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Perspective

Triboelectric nanogenerators: from nano energy to extreme manufacturing

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Abstract
Triboelectric nanogenerators (TENGs), leveraging their capability for ambient energy harvesting and self-powered sensing, have emerged as a revolutionary solution for the Internet of Things (IoTs) and distributed intelligent systems. As human exploration extends into extreme environments such as deep space, abyssal oceans, and polar regions, TENGs exhibit tremendous application potential in extreme conditions, including high humidity, large temperature differences, low temperature, and strong radiation. However, these extreme environments impose unprecedented requirements on both the structural integrity and functional performance of devices and materials. To bridge this gap, an expanding repertoire of advanced extreme manufacturing methods is being employed in TENG fabrication to transcend the performance boundaries of conventional processing. This article begins by introducing fundamental principles of TENGs, provides comprehensive review on state-of-the-art extreme manufacturing technologies and their applications in harsh environments, and offers forward-looking perspectives on future developments in this field.

Keywords: triboelectric nanogenerators, extreme manufacturing, extreme environment, energy harvesting, self-powered sensing

1. Extreme manufacturing strategies for TENGs

Triboelectric nanogenerators (TENGs), first conceptualized by Wang's research group in 2012[1], represent a groundbreaking energy harvesting technology that synergistically combines triboelectrification and electrostatic induction to efficiently convert ubiquitous mechanical energy into usable electricity. This innovative approach has established a new framework for distributed energy harvesting systems. Key advantages of TENG technology include high output voltage (typically 100–1 000 V), exceptional material compatibility (working over 1 000 material combinations), robust environmental adaptability (operating from −20 °C to 80 °C), and precise charge transfer characterization, offering a cornerstone technology for micro/nano/macro-scale/high-voltage energy sources[2], self-powered systems[3] and blue energy[4]. The fundamental working mechanism is illustrated through the electron-cloud-potential-well model (Figure 1(a))[5], which provides a theoretical framework for understanding electron transfer during triboelectrification. In this model, electron clouds are formed by valence electrons that occupy specific atomic or molecular orbitals,

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with these electrons spatially localized within individual atoms or molecules. Each atom constitutes a potential well where outer-shell electrons are loosely bound, collectively forming the atom's or molecule's electron cloud. In the schematic diagram, E_A and E_B represent the occupied energy levels of electrons in materials A and B, respectively, while E_1 and E_2 denote their corresponding escape barrier potentials. Prior to contact, electrons remain confined within their respective potential wells due to local trapping effects, preventing charge transfer. When two materials approach, the distance (d) between their electron clouds decreases. Through the 'screening' induced by physical contact between the two materials, their electron clouds overlap. This transforms the initial single potential well into an asymmetric double-well potential, enabling electrons to transfer from atoms in material A to those in material B. This constitutes the electron transfer mechanism based on the electron cloud-potential well model. TENG operational modes, demonstrated in Figure 1(a)'s insets, encompass contact-separation mode (vertical mechanical actuation), lateral sliding mode (in-plane relative motion), single-electrode mode (simplified device architecture), and freestanding triboelectric-layer mode (enhanced power output). All contemporary TENG designs represent optimized implementations of these four fundamental working principles, enabling diverse applications ranging from self-powered sensors to micro-/nano-/mega- scale energy systems.

To overcome the inherent performance limitations imposed by conventional fabrication processes on TENGs, extreme manufacturing methodologies have emerged as a transformative solution. These advanced manufacturing processes surpass traditional constraints by harnessing specialized energy-field modulation or dynamic structural control. Extreme manufacturing enables unprecedented dimensional precision from atomic-scale to macroscale, focusing on performance-oriented material synthesis through novel processing principles. Based on extensive research developments, extreme manufacturing methods for TENGs are categorized into four distinct classes: novel additive manufacturing (enable complex 3D architectures and facilitate multi-material integration), matter-scale manipulation (achieve atomic-level material control and allow precise defect engineering), energy-matter interaction engineering (utilize advanced energy coupling and enable non-equilibrium processing) and manufacturing from bio-inspiration (mimics natural structures and incorporates hierarchical designs). The classification of extreme manufacturing methods in this study applies distinct criteria. The first three categories are process-driven based on their core fabrication principles, whereas manufacturing from bio-inspiration serves as a design-driven paradigm that achieves biomimetic optimization through coordinated multi-method strategies.

