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Recent trends and future perspectives of triboelectric nanogenerators (TENGs) and applications

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Triboelectric nanogenerators (TENGs) have emerged as a groundbreaking technology for energy harvesting and self-powered sensing applications. Recent advancements in materials and integration with modern technologies have significantly expanded their potential. This review highlights the latest trends and future perspectives of TENGs, focusing on the role of advanced materials such as gels, graphene, polymers, and silicon in enhancing their performance. Furthermore, the convergence of TENGs with artificial intelligence (AI), the Internet of Things (IoT), and machine learning is explored, enabling smart sensing and adaptive energy solutions. The integration of TENGs with robotics presents promising opportunities for self-powered systems in automation and human-machine interactions. Future research directions include optimizing material properties, improving energy conversion efficiency, and developing multifunctional, intelligent TENG-based systems. The fusion of TENGs with emerging digital technologies will drive the next generation of sustainable energy solutions, fostering advancements in self-powered devices and smart applications. This review distinguishes itself by integrating recent advances in the convergence of TENGs with artificial intelligence (AI), internet of things (IoT), robotics, and biomedical systems, offering a forward-looking roadmap for intelligent, self-powered technologies beyond existing general reviews.

1. Introduction

Triboelectric nanogenerators (TENGs) have attracted a lot of interest as a potentially useful technology for wearable electronics, self-powered sensing, and energy harvesting.[1–3] They have rapidly advanced due to their efficient conversion of mechanical energy into electrical energy through electrostatic induction and the triboelectric effect.[4–6] This development has opened the door for their use in a variety of industries, such as next-generation electronics, environmental monitoring, and biomedical equipment. Research into improving TENG performance has been fuelled by the growing need for sustainable energy solutions, guaranteeing their applicability in contemporary technology ecosystems. The main goal of recent research has been to improve TENGs multifunctionality, durability, and efficiency by adding cutting-edge materials.[7,8] The mechanical flexibility, stability, and charge transfer efficiency of TENGs have been enhanced by the integration of materials such as silicon, graphene, gels, and polymers. For instance, graphene's superior mechanical strength and conductivity have improved TENGs output performance, while polymer-based composites provide versatile and affordable substitutes. These material advancements have increased TENGs suitability for a range of settings, including large-scale energy harvesting systems and wearable electronics.[9,10]

TENGs are changing energy systems through their integration with modern technology, including machine learning (ML), artificial intelligence (AI), and the internet of things (IoT).[11–13] IoT enables the networking of self-powered sensors and devices, while AI and ML improve real-time data processing, energy management, and adaptive sensing capabilities. Particularly in smart homes, healthcare monitoring, and environmental sensing, this combination has created new possibilities for intelligent and self-sufficient energy systems.[14,15] The combination of TENGs and these technologies guarantees improved performance and efficiency, laying the groundwork for energy solutions of the future. The combination of TENGs with robotics provides novel approaches to autonomous sensing, human-machine interaction, and self-powered robotic systems.[16–18] Robotic components can be powered by TENGs, which lessen reliance on conventional power sources because of their capacity to produce electricity from motion and vibrations.

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In addition to increasing the operational effectiveness and sustainability of robotic systems this makes it possible for robotics to interact in more dynamic, responsive, and adaptable ways. From autonomous drones to wearable robotic exoskeletons TENGs are essential to the advancement of robotics towards more intelligent, self-sufficient technology.[19,20]

Despite significant advancements, challenges such as optimizing power density enhancing durability under diverse conditions, and minimizing material degradation remain in TENG development. Addressing these issues through innovative material designs, structural optimization, and hybridization with other energy-harvesting technologies is critical for future progress (1). Exploring scalable manufacturing techniques and cost-effective material synthesis will also be essential for broader commercialization. As research continues to push the boundaries of TENG technology, its transformative potential in modern technological ecosystems, particularly in robotics, IoT, and smart environments is set to grow exponentially (Fig. 1).

2. Graphene-based triboelectric nanogenerators

Triboelectric nanogenerators are being researched extensively as a potential power source for wearable technology. Ultrasonic spray-coated graphene nanoplatelets (2) serve as the electrode on a polyester fabric substrate in this genuinely wearable fabric-based TENG device, while PDMS polymer serves as the dielectric layer on one side of the TENGs. This component is tested using a copper electrode against a range of materials, and a triboseries is produced based on the results of the tests. At a frequency of 1 Hz the PDMS side against nylon fabric may generate around

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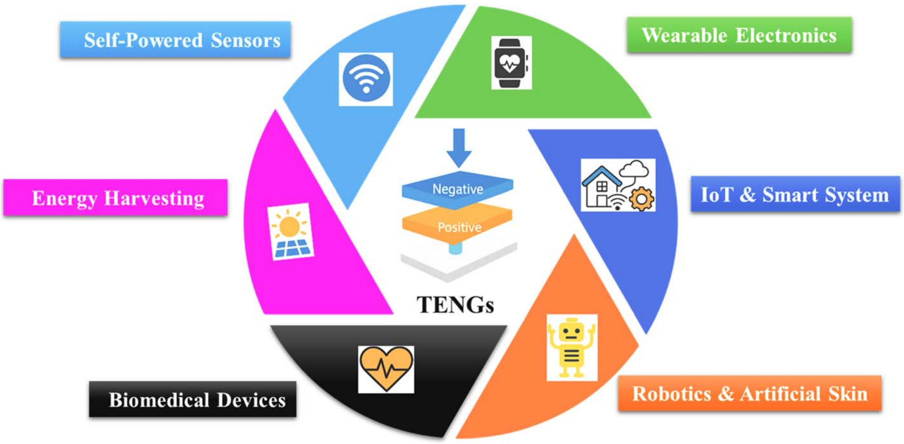

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Fig. 1 Schematic representation of triboelectric nanogenerators (TENGs) and applications.

397 V and 6.8 μA without the need for any output amplifying components. They are further studied in detail to understand various factors, including contact-separation frequency, contact force, separation distance, contact area, and tribolayer chemical modification that affect the TENG operation. The stability and durability of the TENG devices are investigated, and their potential integration as power sources into self-powered smart textiles is demonstrated (Fig. 2a).[21] Moreover, the new rolling type triboelectric nanogenerator (3, RL-TENG) has a lower crest factor than CS mode TENGs and is doped with graphene nanoplatelets and a metal layer. The TENGs dielectric constant and charge storage capacity were enhanced by these changes, resulting in a high electrical output with less surface damage. The open-circuit peak voltage of 75.2 V was roughly 15 times greater and the short-circuit peak current of 7.36 μA was 12 times higher in an RL-TENG than in the pristine device. A dual-side double-belt TENG (DB-TENG) enhanced these values to 10 μA and 164 V. It was able to generate a high voltage output of up to 821 V and was utilized in a real-world application to capture mechanical energy from the motion of the human elbow during

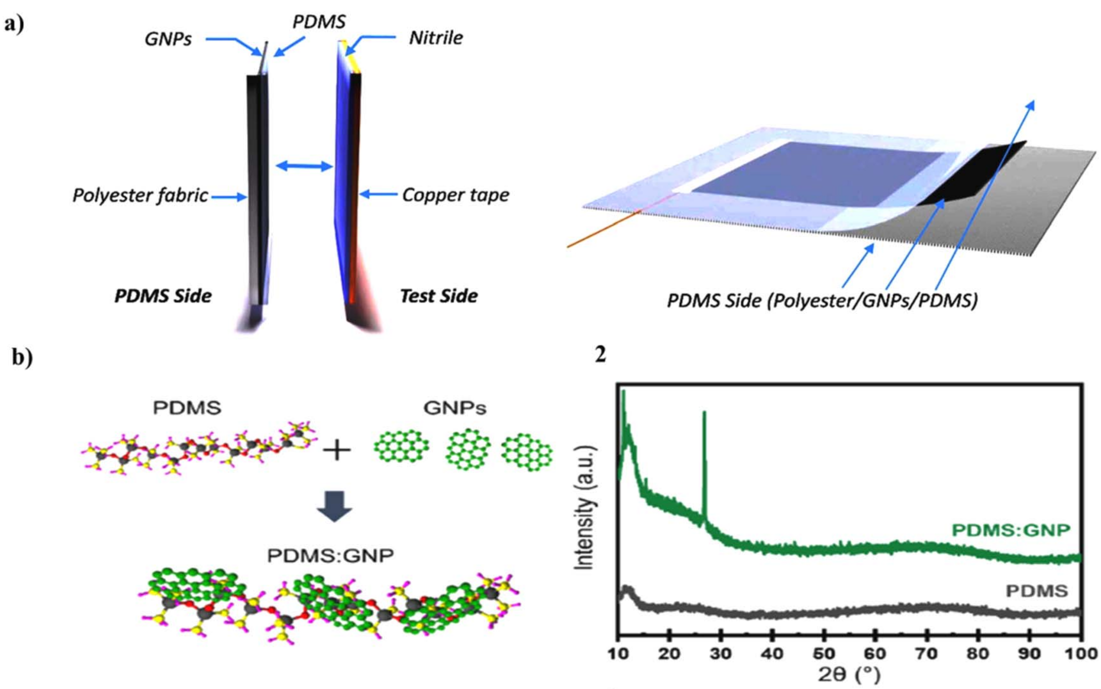

Fig. 2 (a) Fabric-based TENG using graphene electrodes and PDMS for energy harvesting (2) reproduced from ref. 21 with permission from Elsevier Publisher, Copyright 2023. (b) Human motion-powered graphene nanoplatelet-based TENG showing enhanced energy output (3) reproduced from ref. 22 with permission from Elsevier Publisher, Copyright 2022.

walking. These findings demonstrate that high-efficiency energy harvesting from human motion is possible with the DB-TENG (Fig. 2b).[22]

Technologies for wearable mechanical energy harvesting have drawn a lot of interest for applications involving wireless sustainable power sources. In this study, the manufactured polyvinylidene fluoride (PVDF)/graphene quantum dot (GQD) composite nanofibers (NFs) demonstrated better triboelectric nanogenerator (TENG) performance. The process of electrospinning was used to create the PVDF/GQD composite NFs (4). Structural and chemical analyses demonstrated that the particles were embedded in the PVDF NFs and encouraged the development of the polar b-phase. The electronic transitions in the GQDs were responsible for the high photoluminescence observed in the PVDF/GQD NFs at a wavelength of 453 nm. TENG devices maximum output power rose from 35 to 97 mW as the GQD content rose from 0 to 5 vol%, but it fell as more GQDs were added. The improved polar b-phase creation and the negative charge trapping effect of conductive GQDs were the causes of the TENG performance improvement and degradation with increasing GQD concentrations, respectively (Fig. 3a).[23] Combining graphene with polymers such as polydimethylsiloxane (PDMS) and polyvinylidene fluoride (PVDF) enhances TENG performance through synergistic interactions. Graphene contributes high electrical conductivity and mechanical strength, while PDMS provides flexibility and strong negative triboelectric polarity improving contact electrification. PVDF a ferroelectric polymer, further boosts charge generation due to its strong dipole alignment and high dielectric constant. These composites offer improved surface roughness, charge storage, and interfacial bonding, leading to increased voltage output, better stretchability, and stable energy harvesting in dynamic applications like wearables and motion sensors. One important strategy to lessen the current reliance on non-sustainable energy sources is to use all of the clean energy sources that are available. Triboelectric nanogenerators (TENGs) are a new mechanical energy harvesting technology that has attracted attention as a viable battery substitute. They are especially well-suited for portable electronics. Incorporating nitrogen-doped graphene (5, N-graphene) into a few-layer graphene-based electrode results in an enhanced capacitance, which allows TENGs power output to be improved 3-fold.

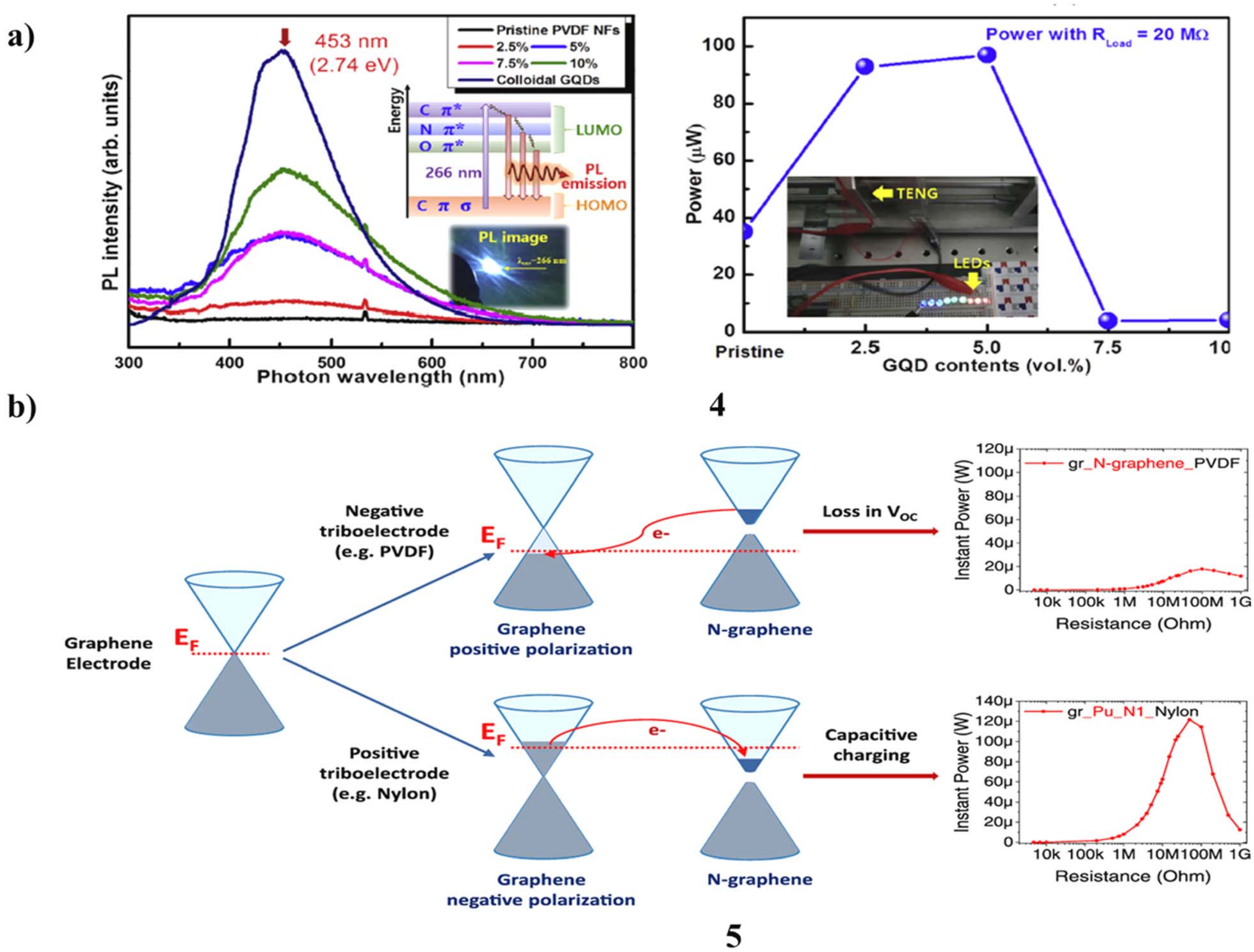

Fig. 3 (a) PVDF/GQD nanofiber-based TENG showing enhanced triboelectric performance (4) reproduced from ref. 23 with permission from Elsevier Publisher, Copyright 2019. (b) Nitrogen-doped graphene-based TENG demonstrating improved charge transfer efficiency (5) reproduced from ref. 24 with permission from Elsevier Publisher, Copyright 2021.

TENGs performance is examined in relation to the electrical characteristics of several N-graphene types that differ in terms of doping concentration and the proportion of N-pyridinic and N-graphitic sites. The capacitive and resistive properties of N-graphene, and therefore the TENG performance are influenced by the unique electron affinities of each of these sites. It is shown that the TENGs power is increased when the N-graphene or n-semiconductor is positioned between the electrode and the positive triboelectric material, whereas a decline in electrical performance is noted when it is positioned between the electrode and the negative triboelectric material. Nitrogen doping alters graphene's electronic structure by introducing bonding types such as pyridinic-N, pyrrolic-N, and graphitic-N, which enhance its triboelectric performance. These dopants increase quantum capacitance by introducing additional electronic states near the Fermi level, improve charge trapping through localized charge sites, and enhance dielectric polarization *via* increased dipole moments. Graphitic-N improves electrical conductivity, facilitating efficient charge transport, while doping also modulates the work function of graphene, enabling better charge transfer with triboelectric materials. Together, these effects lead to significantly improved energy conversion efficiency in TENG devices. The dependency of N-graphene quantum capacitance on the electrode chemical potential, which changes per the opposing polarisation created at the two electrodes upon triboelectrification explains this behavior (Fig. 3b).[24]

A new high-output, transparent, and flexible nanogenerator with a friction layer made of graphene produced by chemical vapor deposition. Wet application of graphene onto copper results in a graphene-based triboelectric nanogenerator (6, TENG) with good optical transmittance and electrical conductivity. Additionally, it has a thin coating of polydimethylsiloxane structure that has been plasma-treated to enhance the nanogenerators output performance. The maximum output voltage of 650 V and current of 12 μA are attained at 4.3 Hz frequency using this graphene-based TENG. In addition to an LCD 50 blue light-emitting LEDs from commercial sources are lighted. It is an inexpensive, straightforward, and reliable method of capturing vibration energy from the environment (Fig. 4a).[25] The triboelectric nanogenerator (TENG) has attracted a lot of interest in wearable applications due to its remarkable properties. Numerous strategies have been used to enhance the output performance. Despite being a significant trend in development, stretchy TENGs power density and stretchability are still far from being used in real-world scenarios. This study used stretchable crumpled graphene (7, CG) with improved performance based on TENG. The output performance of the CG-based TENG was 25.78 μA and 83.0 V. When compared to planar graphene-based TENGs, the power density is 20 times higher at 0.25 mW cm^{-2}. The output performance was shown to be proportional to the degree of crumple. The notable improvement is due to a greater work function difference as well as improved surface roughness and effective contact area. This finding offers a straightforward physical technique for managing the work function of two-dimensional materials. The output performance was fairly consistent, and the stretchy TENG could tolerate significant strain up to 120%. Under a variety of intricate deformations found in real-world wearable scenarios, it might capture energy. The impact of crumple nanostructure on TENG performance was examined, and a very stretchy TENG with improved performance was shown. This suggests a possible strategy for creating useful stretchable TENG for wearable applications (Fig. 4b).[26]

Rapid advancements in personal devices have created difficult demands for sustainable and portable power sources. Vital sign monitoring and bodily movements are combined in the wearable body area network concept. A vital component of this is triboelectric nanogenerators (TENG), which offer portable, sustainable energy that is available anywhere at any time. Due to charge-generating stimuli of varying intensities, this technology typically requires expensive methods and materials and yet produces low power output and unstable output values. Shear exfoliated graphene is used as an electrode in this work an active triboelectric layer is deposited utilizing a straightforward solution technique. TENG devices were made by combining graphene (8) with polymers such as polydimethylsiloxane (PDMS) using low-cost solution processing methods. To improve control and comprehension of device output a cyclic physical stimulus was used to test the electrical power generation of the device. These materials triboelectric response to stimulation at 1.5 Hz showed that their open circuit voltages (V_{OC}) and short-circuit currents (I_{SC}) were approximately 233 V and 731 nA, respectively. When subjected to a 200 MΩ load, they obtained a power density of 13.14 μW cm^{-2}, which can be 40 times more than that of devices produced using PDMS and aluminum. These findings show the promise of the approach for low-cost triboelectric devices for wearable, portable nanogenerators that run on their power utilizing touch and position sensors in security and medical applications (Fig. 5a).[27] A simple production method for enhanced triboelectric performance that uses Al_2O_3 as a CTL between the bottom contact electrode (Al foil) and a positive triboelectric material (graphene). The strong electron rejection propensity and positive charge trapping capabilities of Al_2O_3 increase the charge density on the graphene layer (9). A flexible Gr-TENGs optimal layered structure (3L-Gr) was established by varying the number of graphene layers (1L, 3L, and 5L) and evaluating the electrical performance. The 3L-Gr-TENG with an Al_2O_3 CTL reached maximum V_{OC} and I_{SC} values of approximately ∼55 V and 0.78 μA. Additionally, this TENG had a maximum power of approximately ∼25 Wataload resistance of about ∼300 M, making it 30 times more strong than the pure 3L-Gr-TENG. Finally, the output power provided could light 20 commercially available green LEDs connected in series and activate an electronic timer through the application of a rectifier circuit. Thus, the surface charge density of Gr-TENGs produced *via* CTL fusion may find application in future portable and adaptable energy harvesting devices (Fig. 5b).[28]

The development of portable and wearable gadgets that need a few tens of microwatts of electricity helps in the continuous hunt for low-power energy sources. Furthermore, the growing desire for new sustainable energy sources has led to an increase in the use of energy harvesters that convert mechanical energy

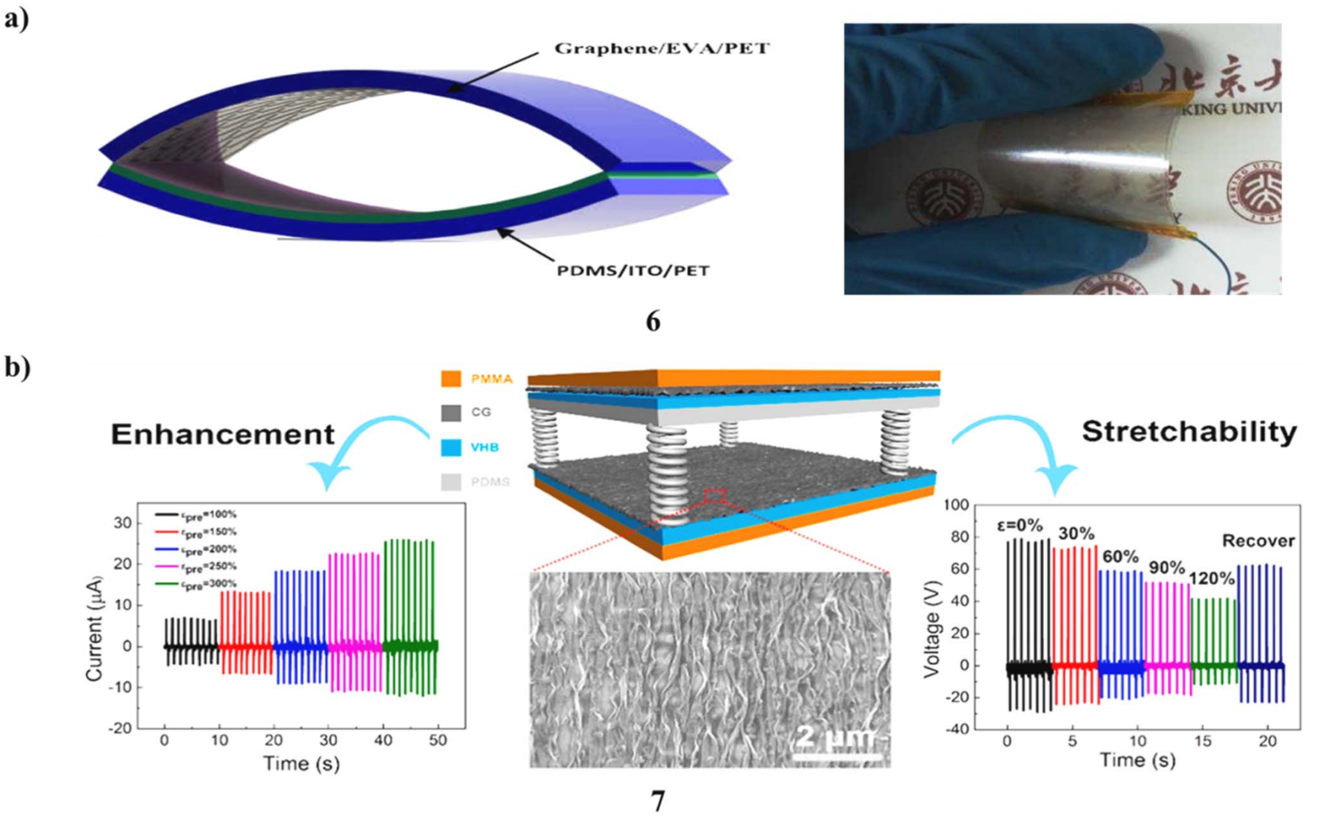

Fig. 4 (a) Wet transfer graphene-based TENG with PDMS layer for high output performance (6) reproduced from ref. 25 with permission from IEEE TNANO Publisher, Copyright 2016. (b) Crumpled graphene-based stretchable TENG showing enhanced power density (7) reproduced from ref. 26 with permission from Elsevier Publisher, Copyright 2019.

into electrical power. Such an environmentally friendly power source can be produced by triboelectric nanogenerators (TENGs). The mechanism by which TENGs operate at the sub-microscale remains poorly understood, despite the large number of TENGs that have been created so far. The interaction between the triboelectric material and the electrode collector is crucial to producing power for the TENG. It demonstrates that a 26-fold increase in power density can be obtained in TENGs operating in vertical contact mode by merely substituting flexible few-layer graphene-based electrodes (10) for the gold electrodes. Outlining recommendations for the combination of the electrode and triboelectric materials to maximize the mechanical energy conversion efficiency in TENGs clarifies the primary mechanism at the heart of such a power output increase (Fig. 6a).[29] A single-electrode TENG was created with PDMS as the packaging and negative triboelectric material, and GO dispersion as the liquid electrode (11). A tiny quantity of GO (10 mg mL^{-1}) significantly increases the output at a contact frequency of 3Hz with V_{OC}, J_{SC}, and maximum power density (power) of 123.1 V, 18.61 mA m^{-2}, and 4.97 W m^{-2} (1.99 mW), respectively. Additionally, the device can be palm-tapped to illuminate its 87 green LEDs. The resilience, longevity, and reproducibility of the device are demonstrated by the fact that its output does not vary after 2200 cycles, 60 days of storage, or across five devices. Additionally, the gadget has a great sensitivity to even the smallest bodily movements on both skin and clothing showing promise for powering wearable devices. Additionally, the device integrates Al sheets in a three-layer structure to display high output with a V_{OC} of 115 V and a J_{SC} of 6.0 mA m^{-2}. The modification of PDMS to enhance the output performance of GO LS-TENG and its possible use in pressure and bending angle monitoring will be the main focus of future development (Fig. 6b).[30]

A triboelectric nanogenerator (TENG) with a high output and minimal environmental impact was developed using cellulose paper and poly (caprolactone) (PCL)/graphene oxide (GO). PCL/GO fibrous layers (12) with different GO nanosheet concentrations (0, 0.5, 1, 2, 4, and 8 wt%) were created by a straightforward and affordable electrospinning method. Additionally, the effects of GO concentration friction layer topography, thickness, and size on triboelectric performance were examined. The results showed that PCL/4 wt% GO cellulose paper generated maximum power density, current density, and open circuit voltage of up to 120 V, 2.5 mA m^{-2}, and 72.5 mW m^{-2}, respectively. Studies confirmed the fibrous structures function in promoting charge density buildup by showing that this open circuit voltage was 33% higher than that of the flat PCL/4 wt% GO layer. The open circuit voltage increased by 98% for the 4 × 4 cm^2 TENG that had PCL 4 wt% GO. A triboelectric nanogenerators output was enough to continuously light up at least 21 blue-light-emitting diodes (LEDs) when it was driven by human hand tapping. The development of nanopores and

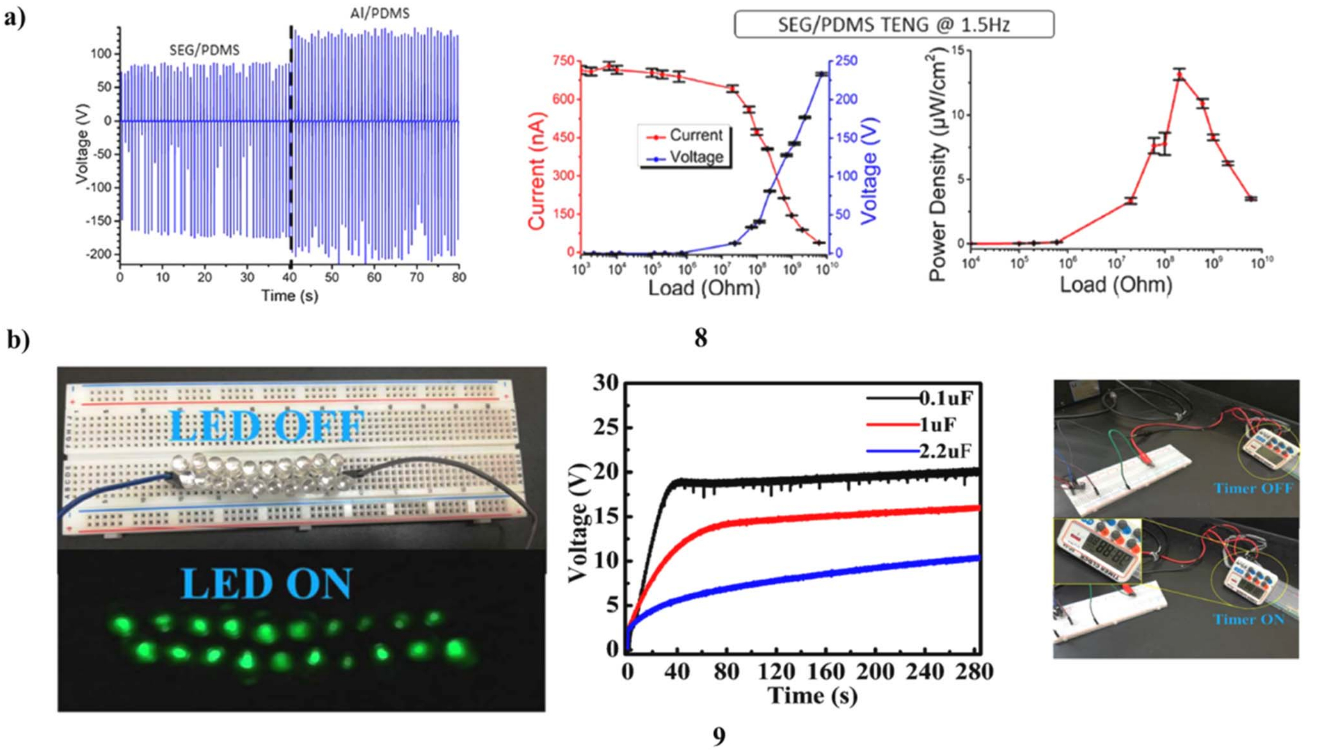

Fig. 5 (a) Solution-processed graphene-PDMS TENG for low-cost wearable energy harvesting (8) reproduced from ref. 27 with permission from Frontiers Publisher, Copyright 2021. (b) Layered graphene-Al_2O_3 TENG showing boosted output through charge trapping (9) reproduced from ref. 28 with permission from MDPI Publisher, Copyright 2021.

