensor.

Group	Mean	Std. Deviation	Median
Toothpaste	2.06	0.70	1.99
Aluminum foil	7.91	0.58	7.98

Note: To verify the potential influence of residual adhesives or polymer components in waste toothpaste packaging materials on triboelectric output performance, pure aluminum foil was selected as a control material. Under identical device configurations and testing conditions, the output responses of triboelectric sensors fabricated from waste toothpaste packaging materials and pure aluminum foil were comparatively investigated.

Table S2. Comprehensive comparison between the proposed sensor and representative waste-derived triboelectric nanogenerator (TENG) devices reported in the literature.

Device Literature	DOI	Waste Source	Processing Requirements	Additional Commercial Materials	Output Performance	Sensitivity	Durability	Motion Recognition Method	Classification Performance	Applications
YL-Sensor (this work)	—	Waste toothpaste tubes composed of aluminum-plastic composite packaging (aluminum-plastic film, aluminum foil, and cardboard)	Simple cleaning, separation, cutting, and assembly; no complex chemical treatment required	Medical PE tape and copper wires (for auxiliary encapsulation and electrical connection)	Output voltage of approximately 15–40 V; output current of approximately 0.1–0.3 μ A (over a pressure range of 10–300 N)	0.39V/N in the low-pressure region; 0.02 V/N in the high-pressure region	Stable over 1,000 loading cycles	Random Forest (RF) motion classification model	Classification of five human activities (walking, running, squat-stand, tiptoe standing, and high-knee lifting); leave-one-subject-out (LOSO) validation recommended upon revision	Plantar pressure monitoring, human motion recognition, human-machine interaction, and cart control
Waste cooling-patch-based TENG	10.1063/5.0343742	Discarded cooling patches (polymer gel and non-woven fabric)	Cleaning, cutting, and simple assembly	Conductive fabric and medical tape	5.03–23.73 V; 0.06–0.15 μ A	0.90V/N (low pressure); 0.28V/N (high pressure)	10,000 cycles	None; only signal response analysis	Not reported	Plantar pressure detection
Kitchen-waste packaging TENG	10.13873/J.1000-9787(2024)05-0067-04	Food packaging films, milk cartons, aluminum foil, etc.	Utilized directly after cleaning	No significant commercial materials	Approximately 1–2.2 V; 25–30 nA	Not reported	Not explicitly reported	None	Not reported	Human motion sensing
Waste X-ray film TENG	10.1039/d3va00018d	Discarded X-ray films (PET substrate)	Cleaning and surface treatment	Silicone and aluminum electrodes	Approximately 201 V; 62.8 μ A	Not reported	10,000 cycles	None	Not reported	Energy harvesting and sensing
Medical-waste TENG	10.1016/j.nanoen.2023.108183	Discarded face masks, nitrile gloves, and PE	Disinfection (ethanol, UV irradiation, heat	Metal electrodes and auxiliary structures	Approximately 50.7 V; 4.8 μ A	Not reported	Long-term stability testing	BCD logic control	Not reported	Intelligent sensing and energy harvesting

Device Literature	DOI	Waste Source	Processing Requirements	Additional Commercial Materials	Output Performance	Sensitivity	Durability	Motion Recognition Method	Classification Performance	Applications
		films	treatment, etc.)	es						ng
Multi-source medical-waste TENG	10.1021/acssuschemeng.4c03742	Aluminum-plastic blister packaging, rubber gloves, X-ray films, paper cartons, etc.	Cleaning and mechanical processing	Silicone and electrode materials	Approximately 180 V; 3.6 μ A	Not reported	5,000 cycles	IoT-based system	Not reported	Smart service system
Waste-tissue/plastic-cup-based TENG	10.1021/acsami.1c20984	Discarded tissue paper and plastic coffee cups	Carbon-coating modification treatment	Carbon coating materials	Approximately 80 V; 3.5 μ A	16.28 V/N	10,000 cycles	SVM machine-learning classification	95.5%	Intelligent motion sensing
Pharmaceutical-blisters-packaging TENG	10.3390/nanoenerg5040019	Waste pharmaceutical aluminum-plastic blister packaging (PVC/PET/PVDC + Al)	Cleaning and assembly	Silicone rubber and sponge structures	Approximately 300 V; 40 μ A	8.17 V/N	10,000 cycles	None	Not reported	Energy harvesting and sensing
Fish-scale-based composite TENG	10.3390/mi17040395	Fish-scale biological waste	Demineralization, carbonization, and material extraction	PVDF substrate, Ag electrodes, EVA, and non-woven fabric	12.8 V; 0.99 μ A	Not reported	Stable cycling test	None	Not reported	Rehabilitation monitoring

Note: To further demonstrate the material advantages and application potential of the proposed waste-derived triboelectric sensor, a comparative analysis was conducted on representative triboelectric nanogenerator (TENG) material systems reported in recent years, covering parameters such as waste source, primary composition, fabrication strategy, electrical output performance, cyclic stability, and application scenarios.