(i) Novel additive manufacturing

Additive manufacturing technologies have gained significant traction in TENG research, with polymeric three-dimensional (3D) printing techniques emerging as a versatile tool for fabricating both structural frameworks and auxiliary testing configurations. Beyond conventional fabrication approaches, advanced additive manufacturing techniques now enable the direct manufacturing of core TENG components, including functional triboelectric layers, conductive electrode materials, and integrated device architectures. A notable advancement is demonstrated in Figure 1(b), presenting an innovative 'pause-and-insert' and 'print-in-place' 3D printing strategy using conductive filaments and non-conductive polymer matrices to fabricate fully enclosed microbead-structured TENG arrays[6]. This structure not only achieves a high average power density of 13.8 $W \cdot m^{-3}$ but also demonstrates the strong potential of 3D printing for scalable TENG fabrication. Driven by the sustainable demands, pioneering studies have

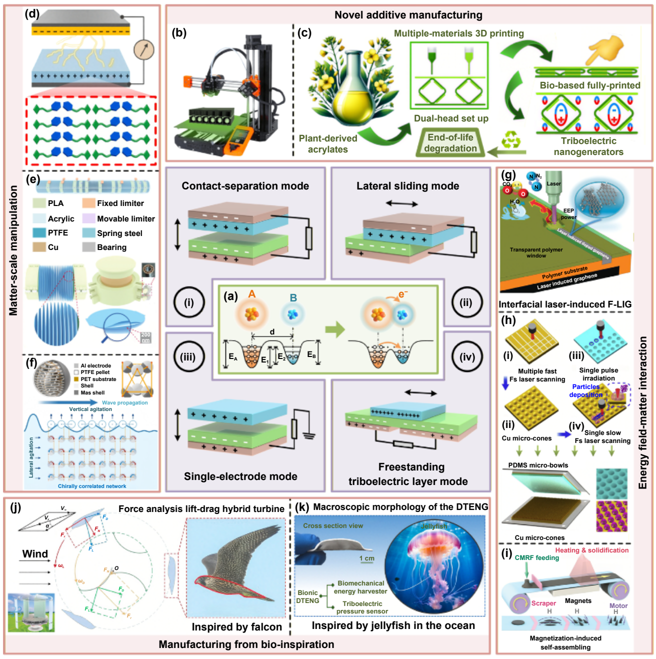

Figure 1. Basic principles of TENG and commonly used extreme manufacturing techniques. (a) Electron-cloud-potential-well model and (I-IV) four common modes of TENG. (b) Fully enclosed microbeads structured TENG arrays. Reprinted from[6], Copyright (2023), with permission from Elsevier. (c) Bioderived and Biodegradable TENG. Reprinted with permission from[7]. Copyright (2025) American Chemical Society. (d) TENG utilizing molecular self-assembly. Reprinted from[9], Copyright (2023), with permission from Elsevier. (e) One Meter TENG.[10] John Wiley & Sons. © 2024 Wiley-VCH GmbH (f) 3D chiral networks of TENGs. Reproduced with permission[10]. Copyright 2023, Royal Society of Chemistry. (g) TENG based on interfacial laser-induced graphene.[12] John Wiley & Sons. © 2021 Wiley-VCH GmbH (h) TENG based on femtosecond laser direct writing. Reprinted from[13], Copyright (2019), with permission from Elsevier. (i) TENG based on magnetization-induced self-assembling.[14] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim (j) TENG based on bionic blade.[16] John Wiley & Sons. © 2023 Wiley-VCH Gmbm (k) TENG based on bioinspired dome architecture.[17] John Wiley & Sons. © 2025 Wiley-VCH GmbH.