enhanced negative charges on PCL from the fibrous structure and oxygen functional groups of GO was credited with this improved performance. It is thought that the proposed triboelectric nanogenerator, which is inexpensive easy to construct, and biocompatible, might be used for environmentally friendly power sources and self-powered biomedical equipment to address the problem of electronic waste (Fig. 7a).[31] Laser-induced graphene (LIG) has made high-throughput graphene patterning a versatile method. Nevertheless, its capacity to produce intricate structures and useful gear has not yet been fully recognized. This work demonstrates that super-hydrophobic fluorine-doped graphene (13) on fluorinated ethylene propylene (FEP)-coated polyimide (PI) may be created using an *in situ* growing LIG technique. This method exploits the distinct spectrum responses of FEP and PI during laser excitation to generate an environment that is ideal for LIG manufacture negating the need for multistep processes or specific atmospheres. A flexible droplet-based electricity generator (DEG) with high power conversion efficiency can be constructed using the structured and water-repellent structures produced by the spectral-tuned interfacial LIG process. The impact of a 105 μL water droplet from a height of 25 cm may produce a peak power density of 47.5 W m^{-2} using this DEG. Crucially, the apparatus demonstrates exceptional cyclability and operational stability in a range of pH and high-humidity settings. The straightforward method that was developed may be expanded to construct a variety of useful gadgets (Fig. 7b).[32]

A flexible, biodegradable, and environmentally friendly TENG based on PCL/GO and SF fiber layers (14) was created. The effect of surface modification of PCL/GO nanosheets with different GO nanosheet concentrations on TENG performance was also investigated. Significant effects on the properties and functionality of the TENG were found with the concentration of GO chemically deposited on the PCL/GO fiber layer surface. Interestingly, TENG showed that at the optimal GO concentration of 6 wt% the open-circuit voltage was a significant 100 V the current density was 3.15 mA m^{-2} and the power density was 72 mW m^{-2}. Also, the current density went up from 2.5 to 3.15 mA m^{-2} in comparison to the PCL/GO fibrous layer. The TENG demonstrated the ability to produce electricity over the 28 day soaking in a simulated buffer solution and demonstrated appropriate stability in wet conditions. Furthermore, the outstanding electrical performance of TENG was able to stimulate the electrical stimulation of PC12 cells as well as the instantaneous operation of 22 LEDs. Through *in vitro* electrical stimulation trials PC12 was shown to proliferate and migrate significantly when given an alternate output voltage of 0.5 V cm^{-1} and an output current of 1.4 μA for 20 minutes per day. The remarkable performance of the TENG confirmed the possibility of electrically stimulating nerve cells, which is essential for repairing neurological injury. However, the impact of this TENG on neurone regeneration will be the next area of study (Fig. 8a).[33] The conventional semiconductor sensors ability to detect triethylamine (TEA) has been enhanced by functionalizing reduced graphene oxide (rGO) with

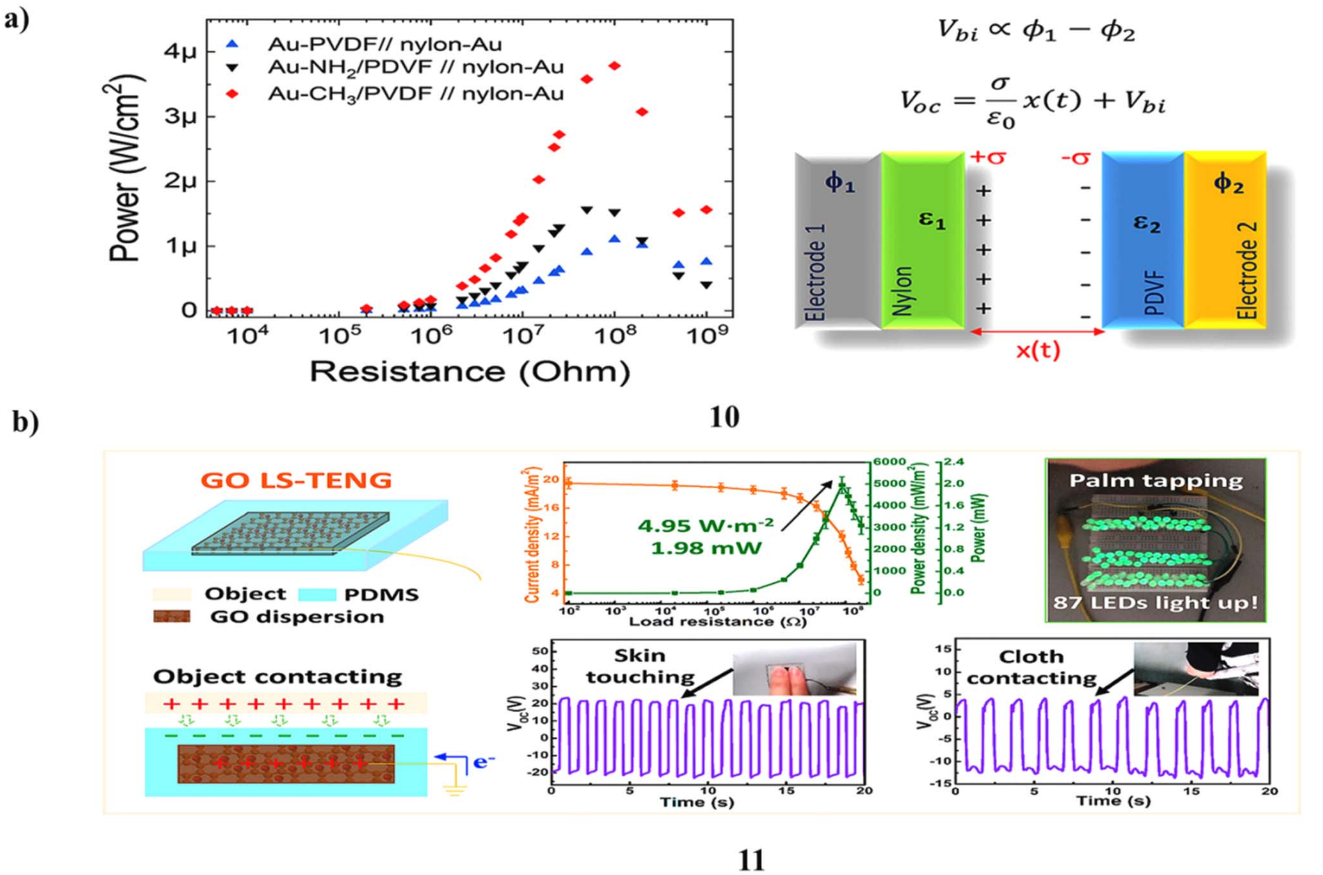

Fig. 6 (a) Few-layer graphene electrode-based TENG showing enhanced power generation (10) reproduced from ref. 29 with permission from Elsevier Publisher, Copyright 2020. (b) GO-based liquid single-electrode TENG delivering high output and sensitivity (11) reproduced from ref. 30 with permission from Elsevier Publisher, Copyright 2019.

poly(diallyldimethylammonium chloride) (PDDA) and then decorating it with polyaniline (PANI) nanocones through an *in situ* polymerization process. The presence of PDDA throughout the synthesis process may effectively inhibit the restacking of rGO and stimulate the reduction of graphene oxide to form consistent PANI nanocones on the rGO sheets and increase sensitivity to TEA. The PDDA-rGO-PANI (15) sensor showed exceptional sensitivity, stability, and selectivity in its capacity to detect the TEA at room temperature. The sensors limit of detection (LOD) is 74 ppb, and its perfect linear coefficient is 0.999 from 2 to 100 ppm TEA. It has also demonstrated exceptional anti-interference capabilities against mechanical bending, humidity, and other interfering gases, such as ammonia and other volatile organic compounds. The last step is the fabrication of a self-powered sensing system that includes an integrated circuit LTC3588, a flexible electrode, a button battery, and a handmade triboelectric nanogenerator (TENG). The sensor is a practical choice for wearable TEA sensing in daily life because of its small TENG size of only 3.5 × 3.5 cm^2 and sensing system integrated on a PI membrane that is only 2 × 4 cm^2 (Fig. 8b).[34]

A successful method for modifying GO to create multifunctional mechanically robust EVA nanocomposites (16). A special Michael addition reaction aided by polydopamine and inspired by mussels was used to modify the surface. This strategy demonstrated more potential in terms of graphene nanosheet interface adhesion and molecular-level dispersion within the EVA matrix because of the strong hydrogen bonding interactions. The resultant polymer nanocomposites, which had a tensile strength of 80% and a storage modulus of 24%, even with only 1.2 wt% graphene amply illustrate the resilience of the functionalization process. Due to the amine-rich surfaces the inclusion of modified GO (PD-PEI rGO) transformed the nanocomposite into an exceptional triboelectric material in addition to its high reinforcing capability. This resulted in remarkable electrical responses from the composite triboelectric nanogenerator, which immediately illuminated the 43 blue LEDs with an output voltage of 7.49 V and a current of 4.06 mA. Additionally, the devices high output voltage suggested that it might work well in large-scale industrial applications. This implies that both the amount of graphene and the degree of amine functionalization can be increased to further enhance the device's performance. Based on the aforementioned intriguing accomplishments, it can be said that the functionalization approach was a flexible platform for GO modification and that it will hopefully draw significant interest from a variety of industries to create additional robust and lightweight composites for broader applications (Fig. 9a).[35] Since O_2 and

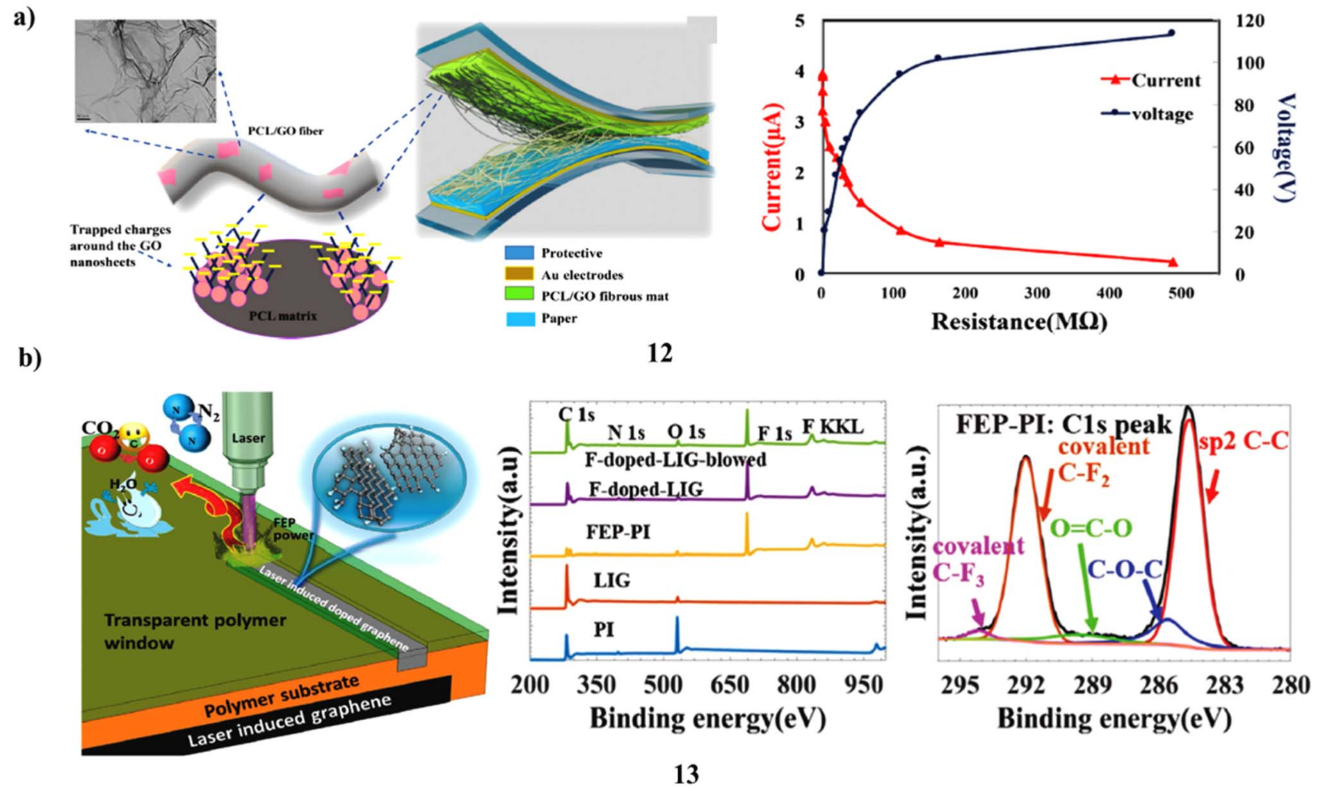

Fig. 7 (a) PCL/GO fiber-based TENG for enhanced biodegradable energy harvesting (12) reproduced from ref. 31 with permission from Elsevier Publisher, Copyright 2019. (b) LIG-based liquid–solid TENG with superhydrophobic graphene for high power output (13) reproduced from ref. 32 with permission from Wiley-VCH Publisher, Copyright 2021.

graphene have different energy levels there is a significant barrier to electron transmission, which prevents O_2 from being chemically adsorbed onto graphene to function as a floating gate. To address this issue, the floating SIG technology based on triboelectric microplasma (17) has been used in this work to alter the adsorption path and achieve O_2 chemical adsorption on graphene. Microplasma first converts the O_2 molecule into O_2 after which it is deposited onto graphene. To shift down the Fermi level and achieve p-type doping of graphene, the adsorbed O_2 with a concentration of 3.45×10^{12} cm^2 has been realized. The desorption barrier is estimated to be 198 meV, and the reversible floating gate of O_2 can be eliminated by heating. By adjusting the heating setting, it is possible to achieve the gradual desorption of O_2. According to the *ab initio* simulation the adsorption barrier is broken in the adsorption path stimulated by microplasma when the O–O. The bond length of the adsorbed O_2 is extended to 1.49 Å and its LUMO level is decreased to 0.85 eV below the Fermi level of graphene. The O_2 floating gate technology on graphene that is presented here can be used to create graphene-based electronic and optoelectronic devices since it can be carried out in the atmosphere without the need for costly equipment (Fig. 9b).[36]

Graphene-based Triboelectric Nanogenerators (TENGs) utilize triboelectrification and electrostatic induction to efficiently convert mechanical energy into electricity. They detect biomechanical signals and physiological movements through contact-separation or sliding modes benefiting biomedical applications. Advantages include high conductivity, flexibility, lightweight nature, and superior charge transfer properties making them ideal for wearable and implantable devices. Despite their excellent conductivity and high surface charge density, graphene-based TENGs face several challenges. The fabrication of high-quality, large-area graphene through chemical vapor deposition (CVD) or exfoliation methods remains expensive and difficult to scale. Non-uniform film formation and poor adhesion to flexible substrates often reduce device reproducibility and mechanical durability. Additionally, surface contamination, oxidation, and environmental exposure can degrade triboelectric performance over repeated operation cycles. Overcoming these issues will require cost-effective synthesis, surface passivation, and flexible electrode engineering strategies.

3. Gel-based triboelectric nanogenerators

Triboelectric nanogenerators (TENGs) are a new type of power supply that has been extensively studied for environmental energy harvesting and self-powered sensing, but they have a greatly limited stretchability, flexibility, and stability. For the first time, a single-electrode TENG based on hydrophobic ionic liquid gel (18) is simultaneously transparent (89%), stretchable

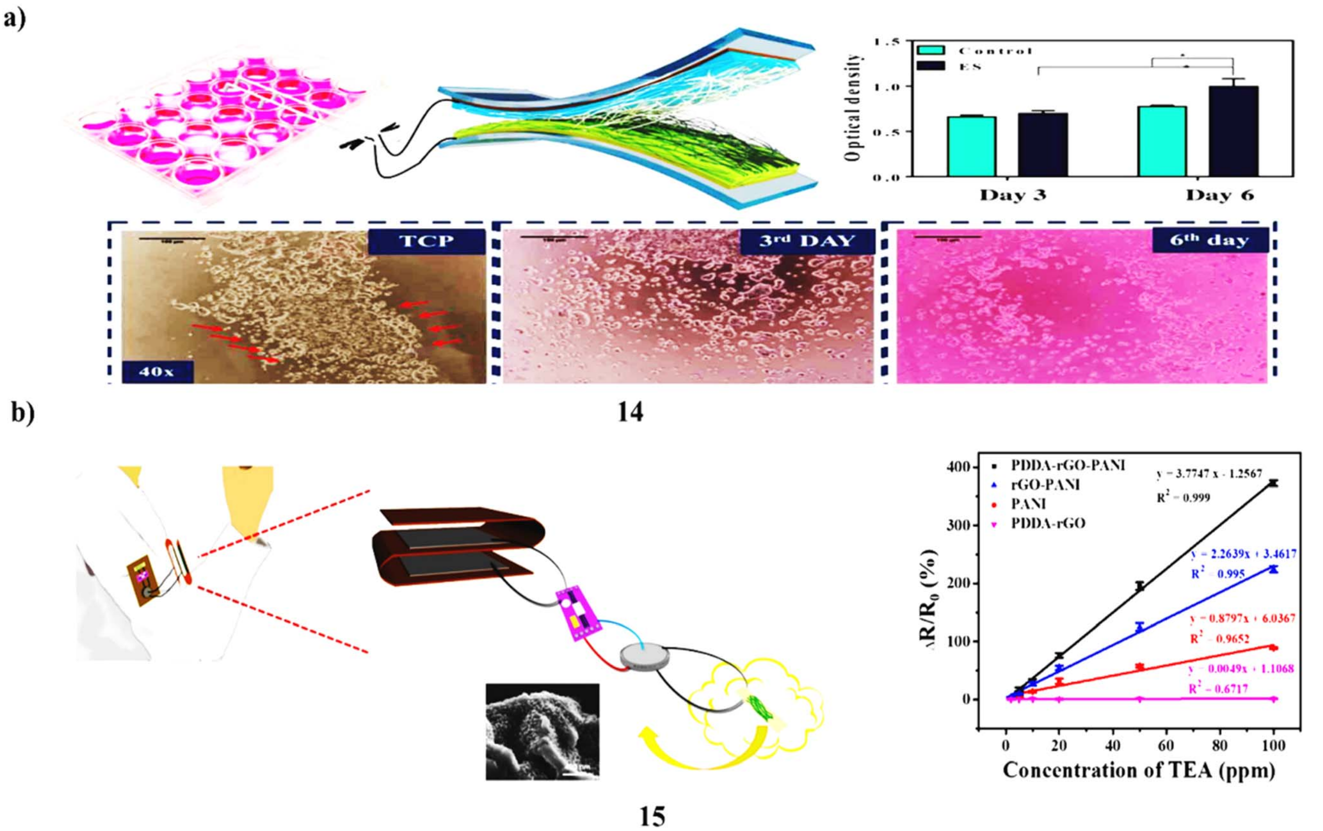

Fig. 8 (a) GO-based biodegradable TENG used for electrical stimulation in biomedical applications (14) reproduced from ref. 33 with permission from IOP Publisher, Copyright 2020. (b) Wearable TEA sensor powered by a graphene-PANI composite TENG (15) reproduced from ref. 34 with permission from Elsevier Publisher, Copyright 2021.

(400%) and has super-stability for up to 3 months in various weather conditions. Wearable devices have become a research hotspot due to their potential applications in wireless sensor networks and the internet of things. A transparent keyboard an arch-shaped finger-bending sensor, and thirty green light-emitting diodes (LEDs) were among the many flexible electronics powered by this TENG. It provides a novel paradigm for obtaining future wearable electronics that are sustainable (Fig. 10a).[37] Triboelectric nanogenerators have garnered a lot of interest as wearable device power source alternatives due to their simple design, cost, simplicity of manufacture, and high power output. This study uses plasticized polyvinyl chloride (PVC)-gel (19) to construct a transparent, stretchy, and attachable triboelectric nanogenerator (TENG) with an enhanced power output. Electrically insulating PVC turned into an electrically active material due to its extremely strong negative triboelectric characteristics. It has been discovered that a single PVC-gel layer can function as both a conducting and a dielectric layer. The single-layer triboelectric nanogenerator (S-TENG) based on PVC-gel generates output signals of 0.83 μA and 24.7 V. Additionally, it can consistently provide output voltage and current in stretching situations. It can be used as a tactile sensor that detects pressure and location without the need to combine different components or electrode grid designs (Fig. 10b).[38]

Triboelectric nanogenerators (TENGs) based on cellulose have drawn more and more interest. This study presents a new technique for creating cellulose-based aerogels (20), which are then utilized to create TENGs that can function as self-powered sensors and mechanical energy harvesters. A green inorganic molten salt hydrate solvent is used in a dissolution–regeneration process to create the cellulose II aerogel. As-fabricated cellulose II aerogel has a large surface area of 221.3 m^2 g^{-1} a higher degree of flexibility, high porosity, and an interconnected open-pore 3D network structure. Considering its architectural qualities the cellulose II aerogel-based TENG exhibits high electrical output performance and outstanding mechanical response sensitivity. Electron-donating and electron-withdrawing groups are added to the composite cellulose II aerogels by blending with other natural polysaccharides greatly enhancing the TENG's triboelectric performance. It is demonstrated to power human gestures, commercial capacitors, light-emitting LEDs, and a calculator. The easy creation of cellulose II aerogel and its use in TENG are demonstrated in this study resulting in a self-powered system with great performance and environmental friendliness (Fig. 11a).[39] A nanoscale porous polyurethane aerogel (21, PUA) based high-performance triboelectric nanogenerator (TENG) for efficient mechanical energy harvesting and biomechanical sensing. Flexible PUA thin films are created using a regulated

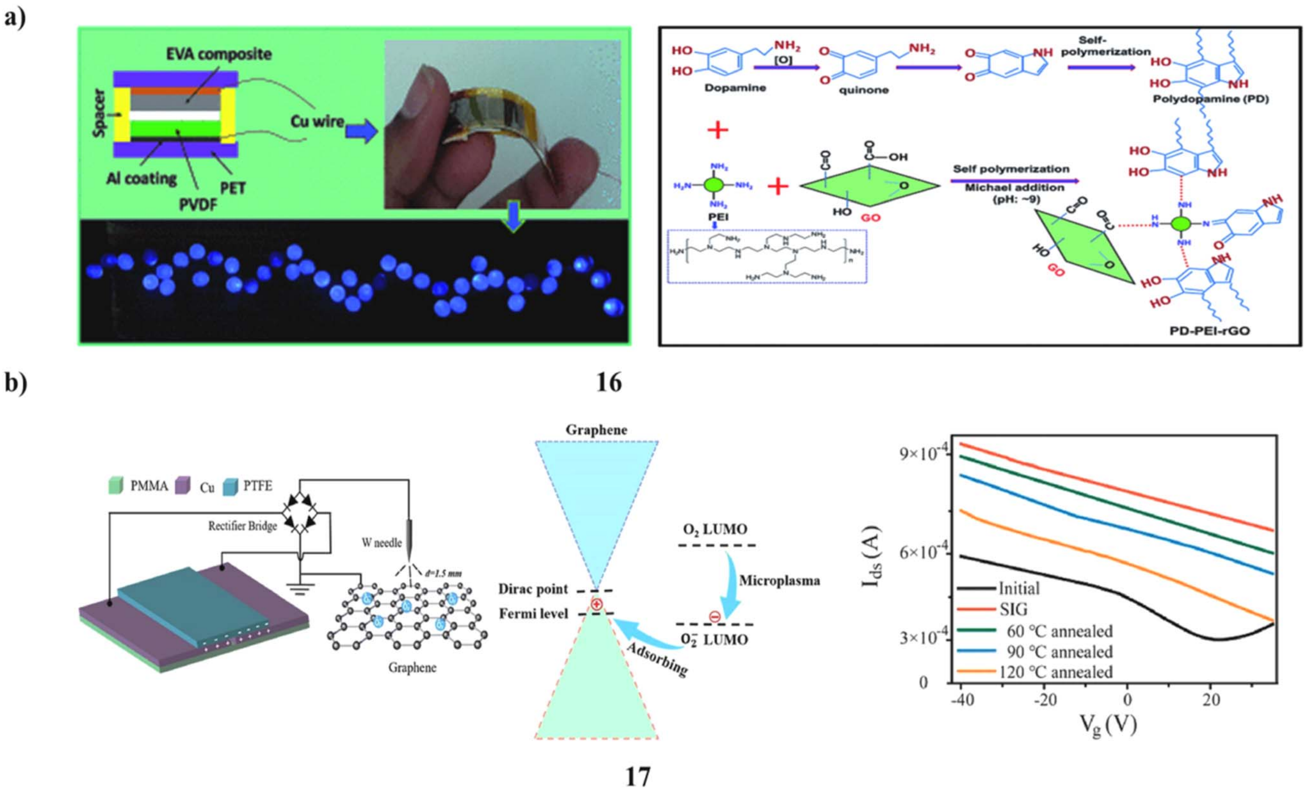

Fig. 9 (a) GO/EVA nanocomposite-based TENG generating high output and flexibility (16) reproduced from ref. 35 with permission from Royal Society of Chemistry Publisher, Copyright 2019. (b) Graphene-based microplasma transistor enabling O_2 adsorption for TENG enhancement (17) reproduced from ref. 36 with permission from Elsevier Publisher, Copyright 2020.

procedure, and their related chemical and physical characteristics are described to integrate them into the TENG device. To study the PUA-TENGs electrical output properties of aerogel films with varying porosity levels from 0 to 94% open-cell content are used. The performance of the PUA-TENG with 33% open-cell content is good. It has an open-circuit voltage and short-circuit current that are 3.5 times higher than the TENG with non-porous film. It results from the added polymeric aerogel layers, improved surface and capacitive qualities. The PUA-TENG can charge different capacitors for energy harvesting applications when mechanically stirred. As a biomechanical sensor the gadget can be affixed to a human arm to track arm motion. Consequently, it is shown that the PUA-TENG is efficient for both biomechanical sensing and energy harvesting (Fig. 11b).[40]

Transparent, flexible, and dependable power sources are in high demand due to the quick development of next-generation electronics that are multifunctional and stretchable. To create a new type of organogel ionic electrode-based triboelectric nanogenerator (TENG) called Og-TENG (22) an organogel electrode made of a poly(4-acryloylmorpholine) frame and low polarity propylene carbonate swelling solvent was prepared. This electrode not only had high transparency (95%) and stretchability (~387%), but it also demonstrated excellent electric reliability and mechanical robustness (foldable and twistable) under the daily operating temperature range of −20 °C to 45 °C. The Og-TENG has remarkable electric performance with an instantaneous power density of 4.03 W m^{-2}. Excellent anti-freezing and solvent retention qualities were provided by the Og-TENGs logical organogel electrode design. In addition, the excellent compatibility between the triboelectric elastomer and organogel enhanced the interface adhesion thus establishing Og-TENG as a highly dependable device under mechanical deformations in contrast to TENGs based on high-polarity gels. It has been proved that the Og-TENG can recognize human motions and capture bio-mechanical energies. A novel approach to creating transparent and stretchable TENGs with a high power density for dependable and durable energy harvesting within the typical operating temperature range shows the ability for the creation of stretchable and multipurpose next-generation electronics (Fig. 12a).[41] Sustainability may be achieved by using environmental energy to power wearable and flexible electronics. This power could take the shape of pulses with different frequencies and amplitudes. The energy produced by a triboelectric nanogenerator (TENG) was stored in quasi-solid lithium-ion batteries (LIBs). The gel electrolyte (23), $LiFePO_4$ cathode, and metallic lithium anode that make up lithium-ion batteries may provide a capacity of approximately 140 mAh g^{-1} at a rate of 0.2C and 120 mAh g^{-1} at a rate of 1C. This quasi-solid electrolyte was used to further manufacture a flexible pouch cell, which exhibits good flexibility, great mechanical strength, and exceptional safety against nail

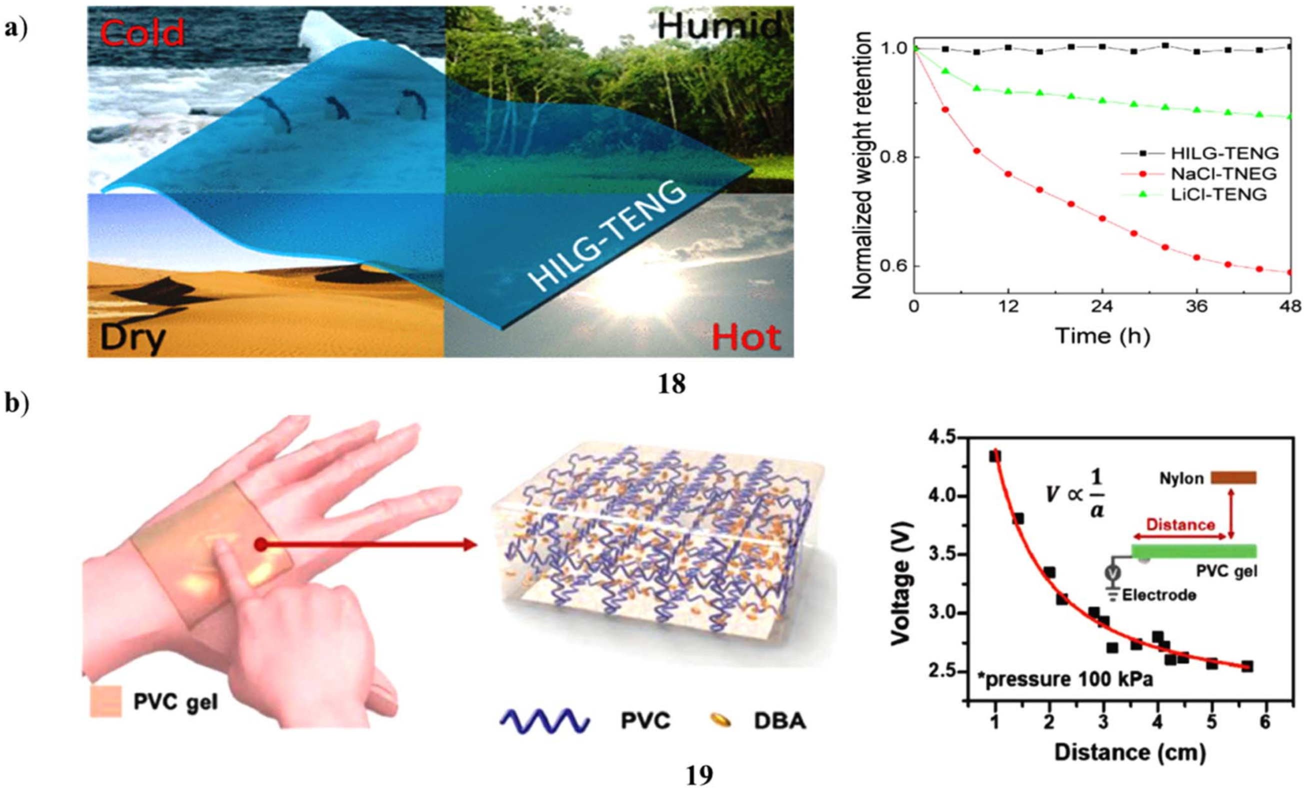

Fig. 10 (a) Transparent, stretchable ionic gel-based single-electrode TENG for wearable energy harvesting (18) reproduced from ref. 37 with permission from American Chemical Society Publisher, Copyright 2020. (b) PVC-gel single-layer TENG functioning as a flexible tactile sensor (19) reproduced from ref. 38 with permission from Wiley-VCH Publisher, Copyright 2022.