begun exploring recyclable plant-derived materials for TENG applications, aiming to achieve a balance between environmental friendliness and triboelectric performance. Figure 1(c) illustrates two distinct biomaterials derived from rapeseed oil-derived biopolymer and soybean oil-based elastomer which can be used for additive manufacturing[7]. These materials were processed via dual-head 3D printing to create electrode-free sustainable TENG devices featuring complete biodegradability, comparable performance to conventional materials, and simplified manufacturing workflow. This approach not only circumvents the traditional challenges of metal electrode integration but also establishes a new paradigm for sustainable energy harvesting systems. The frontier of additive manufacturing in TENGs now extends to four-dimensional (4D) printing, which introduces temporal responsiveness, environmental adaptability, and self-reconfiguring capabilities. By incorporating stimuli-responsive material into 4D-printed TENG, researchers have endowed adaptive energy harvesting devices with autonomous shape-changing capabilities in response to environmental stimuli (temperature/humidity/light exposure, etc.). Kam et al[8]. fabricated an elastic hybrid droplet-based electricity generator (HDEG) using 4D printing technology, with its core innovation lying in the utilization of 4D printing to achieve controllable mechanical buckling characteristics. This structure enables the conversion of dissipated energy from droplet impact into elastic potential energy, which subsequently drives a solid-solid TENG to operate synergistically, achieving two-stage energy scavenging of both droplet energy and mechanical energy. Benefiting from the integrated design and energy recovery mechanism of the 4D-printed structure, the HDEG exhibits an approximately 30% improvement in output performance compared to a single droplet-based electricity generator, significantly enhancing energy harvesting efficiency. Based on the environmentally responsive properties enabled by 4D printing, future TENGs are expected to achieve significant breakthroughs in multimodal sensing applications.

(ii) Matter-scale manipulation
Matter-scale manipulation in TENG fabrication primarily operates at two fundamental dimensional extremes: (1) atomic- and molecular-level precision control (e.g. molecular self-assembly, atomic layer deposition) and (2) macroscale device engineering for large-area and mass-producible TENG arrays. Figure 1(d) demonstrates molecular self-assembly strategy to engineer tribo-positive layers for enhancing TENG performance through dual mechanisms[9]. One is electronic structure modulation by reducing interfacial energy barriers to improve charge-transfer efficiency, and the other is surface morphology optimization through expanding electron-rich regions to enhance electron cloud overlap probability. These synergistic effects yield a threefold improvement in power density compared to conventional materials. For large-scale applications, conventional centimeter-scale TENGs face limitations due to electric field edge effects, localized charge accumulation, and increased air breakdown risk. These challenges can be addressed by developing an innovative meter-scale wave energy harvester that integrates multiple unit into a 1 m^3 chamber (Figure 1(e)), enabling charge transfer up to 60.82 μC per cycle and synchronization with ocean-wave dynamics[10]. Inspired by this structure, another 3D chiral network TENG with a bioinspired mechanical metamaterial architecture is further developed (Figure 1(f))[11]. This innovative architecture endows the network with hyper-elasticity, wave-absorption capability, omnidirectional energy harvesting performance, and remarkably enhanced energy storage efficiency (a 319-fold increase) enabled by paired power management systems. Compared to conventional rigid networks, this design also demonstrates superior environmental adaptability and scalability, establishing a new paradigm for advancing blue energy even in harsh marine environments. Future developments in matter-scale manipulation should focus on atomic-scale surface engineering, optimization of the performance–durability trade-off, and scalable manufacturing techniques.

(iii) Energy field-matter interaction
Energy field-matter interaction represents a cutting-edge manufacturing paradigm that enables precise regulation of material characteristics through non-equilibrium processing assisted by lasers, magnetic fields, and other high-energy physical stimuli. This approach utilizes intense physical fields (e.g. laser irradiation, magnetic fields) to simultaneously control surface topography, chemical composition, and electronic properties. As illustrated in Figure 1(g), an in-situ laser-induced graphene (LIG) growth method is developed which can directly fabricate superhydrophobic fluorine-doped graphene patterns on fluorinated ethylene propylene (FEP)-coated polyimide (PI) substrates[12]. By leveraging the distinct laser-response characteristics of FEP and PI, this method enables selective LIG formation without requiring multi-step processes or controlled atmospheres. The resulting superhydrophobic structures serve as electrodes for flexible droplet-based nanogenerators, achieving a peak power density of 47.5 $W \cdot m^{-2}$ with exceptional cycling stability and operational reliability under high humidity and diverse pH conditions. Compared with conventional laser processing, femtosecond laser direct writing exhibits more advantages to fabricate micro/nano-cone arrays on the TENG electrodes and micro-bowl structures on the polymer triboelectric layers (Figure 1(h))[13]. This technique enables

synchronous control of metal/polymer interface morphology and achieves a 21-fold enhancement in power density for contact-separation mode TENGs, offering a feasible and efficient solution to large-scale manufacturing of high-performance TENGs. A novel magnetization-induced self-assembly fabrication technique is also developed for flexible microneedle array-based TENGs (Figure 1(i))[14]. By employing a rotating magnetic field to guide the dynamic self-assembly of curable magnetorheological fluid, this method enables controllable 3D structuring of microneedle arrays. This approach overcomes the limitations of conventional microneedle fabrication processes, offering a novel approach to roll-to-roll mass production of structure-controllable TENG devices. Accordingly, by further optimizing field-matter coupling mechanisms and developing multi-field synergistic control technologies, more efficient and precise cross-scale manufacturing can be achieved to drive performance breakthroughs and enable broader industrial applications of TENGs.

(iv) Manufacturing from bio-inspiration
Manufacturing from bio-inspiration represents a paradigm-shifting fabrication methodology that emulates the structural and functional features of biological systems to surpass conventional engineering limitations. This approach has found extensive application in TENG development due to the inherent compatibility between biomimetic designs and flexible energy harvesting architectures[15]. For instance, a falcon-inspired hybrid lift–drag turbine generator is developed as show in Figure 1(j)[16]. By optimizing the combination of bionic lift-type blades and drag-type blades, the device allows operation under low wind speeds (as low as 2 $m\cdot s^{-1}$) and delivers a peak power output of 202.4 mW at 4 $m\cdot s^{-1}$. This bioinspired structural design not only endows the device with excellent low-wind-speed starting capability but also enables self-adaptive graded power generation, offering an efficient bio-inspired solution for distributed energy harvesting. A jellyfish-inspired dome-structured TENG is also proposed through an innovative one-step periphery-constrained foaming technique (Figure 1(k)), achieving an open-circuit voltage of 263 V, a power density of 107.7 $mW\cdot m^{-2}$, and excellent durability ($>$60 000 cycles)[17]. The device demonstrates unprecedented environmental resilience, including UV resistance, thermal tolerance, chemical and mechanical robustness, and continuous underwater operability. These advancements highlight the transformative potential of bio-inspired manufacturing for TENG development, particularly in enhancing performance through biomimetic optimization, improving environmental adaptability via nature-derived designs, and enabling sustainable fabrication methodologies. Future research directions should focus on scalable biomimetic manufacturing, multifunctional bio-based material systems, cross-species design integration, and biohybrid energy-harvesting systems.

2. Extreme applications of TENGs

The advancement of TENG manufacturing technologies has facilitated the development of sophisticated architectures and high-performance devices. TENG possesses distinct advantages for extreme environmental applications due to their unique operational principles. Their ability to efficiently convert low-frequency irregular mechanical energy into electricity enables reliable operation where many traditional energy harvesters cannot function. Technology demonstrates exceptional material adaptability allowing operation across ultra-wide temperature ranges and under extreme pressure conditions. A key advantage is the intrinsic integration of energy harvesting and sensing functions which enable self-powered operation without external energy supply modules. These fundamental characteristics make TENGs particularly suitable for autonomous systems in harsh or inaccessible environments. Notably, state-of-the-art TENG