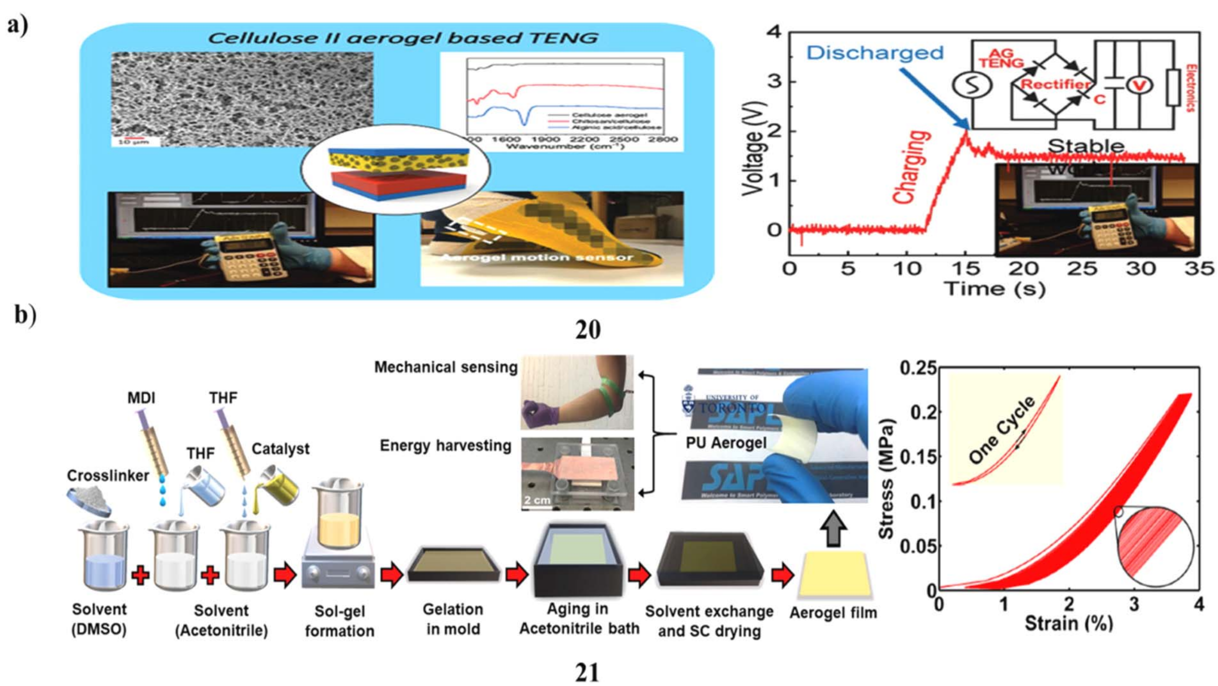

Fig. 11 (a) Cellulose II aerogel-based TENG for self-powered sensing and energy harvesting (20) reproduced from ref. 39 with permission from Wiley-VCH Publisher, Copyright 2020. (b) Porous polyurethane aerogel-based TENG for biomechanical energy harvesting (21) reproduced from ref. 40 with permission from Elsevier Publisher, Copyright 2019.

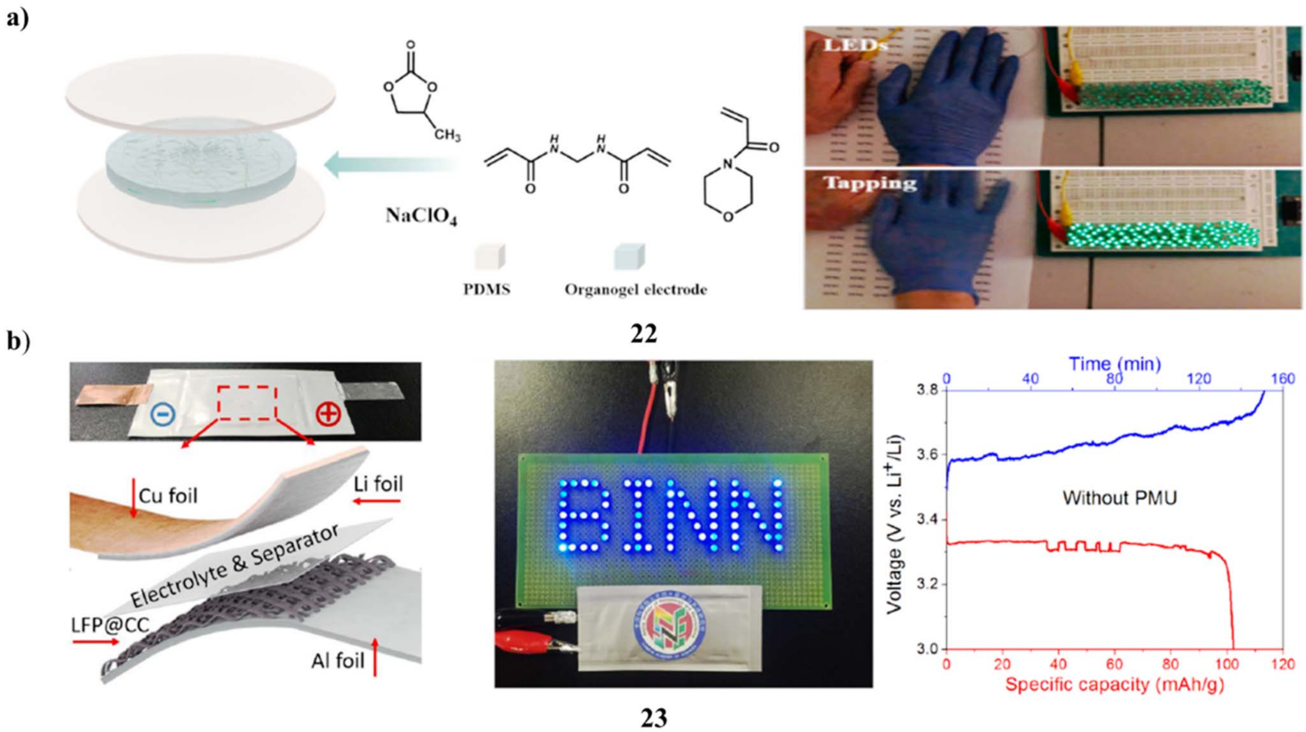

Fig. 12 (a) Organogel-based TENG with high transparency and stretchability for reliable energy harvesting (22) reproduced from ref. 41 with permission from Elsevier Publisher, Copyright 2020. (b) Quasi-solid gel electrolyte-based system integrating TENG with flexible lithium-ion batteries (23) reproduced from ref. 42 with permission from Elsevier Publisher, Copyright 2018.

punctures. The pulse-form energy collected by a TENG was stored in a flexible LIB to produce a more consistent and sustainable power output. TENG can charge the quasi-solid LIB directly three times with a 17% capacity loss. Crucially, a power management unit (PMU) was created to improve TENG's output capacity for charging flexible LIBs. The cells cyclability is enhanced by this PMU, which lowers the output voltage of the TENGs. This makes it appropriate for usage in a range of systems with different batteries and TENGs (Fig. 12b).[42]

Wearable and portable electronics have shown interest in triboelectric nanogenerators. However, one crucial issue that needs to be addressed is TENG's ability to survive in challenging work conditions. A hydrophobic, icephobic, and extremely quick self-healing TENG with remarkable non-drying and non-freezing properties for energy harvesting and self-powered sensors. The TENG has significantly higher electrical output stability over a wide temperature range due to the superior environmental resistance and conductive capabilities of organo-hydrogel as opposed to traditional hydrogel-based TENG (24), which suffers from being frozen at low temperatures and dried at high temperatures. Additionally, the TENGs electrical output performance can be quickly and without delay restored because of its ultrafast self-healing feature. It exhibits a short-circuit charge of 29C, an open-circuit voltage of 157 V, and a short-circuit current of 16 μA. This research may pave the way for novel TENG applications in demanding environments with consistent output performance and self-healing capabilities for practical applications (Fig. 13a).[43] Triboelectric nanogenerators (TENGs) have advanced significantly as a result of current research into tribonegative materials. However, there is little research on tribopositive materials. Thus, it is still challenging to develop tribomaterials with high positive triboelectric properties for triboelectric nanogenerators at a fair price and with a simple process. Spin-coated polydimethylsiloxane is used as the tribonegative material for TENG manufacturing, while a novel technique for creating high-porosity cryogel films based on simple freezing, ultraviolet radiation, and thawing processes is employed as the tribopositive material. The cryogel/PDMS TENG gadget (25) had a 1×2 cm^2 size an open circuit voltage of 170 V a short circuit current density of 17.1 mA m^{-2}, and an instantaneous power density of 2.95 W m^{-2}. It was capable of directly lighting up 180 white LEDs. Extensive studies reveal that the porous structure of the cryogel films and the production of high-density mechanoradicals linked to the porous structure are responsible for TENG's output performance. This is demonstrated by 2,2,6,6-tetramethyl-1piperidinyloxy also referred to as a radical scavenger. Therefore, this study offers a straightforward, affordable, and easy method for creating cryogel films as the tribopositive material for TENGs increasing the likelihood that other materials will be chosen for a triboelectric nanogenerator with amazing potential (Fig. 13b).[44]

Human-machine interaction is essential to the internet of things, intelligent robots, mobile communications, and intelligent healthcare. It is becoming more popular to use stretchy ionic conductive polymer gels to create the next generation of

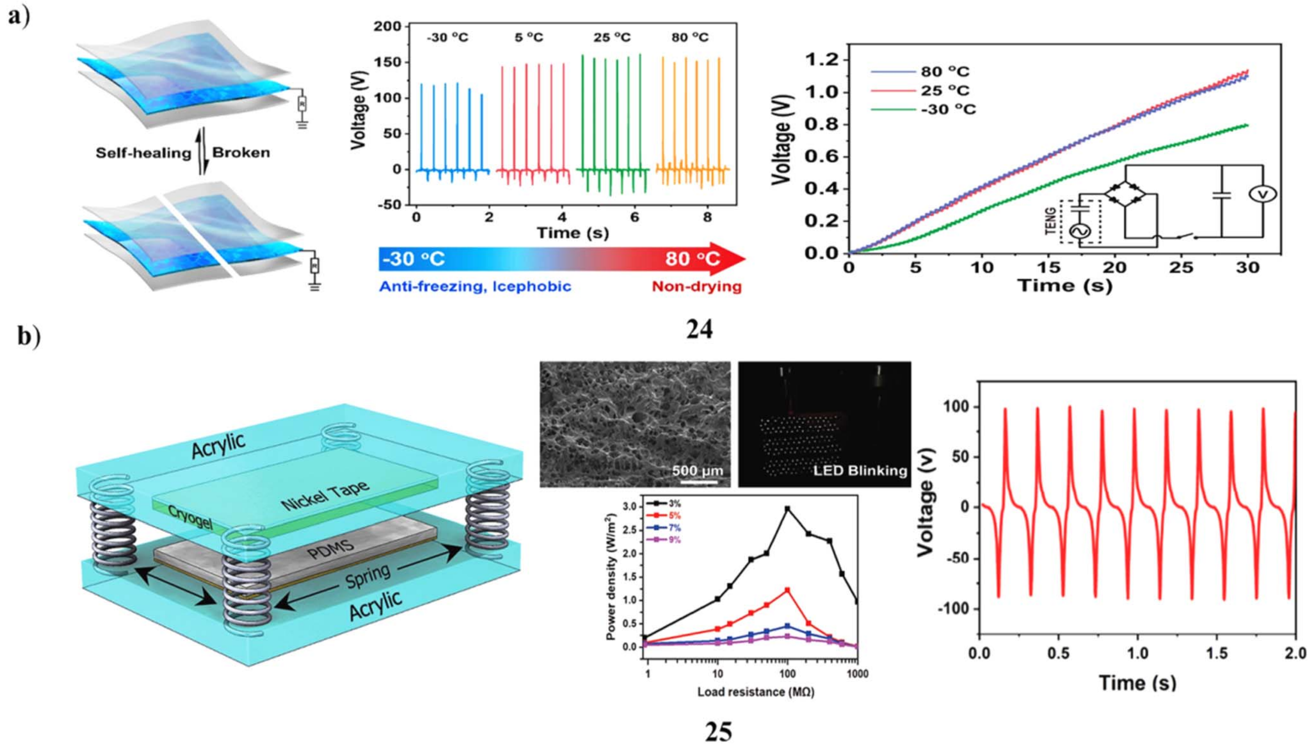

Fig. 13 (a) Self-healing organohydrogel-based TENG with stable output in extreme conditions (24) reproduced from ref. 43 with permission from Elsevier Publisher, Copyright 2021. (b) Porous cryogel-based tribopositive material enhancing TENG output performance (25) reproduced from ref. 44 with permission from Elsevier Publisher, Copyright 2020.

flexible human-machine interactive devices. The devices useful temperature range is limited because of the brittle nature of polymer gels and the sharp decline in ionic conductivity at below-freezing temperatures. Polyacrylamides and nanoclay networks absorbed with ethylene glycol (EG) and water were used to create the anti-freezing organohydrogels. The anti-freezing binary solution gives organohydrogels at −30 °C excellent properties such as a tensile modulus of 29.2 kPa an ultimate tensile strain of 700%, ionic conductivity of 1.5×10^{-3} S m^{-1}, transparency of 91%, and rapid self-healing. The flexible organohydrogel electrodes (26) were assembled using elastomers to produce triboelectric nanogenerators (TENGs). These were then affixed to fingers to create interactive keyboards between humans and machines. A monitor displayed the voltage signals produced by the keyboards in touch with different surfaces after they had been gathered, coded, and deciphered into letters and punctuation. It might be useful for anti-freezing soft materials, self-powered sensors, and wearable human-machine interface communication device systems (Fig. 14a).[45] The next generation of multifunctional soft electronic devices requires the development of energy devices with comparable features. This work prepares a hydrogel-based triboelectric nanogenerator (TENG) (27) that is ultra-stretchable and healable for self-powered sensing and mechanical energy harvesting. Graphene oxide and LAPONITE® were used as the physical cross-linking points to create an ionic conductive hydrogel that has a high stretchability (about 1356%) and the ability to repair. When the hydrogel is used as the electrode, the TENG can function normally at 900% tensile strain, and once the damage has healed, its electrical output can fully return to its initial value. Wearable electronics are driven by this hydrogel-based TENG, which also serves as a self-powered sensor for pressure and motion detection in humans. It displays potential uses in wearable electronics as well as prospects for multipurpose power sources (Fig. 14b).[46]

Flexible and transparent wearable devices are among the many applications that call for triboelectric nanogenerators (TENGs) with high energy output, flexibility, and transparency. Triboelectric nanogenerators (TENGs) generate electricity due to the triboelectric characteristics of tribomaterials. However, the available transparent elastomeric tribopositive materials are limited. This study synthesized and employed a poly[(butyl acrylate)-*co*-(butyl methacrylate)] (PBA-PBMA) block copolymer as a tribopositive material for TENGs. The PBA-PBMA copolymer that was synthesized possesses a very high molecular weight, good elasticity, and high transparency. The tribopositive and tribonegative layers of a hydrogel-based dual-electrode TENG (28, HDTENG) were made of PBA-PBMA copolymer and polydimethylsiloxane (PDMS), respectively. The electrodes were sodium chloride-containing polyacrylamide (PAM) hydrogels. A remarkable triboelectric output capability, moderate transparency (about 58% transmittance), and high adaptability are all features of the HDTENG. The HDTENG achieved a peak power density of 1.1 W m^{-2}, a high open-circuit voltage of about 280 V, and a short-circuit current of about 34 μA with an external resistance of 4.7 MΩ. The energy produced by

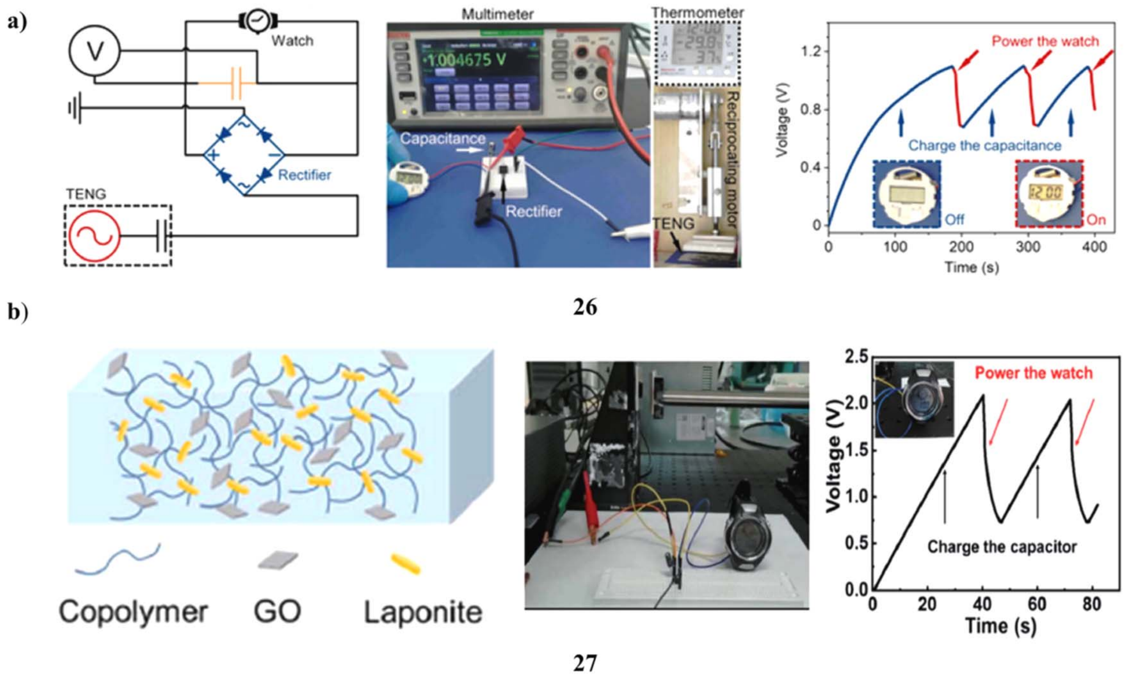

Fig. 14 (a) Anti-freezing organohydrogel-based TENG used for flexible human-machine interfaces (26) reproduced from ref. 45 with permission from Elsevier Publisher, Copyright 2021. (b) Self-healing hydrogel-based TENG for self-powered motion sensing (27) reproduced from ref. 46 with permission from Royal Society of Chemistry Publisher, Copyright 2021.

the HDTENG may power a variety of devices, such as a digital timer, a swimming watch, and a pedometer, and it can also be used to light up 240 blue and green LEDs when the alternating current is converted to direct current using a bridge rectifier. It demonstrated the ability to detect human movements, including bending of the arms (Fig. 15a).[47] Energy harvesting

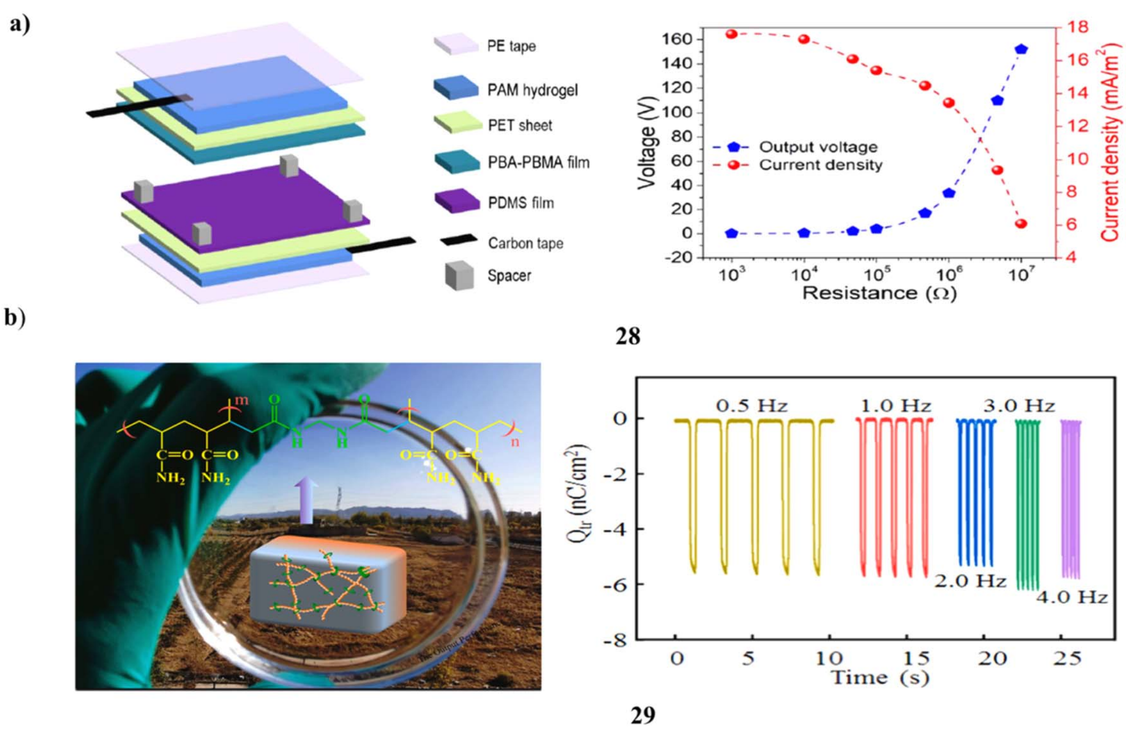

Fig. 15 (a) PBA-PBMA hydrogel-based transparent TENG for wearable energy harvesting and motion sensing (28) reproduced from ref. 47 with permission from American Chemical Society Publisher, Copyright 2020. (b) Durable hydrogel-based TENG operating stably in harsh environmental conditions (29) reproduced from ref. 48 with permission from Elsevier Publisher, Copyright 2021.

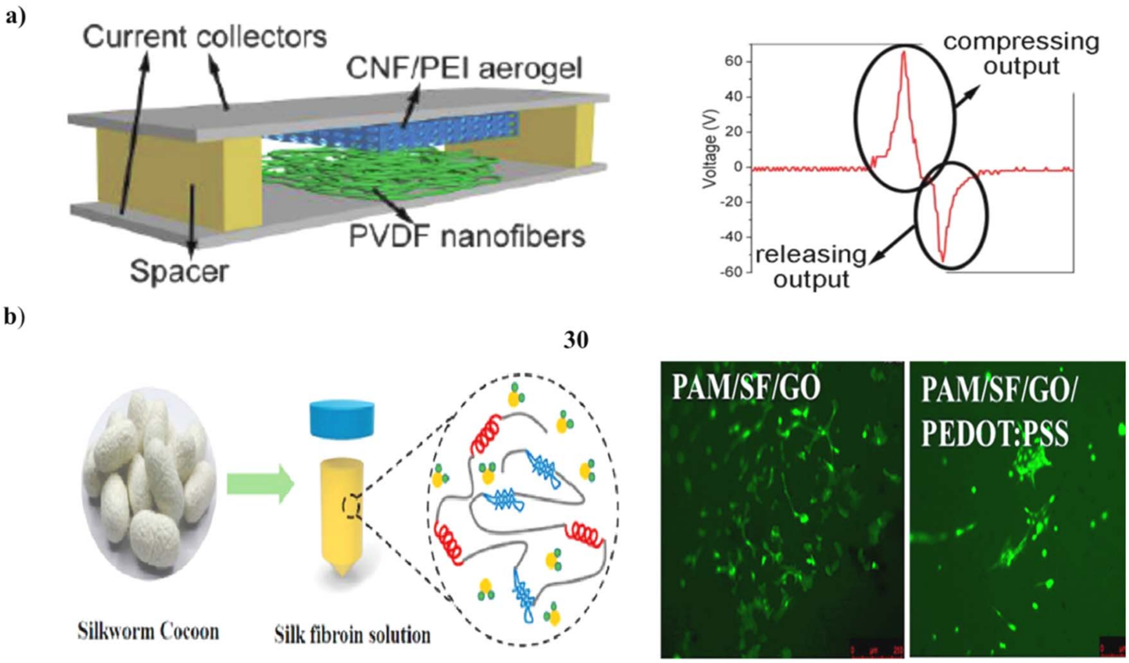

Fig. 16 (a) CNF/PEI aerogel-based TENG for high-performance energy harvesting and sensing (30) reproduced from ref. 49 with permission from Elsevier Publisher, Copyright 2018. (b) Silk fibroin-based hydrogel TENG used as a flexible self-powered energy source (31) reproduced from ref. 50 with permission from American Chemical Society Publisher, Copyright 2020.

systems are constantly subjected to a variety of challenging environmental conditions during real-world applications, including salty, acidic, and alkaline environments. The electrode would unavoidably come into contact with the harsh external environment due to the device's small leakage, which would rapidly deteriorate the electrode materials even if the entire device was covered by an enclosed approach. The strong and resilient hydrogel (29, Cyc-hydrogel) is capable of withstanding very hostile circumstances, including salty, acidic, and alkaline environments. It was discovered that the TENGs output performance remained nearly unchanged when utilized as the electrode maintaining a high output performance with good stability. It indicated significant potential for the electrode materials used in TENGs (Fig. 15b).[48]

The combination of electrospun PVDF nanofiber mats and extremely porous CNF/PEI aerogel (30) has been shown to produce a novel kind of high-performance TENG. The CNF was altered with PEI *via* a simple amidization process to produce a CNF/PEI aerogel with enhanced tribopositivity better mechanical properties, and a noticeably higher TENG triboelectric output. For instance, the CNF aerogels power density increased 14.4 times and their output voltage increased 4.5 times when 10.4% PEI was added. The thickness of the PVDF nanofiber mats also had a significant impact on the TENG's triboelectric performance. In comparison to the TENG built of the original CNF aerogel coupled with 1 layer of PVDF nanofiber mat the output voltage and power density were further enhanced by 18.3 and 97.6 times when the CNF/PEI aerogel was combined with 4 layers of PVDF nanofiber mats in the TENG device. A micro TENG was used to achieve a high open-circuit voltage of 106.2 V and a short-circuit current of 9.2 μA with a modest force (∼6 N). The maximum output power density of 13.3 W m^{-2} with a load resistance of 106 Ω demonstrated an extraordinary ability to capture energy. This unique TENG also demonstrated exceptional sensitivity as a self-powered sensor. In addition to being able to detect human motion, such as an arm bending or a foot walking. It also showed exceptional sensitivity in detecting light forces, such as finger tapping, water drops, and even the vibration of the substrate itself. It can detect pressure within 1 Pa and forces within 0.2 mN. Therefore, flexible TENG made of highly porous CNF/PEI aerogel and electrospun PVDF nanofiber mats has demonstrated remarkable performance as an energy harvesting device and self-powered sensor (Fig. 16a).[49] The logical design of a soft conductive hydrogel (31) involves proportionately combining silk fibroin. A strain/pressure sensor with a broad sensing range and dependable stability can be built using the resulting hydrogels significant stretchability and compressibility. Consequently, the corresponding sensor can track a number of bodily signals. In particular, the hydrogel-based sensor doesn't cause an allergic reaction on human skin making it biocompatible. More intriguingly, this conductive hydrogel lights up 20 commercial green light-emitting diodes with a positive reaction when it operates in a triboelectric nanogenerator. This silk fibroin-based hydrogel is therefore a type of multipurpose material for wearable electronics with adaptable uses in power sources, soft robots, health and fitness monitoring (Fig. 16b).[50]

Environmentally friendly reaction conditions were used to produce a new class of N-glycosyl naphthalimide ricinoleate (NGNR) amphiphiles (32) in good yields. A wide range of

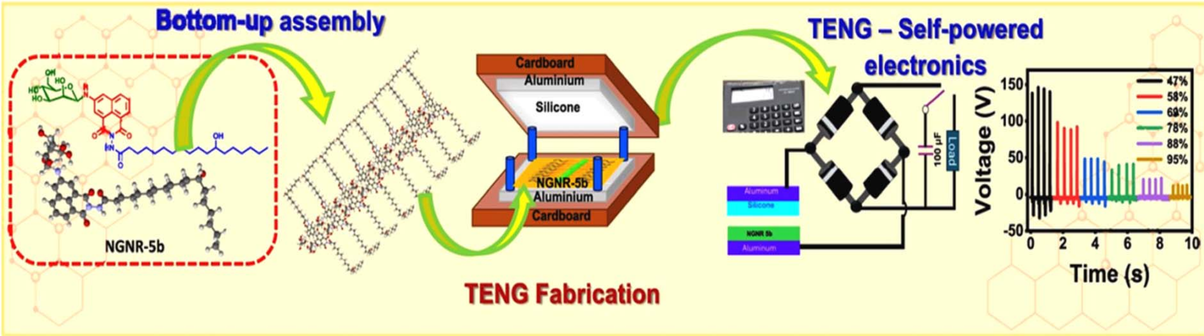

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Fig. 17 Sugar-derived naphthalimide gel-based TENG with high output and humidity sensing capability (32) reproduced from ref. 51 with permission from Elsevier Publisher, Copyright 2024.

solvents and oils was used in molecular self-assembly studies to examine the possible uses of NGNR amphiphiles in the field of supramolecular materials. The gel formation was then observed. A tenable assembly mechanism was suggested after molecular-level interactions and assembly patterns were examined using FTIR, SAXRD, UV-vis, and fluorescence spectroscopy. SEM microscopy was used to determine the supramolecular architecture's morphology. Furthermore, the strength and processability of these soft materials were shown by rheological investigations. Furthermore, the constructed NGNR acts as an electron donor and silicone rubber as a receiver of electrons during the fabrication of a triboelectric nanogenerator (TENG) device. The created TENG significantly outperforms TENG made using amorphous NGNR as demonstrated by its output voltage, current, and power density of 410 V, 100 μA, and 5.1 W m^{-2}, respectively. Furthermore, TENG may be used to continually power tiny electronic devices, which is useful for developing self-powered electronic devices. The textile, agricultural, and food processing sectors used the TENG to detect ambient humidity due to its great sensitivity and endurance. It is noteworthy that the TENG response changes up to 70% relative humidity (RH). This work demonstrates the creation of humidity sensors that run on their power (Fig. 17).[51]

Gel-based triboelectric nanogenerators (TENGs) utilize the principles of triboelectrification and electrostatic induction to convert mechanical energy into electrical power, leveraging the flexibility, stretchability, and biocompatibility of hydrogels and ionic gels. These TENGs operate through contact-separation or sliding modes, detecting biomechanical signals, physiological movements, and environmental stimuli in biomedical applications. Their advantages include excellent adaptability to soft tissues, high transparency for optical applications, and self-healing properties, making them ideal for wearable and implantable devices. Although gel-based TENGs offer remarkable flexibility and biocompatibility, they suffer from critical stability issues. Many hydrogels lose water content over time, leading to dehydration, ion leakage, and reduced electrical output. Their sensitivity to humidity and temperature variations limits consistent performance in real-world environments. Mechanical wear and poor encapsulation further restrict their long-term usability in wearable and biomedical systems. Therefore, future work should focus on developing non-volatile, stretchable ionogels or encapsulation techniques that maintain ionic conductivity and mechanical integrity.