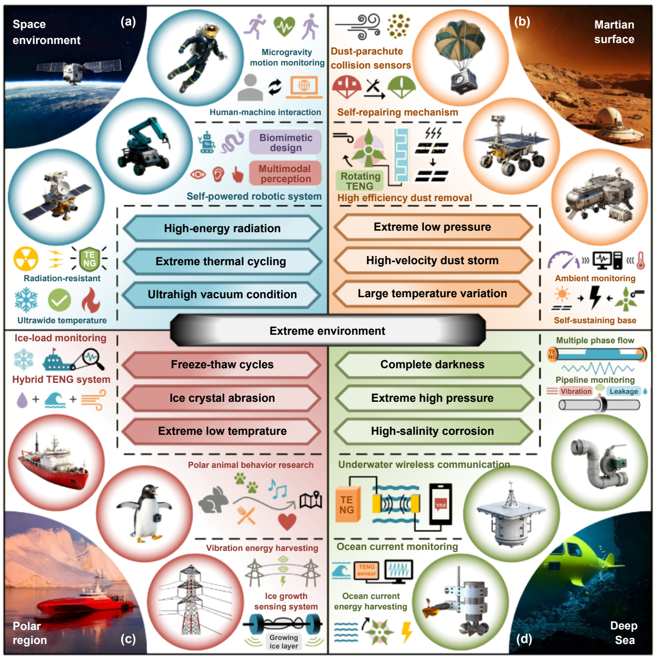

Figure 2. Challenges, progress and future prospects of TENGs in extreme environments. Extreme environments include (a) space environment (upper left panel), (b) Martian surface (upper right panel), (c) polar region (lower left panel) and (d) deep sea (lower right panel). Reproduced from[22]. CC BY 4.0.

designs have enabled transformative applications in four extreme environments: (i) space environment, (ii) Martian surfaces, (iii) polar regions, and (iv) deep sea (Figure 2). This systematic categorization demonstrates TENGs' potential to revolutionize energy harvesting in harsh environments where traditional technologies fail.

(i) Space environment
The deployment of TENGs in space environments faces several formidable challenges, including extreme thermal cycling (-150 °C to $+120$ °C) threatening material stability, high-energy cosmic radiation causing progressive component degradation, and microgravity conditions complicating mechanical energy harvesting mechanism. Despite these challenges, TENGs have demonstrated tremendous potential for space applications. The core material-level challenge centers on achieving radiation resistance and thermal cycling stability. This issue can be addressed by utilizing a flame-retardant triboelectric basalt textile (TBT) capable of stable operation across an ultra-wide temperature range[18]. The TBT demonstrates exceptional performance stability under extreme high temperature (520 °C) and low temperature (-196 °C) conditions. Its outstanding comprehensive performance stems from effective suppression of key failure mechanisms through design. On the high-temperature side, the outer basalt fabric layer effectively delays the thermal decomposition of the inner composite film and maintains its dielectric properties through thermal insulation. On the low-temperature side, the all-solid structure avoids the freezing issue of liquid electrolytes, while its performance degradation in humid environments primarily originates from charge leakage caused by surface condensation film. More importantly, the TBT exhibits excellent long-term durability, with less than 15% performance degradation after 30 severe thermal cycles between extreme temperatures. This indicates that its material interfaces can effectively resist thermal stress fatigue induced by differences in thermal expansion coefficients, thereby ensuring long-term service life and reliability under drastic temperature

variations. Such robustness enables deployment in extreme terrestrial and extraterrestrial environments. While significant progress has been made in TENG designs for extreme temperature environments, the development of radiation-resistant TENG materials and devices remains ongoing. As a promising emerging technology, TENG offers innovative solutions for space robotics, particularly in the field of self-powered sensing. Combining conventional energy harvesting methods (e.g., photovoltaic, thermoelectric) paired with advanced processing techniques (e.g. bio-inspired manufacturing and 4D printing), TENGs hold significant potential for future space exploration missions and sustainable space-equipment maintenance. In addition, TENG technology enables multifunctional integration for next-generation smart spacesuits, aiming to realize high-precision, self-powered motion monitoring and advanced human–machine interfaces during the manned spaceflight.

(ii) Martian surface

The Martian surface presents a uniquely hostile environment characterized by atmospheric extremes such as ultra-low pressure (0.6 kPa, $\approx$1% Earth's sea-level pressure), diurnal temperature fluctuations (-73 °C to $+20$ °C), and frequent global dust storms (wind speed up to 100 km$\cdot$h^{-1}). In addition, persistent geochemical hazards exist, including perchlorate-rich regolith with strong corrosivity and continuous cosmic radiation exposure. These extreme conditions necessitate power systems built with radiation-hardened materials, thermal-cycling resilience, and corrosion-resistant interfaces. Although Mars exploration is still in its early phases, several forward-looking studies have proposed potential TENG applications for future Martian missions. An intelligent parachute system for Mars missions is proposed which can effectively address dust storm-induced damage by integrating TENG-based collision sensors with shape memory alloy[19]. This system employs triboelectric sensing technology to precisely locate impact positions while utilizing autonomous repair functions to reinforce damaged areas, providing a cost-effective and reliable solution for planetary landing in extreme environments. The study uncovers the potential failure mechanisms of TENG sensors under extreme Martian environmental conditions and validates their applicability through simulated experiments. Under Martian conditions, thermal fluctuations and mechanical factors collectively contribute to charge output degradation. Additionally, higher ambient atmospheric pressure diminishes the medium's charge storage capacity by reducing its permittivity, thereby leading to performance deterioration. Performance test results indicate that the sensor maintains stable output within the low-temperature range (-90 °C to 0 °C), and the low-pressure environment on Mars exerts a positive influence on its performance compared to Earth's standard atmospheric pressure, confirming its reliability under typical Martian operating conditions. A novel self-powered dust removal system for Martian missions is also demonstrated, employing a wind-driven TENG to supply power for cleaning solar panel surfaces[20]. The system adopts a four-phase soft-contact architecture to generate a traveling wave electric field, achieving 91.8% dust removal efficiency without external power input. The study systematically evaluated the power generation performance of the TENG in a simulated Martian environment. Using the Earth-Mars wind speed conversion relationship, the output voltage of the device increased significantly with rotational speed under conditions equivalent to Martian wind speeds (15–42.28 m$\cdot$s^{-1}), demonstrating its efficient utilization of wind energy on Mars. Meanwhile, the TENG exhibited excellent adaptability in simulated Martian low-pressure (610 Pa) and low-temperature (-73.15 °C–16.95 °C) environments. The output voltage under low pressure (2.81 kV) substantially exceeded that under normal atmospheric pressure (1.08 kV). Although the output voltage slightly decreased with increasing temperature, the device maintained stable operation across the entire Martian temperature range, highlighting its potential for enhanced power generation in extreme Martian conditions. Additionally, the durability of the device was evaluated at a rotational speed of 100 rpm, showing no significant performance degradation after 30 000 cycles. This technological breakthrough offers a practical solution for sustaining energy systems in the Martian environment. Future application of TENG technology on the Martian surface can be expanded to construct hybrid energy systems and intelligent monitoring networks. By coupling TENG with conventional energy technologies such as photovoltaics and thermoelectrics, synergistic harvesting of wind energy, mechanical vibration energy, and even dust kinetic energy becomes feasible. Furthermore, the system can integrate environmental sensing functions to monitor critical parameters in real time, including temperature fluctuations and dust-storm particle concentrations. Ultimately, TENG strategies could enable the formation of fully self-powered distributed monitoring networks, providing innovative solutions for energy security and environmental early-warning systems in Martian bases.

(iii) Polar regions
The polar environment presents three principal challenges for conventional energy-supply systems, including (i) thermal extremes involving sustained cryogenic conditions and rapid freeze–thaw cycling, (ii) unusual mechanical stresses caused by ice-crystal abrasion and glacial wind erosion, and (iii) poor electrical reliability due to dielectric breakdown at low temperatures and transmission instability. Diversified TENG designs can provide effective solutions to these challenges. Diversified TENG designs can provide effective solutions to address these challenges. For instance, to address the icing problem of transmission lines, a self-powered, multi-dimensional ice monitoring system is developed, which can realize ice thickness detection (0–20 mm range), 3D shape reconstruction, and sag measurement on power lines with high precision[21]. The system employs dedicated signal processing units to achieve accurate ice shape recognition and efficient sag calculation, demonstrating exceptional durability and stability in extreme cold environments. The study compared the relationship between the output voltage and ice thickness of the device before and after 5 000 cycles. The results show that a significant linear correlation between the two was maintained even after repeated cycling. This innovative solution provides reliable technical support for ensuring power-grid safety and operational stability. With advancements in cryogenic materials and self-powered sensing technologies, TENG is emerging as a pivotal technology for polar ice load monitoring. By developing wear-resistant interfaces and cryo-adaptive circuits, TENG-based sensors facilitate the establishment of intelligent monitoring networks capable of tracking glacier dynamics, sea ice stresses, and ice shelf collapse warnings. This autonomous sensing solution provides high-precision, long-term monitoring solutions for polar scientific research and climate change observation. Additionally, cryogenic-resistant TENG sensors present new potential for polar wildlife studies. Their wearable configurations permit real-time migration tracking, collective-behavior analysis, and metabolic monitoring, delivering high-precision, long-term datasets that can advance polar ecosystem preservation and climate research.