4. Polymer-based triboelectric nanogenerators

Triboelectric nanogenerators are devices that transform mechanical energy into electrical energy and other sensor-based applications depend on their functioning being controlled. Triboelectric nanogenerator based on ferroelectric PVDF-$NaNbO_3$ nanocomposite film (33) demonstrated a notable tuning (64%) of the triboelectric nanogenerators output by changing its electrical polarization state. A triboelectric nanogenerator's instantaneous output power is 0.17 mW when it is built with a negatively polarized PVDF-$NaNbO_3$ nanocomposite film, compared to 0.06 mW when it is built with a positively polarized PVDF-$NaNbO_3$ nanocomposite film. To investigate the reason for the output shift in response to the films altered polarization state Kelvin probe force microscopy studies were performed. It was discovered that the polarization of the PVDF-$NaNbO_3$ film altered its work function, which in turn caused a change in the output. The effects of the polarization state on the performance of the triboelectric nanogenerator have been described in greater detail using an electronic energy level diagram of the contacting materials (Fig. 18a).[52] A straightforward casting technique was also used to create flexible and environmentally safe chitosan-silk fibroin-air lay paper composite films. The electrical output performance of the manufactured CSA-TENG (34) was satisfactory. A maximum output power density of 268.8 mW m^{-2} was achieved for mechanical energy harvesting allowing the CSA-TENG to illuminate 30 LEDs at once. Furthermore, the CSA-D-TENG as developed is capable of tracking human movements and harvesting biomechanical energy on a large scale. This work offers a cost-effective and environmentally benign approach to the design of wearable electronics and a multipurpose TENG-based self-powered system (Fig. 18b).[53]

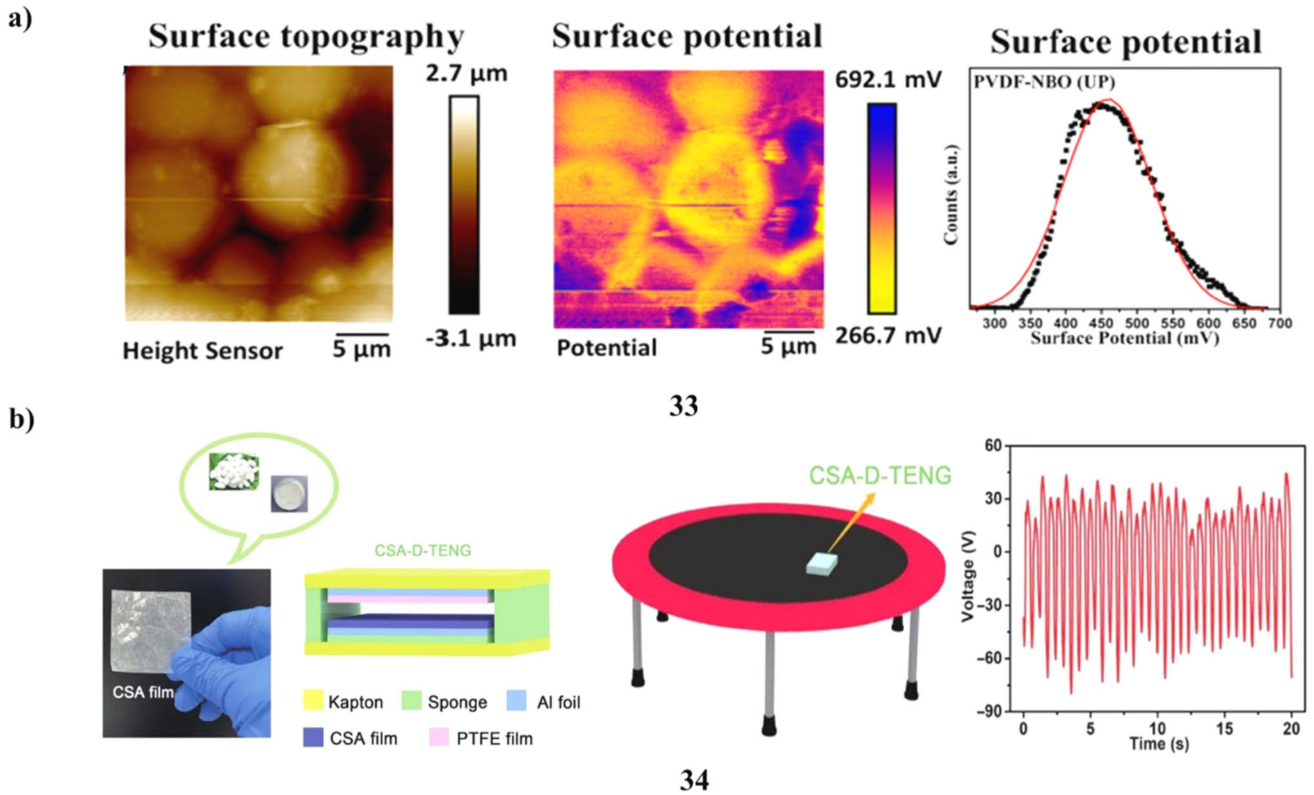

Fig. 18 (a) Polarized PVDF-$NaNbO_3$ nanocomposite TENG showing tunable output performance (33) reproduced from ref. 52 with permission from American Institute of Physics Publisher, Copyright 2021. (b) Chitosan-silk fibroin-based TENG for biomechanical energy harvesting and motion sensing (34) reproduced from ref. 53 with permission from Springer Science Publisher, Copyright 2022.

Polyethylene (PE) and polycarbonate (PC) (35) are used in a standard digital versatile disc to create a cost-effective vertical contact separation mode triboelectric nanogenerator. This low-cost nanogenerator with simplified architecture can produce an open-circuit voltage of 215.3 V and a short-circuit current of 80 μA. Additionally tested are the impacts of the air gap between the triboelectric layers and the impact distance, which range from 0.25 to 1 cm and 3 to 9 cm, respectively. The ideal air gap is found to be 0.5 cm. This work demonstrates the possibility of highly effective, mechanically robust triboelectric nanogenerators using the comparatively inexpensive PE and PC triboelectric combination (Fig. 19a).[54] The nanogenerator is also tested in a variety of real-world situations, including walking, driving, and rolling skateboard loads. Surface-charge engineering is used to further modify the surfaces of the triboelectric layers resulting in a 460% increase in the output power. High-performance and environmentally safe materials are needed for wearable triboelectric nanogenerators (TENGs) (36) to capture energy sustainably. Blends of biodegradable polymers show potential as a solution providing favorable mechanical and triboelectric qualities in addition to environmental advantages. This work showed that melanin-like nanoparticles (MNPs) produced from biomass improve phase compatibility in PLA/PBS blends by acting as an environmentally friendly compatibilizer. Tensile toughness increased 13.5 times, tensile strength increased 1.1 times, and elongation at break increased 10.4 times with the addition of just 0.4 weight percent MNPs. Triboelectric performance also improved dramatically reaching 414.88 μC m^{-2} with a 1.78-fold increase in charge density. After seven days, the MNPs-modified blends showed just a 7.5% decrease in performance, demonstrating high stability under UV exposure. MNPs facilitated a regulated pace of degradation that might quicken in specific circumstances, guaranteeing the composite's stability and biocompatibility over time. Wearable motion sensors that employed M-TENGs demonstrated steady and powerful signals precisely identifying a variety of human motions such as walking, running, and jumping. These results demonstrate that MNPs are a novel and sustainable approach to improving the mechanical, triboelectric, and environmental performance of biodegradable polymer-based triboelectric materials allowing for their application in long-lasting and environmentally responsible wearable TENGs (Fig. 19b).[55]

High-performance triboelectric nanogenerators (37, A-NGs) based on porous aerogel films of polymers are exhibited. The equivalent dense polymer film-based triboelectric nanogenerators (D-NGs) exhibit substantially lower triboelectric outputs under the same mechanical stress as this device, which is made up of two very porous polymer films. The triboelectric outputs of the A-NGs increase considerably with increasing porosity due to the increased contact area and electrostatic induction in the porous structure, which produces more

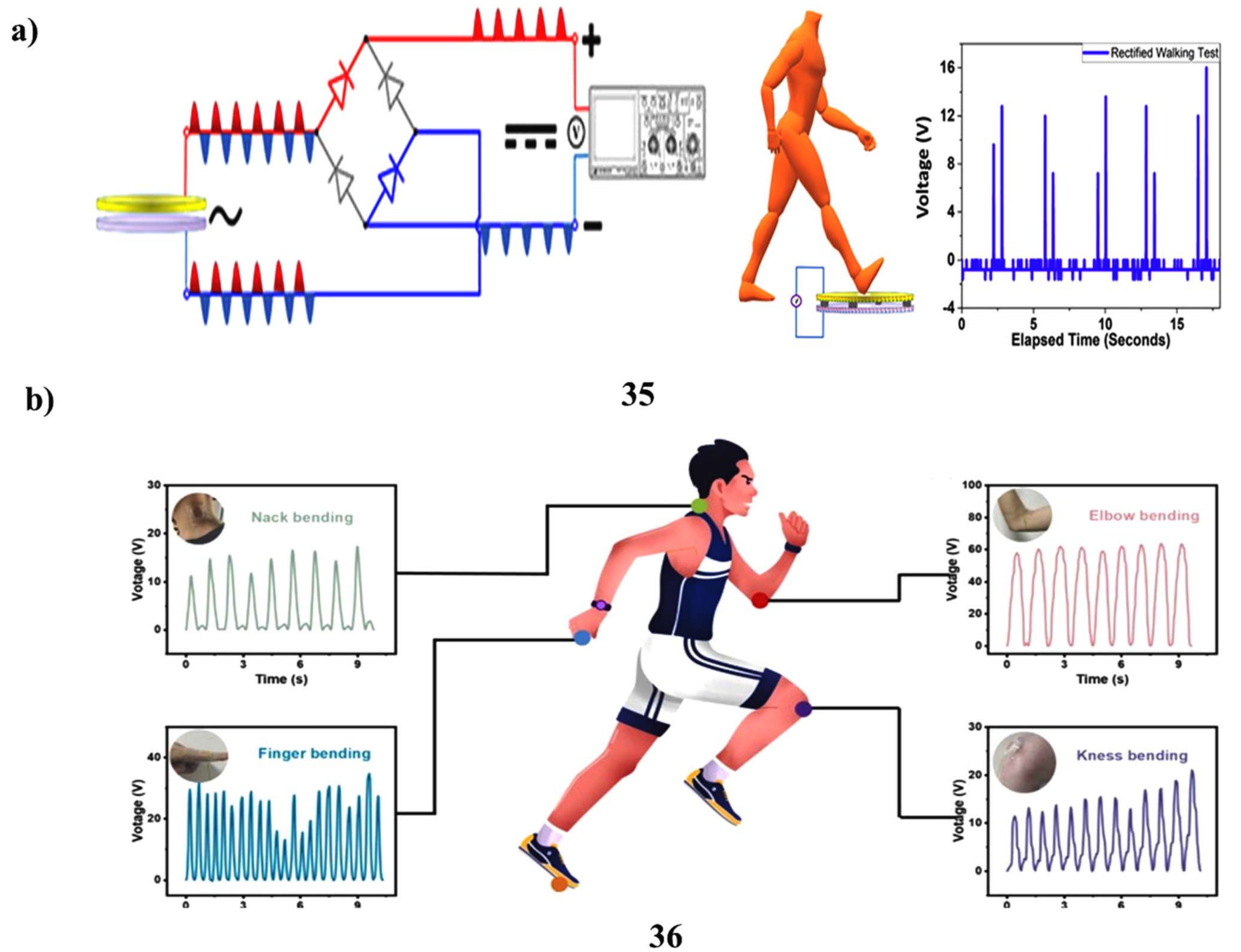

Fig. 19 (a) PE/PC-based TENG from DVD components for low-cost green energy harvesting (35) reproduced from ref. 54 with permission from Wiley-VCH Publisher, Copyright 2021. (b) Melanin nanoparticle-enhanced biodegradable polymer TENG for stable wearable energy harvesting (36) reproduced from ref. 55 with permission from Elsevier Publisher, Copyright 2025.

charges on the porous surface. It is notable that the A-NG, which was created by combining the most porous polyimide aerogel film with porous chitosan aerogel film, exhibits a very high voltage of 60.6 V and current of 7.7 μA. This translates to a power density of 2.33 W m^{-2}, which is enough to power 22 blue light-emitting diodes (LEDs). This is the first report on the use of porous polymer aerogel sheets as both positive and negative materials to improve triboelectric outputs in triboelectric nanogenerators (TENGs). Additionally, the triboelectric performance can be significantly enhanced by silanizing the cellulose aerogel sheet with amino silane to increase its tribopositive polarity. Consequently, this work offers fresh perspectives on the exploration of porous materials with adjustable triboelectric polarities for high-performance TENGs (Fig. 20a).[56] Additionally, a biomedical TENG based on electrostatic induction and triboelectrification between biocompatible polymer–polymer sheets (38). It has been demonstrated that increasing the polymer film thickness significantly enhances electrostatic induction. One efficient way to raise the electric charges is by coating the electrode with a new folding line pattern. It has already achieved a peak voltage of 310.5 V and a current density of 16.2 μA, which is the maximum electricity output performance. Several commercial LEDs are powered simultaneously without any rectification by the power produced by the TENG. TENG-stimulated mouse L929 cells had a substantially greater survival rate than the negative control test. The use of the biocompatible material increases the potential uses of TENG in biomedical sectors compared to the traditional TENG (Fig. 20b).[57]

Designing and creating dual-purpose materials that combine photocatalytic activity with electrical output from a triboelectric nanogenerator (TENG) is a potential first step toward using human movement energy to power self-powered systems through flooring. Cobalt coordination polymer (Co-CP) was used as a catalyst and tribomaterial to create a dual-purpose TENG/photocatalytic system to overcome this difficulty. The power output was shown to be influenced by the size of the triboelectric layers when different sizes of Co-CP-based

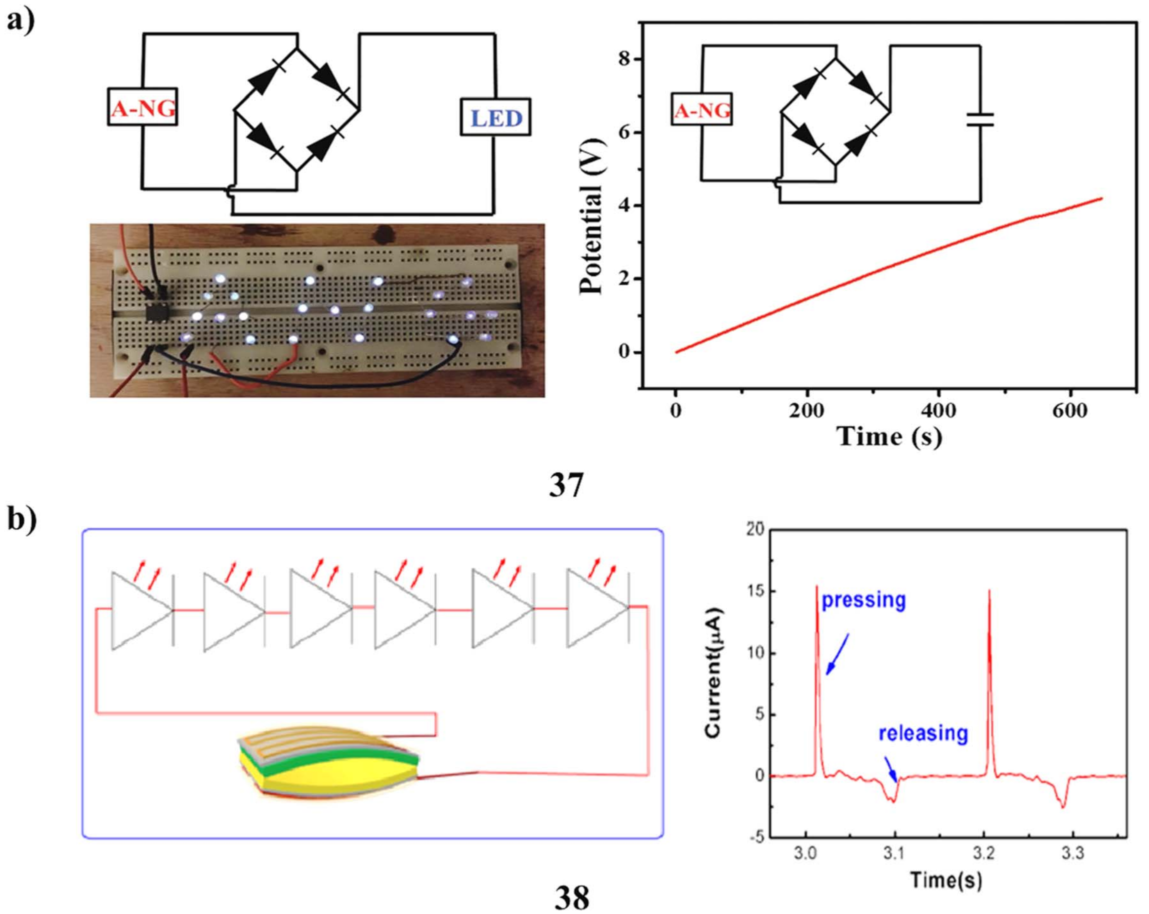

Fig. 20 (a) Porous polymer aerogel-based TENG delivering high voltage and power output (37) reproduced from ref. 56 with permission from Wiley-VCH Publisher, Copyright 2018. (b) Biocompatible polymer-based TENG generating high output for biomedical applications (38) reproduced from ref. 57 with permission from American Chemical Society Publisher, Copyright 2015.

triboelectrodes (39) were used to construct TENGs. Flexible Co-CP@CA composite films were made by combining different amounts of Co-CP with cellulose acetate (CA) to allow for broad application. This effectively increased the TENG devices output with the 12% Co-CP@CA-TENG producing the maximum output. The multiple TENG devices (M-TENG), which are extended daily-life flooring that can gather human walking energy for constantly driving blue LEDs were then created by combining 12% Co-CP@CA-TENGs. This allows for the efficient implementation of selective self-powered photocatalytic oxidation reactions using Co-CP as the photocatalyst through the use of blue light irradiation. According to this study, bifunctional CPs can be employed as photocatalysts to control self-powered photocatalytic systems and for large-scale integration through flooring systems to capture and track human mechanical energy (Fig. 21a).[58] Triboelectric nanogenerators (TENGs) convert mechanical energy from the surroundings into electrical energy, which has a wide range of applications in wearable electronics and tactile sensors. Energy generators are more prominent and useful due to attributes including flexibility, low weight, biocompatibility, and transparency. The silicone-based polymer (40) used in this work to create the TENGs charge-generating layer is elastic and opaque. Additionally, it was composited with TiO_2, $BaTiO_3$, Al_2O_3, ZnO, $CaCO_3$, and graphene oxide to boost the induced electrical charge and improve the triboelectric characteristics. The Si polymer/$BaTiO_3$ composite layer with a fracture strain of 260% on the aluminum contact produced the greatest output power density of 10.10 W m^{-2}, voltage of 660 V, and current of 72 μA for the flexible TENG. A composite layer based on silver nanowires (AgNWs) was coated on a conductive electrode to create a transparent, elastic, and ultra-lightweight TENG. The integrated nanogenerator was a lightweight device with 79% transparency, an output power density of 27 kW m^{-3}, and an 8 mg cm^{-2} density. It is used as a flexible wristband to turn on and off LEDs, thermometers, and oximeters. It is also a transparent, elastic, flexible, and incredibly lightweight touch-on/off switch that may be used in tough environments. The large-scale transparent and flexible TENG that has been introduced has a lot of potential for use in wearable electronics and smart home applications (Fig. 21b).[59]

The durability and robustness of triboelectric nanogenerators (TENGs) are severely threatened by frequent and unavoidable mechanical impacts while in operation. For the

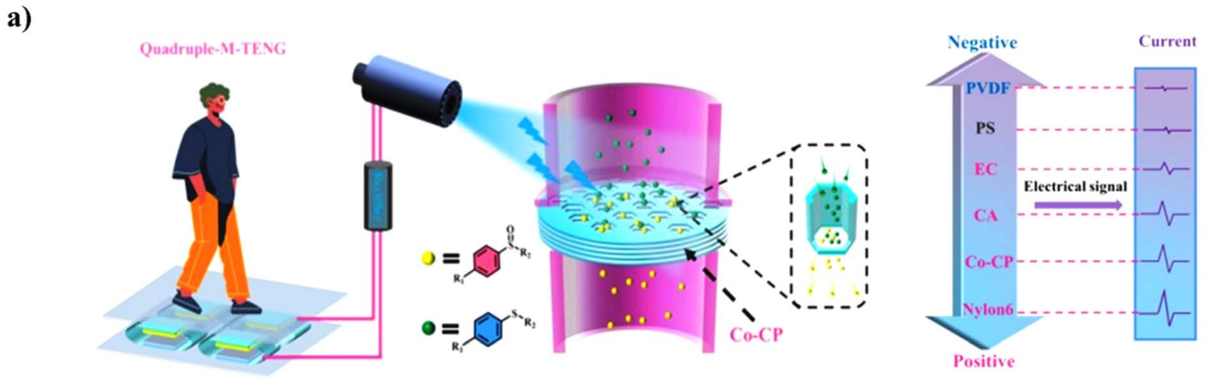

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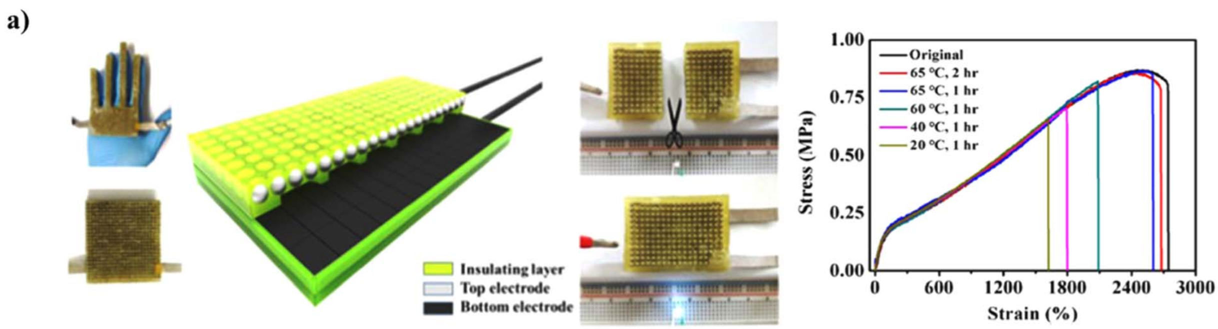
Fig. 21 (a) Co-CP-based TENG enabling self-powered photocatalytic reactions and energy harvesting (39) reproduced from ref. 58 with permission from Elsevier Publisher, Copyright 2025. (b) $BaTiO_3$/silicone polymer-based TENG for smart home and wearable applications (40) reproduced from ref. 59 with permission from Elsevier Publisher, Copyright 2022.



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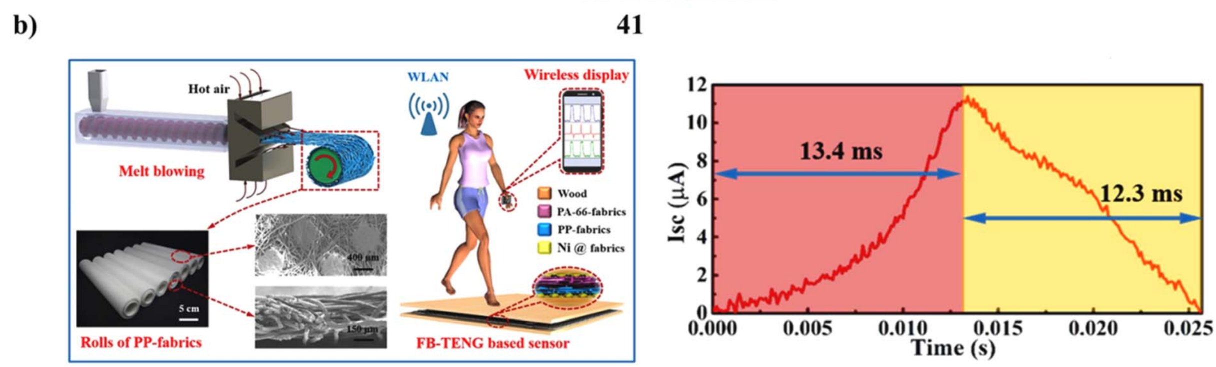

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Fig. 22 (a) Self-healing, shape-adaptable polymer TENG for robust energy harvesting (41) reproduced from ref. 60 with permission from Elsevier Publisher, Copyright 2017. (b) Fabric-based TENG for self-powered sensing and large-area energy collection (42) reproduced from ref. 61 with permission from Elsevier Publisher, Copyright 2019.

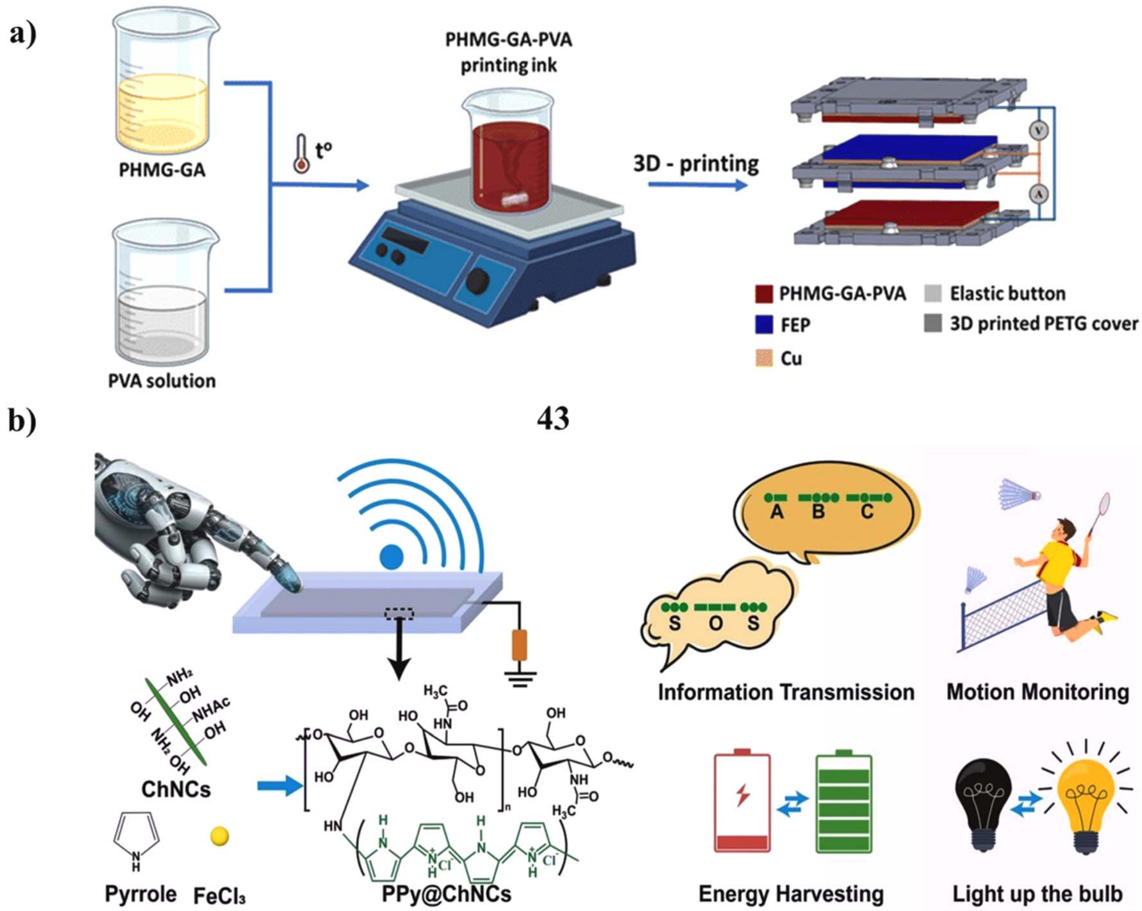

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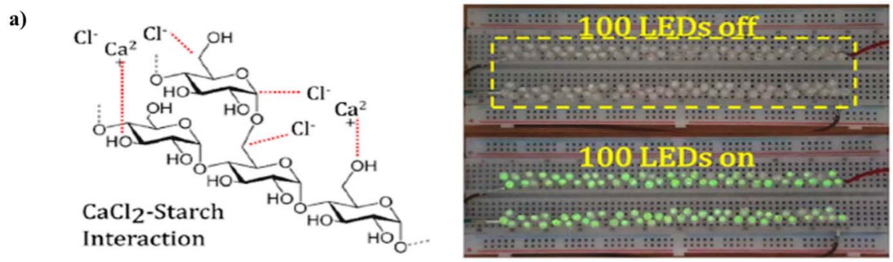
Fig. 23 (a) PHMG-based antimicrobial polymer TENG with high output performance (43) reproduced from ref. 62 with permission from Royal Society of Chemistry Publisher, Copyright 2025. (b) Conductive PPy-ChNC-based TENG for wearable motion sensing and energy harvesting (44) reproduced from ref. 63 with permission from Elsevier Publisher, Copyright 2025.

first time a completely self-healing TENG can restore its functionality following damage by adding electrodes made of small magnets and healable polymer materials (41). It suggests that high-performance self-healing TENG can be easily achieved, which is due to both the new magnetic-assisted electrodes made specifically for the TENG and the superior mechanical-healing capabilities of the used healable polymer. The results of the experiments indicate that the output voltage and current of the repaired device can remain above 95% of their starting values even after the fifth breakage-healing cycle. The TENG that is being given additionally exhibits object-adaptability and shape-tailorability. To support energy harvesting and self-powered sensing of various mechanical actions, this optimizes the device's effective contact area and elevates the electric output performance even more. In this study, practical methods for creating new mechanical energy harvesting devices and self-powered sensors that are robust, adaptive, and recoverable will be provided (Fig. 22a).[60] A fabric-based functional TENG (42, FB-TENG) is produced using an easy, continuous, and environmentally friendly approach. Its exceptional stability makes it possible for self-powered sensing and large-area mechanical energy harvesting. The greatest electrical output performance as a power source is demonstrated by FB-TENG, including PP-NWF with a fabric weight of 60 g m^{-2}. This kind of FB-TENG is capable of powering electronic timepieces, charging different capacitors, and lighting up LEDs. On the other hand, it can be used as a self-powered sensor in pugilism training monitors (SP-PTM) and pedestrian volume collectors (SP-PVC) with a very quick response time and real-time wireless display. Self-powered motion tracking, tactile sensing, and remote wireless training monitoring systems are just a few of the other sectors in which FB-TENG's superior energy harvesting capabilities and adaptable pressure sensing features might find scaled applications (Fig. 22b).[61]

A polymer called PHMG material has been effectively used as a positive electrode in a TENG device (43). The findings show that the output of the TENG device is influenced by the amount of PHMG present in the positive electrode. The device can achieve remarkable triboelectric performance with a peak-to-peak open circuit voltage of up to 664.5 V and a short-circuit current of 116.8 μA at a low operating frequency of 1 Hz when using a PHMG-GA because of the presence of amine functional



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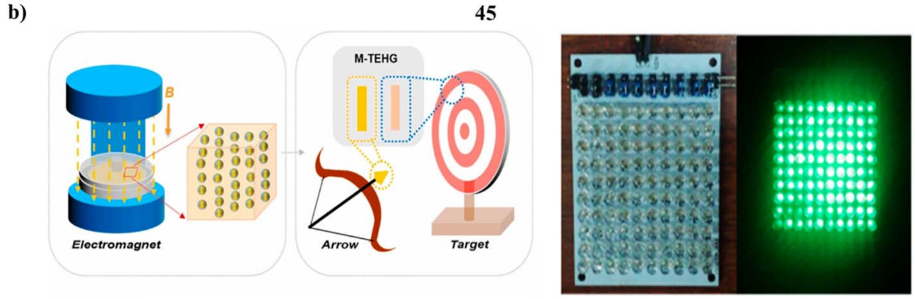

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Fig. 24 (a) Starch-based bio-TENG demonstrating low-cost, eco-friendly energy generation (45) reproduced from ref. 64 with permission from Elsevier Publisher, Copyright 2019. (b) Magnetic polymer composite TENG used for enhanced output and self-powered sensing (46) reproduced from ref. 65 with permission from Elsevier Publisher, Copyright 2020.

groups of the PHMG combined with GA as a cross-linker and PVA. The device maintains an output of 572 V and 172 μA at a higher frequency of 20 Hz when 10 N is applied as an actuation force. Furthermore, the device retains 98% of its initial output voltage after 360 000 running cycles suggesting that it might be used in sensors, self-powered devices, and particularly in antibacterial facemasks and self-deodorizing smart shoes (Fig. 23a).[62] A conducting polypyrrole (PPy) graft onto the surface of chitin nanocrystals (ChNCs) was used to create multifunctional, flexible, and very sensitive single-electrode TENGs (44). ChNCs successfully increased PPy's dispersibility in aqueous solution, which enhanced the suspensions electrochemical performance. Polydimethylsilane (PDMS) was used as the encapsulating material and friction layer, while PPy@ChNCs solution was used as the electrode material to create a single-electrode triboelectric nanogenerator (PC-TENG). Higher triboelectric performance is facilitated by the solid–liquid double layer that sits between the liquid electrode and the PDMS. A maximum output voltage of around 65 V an output current of approximately 8.6 μA, and a transferred charge of approximately 38 nC were observed for PC-TENG at a 1 : 2 ratio of ChNCs to PPy. The power density of PC-TENG may reach 353 mW m^{-2} after 1000 cycles with fast reaction times and reliable output performance. The self-powered PC-TENG system is capable of human motion tracking and touch perception. This study exploited biologically produced ChNCs to improve the conductivity and dispersibility of PPy. The resulting PC-TENG shows ability for use in wearable energy harvesting technologies (Fig. 23b).[63]

Triboelectric nanogenerators (TENGs) have made increasing triboelectrifying capacity a major focus. However, this has not yet been studied in a range of materials. Renewable materials such as biopolymer electrolytes are still poorly understood about TENG performance. A polymer electrolyte starch-based bio-TENG (45) was produced using a low-cost production method. The films were electrically characterized at various thicknesses, loads, and frequencies. The highest voltage output (1.2 V) was achieved by starch films at a 0.5% concentration of salt, which was three times higher than the initial output of the non-complexed virgin biopolymer (0.4 V). Moreover, it has been demonstrated that film moisture is a crucial factor in TENG electrical performance with well-dried films exhibiting a higher electrical output than moist samples. The electrical output performance also varies favorably at both lower film thicknesses and higher loads. Moreover, starch electrolyte sheets of TENGs demonstrated an unchangeable electrical performance appropriate for a variety of applications, even when cracks developed after fatigue. It used silicone ecoflex and starch electrolytes as competitors in a TENG to successfully turn on 100 LEDs to illustrate one of these applications (Fig. 24a).[64] A magnetic field-controlled arrangement of magnetic particles gives magnetic polymeric composites their variable capacitance. Studying the magnetic polymeric composite as the TENG tribo-material from a microscopic perspective is crucial because the capacitive effect on the surface charge density of tribo-materials has a significant impact on the output performance of TENG. To successfully improve the output performance of TENG (46, M-TENG), a magnetic polymeric composite sheet is suggested as the tribo-material. A sustainable and enhanced output of 32.6 μA (short-circuit current) and 233.4 V (open-circuit voltage) was obtained after examining the effects of the cured magnetic flux density, filling particle concentration, and particle size. The M-TENG showed a peak output power of 2.5 mW under a loading resistance of 3 MΩ, which was more than 4.7 times the output of the TENG, which was based on the pure silicone rubber mixture film (0.53 mW). Finally, a real-time automated target-scoring system was constructed to show the value of M-TENG as a self-powered sensor (Fig. 24b).[65] Recent studies have also explored perovskite nanomaterials such as barium titanate ($BaTiO_3$), strontium titanate ($SrTiO_3$), and organic-inorganic hybrid perovskites as functional fillers to enhance polymer-based TENG performance. These materials possess high dielectric constants and intrinsic ferroelectric polarization, which effectively increase the charge storage capacity and surface potential of the composite dielectric layer. Incorporating perovskite nanostructures into flexible polymer matrices such as PVDF has been shown to significantly enhance the output voltage and current density by promoting efficient charge separation and trapping. Such perovskite-polymer composites offer a promising pathway for next-generation high-performance TENGs.[66–68]

Polymer-based triboelectric nanogenerators (TENGs) utilize the triboelectrification effect and electrostatic induction to convert mechanical energy into electrical power, leveraging the flexibility, lightweight nature, and biocompatibility of polymers. These TENGs operate through contact-separation, sliding, or single-electrode modes, detecting biomechanical movements, physiological signals, and environmental stimuli in biomedical applications. Their advantages include high flexibility, ease of fabrication, cost-effectiveness, and tunable properties for enhanced performance in wearable and implantable devices. Polymer-based TENGs provide good flexibility and low-cost manufacturability, but their performance is hindered by several material-related drawbacks. Surface charge decay due to humidity, dielectric aging, and mechanical fatigue often reduces long-term output stability. Maintaining dipole alignment in ferroelectric polymers like PVDF is difficult during repeated deformation, affecting charge retention. Furthermore, achieving a balance between high dielectric constant and mechanical stretchability remains a design challenge. Research into nanocomposite fillers, cross-linking stabilization, and environmentally degradable polymers may help address these issues.

5. Silicon-based triboelectric nanogenerators

A freestanding dielectric layer made of powder that may move in any direction allows the S-TENG (47) to gather electrical energy independent of the direction of vibration. The maximum V_{OC} and I_{SC} are produced by the TENG when 50% of the volume is made up of SiO_2 powder. Five serially connected LEDs were activated by a simple handshake. Furthermore, when multiple S-TENG devices are placed at various locations throughout the human body to gather ambient energy a large amount of electrical energy will be produced. Given the growing propensity of V_{OC} and I_{SC} to reduce sand particle size the S-TENG that uses finer sand particles may produce more electricity than 3.7 V. A discarded bottle a pair of aluminum foils, and a few sand particles can be used to create an electric power generator. This S-TENG gadget can be used as a low-cost and efficient electric power generator (Fig. 25a).[69] The silica-based solid polymer electrolyte-based TENGs (48) showed distinct benefits in terms of high-performance TENGs, such as mechanical, thermal, and triboelectric positive film properties. The FIM-PVA/PDMS TENGs-based SSPE produced more positive polarities than pure PVA, which has 2.48 W m^{-2}, and showed a high output

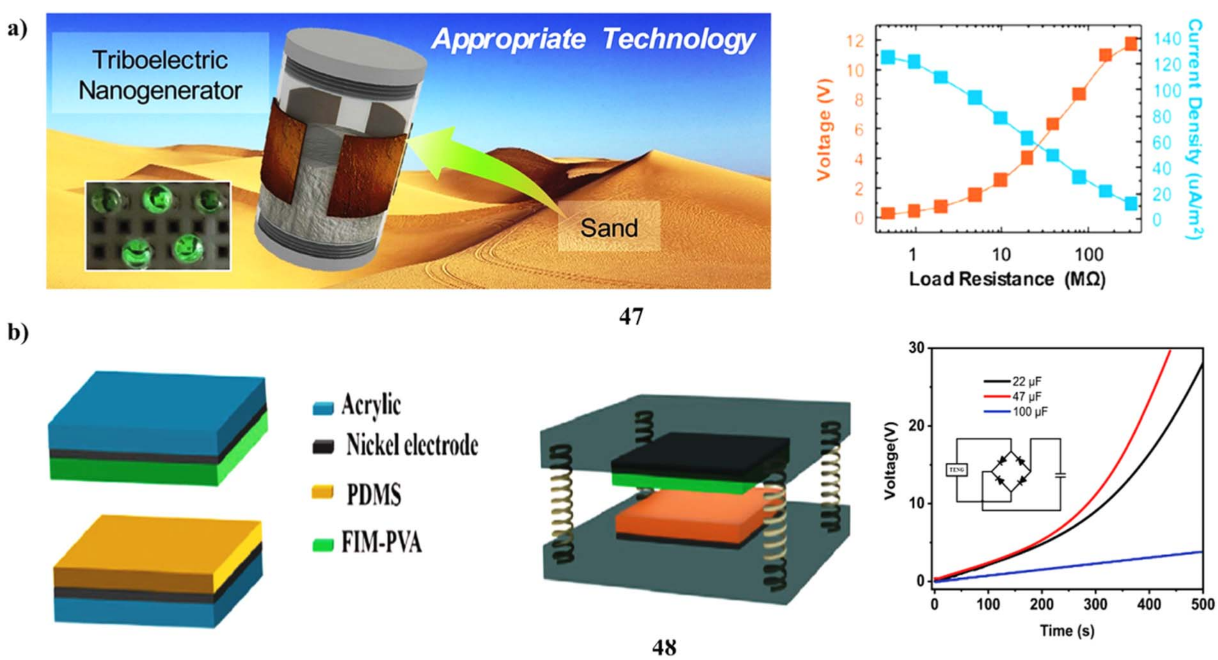


Fig. 25 (a) Sand-based silica TENG for low-cost mechanical energy harvesting (47) reproduced from ref. 69 with permission from Elsevier Publisher, Copyright 2018. (b) Imidazolium-functionalized PVA/silica TENG with enhanced positive triboelectric output (48) reproduced from ref. 70 with permission from Wiley-VCH Publisher, Copyright 2020.

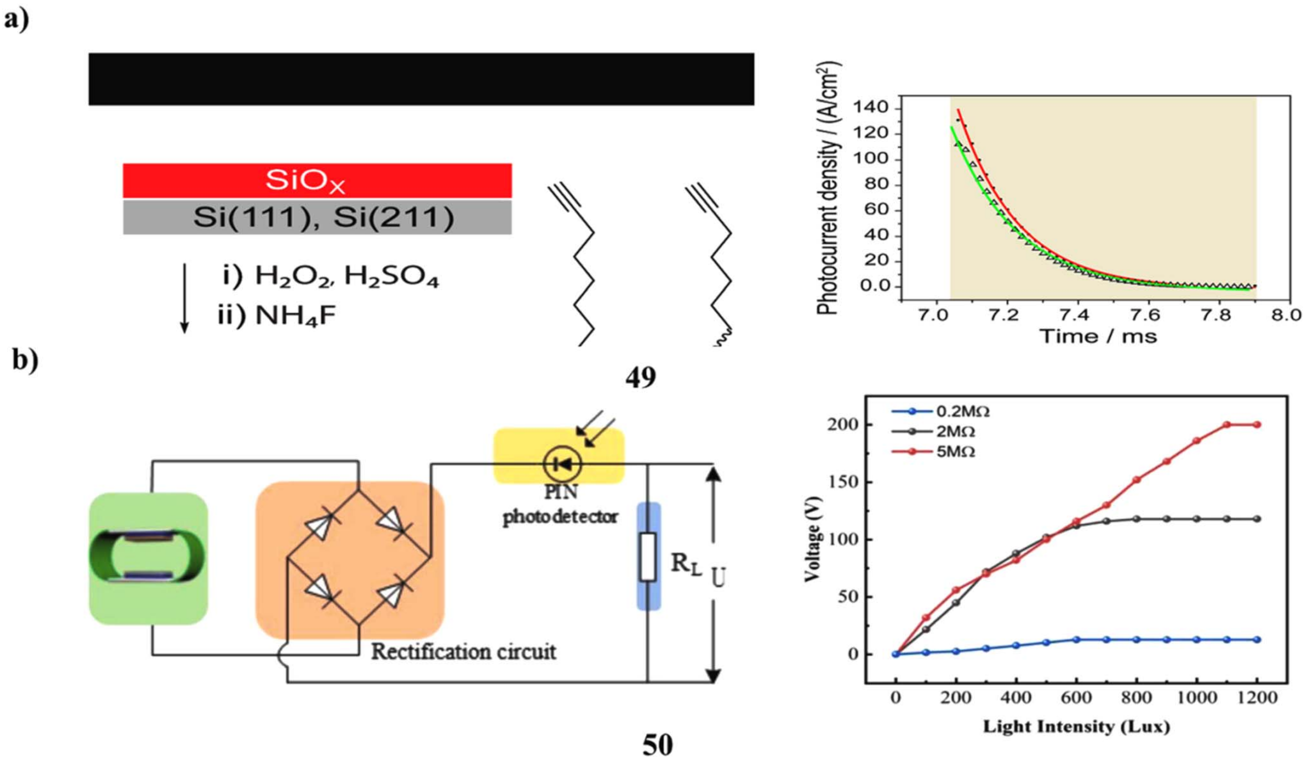
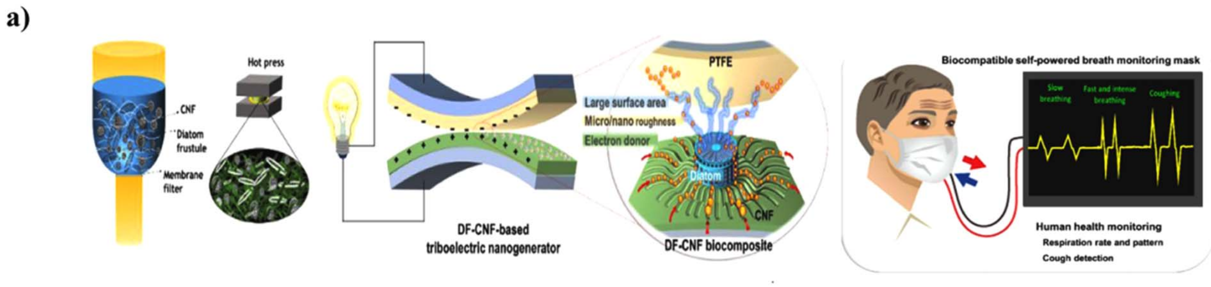


Fig. 26 (a) Si(211)-based DC-TENG showing performance degradation due to surface wear and oxidation (49) reproduced from ref. 71 with permission from MDPI Publisher, Copyright 2023. (b) Self-powered photoelectric detection system using paper-based TENG and silicon PIN photodetector (50) reproduced from ref. 72 with permission from Elsevier Publisher, Copyright 2020.

power of 5.2 W m^{-2} under optimal working circumstances. The electrical output increases as the concentration of ion precursor in PVA increases to a specific level, according to more research on the material qualities. In addition, FIM-PVA was examined using tribo-materials other than PDMS. The substantial increase in triboelectric outputs can be ascribed to the hydrogen bonding of PVA's –OH groups with ethoxy groups and the positive charge that the imidazole's nitrogen has due to the presence of imidazolium groups, which increases positive polarity. Imidazolium-functionalized PVA-based TENGs could serve as a strong alternative to conventional metal-based systems. The performance of silicon-based TENGs is greatly influenced by their surface micro- and nanostructuring. Features such as nanopillars, etched patterns, or porous textures increase the effective contact surface area and enhance charge separation by promoting stronger triboelectric interactions. These nanostructures also improve surface roughness, resulting in better electron trapping and charge retention. Moreover, structured silicon surfaces reduce dielectric breakdown risks and improve contact intimacy, thereby increasing energy conversion efficiency. These design enhancements make silicon-based TENGs highly stable and suitable for precision applications such as implantables, MEMS, and micro-sensors. It provides a straightforward, scalable, and economical approach to constructing high-performance TENGs, with enormous potential for TENG applications in implantable electronic devices in the future (Fig. 25b).[70]

Assessing the operational damage of DC-TENGs based on sliding Si (211)-organic monolayer-platinum Schottky diodes (49) and attempting to determine the relative significance of wear caused by friction or pressure *versus* oxidative damage to the semiconductor as a result of the flow of the high current densities ($\sim 2 \times 10^6$ A m^{-2}) attained during the operation of these tiny autonomous power sources. It was discovered through the use of photocurrent decay measurements (PCM) and conductive atomic force microscopy (C-AFM) experiments that oxide growth and decrease in TENG performance during operation are more closely related to friction and pressure-induced surface wear than to current flow. The current density decreases from around 2×10^6 A m^{-2} to about 3×10^5 A m^{-2}, which is an approximate 83% current decay. The impact of surface defects on charge recombination was highlighted by the carrier lifetime, which was determined to be 147.9 ± 10.7 μs inside damaged regions and 188.1 ± 15.7 μs outside damaged areas. Additionally, it shows that there was a lag between the friction/pressure incident and the surface damage (Fig. 26a).[71] A self-powered photoelectric detecting system based on the impedance matching effect of the ultra-thin dead layer silicon PIN photodetector (50) and paper-based TENG is proposed in the study. The power source was the paper-based TENG. The silicon PIN photodetector was developed using silicon-integrated processing for photo-detection. Sensitive photoelectric sensing, minimal cost, and no need for an external power source are the main benefits of the suggested system. It is recyclable and bendable as well. Additionally, the photodetector a)



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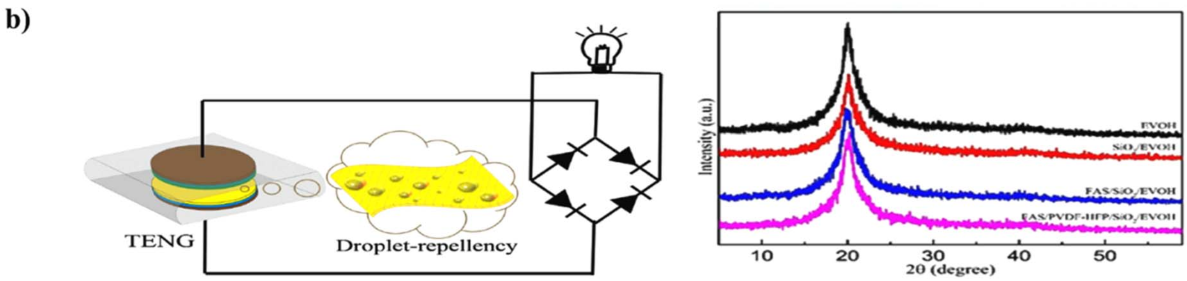

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Fig. 27 (a) Diatom frustule-based TENG showing enhanced output through natural micro-nano structures (51) reproduced from ref. 73 with permission from American Chemical Society Publisher, Copyright 2020. (b) Bioinspired diatom-patterned TENG for improved energy harvesting efficiency (52) reproduced from ref. 74 with permission from Royal Society of Chemistry Publisher, Copyright 2020.

system's operational state was modelled and examined, and a strategy for regulating the optical intensity detection range of the system was suggested. Lastly, it created a portable and easy-to-use photoelectric detection device that uses LEDs to show variations in light intensity. This study offers a potential path for the widespread use of reasonably priced silicon photodetectors in the internet of things self-powered domain (Fig. 26b).[72]

A biomaterial additive called diatom bio-silica enhances the functionality of TENGs made of cellulose nanofibril (CNF). Diatom frustules (DFs) are tribopositive bio-silica with a large surface area and hierarchically porous three-dimensional structures. They form hydrogen bonds with CNFs, which improves their ability to donate electrons and roughens the surface of the DF-CNF composite film. A tribopositive composite film was created using DFs and CNFs.The DF-CNF biocomposite film is electron-rich, mechanically strong, frictionally rough, and reasonably priced. The DF-CNF TENG (51) demonstrated an efficient contact area of 4.9 cm^2, an output voltage of 388 V, and a time-averaged power of 85.5 mW m^{-2} in the contact-separation mode. There was enough electricity produced to immediately light up 102 light-emitting LEDs. A cytotoxicity investigation and biocompatibility tests conducted on rabbit skin also indicated that the DF-CNF composite was safe for biological systems. A self-powered smart mask for monitoring human respiration was also used to test a real-world implementation of the DF-CNF TENG. In addition to suggesting that biomaterial-based TENGs have high output performance, this study highlights the various benefits of DFs in applications connected to the human body, including skin-attachable power generators, self-powered health monitoring masks, and tactile feedback systems (Fig. 27a).[73] The initial proposal was for a flexible amphiphobic TENG (52) made using silica-enhanced thermoplastic nanofiber membranes. To enhance the electrical output performance and amphiphilicity of the obtained TENGs, simple techniques like *in situ* polycondensation and dip-coating were taken into consideration after thermoplastic polymer resin was stretched into nanofibers using melt-blending extrusion following the phase separation behavior of thermoplastic polymeric immiscible systems. By adding SiO_2 nanoparticles, the surface roughness and triboelectric charges were better retained, and the peak voltage and current increased to 144.9 V and 23.7 μA, respectively. This output correlated to an impressive peak power density of 2.14 W m^{-2}, demonstrating the function of the power supply in illuminating many green LEDs. The device's exceptional stability and droplet-repellency as produced may result in resistance to antistatic agents and humidity, which should be available to optimize output in real-world applications. All things considered, this study provides a straightforward and efficient technique for creating TENGs that might be applied in a challenging setting (Fig. 27b).[74]

The silicone-based TENG (53) uses a spring framework and an electrode made of silicone rubber and carbon black to capture the energy of water waves. The gadget resembles a box with two silicone-based electrodes fixed on two inside walls and two PTFE-Cu-covered acrylic blocks connected by a spring. Although the spring structure may increase energy harvesting efficiency by converting low-frequency water wave movements into high-frequency vibrations, the inclusion of flexible electrodes can improve material contact and increase TENG outputs, especially when the water waves are flowing randomly. The effects of the segmented electrode structure, triboelectric material pair, and tribo-surface area were examined while the output performance of such a TENG was tested under the normal action of a linear motor. A lower tribo-surface area can result in a greater charge density and current density. The TENG with the C/PTFE-C tribo-material pair can yield 75.2%, 60.4%, and 103.9% increases in the transferred charge density, output current density, and voltage over the Cu/PTFE-Cu one. This can then further boost the output power of the silicone-based and spring-assisted TENG by 23.5% through segmentation on the silicone rubber/carbon black electrode. Furthermore, when the water waves activate the silicone-based and spring-assisted TENG, its segmented electrode structure, which is enclosed in a waterproof box has been demonstrated to efficiently harvest water wave energy generating a maximum power density of 2.40 W m^{-3}. It might offer guidelines for enhancing TENG performance by combining spring structure and flexible electrodes to effectively harvest water wave energy (Fig. 28a).[75] The graphene-based electrode with silicone elastomer sheets (54) was effectively XL using a solution of hydrolyzed APTES. The modified silicone elastomer films were coated with the graphene-based multilayer electrode by layer-by-layer construction. ATR/FT-IR spectrum analysis and fluorescent tagging were used to validate the modified silicone elastomer surface. The W-TENGs output power was about double that of the device without the silicone elastomer known as the XL electrode. The chemically XL conductive silicone elastomer layer also showed remarkable durability despite repeated mechanical deformation and rapidly reached 12, 18, and 102 V for bending, twisting, and tapping using charged capacitors and fingers. Additionally, it showed that these chemically XL films had exceptional sensitivity and could sense even the smallest movement as a strain sensor. Thus, the performance and sensitivity of this improved conductive XL silicone elastomer sheet construction method might ultimately make it a fantastic choice for wearable electronics (Fig. 28b).[76]

The Ag/PDMS electrode is integrated with a conventional monocrystalline Si solar cell to demonstrate a TENG/Si tandem hybrid (55) solar cell that harvests solar and rain energy concurrently. To create a two-electrode TENG by joining the top Ag and bottom Al electrodes the exposed Ag electrode at the PDMS surface stands out in contrast to the most advanced hybrid solar panels. Both photovoltaic and triboelectric performances have been greatly improved as a result of the greater light transmittance and built-in electric field-induced charge redistribution that results from the interaction between the two electrodes TENG and solar cells. A single raindrop stimulus may provide a maximum power output of 147 μW with a voltage of 37.19 V and a current of 7.59 μA, while a single sun irradiation can attain a champion efficiency of up to 22.04%. The physical proof-of-concept TENG/Si tandem hybrid solar cell's compelling advantages of higher power output and longer operating duration provide new ways to

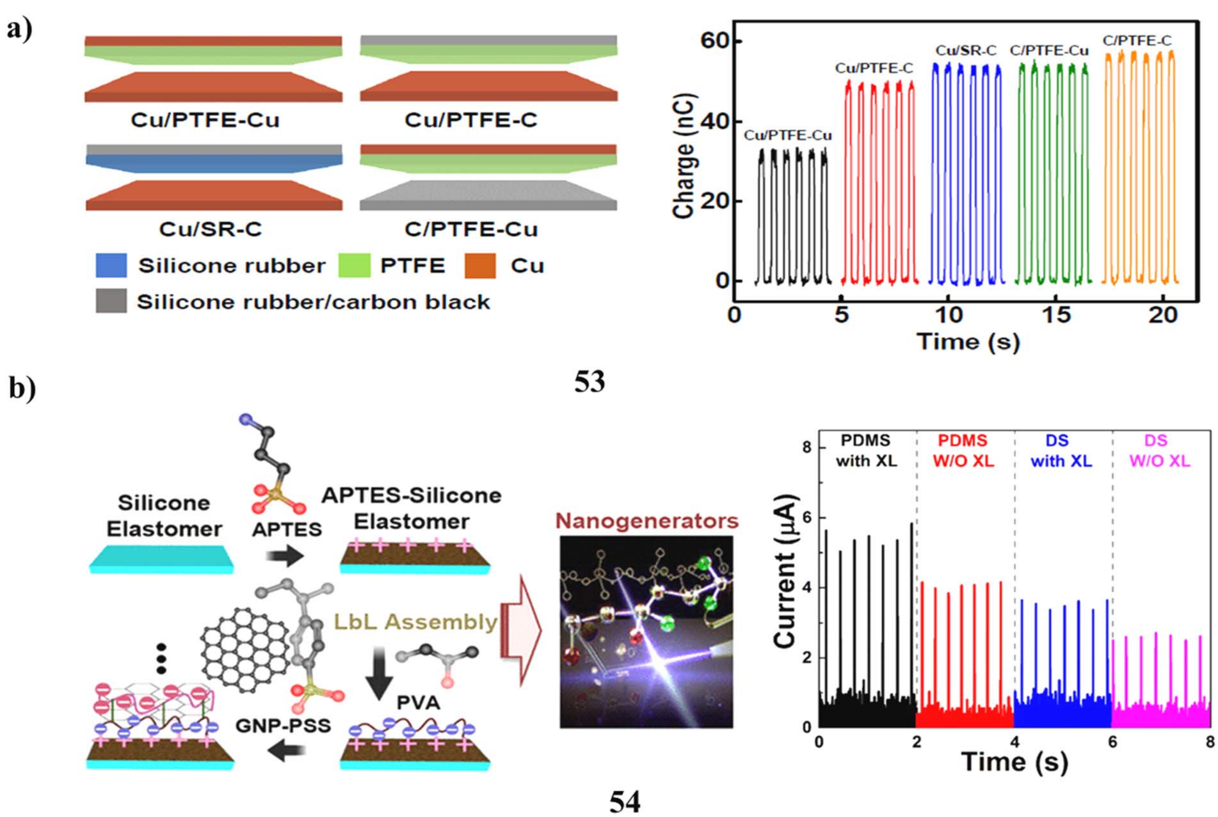

Fig. 28 (a) Porous PDMS and MXene-based stretchable TENG for high-output wearable applications (53) reproduced from ref. 75 with permission from American Chemical Society Publisher, Copyright 2018. (b) MXene-silicone composite TENG with improved conductivity and durability for energy harvesting (54) reproduced from ref. 76 with permission from American Chemical Society Publisher, Copyright 2023.

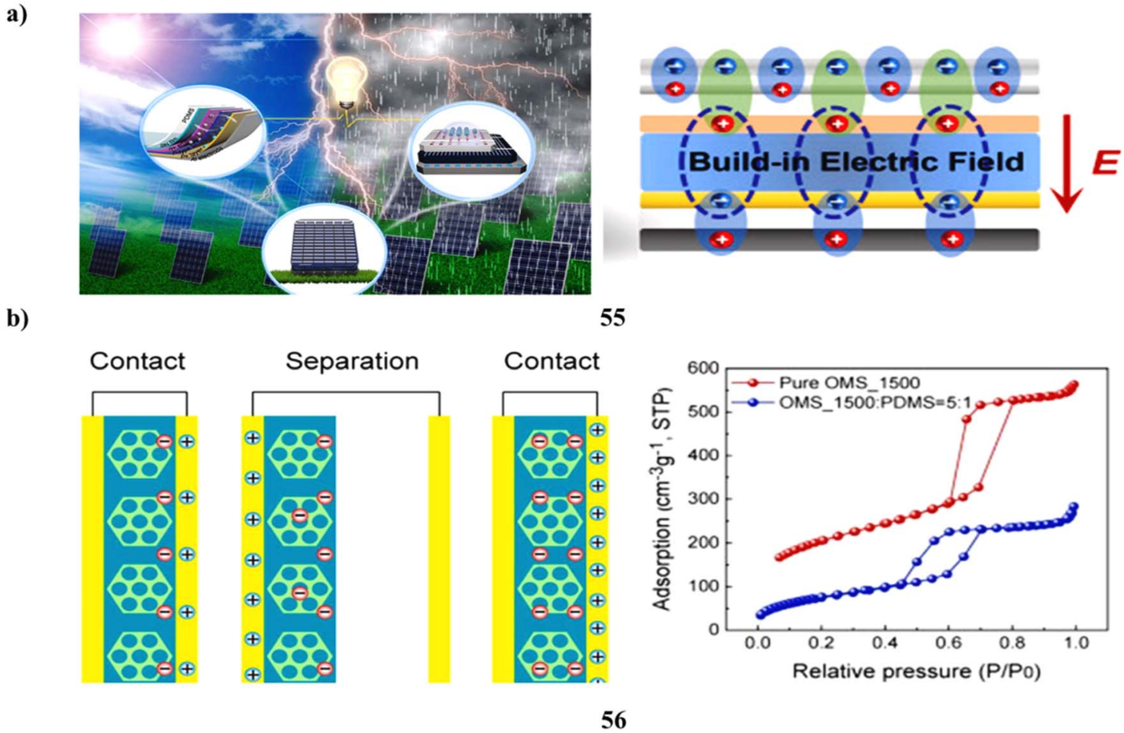

Fig. 29 (a) Diatom-inspired porous silica TENG with enhanced surface charge generation (55) reproduced from ref. 77 with permission from Elsevier Publisher, Copyright 2021. (b) Fish-scale-derived biowaste TENG showing improved flexibility and sustainable energy harvesting (56) reproduced from ref. 78 with permission from Elsevier Publisher, Copyright 2023.

gather a variety of natural energies and advance the development of weather-independent solar cells (Fig. 29a).[77] Large SSA mesoporous SiO_2 nanoparticles (56) serve as efficient body charge storage locations to improve TENG output performance. The TNEGs transmitted charge rose dramatically from 21 °C to 60 °C when 1 wt% OMS nanoparticles were used as the ideal concentration. Due to the OMS nanoparticles appearance on the composite surface an excessive concentration of OMS nanoparticles may cause the enhancing effect to diminish because the PDMSs effective area would be diminished. The OMS nanoparticles improving impact on the TENGs output performance increased linearly with their SSA. Furthermore, the TENG with OMS-PDMS showed a better capacity for charge retention than the TENG with pure PDMS. The V_{OC} of the TENG with OMS-PDMS remained at 68% for a considerable amount of time after the contact-separation motion was stopped, but the V_{OC} of the pure PDMS rapidly decreased to almost 0 V. Lastly, the TENG with OMS-PDMS achieved an instantaneous output power density of 5.26 W m^{-2}, which was 26 times higher than the TENG with pure PDMS. To improve the output performance of TENGs the OMS nanoparticles large specific surface area served as an efficient charge storage site (Fig. 29b).[78]

Positive and negative triboelectric layers in a high-performance TENG were created using the superhydrophobic Al plate and the high-dielectric $SiC@SiO_2$/PDMS nanocomposite films (57). The addition of $SiC@SiO_2$ core–shell nanoparticles to the PDMS layer may significantly improve the TENGs output performance. This results from the $SiC@SiO_2$ nanoparticles strong electric insulation, which raises the PDMS composite films dielectric permittivity and lowers their dielectric loss. In contrast to the pure PDMS triboelectric layer the output voltage/current of the TENG may be significantly increased from 50 V/5 μA to 200 V/30 μA when 7 wt% $SiC@SiO_2$ core–shell nanoparticles are added to the PDMS film. The remarkable self-cleaning performance of the TENG is also a result of the positive and negative triboelectric layers exceptional hydrophobicity. The TENG has also been shown to be a useful tool for continually powering an electronic watch and charging a commercial capacitor. It enables the rational design of high-performance TENGs by efficiently controlling the dielectric properties of triboelectric materials based on core–shell nanowhiskers (Fig. 30).[79]

Silicon-based triboelectric nanogenerators (TENGs) operate on the principles of triboelectrification and electrostatic induction efficiently converting mechanical energy into electrical energy. Utilizing silicon's superior conductivity, structural stability, and microfabrication compatibility, these TENGs function through contact-separation or sliding modes to detect biomechanical motions, physiological signals, and environmental changes in biomedical applications. Their advantages include high sensitivity, durability, miniaturization potential, and seamless integration with microelectromechanical systems (MEMS). Silicon-based TENGs benefit from precise micro/nanostructuring and high charge density but face significant limitations for practical applications. Their rigid and brittle nature restricts flexibility, making integration with wearable or curved surfaces difficult. Fabrication through etching and lithography is complex and costly, hindering scalability. Surface

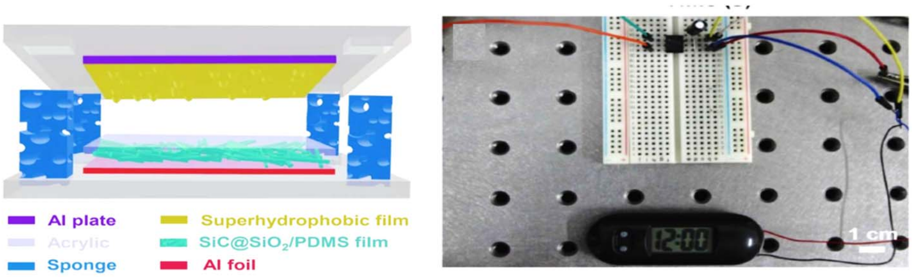

Fig. 30 CNF/PEI aerogel-PVDF hybrid TENG for high-output energy harvesting and sensitive motion detection (57) reproduced from ref. 79 with permission from Springer Publisher, Copyright 2023.

oxidation and mechanical fragility can lead to rapid degradation during prolonged use. Addressing these challenges will require the development of flexible silicon composites, simplified microfabrication methods, and robust surface coatings for stability enhancement.

5.1. Mechanistic insights into material-dependent TENG performance

A deeper understanding of the mechanisms of charge generation and transfer is essential for optimizing TENG performance. In all TENG systems, mechanical contact induces triboelectrification, where charge transfer occurs due to differences in electron affinity between two materials. Graphene-based TENGs enhance this process through high carrier mobility and quantum capacitance, which facilitate rapid charge transport and efficient electrostatic induction. Gel-based TENGs rely on ion migration within polymeric or ionic matrices; their soft interfaces allow intimate contact and reversible deformation, improving charge separation but limiting long-term stability due to dehydration or ion leakage. In polymer-based TENGs, dipole alignment (as in PVDF or PCL) and surface polarization strongly influence charge density and dielectric strength, making ferroelectric and porous polymers especially effective. Silicon-based systems benefit from surface nanostructuring that amplifies effective contact area and local electric fields, leading to stronger electron exchange. Collectively, these mechanisms reveal how interfacial chemistry, surface morphology, and electronic structure jointly dictate triboelectric output and device durability (Table 1).

6. Intelligent automation systems based on triboelectric nanogenerators

A RepNet-based wireless self-powered sensor system is composed of only two components and a deep learning algorithm resulting in a simple structure and great accuracy even in the absence of an integrated circuit. The artificial intelligence (AI) sensor (58) is directly powered by a triboelectric nanogenerator (TENG), and the algorithm takes local temporal information and convolutional features from a video and encodes them. It creates a test dataset of 192 videos with 32 TENG frequencies to evaluate this model. It displays the RepNet-based real-time detection backend. In applications like counting the number of LED flashes evaluating the likelihood of LED flashing, and detecting frequency changes this deep learning-based backend also performs admirably and shows a great deal of feasibility and potential. It is a promising and innovative method for measuring and transmitting data from self-powered sensors based on TENG (Fig. 31a).[80] Modern medicine relies heavily on vancomycin to treat severe Gram-positive infections particularly those that are resistant to other antibiotics. In the meantime, tracking the vancomycin concentration is essential for evaluating the health of patients. The development of a biosensor with a quick response time and high reliability is urgent. Self-powered vancomycin concentration detection was achieved using a droplet-driven triboelectric nanogenerator (59, DD-TENG). To maximize the performance of DD-TENG texture and fluorination techniques were used. The triboelectrification between the droplets and the triboelectric material changed causing the triboelectric signals to decrease as the vancomycin concentration in the droplets increased and to reverse when the concentration surpassed a point. Additionally, a deep learning algorithm was used to obtain great accuracy in identifying various vancomycin concentrations. DD-TENG was incorporated into medical droppers to track the concentration of vancomycin. Additionally, the measurement of vancomycin concentration in human serum is another area in which DD-TENG exhibits considerable promise. This study presents a convincing method for intelligent detection in medical systems (Fig. 31b).[81]

Table 1 Summarizing dominant mechanisms

Material type	Dominant mechanism	Key factors affecting output	Typical challenge
Graphene	Electron transport and surface charge trapping	Carrier mobility, work function	Cost, complex fabrication
Gel	Ion migration and interfacial polarization	Ionic conductivity, hydration	Dehydration, leakage
Polymer	Dipole alignment and dielectric polarization	Molecular orientation, porosity	Aging, low dielectric loss
Silicon	Surface charge amplification *via* nanostructuring	Surface roughness, electric field	Wear, fabrication precision

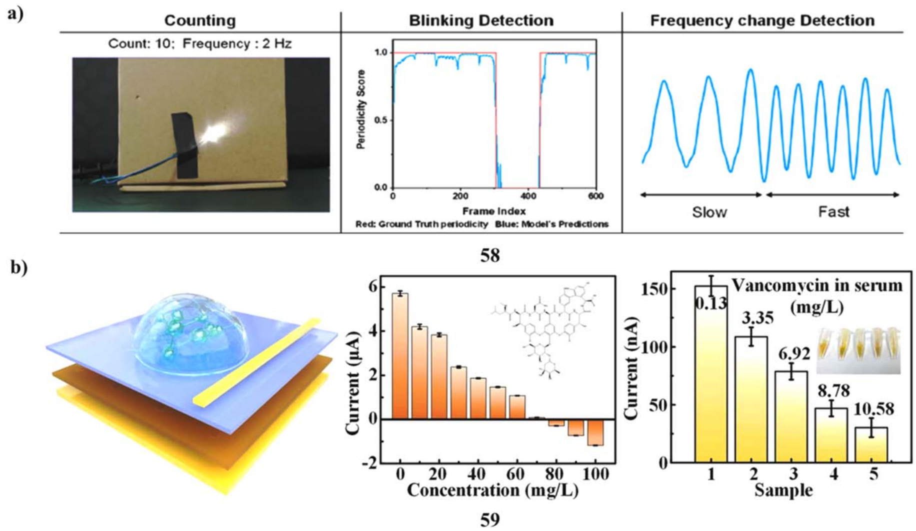

Fig. 31 (a) AI-powered wireless real-time monitoring system based on TENGs (58) reproduced from ref. 80 with permission from Elsevier Publisher, Copyright 2024. (b) AI-smart medical monitoring using droplet-driven triboelectric nanogenerator (DD-TENG) (59) reproduced from ref. 81 with permission from Elsevier Publisher, Copyright 2025.

The development of self-monitoring and smart diagnosis bearings has emerged as a significant yet difficult topic in the age of artificial intelligence (AI) and digitization. In this study, an AI-enabled bearing-structural rolling triboelectric nanogenerator (60, B-TENG) that can monitor bearing wear conditions and identify issues is investigated. Rolling balls are intended to be used directly as the freestanding layer in the geometrical framework of B-TENG. Additionally, a signal decomposition method is used to first show the mapping mechanism of wear flaws and the sensing principle of

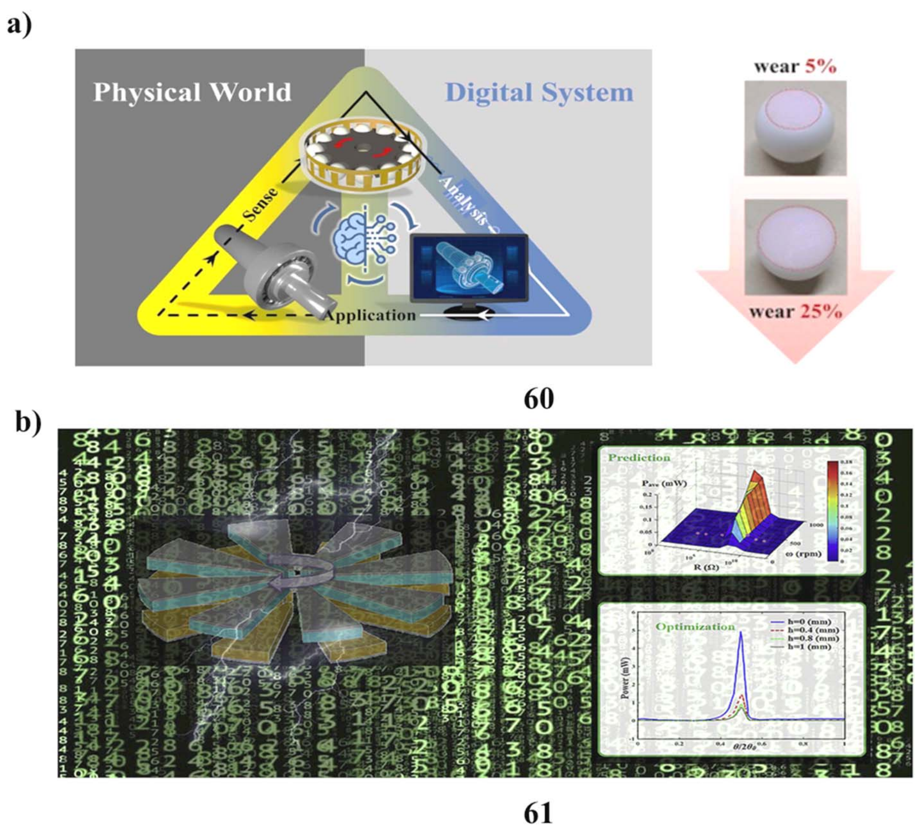

Fig. 32 (a) Digital twin study of AI-enabled rolling triboelectric nanogenerators (B-TENGs) (60) reproduced from ref. 82 with permission from Elsevier Publisher, Copyright 2025. (b) AI-based kinematic and geometric modeling of rotary triboelectric nanogenerators (61) reproduced from ref. 83 with permission from Elsevier Publisher, Copyright 2020.

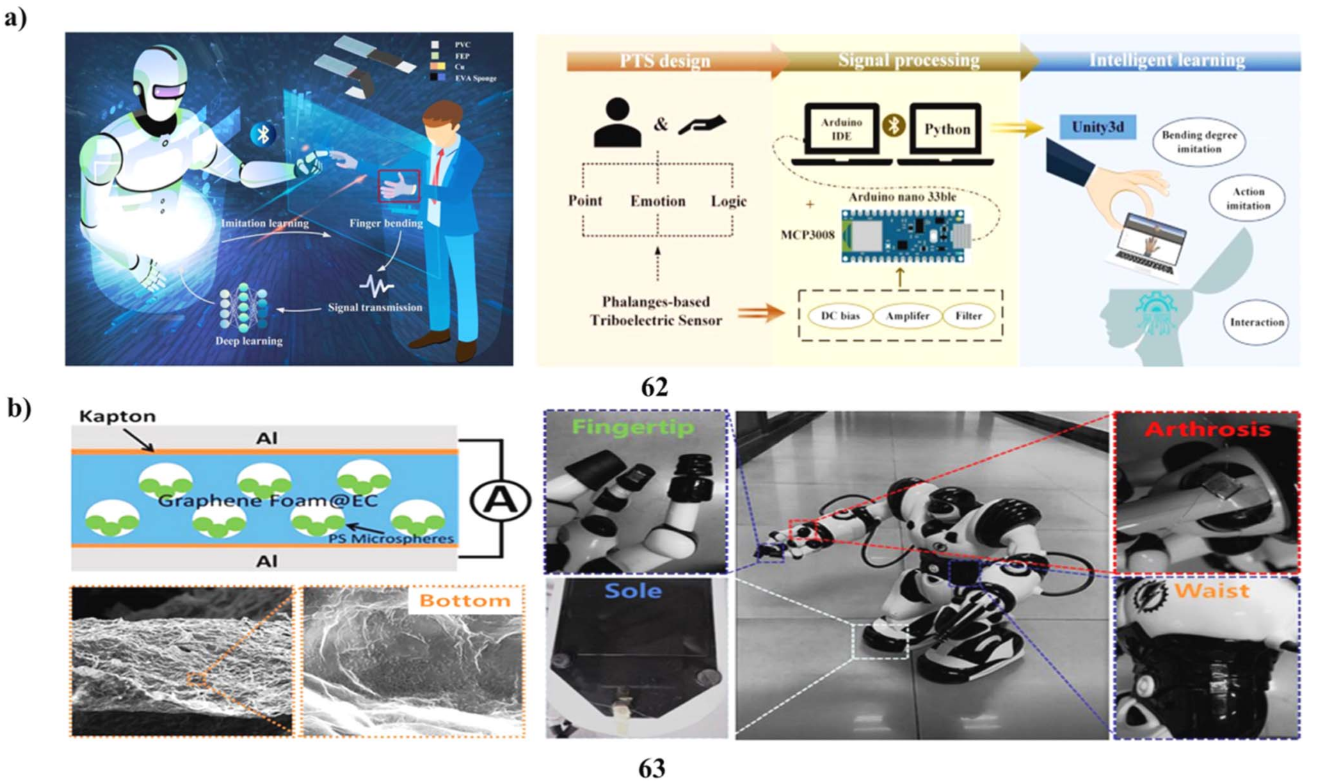

Fig. 33 (a) AI-enabled smart glove with triboelectric sensors for gesture-based human-robot interaction (62) reproduced from ref. 84 with permission from Elsevier Publisher, Copyright 2025. (b) IoT-based triboelectric nanogenerator for motion sensing and perceptual layer applications (63) reproduced from ref. 85 with permission from Elsevier Publisher, Copyright 2018.

triboelectric signal waveforms. A deep learning system can also classify rolling balls with different kinds, locations, and degrees of wear with a greater accuracy of 95.20–98.40% for the feature components. This is the first instance of wear degree detection for bearing health and failure evolution. AI-identified real-time diagnosis may be utilized to build digital twins by interacting with professional simulation software(Fig. 32a).[82] Triboelectric nanogenerators (TENGs) are state-of-the-art technology for micro/nanoscale sustainable electrical energy generation. Experimental and theoretical models for augmented rotary TENGs are presented in this paper. Tribo-surface spacing, rotational speed, and segment count are discovered to affect the power produced by TENGs. The TENG (61) output is described using mathematical modelling in combination with artificial intelligence under various kinematics and geometric conditions. The sensitivity analysis shows that segmentation and angular velocity rate have a substantial impact on the produced energy and the related resistance. The ideal energy collected at each cycle is shown to be 0.369 mJ. The TENG dynamic outputs for various structural features are recognized and described. This work improves knowledge of periodic TENGs caused by rotation and identifies optimal features for disk-shaped TENG energy harvesters (Fig. 32b).[83]

Embodied artificial intelligence (EAI) enables robots to learn independently *via* complex interactions with their external environment. It is reinforced by integrated voice and visual capabilities for effective user engagement. In contrast, human learning happens first without words, and gestures serve as an essential form of communication and a powerful teaching tool. This work introduces a kind of smart glove that makes use of triboelectric nanogenerators (TENGs) and is designed to serve as an advanced teaching interface for EAI (62, Ti-EAI) to facilitate human-robot interactions. The segmented architecture of the phalanges-based triboelectric sensor (PTS) promotes natural mobility and minimizes sensor interference by adjusting to finger motions. The connection mechanism incorporates a double-layer electrode design with a phase difference to enhance the gesture information inherent in the signals and optimize signal outputs. The human operator in the Ti-EAI system uses PTS-capable gloves as a teaching tool to methodically communicate instructions and information to the robots. This configuration improves the robots intrinsic intelligence by utilizing gesture-based communication to greatly increase its capacity to notice environmental details. The Ti-EAI technology allows robots to independently detect gestures, interact logically with subjective actions, and have a conversation using a large-scale model. Notably, the results from this system show significant advancements in EAI expanding its use in humanoid robots and enabling a more thorough integration into a variety of everyday situations (Fig. 33a).[84] A key component of the internet of things (63, IoT) is the motion sensor at the perceptual layer, which is at the forefront of information collecting. However, a number of motion sensor issues including limited mobility, low environmental adaptation, and excessive energy

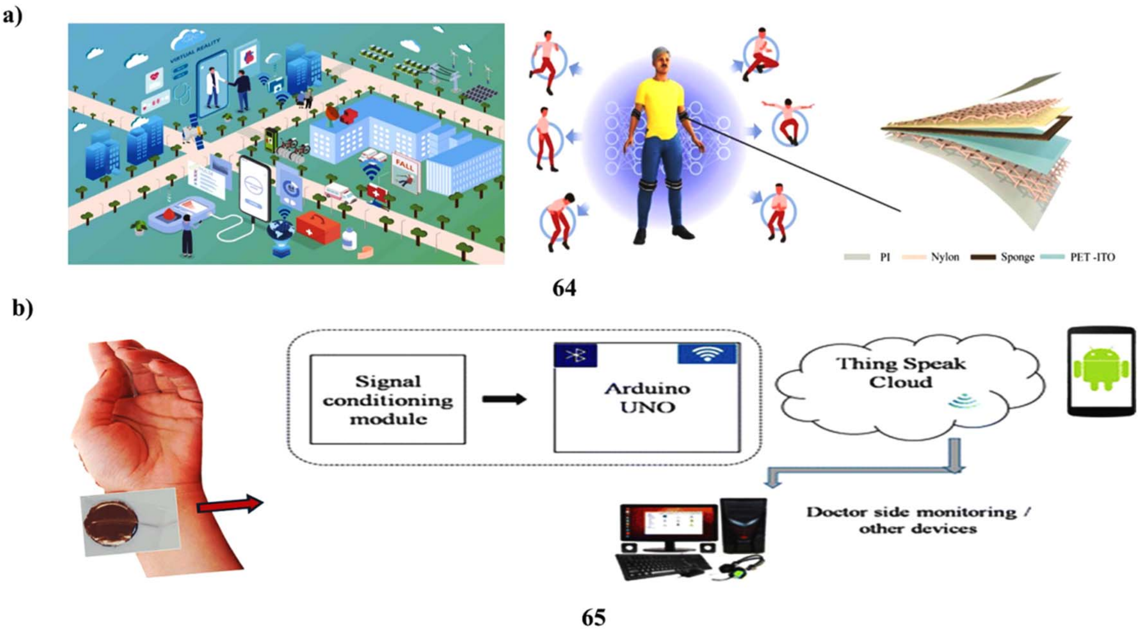

Fig. 34 (a) IoT-based flexible triboelectric sensor for intelligent health monitoring of Parkinson's patients (64) reproduced from ref. 86 with permission from Elsevier Publisher, Copyright 2023. (b) IoT-enabled triboelectric nanogenerator for wrist pulse acquisition and medical diagnostics (65) reproduced from ref. 87 with permission from Royal Society of Chemistry Publisher, Copyright 2025.

consumption restrict the growth of IOT despite its many commercial uses. The UMS has a mass of less than 20 mg. The UMS's self-powered capacity is achieved by connecting electrostatic induction and triboelectrification, which is regulated by the Maxwell displacement current and is based on the triboelectric nanogenerator concept. Additionally, the UMS shows strong self-adaptive performance for both temperature and humidity between 15 °C and 60 °C with ambient humidity below 90% relative humidity. Additionally, the CPU can clearly distinguish between sensory signals caused by various motion behaviors like gripping, walking, stooping, and so on. This capability can be used for motion recognition and machine control. This paper introduces a revolutionary UMS that is environmentally friendly, portable, and energy-efficient. It demonstrates a wide range of potential applications for the perceptual layer in IoT (Fig. 33b).[85]

Precision medicine, intelligent healthcare, and telemedicine are made possible in the age of digitalization and intelligence by the internet of medical things (IoMT), a platform that blends internet of things (IoT) technology with medical applications. However, there are some obstacles that the IoMT must overcome, such as the need for a sustainable power source, human sensor adaptation, and sensor intelligence. Construct a resilient and perceptive IoMT system by combining deep learning-assisted data analytics with flexible wearable triboelectric sensors (64) in a complementary manner. A bracelet with four triboelectric sensors is used to track and evaluate limb movements in Parkinson's disease (PD) patients. A smart healthcare monitoring system for the surveillance and engagement of PD patients was realized by further integrating deep learning-assisted data analytics. This system incorporates identity identification, location/trajectory tracking, and heart monitoring. This creative method allowed us to precisely record and examine the fine motor skills and delicate movements of PD patients resulting in enlightening comments and a thorough evaluation of the patient situations. The enormous potential of human body sensing technology in a Health 4.0 society is highlighted by this monitoring system's affordability, ease of fabrication, high sensitivity, and intelligence (Fig. 34a).[86] The three nadi signals of three different groups, which are required to diagnose BP-related disorders may be acquired using the developed TENG (65). This study looked at three different groups of healthy people and recorded their three nadi signals. The three nadi signals frequency and temporal domains were examined. If a patient fits into any of the aforementioned categories an Ayurvedic physician can use this fact as a guide to assess the patient's blood pressure and other conditions. Additionally, the frequencies of the nadi pulses of three different groups of male and female volunteers were determined. The created TENG's features include low cost, lightweight, reusable, and user-friendly. The anticipated TENG output performance is also unaffected by the relative humidity during testing. Its size constraint means that it is only appropriate for medical monitoring (Fig. 34b).[87]

The internet of things (IoT) is many sensor nodes that rely mostly on batteries for electricity, which has reduced their lifespan and raised maintenance expenses. A triboelectric nanogenerator (66, TENG) based self-powered Internet of Things sensing node is suggested for long-term environmental monitoring. Six pairs of finger electrodes and rabbit hair are used in the freestanding mode of the wind-powered TENG (W-TENG). The energy management module can transform the

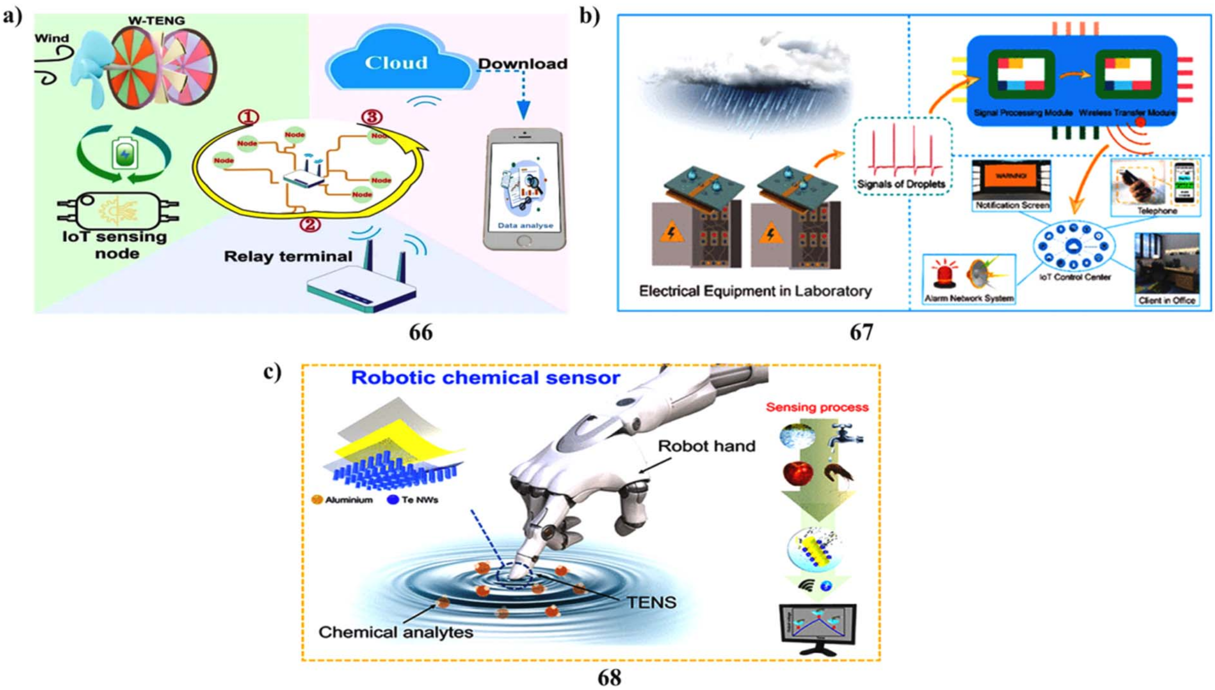

Fig. 35 (a) IoT-based wind-driven TENG for sustainable environmental monitoring applications (66) reproduced from ref. 88 with permission from Springer Science Publisher, Copyright 2023. (b) Self-powered droplet-driven TENG alarm system for water leakage detection (67) reproduced from ref. 89 with permission from American Chemical Society Publisher, Copyright 2023. (c) Robotic triboelectric nanosensor for rapid on-site hazardous chemical detection (68) reproduced from ref. 90 with permission from American Chemical Society Publisher, Copyright 2023.

weak electrical energy from W-TENG into a steady 2.5 V direct current (DC) voltage so that the IoT sensor node can function. The microprogrammed control unit (MCU) delivers the monitoring data once the node is triggered when the stored energy surpasses 4.4 V. The narrowband IoT (NB-IoT) module will then identify the monitoring data and transmit it to the IoT cloud platform. The node is capable of wirelessly monitoring and transmitting temperature and atmospheric pressure data every 30 seconds at a wind speed of 8.4 m s^{-1}. It has shown promise for use in big data, environmental monitoring, and the Internet of Things by offering a universal approach for sustainable IoT sensor nodes driven by environmental micro-nano mechanical energy (Fig. 35a).[88] The stability and dependability of contemporary electrical equipment in damp conditions are severely challenged by water leaks and condensation, which cause metal component corrosion and even short circuits, further resulting in emergency equipment shutdowns or safety events. A wireless transmission module, a microcontroller unit (MCU), a signal processing module, and a droplet-based triboelectric nanogenerator (67, DTNG) are integrated into a self-powered alarm system that can quickly and sensitively detect and identify water leakage or condensation in the surrounding environment. These include the high-sensitivity, inexpensive, and long-lasting DTNG, which can transform the low-frequency disordered kinetic energy of water droplets into concentrated, ordered, and useful electrical energy, allowing an alarm system to run continuously. It examines the effects of tilt angle, droplet volume, and hydrophobic modified poly(tetrafluoroethylene) (PTFE) film thickness on the devices output properties. The perfect DTNG produces consistent cycle performance (95.5% for 28 days) and outstanding output characteristics (111.6 V, 8.497 μA, and 388.60 μW m^{-2}). More significantly, it installed a wireless alarm system and a remote hyetometer for expensive electrical equipment that is susceptible to moisture or water, offering fresh concepts and distinctive perspectives for growth in the IoT alarm system and DTNG-based environmental monitoring fields (Fig. 35b).[89] Hazardous chemical detection must be done quickly on-site for applications including remote security and environmental monitoring. However, present sensing technologies low selectivity, sensitivity, and extremely high power needs limit their use in real-world settings. A novel self-powered triboelectric nanosensor (68) that detects hazardous chemical pollutants like Hg^{2+} ions in a quick, one-step on-site diagnostic method. According to the solid–liquid contact electrification mechanism, mercury telluride nanowires (HgTe NWs) were formed *in situ* as a result of the selective binding affinity of Te NWs towards Hg^{2+} ions. This occurred when the sensing probe and tellurium nanowire (Te NW) arrays acting as a solid triboelectric material periodically came into contact with and separated from the Hg^{2+} solution. Te NW arrays were affixed to the robotic hands with extra wireless transmission capabilities to achieve the on-site sensing potential. This allowed for the quick detection of Hg^{2+} ions in environments with limited resources by using a straightforward "touch and sense" approach. Such an example of the direct integration of robotics with self-powered sensors would result

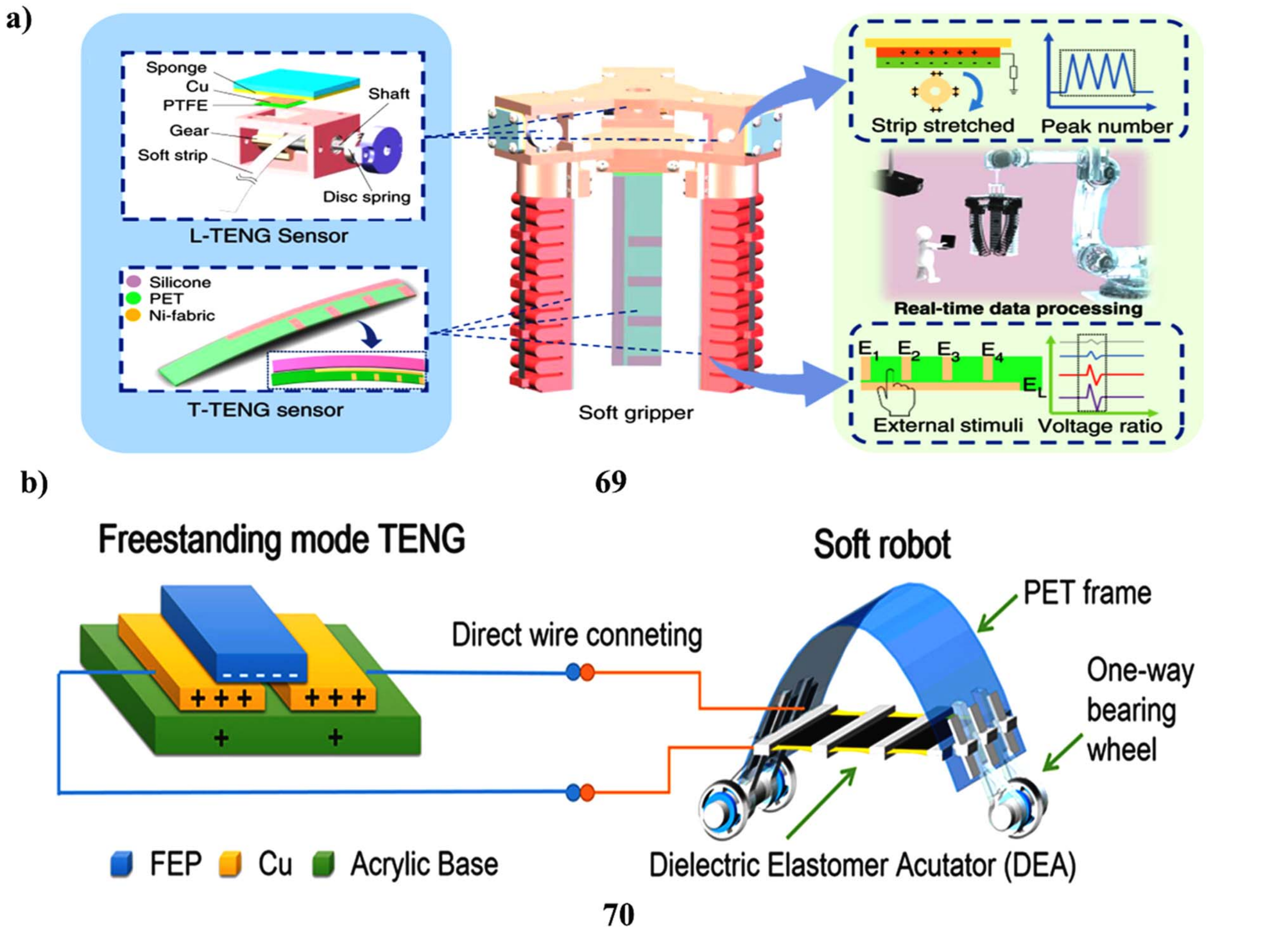

Fig. 36 (a) AI-driven digital twin modeling of soft robotic gripper based on triboelectric nanogenerator sensors (69) reproduced from ref. 91 with permission from Nature Publisher, Copyright 2020. (b) Environment-powered soft TENG-Bot demonstrating autonomous robotic motion (70) reproduced from ref. 92 with permission from Elsevier Publisher, Copyright 2021.

in the creation of inexpensive, automated chemical sensing equipment for the on-field identification of hazardous analytes (Fig. 35c).[90]

Developing effective sensors for soft robotics that aim to facilitate human-machine contact is still difficult. Triboelectric nanogenerator sensors (69) are the basis of an intelligent soft-robotic gripper system that records tactile data and continuous motion. The tactile sensor is capable of detecting the location of contact and the region of external stimuli thanks to its unique dispersed electrodes. The continuous measurement of elongation through the sequential contact of each tooth is made possible by the stretchable strip and gear-based length sensor. To detect a variety of items with a 98.1% accuracy rate, the support vector machine algorithm further trains the triboelectric sensory data gathered during the soft gripper operation. Effective sensor design is still a difficulty for soft robotics aimed at human-machine interaction. Digital twin applications have been successfully developed for virtual assembly lines and unmanned warehouse applications. These applications demonstrate object identification and duplicate robotic manipulation in a virtual environment based on the real-time operation of the soft-robotic gripper system (Fig. 36a).[91] A flexible body and agile movement are characteristics of a soft robot that uses dielectric elastomer actuators (70, DEAs) in unstructured situations. The conventional power sources used by DEAs hinder small-scale robotic systems. Triboelectric nanogenerators (TENGs) can produce matching power for DEA by capturing kinetic energy from the surroundings. However, the nonlinear and inadequate mechanical transmission in robotic motion hinders a TENG-driven, DEA-based robot. It achieves high-efficiency energy conversion by aligning the DEAs extension orientation with the robot's motion, resulting in a maximum crawling pace of 110 mm (2.2 body length)/second and a 40 g payload capacity. Because of the robots great efficiency and straightforward design, the electrical energy produced by the TENG can power the robot directly without the need for further control panels. The results of the experiments show a direct control connection between the TENGs sliding speed and the soft robots velocity. The TENG-Bot offers a way forward for the creation of soft robots that can function independently by using motion from the environment (Fig. 36b).[92]

Robotic exploration platforms with high levels of flexibility, manoeuvrability, and recognition ability are necessary in the demanding and unstructured environment found in pipelines.

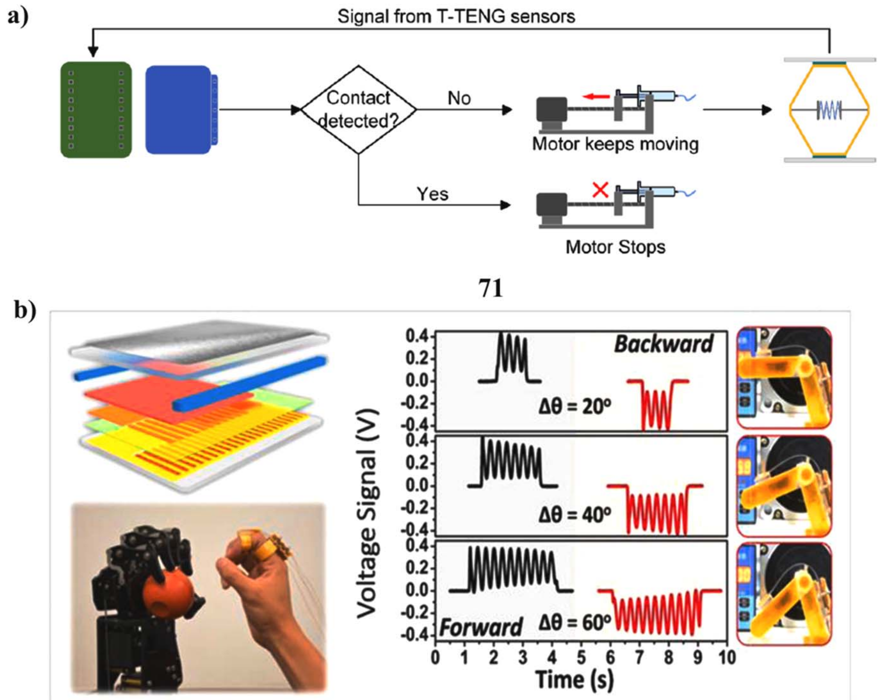

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Fig. 37 (a) Pipeline inspection soft robot integrated with triboelectric nanogenerators (T-TENGs) (71) reproduced from ref. 93 with permission from Wiley-VCH Publisher, Copyright 2024. (b) Joint motion triboelectric quantization sensor (jmTQS) for robotic hand control and rotation sensing (72) reproduced from ref. 94 with permission from Elsevier Publisher, Copyright 2018.

The material compliance and morphological plasticity of modern soft robots with state-of-the-art actuators have shown inherent advantages in navigating pipeline environments. It is challenging to include sensors for inner-pipe identification for pipeline-climbing robots without compromising the robot's operating skills and flexibility. A soft robot with exteroception and locomotion inside pipes is demonstrated. The primary body of the robot is made using origami patterns and has triboelectric nanogenerators as touch sensors (71, T-TENGs) and is propelled by pneumatic actuators for movement. The soft robots ability to crawl in many pipeline circumstances, including curved, vertical, and horizontal arrangements, has been shown in physical trials. A 1D-convolutional neural network method is used to handle the sequential signals produced by the T-TENG-based sensory system when it is subjected to various material and structural circumstances. The robot can identify between eight different pipe inner surface structures and four different types of materials with an overall recognition accuracy of 99% (Fig. 37a).[93] Robotic hands are supposed to function similarly to human hands in human-machine contact although in some circumstances they should be even more sensitive or stronger. The human-robot interface will be more accurate and natural if robotic hands are controlled by human gestures rather than by a handle or button. To build a robotic hand synchronous control system design a joint motion triboelectric quantization sensor (72, jmTQS). To immediately quantify the flexion-extension degree/speed of a joint the jmTQS was built as a grating-sliding mode, which is based on the triboelectric nanogenerators (TENG) ultrahigh sensitivity to mechanical displacement. The joint angular position can be ascertained with absolute value based on the initial human-robotic synchronizing position value by counting the pulses produced by jmTQS and signifying the positive/negative of the pulses to indicate flexion/extension. The intuitionistic human-robotic hand two-dimensional motion mapping can be maintained during the entire operation. The manufactured jmTQSs have a minimum resolution angle of 3.8°, which can be increased by reducing the grating width. To achieve the natural, high-precision, and real-time interface the signal processing and classification algorithms were significantly reduced by direct quantization and intuitionistic mapping at the sensing stage (Fig. 37b).[94]

Triboelectric nanogenerators (TENGs) are essential for creating intelligent systems, yet the majority of handwriting recognition systems lack machine learning and self-powered sensing capabilities. The electrical behavior of TENGs can be improved by creating a negative friction film made of polydimethylsiloxane (PDMS) with pore features and doped with 2D hexagonal boron nitride (100% h-BN) and defective h-BN (50%) as an effective dielectric material (73). To generate pores in the triboelectric film a straightforward, scalable, and easy method has been utilized. It performed optimally and reached a power density of 7.86 W m^{-2} at 40 MΩ with a voltage of 198.6 V and a current of 13.5 μA. Additionally, the devices surface roughness and energy-harvesting capabilities were improved by introducing pores into the composite sheet. The decision tree and gradient-boosting machine learning methods

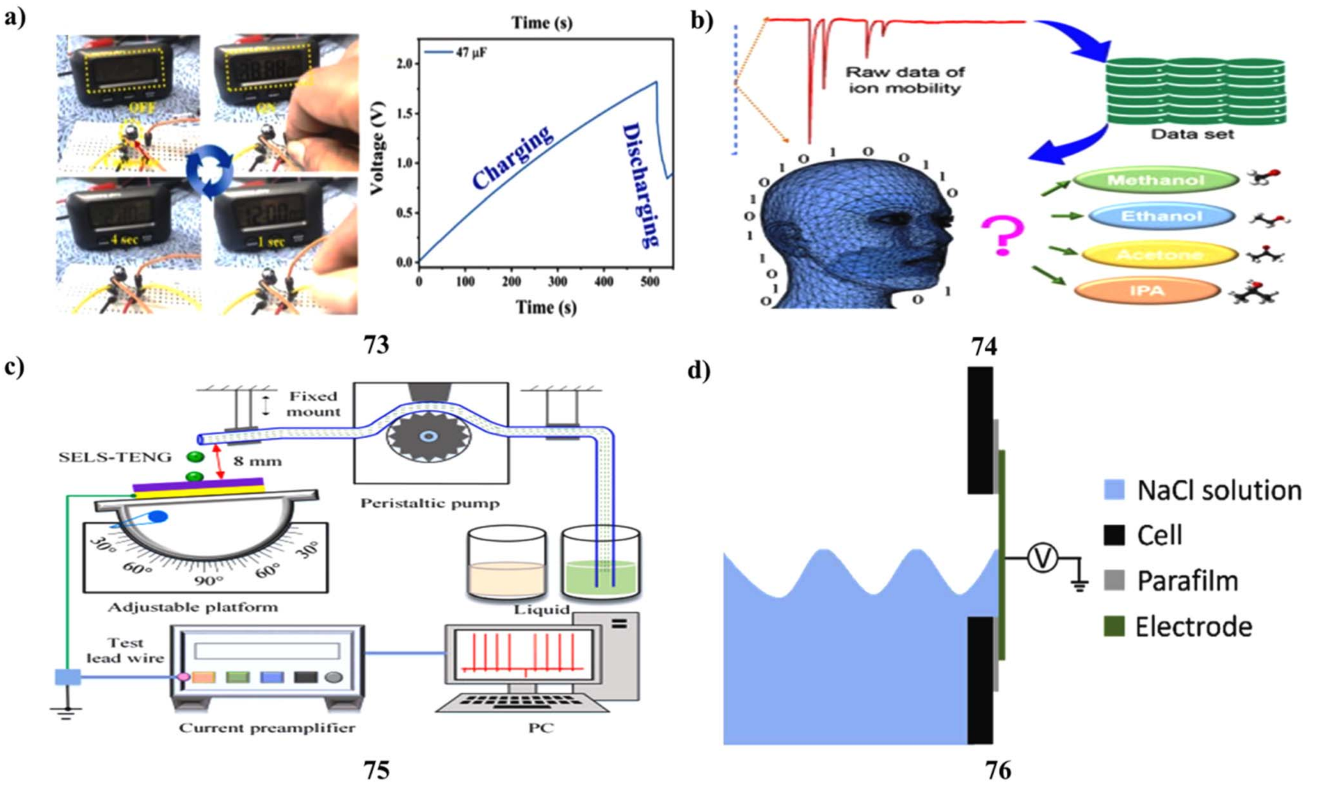

Fig. 38 (a) Machine learning-based TENG for intelligent handwriting recognition and sensing (73) reproduced from ref. 95 with permission from Elsevier Publisher, Copyright 2025. (b) ML-assisted ion mobility TENG for real-time V_{OC} detection and analysis (74) reproduced from ref. 96 with permission from Elsevier Publisher, Copyright 2021. (c) Smart liquid-leak detection using ML-integrated triboelectric nanogenerator sensor (75) reproduced from ref. 97 with permission from Elsevier Publisher, Copyright 2019. (d). ML-based corrosion monitoring using self-powered solid–liquid triboelectric nanogenerator (76) reproduced from ref. 98 with permission from Elsevier Publisher, Copyright 2024.

were utilized to identify the handwriting of English letters penned by three volunteers using the TENG sensor. The findings indicate that the manufactured TENG showed a sizable power source for portable electronics indicating high potential for use in machine learning-assisted handwriting recognition and personal handwriting sensing (Fig. 38a).[95] One popular analytical method for locating gas-phase chemicals in fast-response gas-monitoring systems is ion mobility analysis. However, the traditional plasma discharge device is large, hot, and unsuitable for detecting the concentration of volatile organic compounds (V_{OC}s). Hence, a triboelectric-based ionizer (74) with an ion mobility analyzer augmented by machine learning (ML) offers good ion mobility selectivity and the capacity to recognize volatile organic compounds (V_{OC}s) in a small device with a flexible working environment. A few hundred volts of direct current (DC) bias can be generated by a multi-switched manipulation triboelectric nanogenerator (SM-TENG) depending on the charge accumulation method. This can then be used as the power source to produce a distinct and repeatable discharge characteristic of various volatile organic compounds (V_{OC}s) and their mixtures using a particular tip-plate electrode configuration. The successful demonstration of the ML-enhanced ion mobility analysis approach involved the automated extraction of particular characteristics from ion mobility spectrometry data using ML algorithms.To demonstrate a portable real-time V_{OC} monitoring solution with low power consumption and quick response for upcoming Internet of Things-based environmental monitoring applications, this significantly enhances the detection capability of the SM-TENG-based V_{OC} analyzer(Fig. 38b).[96] A sensor that is self-powered, quick to react, and reasonably priced is essential for detecting liquid leaks. The ability of a single-electrode liquid–solid (SELS) triboelectric nanogenerator (TENG) to identify and detect liquid leaks was investigated using a triboelectric layer of p-type silicon. The outcomes showed that the SELS TENG (75) was sensitive to the leaking of very tiny liquids and could qualitatively describe the rate of liquid leakage. The SELS TENGs short-circuit output currents varying responses to various liquids were mostly attributed to their varying wettability and conductivity. Furthermore, the short-circuit output currents of SELS TENG in response to various liquids were used to identify the liquids and were thought of as their fingerprint. Based on big data and machine learning technologies, an intelligent detecting and identifying system was created to recognize various liquids since a large number of sensors in practical applications produced a large amount of data. In the majority of situations, a high classification accuracy of over 90% was achieved for each pair of liquids. These results provide insight into the use of TENG-based self-powered sensors in the fields of environment monitoring and liquid leak detection. Most significantly, TENG's enormous potential for use in conjunction with big data and machine learning technologies was effectively investigated and demonstrated (Fig. 38c).[97] The limitations of current coating corrosion monitoring techniques are their reliance on external power sources and the inability to give real-time data. A solid–liquid triboelectric nanogenerator (76, TENG), which transforms mechanical energy into electrical signals for self-powered sensing, is used in this work to introduce a unique *in situ* corrosion monitoring system. A dopamine-modified lignin-polydimethylsiloxane coating on steel in 1 M NaCl solution was subjected to TENG signals and electrochemical impedance spectra under conditions of no corrosion, indentation, pitting, and breaking, respectively. They use a tailored convolutional neural network (CNN) to extract time-frequency information from the TENG signals to predict the corrosion condition of the coating. A custom CNN was used to extract time-frequency information from the TENG signals resulting in a 99% prediction accuracy for corrosion classification. Additionally, the CNN regression model demonstrated its efficacy in monitoring corrosion advancement by predicting coating impedance values with a high coefficient of determination ($R^2 = 0.98$). Additionally, the new TENG makes it easier to locate defects using a matrix electrode underneath the coating (Fig. 38d).[98]

The internet of things (IoTs) and artificial intelligence (AI) eras have sparked a boom in the processing of massive amounts of data collected from numerous dispersed sensors. The main goal of this effort is to carry out complex recognition tasks, which often require excessive energy usage. As a result, developing a reduced architecture that can accomplish these functions just as well is still a difficult undertaking. The rigiflex pillar-membrane triboelectric nanogenerator (77, PM-TENG) is suggested for machine learning-based global stereoscopic recognition. To produce dynamic sensing signals in time series and acquire a wealth of high-resolution stereoscopic structure information an integrated design is used. The proposed rigiflex PM-TENG incorporates data from multiple sensing pillar pixels and concentrates on the analysis of dynamic changes during the whole contact cycle by integrating the benefits of both rigid steel pillars and flexible/elastic membranes. It can effectively detect items in nine distinct categories with a 96.39% accuracy rate by using machine learning algorithms. This technology has a lot of promise for usage in unattended warehouse workshops and assembly lines for production control management in future smart factories (Fig. 39a).[99] Big data analysis using sensor units is crucial for intelligent motion in the smart era. A recyclable flexible triboelectric nanogenerator (78, RF-TENG) sensor module a data processing hardware module, and an upper computer intelligence analysis module form the basis of the dance sports and injury monitoring system (DIMS) developed in this study to support intelligent motion. The resultant RF-TENG exhibits high stability over 4200 operating cycles with an output voltage fluctuation of 6% and an ultra-fast reaction time of 17 ms. The DIMS enables immersive training through virtual game interaction and visual feedback on sports status. When combined with machine learning (K-nearest neighbour), ground-jumping techniques yield good classification results. It also exhibits some promise in the prediction of sports injuries. All things considered, the sensing system developed in this work offers a wide range of potential future uses in intelligent mobility and healthcare (Fig. 39b).[100–103]

Intelligent Automation Systems based on TENGs leverage triboelectrification and electrostatic induction to autonomously convert mechanical energy into electrical signals for smart biomedical and biomaterial applications. These systems operate through self-powered sensing mechanisms, detecting biomechanical movements, physiological parameters, and environmental changes, enabling real-time health monitoring and automation in medical devices. Their advantages include high energy efficiency, seamless integration with IoT, adaptability for remote healthcare, and reduced reliance on external

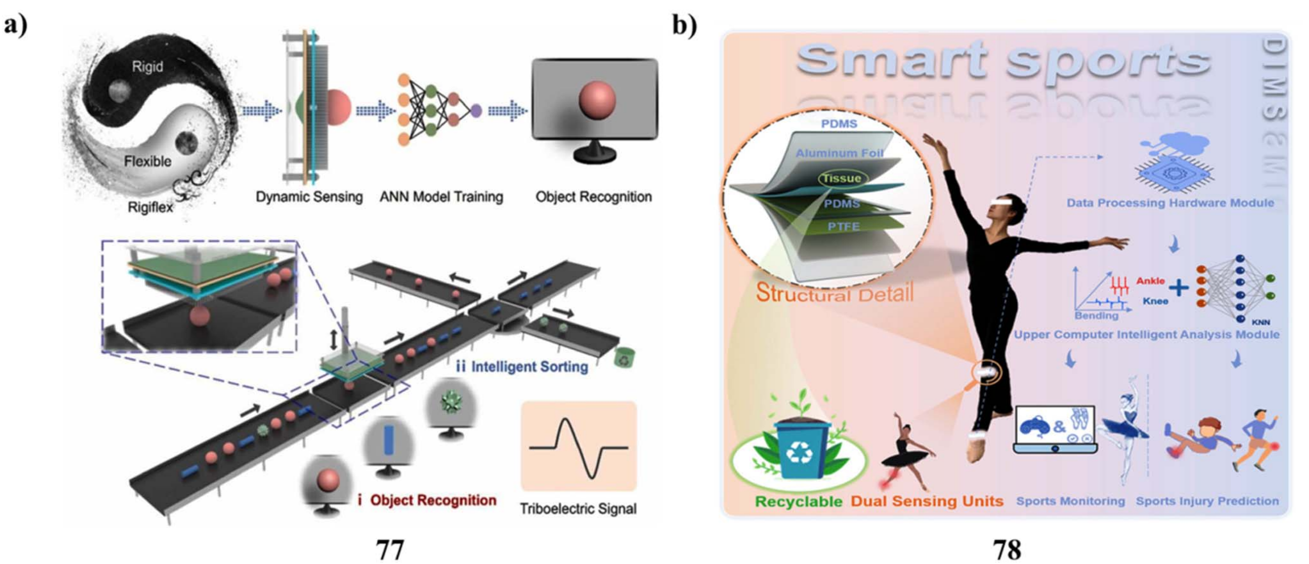

Fig. 39 (a) Machine learning-based rigiflex pillar-membrane TENG for global stereoscopic recognition (77) reproduced from ref. 99 with permission from Elsevier Publisher, Copyright 2024. (b) Flexible ML-integrated TENG for intelligent motion sensing and injury monitoring (78) reproduced from ref. 100 with permission from Elsevier Publisher, Copyright 2024.

Table 2 A structured overview of the TENG type, including their representative composition, stretchability/flexibility, stability/durability and key remarks, is provided in this table

Material type	Representative composition	V_{OC} (V)	I_{SC} (μA)	Stretchability/flexibility	Stability/durability	Key remarks
Graphene	Graphene/PDMS composite	400–800	6–12	Moderate (∼50%)	High (≥5000 cycles)	Excellent conductivity; high cost
Gel	Hydrogel/PVC-gel	20–150	0.5–5	Excellent (400–1000%)	Moderate	Biocompatible but moisture-sensitive
Polymer	PVDF/PDMS composite	200–600	5–20	Good (100–300%)	High (≥10 000 cycles)	Flexible, low-cost fabrication
Silicon	Micro/nanostructured Si wafer	300–700	10–25	Poor (rigid)	Moderate	High charge density, precise patterning

power sources. However, challenges such as system complexity, energy storage limitations, and the need for advanced data processing algorithms hinder widespread adoption. Further advancements in material science and AI-driven automation will enhance their performance and expand their biomedical applications.

A summary of TENG Type, representative composition, stretchability/flexibility, stability/durability and key remarks is found in Table 2 below.

7. Future perspectives and research directions

To advance TENGs toward real-world use, future studies should focus on scalable fabrication methods such as roll-to-roll printing and 3D microstructuring for cost-effective mass production. Establishing standardized performance metrics including power density, charge output, and durability will ensure consistent benchmarking across material systems. Developing hybrid systems that combine triboelectric, piezoelectric, or photovoltaic effects can enhance efficiency and energy stability. New opportunities also lie in integrating TENGs with AI, IoT, and soft robotics for intelligent, self-powered devices, and exploring biodegradable or self-healing materials for sustainable applications.

8. Conclusion

Triboelectric nanogenerators (TENGs) have revolutionized energy harvesting, with advancements in gels, graphene, polymers, and silicon enhancing their efficiency and durability. The integration of artificial intelligence (AI), machine learning (ML), the internet of things (IoT), and robotics is further transforming TENG-based systems by enabling real-time sensing, data processing, and automation. These innovations are driving TENGs toward applications in wearable electronics, biomedical devices, environmental monitoring, and industrial automation. They are expected to play a crucial role in self-sustaining smart devices, contributing to sustainable energy solutions. The combination of AI and IoT with TENGs will facilitate intelligent, self-powered systems, reducing reliance on traditional power sources. However, challenges such as material stability, large-scale production, and energy conversion efficiency remain. With continuous research and interdisciplinary collaboration, TENGs will evolve into a key technology for future smart and energy-efficient applications. Overall, this review not only consolidates current advancements in TENG materials and mechanisms but also establishes a new perspective on their integration with AI, IoT, robotics, and biomedicine, thereby bridging the gap between nanogenerator research and intelligent, self-powered technologies.

Abbreviation

TENGs	Triboelectric nanogenerators
PVDF	Polyvinylidene fluoride
GQD	Graphene quantum dot
NFs	Nanofibers
PDMS	Polydimethylsiloxane
PCL	Poly(caprolactone)
LEDs	Light emitting diodes
LIG	Laser-induced graphene
FEP	Fluorinated ethylene propylene
PI	Polyimide
PUA	Polyurethane aerogel
LIBs	Lithium-ion batteries
PMU	Power management unit
NGNR	N-glycosyl naphthalimide ricinoleate
MNPs	Melanin nanoparticles
AgNWs	Silver nanowires
AFM	Atomic force microscopy
DFs	Diatom frustules
MEMS	Microelectromechanical systems
AI	Artificial intelligence
IoTs	Internet of things
PD	Parkinson's disease
DC	Direct current
MCU	Microcontroller unit
PTFE	Poly(tetrafluoroethylene)
DEAs	Dielectricelastomer actuators
jmTQS	joint motion triboelectric quantization sensor
V_{OC}s	Volatile organic compounds
ML	Machine learning
SELS	Single electrode liquid-solid
CNN	Convolutional neural network

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results and no new data were generated or analysed as part of this review.

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References

1 Y. Huang, H. Zheng, J. Zhang, Y. Shen and X. Xu, Native proteins for triboelectric nanogenerators, *J. Mater. Chem. C*, 2025, **13**, 2578–2605.

2 X. Li, Q. Yang, D. Ren, Q. Li, H. Yang, X. Zhang and Y. Xi, A review of material design for high performance triboelectric nanogenerators: performance improvement based on charge generation and charge loss, *Nanoscale Adv.*, 2024, **6**, 4522–4544.

3 S. G. Ramaraj, D. Elamaran, H. Tabata, F. Zhang and X. Liu, Biocompatible triboelectric energy generators (BT-TENGs) for energy harvesting and healthcare applications, *Nanoscale*, 2024, **16**, 18251–18273.

4 P. Baskaran and M. Rajasekar, Recent progress in thermoelectric devices and applications, *Chem. Eng. J.*, 2025, **506**, 159929.

5 P. Baskaran and M. Rajasekar, Recent trends and future perspectives of thermoelectric materials and their applications, *RSC Adv.*, 2024, **14**, 21706–21744.

6 J. C. Ye, C. He, X. Gong, H. Zhang and X. Li, Blue energy harvesting based on triboelectric nanogenerators (TENG): Structural design, performance optimization, and application prospects, *J. Alloys Compd.*, 2025, **1014**, 178710.

7 K. G. G. Shivanna, V. K. Thammannagowda, S. A. Shankaregowda, S. Panier and P. Kalappa, Poly (lactic acid)-Based triboelectric nanogenerators: Pathways toward sustainable energy harvesting, *Hybrid Adv.*, 2025, **9**, 100395.

8 S. Gangwar, P. Yadav, A. Rani, A. Verma, S. K. Jha and B. C. Yadav, 2D materials integrated with polymers for sustainable energy harvesting through triboelectric nanogenerators, *Mater. Sci. Eng. B*, 2025, **312**, 117859.

9 J. Zhao, J. Mo, B. Luo, C. Cai, Y. Liu, G. Du, Y. Shao, X. Meng, Z. Wei and S. Nie, Self-powered wastewater and air pollution remediation enabled by triboelectric nanogenerators, *Device*, 2025, **3**, 100557.

10 J. Xiong, H. Luo, D. Gao, X. Zhou, P. Cui, G. Thangavel, K. Parida and P. S. Lee, Self-restoring, waterproof, tunable microstructural shape memory triboelectric nanogenerator for self-powered water temperature sensor, *Nano Energy*, 2019, **61**, 584–593.

11 R. Garg, A. Majhi, P. Nagasreenivasarao, N. R. Patra, R. Barve and K. Parida, Polarization-Induced Mechanically Socketed Ultra-Stretchable and Breathable Textile-Based Nanogenerator and Pressure Sensor, *Adv. Funct. Mater.*, 2024, **34**, 2401593.

12 X. Chen, J. Xiong, K. Parida, M. Guo, C. Wang, C. Wang, X. Li, J. Shao and P. S. Lee, Transparent and stretchable bimodal triboelectric nanogenerators with hierarchical micro-nanostructures for mechanical and water energy harvesting, *Nano Energy*, 2019, **64**, 103904.

13 S. Rani, G. Khandelwal, S. Kumar, S. C. Pillai, G. K. Stylios, N. Gadegaard and D. M. Mulvihill, Flexible self-powered supercapacitors integrated with triboelectric nanogenerators, *Energy Storage Mater.*, 2025, **74**, 103977.

14 A. Chakraborthy, S. Nuthalapati, A. Nag, M. E. Altinsoy and S. He, Graphene-based triboelectric nanogenerators for energy-harvesting applications, *Sens. Actuators, A*, 2024, **380**, 116046.

15 J. Cui, H. Li, B. Chen and Z. L. Wang, A review of spherical triboelectric nanogenerators for harvesting high-entropy ocean wave energy, *Chem. Eng. J.*, 2024, **499**, 156193.

16 A. M. Tamim, Y. Lee, J. H. Park, G. T. Hwang and C. K. Jeong, Journey across extrinsic tactics for power improvements of triboelectric energy harvesting beyond intrinsic materials and device structures: A concise review, *Nano Trends*, 2025, **9**, 100086.

17 A. Khan, H. A. Rashid, D. C. Kabiraz, A. C. Sarker and S. I. Chowdhury, Self-powered wearable biosensors for metabolites and electrolytes detection: Harnessing nanogenerators and renewable energy sources, *Sens. Actuators, A*, 2025, **386**, 116339.

18 Y. Cui, H. Luo, T. Yang, W. Qin and X. Jing, Bio-inspired structures for energy harvesting self-powered sensing and smart monitoring, *Mech. Syst. Signal Process*, 2025, **228**, 112459.

19 W. G. Kim, D. W. Kim, I. W. Tcho, J. K. Kim, M. S. Kim and Y. K. Choi, Triboelectric Nanogenerator: Structure, Mechanism, and Applications, *ACS Nano*, 2021, **15**(1), 258–287.

20 S. Xu, F. Manshaii, X. Xiao and J. Chen, Artificial intelligence assisted nanogenerator applications, *J. Mater. Chem. A*, 2025, **13**, 832–854.

21 K. S. Sadanandan, Z. Saadi, C. Murphy, I. Grikalaite, M. F. Craciun and A. I. Neves, Fabric-based triboelectric nanogenerators with ultrasonic spray coated graphene electrodes, *Nano Energy*, 2023, **116**, 108797.

22 I. Shabbir, D. M. Lee, D. C. Choo, Y. H. Lee, K. K. Park, K. H. Yoo, S. W. Kim and T. W. Kim, A graphene nanoplatelets-based high-performance, durable triboelectric nanogenerator for harvesting the energy of human motion, *Energy Rep.*, 2022, **8**, 1026–1033.

23 G. J. Choi, S. H. Baek, S. S. Lee, F. Khan, J. H. Kim and I. K. Park, Performance enhancement of triboelectric nanogenerators based on polyvinylidene fluoride/ graphene quantum dot composite nanofibers, *J. Alloys Compd.*, 2019, **797**, 945–951.

24 G. Pace, M. Serri, A. E. del Rio Castillo, A. Ansaldo, S. Lauciello, M. Prato, L. Pasquale, J. Luxa, V. Mazánek, Z. Sofer and F. Bonaccorso, Nitrogen-doped graphene based triboelectric nanogenerators, *Nano Energy*, 2021, **87**, 106173.

25 S. A. Shankaregowda, C. B. Nanjegowda, X. L. Cheng, M. Y. Shi, Z. F. Liu and H. X. Zhang, A flexible and transparent graphene-based triboelectric nanogenerator, *IEEE Trans. Nanotechnol.*, 2016, **15**(3), 435–441.

26 H. Chen, Y. Xu, J. Zhang, W. Wu and G. Song, Enhanced stretchable graphene-based triboelectric nanogenerator via control of surface nanostructure, *Nano Energy*, 2019, **58**, 304–311.

27 I. Domingos, A. I. Neves, M. F Craciun and H. Alves, Graphene based triboelectric nanogenerators using water based solution process, *Front. Phys.*, 2021, **9**, 742563.

28 M. Sahoo, S. N. Lai, J. M. Wu, M. C. Wu and C. S. Lai, Flexible layered-graphene charge modulation for highly stable triboelectric nanogenerator, *Nanomater. Nanosci.*, 2021, **11**(9), 2276.

29 G. Pace, A. Ansaldo, M. Serri, S. Lauciello and F. Bonaccorso, Electrode selection rules for enhancing the performance of triboelectric nanogenerators and the role of few-layers graphene, *Nano Energy*, 2020, **76**, 104989.

30 Y. Wu, Y. Luo, J. Qu, W. A. Daoud and T. Qi, Liquid single-electrode triboelectric nanogenerator based on graphene oxide dispersion for wearable electronics, *Nano Energy*, 2019, **64**, 103948.

31 S. Parandeh, M. Kharaziha and F. Karimzadeh, An eco-friendly triboelectric hybrid nanogenerators based on graphene oxide incorporated polycaprolactone fibers and cellulose paper, *Nano Energy*, 2019, **59**, 412–421.

32 Y. Chen, B. Xie, J. Long, Y. Kuang, X. Chen, M. Hou, J. Gao, S. Zhou, B. Fan, Y. He and Y. T. Zhang, Interfacial laser-induced graphene enabling high-performance liquid-solid triboelectric nanogenerator, *Adv. Mater.*, 2021, **33**(44), 2104290.

33 S. Parandeh, M. Kharaziha, F. Karimzadeh and F. Hosseinabadi, Triboelectric nanogenerators based on graphene oxide coated nanocomposite fibers for biomedical applications, *Nanotechnol.*, 2020, **31**(38), 385402.

34 Z. Wang, J. Chang, Q. Hu, H. Zhi and L. Feng, A novel wearable TEA sensor based on PDDA-functionalized graphene/polyaniline composite self-powered by a triboelectric nanogenerator, *Sens. Actuators, B*, 2021, **345**, 130308.

35 S. Roy and J. Kim, Synergistic effect of polydopamine–polyethylenimine copolymer coating on graphene oxide for EVA nanocomposites and high-performance triboelectric nanogenerators, *Nanoscale Adv.*, 2019, **1**(6), 2444–2453.

36 L. Zhao, J. Guo, L. Liu, S. Zhang, Y. Gao, F. Yang, J. Gan, G. Gu, B. Zhang, P. Cui and Y. Jia, The triboelectric microplasma transistor of monolayer graphene with a reversible oxygen ion floating gate, *Nano Energy*, 2020, **78**, 105229.

37 P. Lv, L. Shi, C. Fan, Y. Gao, A. Yang, X. Wang, S. Ding and M. Rong, Hydrophobic ionic liquid gel-based triboelectric nanogenerator: next generation of ultrastable, flexible, and transparent power sources for sustainable electronics, *ACS Appl. Mater. Interfaces*, 2020, **12**(13), 15012–15022.

38 H. Park, S. J. Oh, D. Kim, M. Kim, C. Lee, H. Joo, I. Woo, J. W. Bae and J. H. Lee, Plasticized PVC-gel single layer-based stretchable triboelectric nanogenerator for harvesting mechanical energy and tactile sensing, *Adv. Sci.*, 2022, **22**, 2201070.

39 L. Zhang, Y. Liao, Y. C. Wang, S. Zhang, W. Yang, X. Pan and Z. L. Wang, Cellulose II aerogel-based triboelectric nanogenerator, *Adv. Funct. Mater.*, 2020, **28**, 2001763.

40 Z. Saadatnia, S. G. Mosanenzadeh, T. Li, E. Esmailzadeh and H. E. Naguib, Polyurethane aerogel-based triboelectric nanogenerator for high performance energy harvesting and biomechanical sensing, *Nano Energy*, 2019, **65**, 104019.

41 T. Jing, B. Xu, Y. Yang, M. Li and Y. Gao, Organogel electrode enables highly transparent and stretchable triboelectric nanogenerators of high power density for robust and reliable energy harvesting, *Nano Energy*, 2020, **78**, 105373.

42 S. Li, D. Zhang, X. Meng, Q. A. Huang, C. Sun and Z. L. Wang, A flexible lithium-ion battery with quasi-solid gel electrolyte for storing pulsed energy generated by triboelectric nanogenerator, *Energy Storage Mater.*, 2018, **12**, 17–22.

43 L. B. Huang, X. Dai, Z. Sun, M. C. Wong, S. Y. Pang, J. Han, Q. Zheng, C. H. Zhao, J. Kong and J. Hao, Environment-resisted flexible high performance triboelectric nanogenerators based on ultrafast self-healing non-drying conductive organohydrogel, *Nano Energy*, 2021, **82**, 105724.

44 Z. Haider, A. Haleem, U. Farooq, L. Shi, U. P. Claver, K. Memon, A. Fareed, I. Khan, M. K. Mbogba, S. C. Hossain and F. Farooq, Highly porous polymer cryogel based tribopositive material for high performance triboelectric nanogenerators, *Nano Energy*, 2020, **68**, 104294.

45 Z. Xu, F. Zhou, H. Yan, G. Gao, H. Li, R. Li and T. Chen, Anti-freezing organohydrogel triboelectric nanogenerator toward highly efficient and flexible human-machine interaction at- 30 °C, *Nano Energy*, 2021, **90**, 106614.

46 G. Li, L. Li, P. Zhang, C. Chang, F. Xu and X. Pu, Ultra-stretchable and healable hydrogel-based triboelectric nanogenerators for energy harvesting and self-powered sensing, *RSC Adv.*, 2021, **11**(28), 17437–17444.

47 H. Y. Mi, X. Jing, Y. Wang, X. Shi, H. Li, C. Liu, C. Shen, L. S. Turng and S. Gong, Poly [(butyl acrylate)-co-(butyl methacrylate)] as transparent tribopositive material for high-performance hydrogel-based triboelectric nanogenerators, *ACS Appl. Polym. Mater.*, 2020, **2**(11), 5219–5227.

48 B. Jiang, Y. Long, X. Pu, W. Hu and Z. L. Wang, A stretchable, harsh condition-resistant and ambient-stable

hydrogel and its applications in triboelectric nanogenerator, *Nano Energy*, 2021, **86**, 106086.

49 H. Y. Mi, X. Jing, Q. Zheng, L. Fang, H. X. Huang, L. S. Turng and S. Gong, High-performance flexible triboelectric nanogenerator based on porous aerogels and electrospun nanofibers for energy harvesting and sensitive self-powered sensing, *Nano Energy*, 2018, **48**, 327–336.

50 F. He, X. You, H. Gong, Y. Yang, T. Bai, W. Wang, W. Guo, X. Liu and M. Ye, Stretchable, biocompatible, and multifunctional silk fibroin-based hydrogels toward wearable strain pressure sensors and triboelectric nanogenerators, *ACS Appl. Mater. Interfaces*, 2020, **12**(5), 6442–6450.

51 A. K. Rachamalla, M. Navaneeth, T. Banoo, V. P. Rebaka, Y. Kumar, R. K. Rajaboina and S. Nagarajan, A high performance triboelectric nanogenerator using assembled sugar naphthalimides for self-powered electronics and sensors, *Chem. Eng. J.*, 2024, **490**, 151800.

52 H. H. Singh, D. Kumar and N. Khare, Tuning the performance of ferroelectric polymer-based triboelectric nanogenerator, *Appl. Phys. Lett.*, 2021, **119**, 053901.

53 H. Chen, Q. Lu and X. Cao, Natural polymers based triboelectric nanogenerator for harvesting biomechanical energy and monitoring human motion, *Nano Res.*, 2022, **15**, 2505–2511.

54 D. Lopez, A. R. Chowdhury, A. M. Abdullah, M. U. K. Sadaf, I. Martinez, B. D. Choudhury, S. Danti, C. J. Ellison, K. Lozano and M. J. Uddin, Polymer Based Triboelectric Nanogenerator for Cost-Effective Green Energy Generation and Implementation of Surface-Charge Engineering, *Energy Technol.*, 2021, **9**, 2001088.

55 C. Pei, H. Zhang, Y. Li, Z. Gu, X. Chen and T. Kuang, Robust and durable biodegradable polymer-based triboelectric nanogenerators enabled by trace amounts of melanin-like nanoparticles, *Nano Energy*, 2025, **135**, 110643.

56 Q. Zheng, L. Fang, H. Guo, K. Yang, Z. Cai, M. A. B. Meador and S. Gong, Highly Porous Polymer Aerogel Film-Based Triboelectric Nanogenerators, *Adv. Funct. Mater.*, 2018, **28**, 1706365.

57 J. Sun, W. Li, G. Liu, W. Li and M. Chen, Triboelectric Nanogenerator Based on Biocompatible Polymer Materials, *J. Phys. Chem. C*, 2015, **119**, 9061–9068.

58 F. Wang, Y. Y. Zhang, S. Li, L. Zhang, Y. Tao, J. Cui, D. Wang, M. Jiao and C. Haung, Integration of Cobalt Coordination Polymer-Based Triboelectric Nanogenerators as Sustainable Power Sources for Self-Driven Selective Photocatalytic Reactions, *Chem. Eng. J.*, 2025, **503**, 158194.

59 F. Zamanpour, L. Shooshtari, M. Gholami, R. Mohammadpour, P. Sasanpour and N. Taghavinia, Transparent and flexible touch on/off switch based on BaTiO3/silicone polymer triboelectric nanogenerator, *Nano Energy*, 2022, **103**, 107796.

60 W. Xu, L. B. Huang and J. Hao, Fully self-healing and shape-tailorable triboelectric nanogenerators based on healable polymer and magnetic-assisted electrode, *Nano Energy*, 2017, **40**, 399–407.

61 F. Peng, D. Liu, W. Zhao, G. Zheng, Y. Ji, K. Dai, L. Mi, D. Zhang, C. Liu and C. Shen, Facile fabrication of triboelectric nanogenerator based on low-cost thermoplastic polymeric fabrics for large-area energy harvesting and selfpowered sensing, *Nano Energy*, 2019, **65**, 104068.

62 D. T. Tung, L. T. T. Tam, N. T. T. Duong, H. T. Dung, N. T. Dung, N. A. Duc, P. N. Hong, N. T. Dung, P. N. Minh and L. T. Lu, A novel polymer composite from polyhexamethylene guanidine hydrochloride for high performance triboelectric nanogenerators (TENGs), *RSC Adv.*, 2025, **15**, 844–850.

63 C. Ma, Y. He, L. Zeng and M. Liu, Surface modification of chitin nanocrystals using conducting polymer for triboelectric nanogenerator, *Nano Energy*, 2025, **135**, 110660.

64 R. Ccorahua, J. Huaroto, C. Luyo, M. Quintana and E. A. Vela, Enhanced-performance bio-triboelectric nanogenerator based on starch polymer electrolyte obtained by a cleanroom-free processing method, *Nano Energy*, 2019, **59**, 610–618.

65 R. Sun, L. Gao, M. Shou, B. Li, X. Chen, F. Wang, X. Mu, L. Xie and C. Liao, Tribo-material based on a magnetic polymeric composite for enhancing the performance of triboelectric nanogenerator, *Nano Energy*, 2020, **78**, 105402.

66 M. Kim, S. Lee, V. A. Cao, M. C. Kim and J. Nah, Performance enhancement of triboelectric nanogenerators via photo-generated carriers using a polymer-perovskite composite, *Nano Energy*, 2023, **112**, 108474.

67 S. Zhang, High entropy design: a new pathway to promote the piezoelectricity and dielectric energy storage in perovskite oxide, *Microstructures*, 2023, **3**, 2023003.

68 P. Zhao, L. Li and X. Wang, $BaTiO_3$-$NaNbO_3$ energy storage ceramics with an ultrafast charge-discharge rate and temperature stable power density, *Microstructures*, 2023, **3**, 2023002.

69 I. Kim, H. Roh, J. Yu, H. Jeon and D. Kim, A triboelectric nanogenerator using silica-based powder for appropriate technology, *Sens. Actuators, A*, 2018, **280**, 0924–4247.

70 P. C. Uzabakiriho, Z. Haider, K. Emmanuel, R. S. Ahmad, A. Haleem, U. Farooq, J. D. D. Uwisengeyimana, M. K. Mbogba, A. Fareed, K. Memon, I. Khan, P. Hu and G. Zhao, High-Performance, Mechanically and Thermally Compliant Silica-Based Solid Polymer Electrolyte for Triboelectric Nanogenerators Application, *Adv. Mater. Technol.*, 2020, **5**, 2000303.

71 C. Hurtado and S. Ciampi, Oxidative Damage during the Operation of Si (211)-Based Triboelectric Nanogenerators, *Surfaces*, 2023, **6**, 281–290.

72 J. Wang, K. Xia, J. Liu, T. Li, X. Zhao, B. Shu, H. Li, J. Guo, M. Yu, W. Tang and Z. Zhu, Self-powered silicon PIN photoelectric detection system based on triboelectric nanogenerator, *Nano Energy*, 2020, **69**, 104461.

73 A. R. Abhari, J. N. Kim, J. Lee, R. Tabassian, M. Mahato, H. J. Youn, H. Lee and Il-K. Oh, Diatom Bio-Silica and Cellulose Nanofibril for Bio-Triboelectric Nanogenerators

and Self-Powered Breath Monitoring Masks, *ACS Omega*, 2020, **5**(16), 9291–9300.

74 S. Yan, K. Dong, J. Lu, W. Song and R. Xiao, Amphiphobic triboelectric nanogenerators based on silica enhanced thermoplastic polymeric nanofiber membranes, *Nanoscale*, 2020, C9NR09925.

75 T. X. Xiao, T. Jiang, J. X. Zhu, X. Liang, L. Xu, J. Shao, C. Zhang, J. Wang and Z. L. Wang, Silicone-Based Triboelectric Nanogenerator for Water Wave Energy Harvesting, *ACS Appl. Mater. Interfaces*, 2018, 7b17239.

76 H. G. Menge, M. W. Kim, S. Lee and Y. T. Park, Silicone-Based Multifunctional Thin Films with Improved Triboelectric and Sensing Performances via Chemically Interfacial Modification, *ACS Omega*, 2023, **8**, 7135–7142.

77 L. Zhao, J. Duan, L. Liu, J. Wang, Y. Duan, L. V. Roca, X. Yang and Q. Tang, Boosting power conversion efficiency by hybrid triboelectric nanogenerator/silicon tandem solar cell toward rain energy harvesting, *Nano Energy*, 2021, **82**, 105773.

78 W. Li, Y. Xiang, W. Zhang, K. Loos and Y. Pei, Ordered mesoporous SiO_2 nanoparticles as charge storage sites for enhanced triboelectric nanogenerators, *Nano Energy*, 2023, **113**, 108539.

79 K. Zhao, W. Sun and S. Li, Rational design on high-performance triboelectric nanogenerator consisting of silicon carbide@silicon dioxide nano whiskers/polydimethylsiloxane ($SiC@SiO_2$/PDMS) nanocomposite films, *Discover Nano*, 2023, **18**, 03822.

80 D. Tang, Y. Zhou, X. Cui and Y. Zhang, Wireless real-time monitoring based on triboelectric nanogenerator with artificial intelligence, *Internet Things Cyber-Phys. Syst*, 2024, **4**, 77–81.

81 J. Yu, B. Xiao, J. Qiu, Y. Tang, Y. Guo, L. Yang, N. Li and K. Jiang, Artificial intelligence-enabled smart monitoring of vancomycin concentration using a droplet-driven triboelectric nanogenerator, *Nano Energy*, 2025, **136**, 110691.

82 F. Dong, M. Zhu, Y. Wang, Z. Chen, Y. Dai, Z. Xi, T. Du and M. Xu, AI-enabled rolling triboelectric nanogenerator for bearing wear diagnosis aiming at digital twin application, *Nano Energy*, 2025, **134**, 110550.

83 M. Khorsand, J. Tavakoli, H. Guan and Y. Tang, Artificial intelligence enhanced mathematical modelling on rotary triboelectric nanogenerators under various kinematic and geometric conditions, *Nano Energy*, 2020, **75**, 104993.

84 L. Liu, T. Hu, X. Zhao, Y. Su, D. Yin, C. Lee and Z. L. Wang, Innovative smart gloves with Phalanges-based triboelectric sensors as a dexterous teaching interface for Embodied Artificial Intelligence, *Nano Energy*, 2025, **133**, 110491.

85 X. Zhao, Z. Kang, Q. Liao, Z. Zhang, M. Ma, Q. Zhang and Y. Zhang, Ultralight, self-powered and self-adaptive motion sensor based on triboelectric nanogenerator for perceptual layer application in Internet of things, *Nano Energy*, 2018, **48**, 312–319.

86 J. Mao, P. Zhou, X. Wang, H. Yao, L. Liang, Y. Zhao, J. Zhang, D. Ban and H. Zheng, A health monitoring system based on flexible triboelectric sensors for intelligence medical internet of things and its applications in virtual reality, *Nano Energy*, 2023, **118**, 108984.

87 V. Karthikeyan and S. Vivekanandan, IoT-based triboelectric nanogenerator for wrist pulse acquisition and analysis, *RSC Adv.*, 2025, **15**, 3592–3601.

88 Y. Qin, X. Fu, Y. Lin, Z. Wang, J. Cao and C. Zhang, Self-powered Internet of Things sensing node based on triboelectric nanogenerator for sustainable environmental monitoring, *Nano Res.*, 2023, **16**, 5689.

89 J. Li, Y. Zhang, X. Gao, Y. Mao, C. Hu, K. Long, C. Sun and S. Guo, Self-Powered Droplet Sensor Based on Triboelectric Nanogenerator toward the Internet-of-Things (IoT) Alarm System, *ACS Appl. Electron. Mater.*, 2023, **5**(11), 6026–6036.

90 S. Roy Barman, Y. J. Lin, K. M. Lee, A. Pal, N. Tiwari, S. Lee and Z. H. Lin, Triboelectric nanosensor integrated with robotic platform for self-powered detection of chemical analytes, *ACS Nano*, 2023, **17**(3), 2689–2701.

91 T. Jin, Z. Sun, L. Li, Q. Zhang, M. Zhu, Z. Zhang, G. Yuan, T. Chen, Y. Tian, X. Hou and C. Lee, Triboelectric nanogenerator sensors for soft robotics aiming at digital twin applications, *Nat. Commun.*, 2020, **11**(1), 5381.

92 W. Sun, B. Li, F. Zhang, C. Fang, Y. Lu, X. Gao, C. Cao, G. Chen, C. Zhang and Z. L. Wang, TENG-Bot: Triboelectric nanogenerator powered soft robot made of uni-directional dielectric elastomer, *Nano Energy*, 2021, **85**, 106012.

93 R. Chen, H. Wang, H. Wang, H. Wang, L. Bai, X. Ai, L. Liu, Z. Hu and Z. Yuan, A Motion-Sensing Integrated Soft Robot with Triboelectric Nanogenerator for Pipeline Inspection, *Adv Intell. Syst.*, 2024, 2400643.

94 X. Pu, H. Guo, Q. Tang, J. Chen, L. Feng, G. Liu, X. Wang, Y. Xi, C. Hu and Z. L. Wang, Rotation sensing and gesture control of a robot joint via triboelectric quantization sensor, *Nano Energy*, 2018, **54**, 453–460.

95 R. Umapathi, M. Rethinasabapathy, V. Kakani, H. Kim, Y. Park, H. K. Kim, G. M. Rani, H. Kim and Y. S. Huh, Hexagonal boron nitride composite film based triboelectric nanogenerator for energy harvesting and machine learning assisted handwriting recognition, *Nano Energy*, 2025, **136**, 110689.

96 J. Zhu, Z. Sun, J. Xu, R. D. Walczak, J. A. Dziuban and C. Lee, Volatile organic compounds sensing based on Bennet doubler-inspired triboelectric nanogenerator and machine learning-assisted ion mobility analysis, *Sci. Bull.*, 2021, **66**, 1176–1185.

97 W. Zhang, P. Wang, K. Sun, C. Wang and D. Diao, Intelligently detecting and identifying liquids leakage combining triboelectric nanogenerator based self-powered sensor with machine learning, *Nano Energy*, 2019, **56**, 277–285.

98 D. Wang, Y. Li, P. Claesson, F. Zhang, J. Pan and Y. Shi, Real-time in-situ coatings corrosion monitoring using machine learning-enhanced triboelectric nanogenerator, *Sens. Actuators, A*, 2024, **379**, 115983.

99 Y. Xiong, Y. Liu, J. Yang, Y. Wang, N. X. Z. L. Wang and Q. Sun, Machine learning enhanced rigiflex pillar-

membrane triboelectric nanogenerator for universal stereoscopic recognition, *Nano Energy*, 2024, **129**, 109956.

100 Y. Wen, F. Sun, Z. Xie, M. Zhang, Z. An, B. Liu, Y. Sun, F. Wang and Y. Mao, Machine learning-assisted novel recyclable flexible triboelectric nanogenerators for intelligent motion, *iScience*, 2024, **27**, 109615.

101 B. Zhang, Y. Jiang, T. Ren, B. Chen, R. Zhang and Y. Mao, Recent advances in nature inspired triboelectric nanogenerators for self-powered systems, *Int. J. Extrem. Manuf.*, 2024, **6**, 062003.

102 T. Feng, D. Ling, C. Li, W. Zheng, S. Zhang, C. Li, A. Emelyanov, A. S. Pozdnyakov, L. Lu and Y. Mao, Stretchable on-skin touchless screen sensor enabled by ionic hydrogel, *Nano Res.*, 2024, **17**, 4462–4470.

103 L. Lu, G. Hu, J. Liu and B. Yang, 5G NB-IoT System Integrated with High-Performance Fiber Sensor Inspired by Cirrus and Spider Structures, *Adv. Sci.*, 2024, **11**, 2309894.