(iv) Deep sea
The deep-sea environment poses significant challenges for equipment operation, including extreme hydrostatic pressure causing structural deformation, high salinity accelerating material degradation, and perpetual darkness limiting photoelectric energy systems. These harsh conditions render conventional detection devices inadequate for deep-sea applications. To overcome these limitations, a TENG-based self-powered deep-sea current monitoring system is proposed by incorporating a magnetic coupling structure and variable-spacing

design[22]. The system demonstrates remarkable performance metrics with extended measurement range of 0.02–6.69 m·s^{-1} (a 67% improvement over commercial devices) while maintaining stable operation under hydrostatic pressure of 45 MPa. Notably, it can be successfully deployed at a depth of 4 531 m in the South China Sea, establishing a new depth record for TENG sensors and provides an innovative solution for deep-sea environmental monitoring. The Maxwell's displacement current mechanism of TENGs has enabled breakthroughs in aquatic monitoring. Accordingly, a displacement-current-based multiphase flow sensor with ring-wire electrode architecture is fabricated, achieving 97% accuracy in detecting slug frequency, length, and flow patterns[23]. This solution effectively addresses power supply constraints in remote oil/gas pipelines across desert and deep-sea environments. To expand more applications, an underwater wireless communication system is implemented utilizing displacement-current principle of TENGs[24]. The system achieved 16 bit·s^{-1} transmission of text and image data, robust performance under varying salinity/turbidity ($\leqslant$3% signal fluctuation), and stable signal propagation through 100 m spiral pipelines without waveform distortion. This technology establishes a new paradigm for wireless communication in complex underwater environments.

3. Perspectives

Although TENGs developed for extreme applications have shown initial success in laboratory settings, their path from research to industrialization faces interconnected challenges in performance cost and market applicability. The high voltage and low current output characteristics of TENGs are difficult to match with the power requirements of conventional electronic devices, necessitating the use of complex power management circuits. Besides, material wear caused by continuous friction as well as the significant impact of environmental factors (e.g. humidity and temperature) on output performance imposes stricter demands on the reliability and adaptability of encapsulation technologies. In addition, different manufacturing processes suitable for large-scale production are still under development and National industry standards for TENGs have just been proposed in China, both of which urgently call for widespread adoption. Although TENGs demonstrate broad potential in low-power distributed scenarios such as IoT and wearable devices, they still need achieve breakthroughs in fields where they offer irreplaceable values such as implantable medical electronics and environmental monitoring in remote areas where frequent battery replacement is impractical. To overcome these obstacles, both the academic and industrial communities are actively exploring engineering solutions and seeking the way for the broad commercialization of TENG technology. At present, preliminary successes in its industrialization have been achieved in some key fields. For instance, the Beijing Institute of Nanoenergy and Nanosystems (BINN) has developed a self-powered, lightweight stall sensing system for in-situ monitoring of airflow separation over wing surfaces[25]. This system is based on the coupling of triboelectric and piezoelectric sensing technologies, enabling visualized and array-based perception of stall conditions. The system has already been validated in flight tests on small aircraft and is currently undergoing industrialization testing. Additionally, BINN has designed a self-powered marine IoT system based on TENG[26], which achieves autonomous energy supply in harsh marine environments and offers continuous, stable power support for ocean monitoring equipment and sensor networks. In collaboration with the East China Sea Maritime Security Center of the Ministry of Transport, the developed self-powered navigation light system has significantly extended the service life of

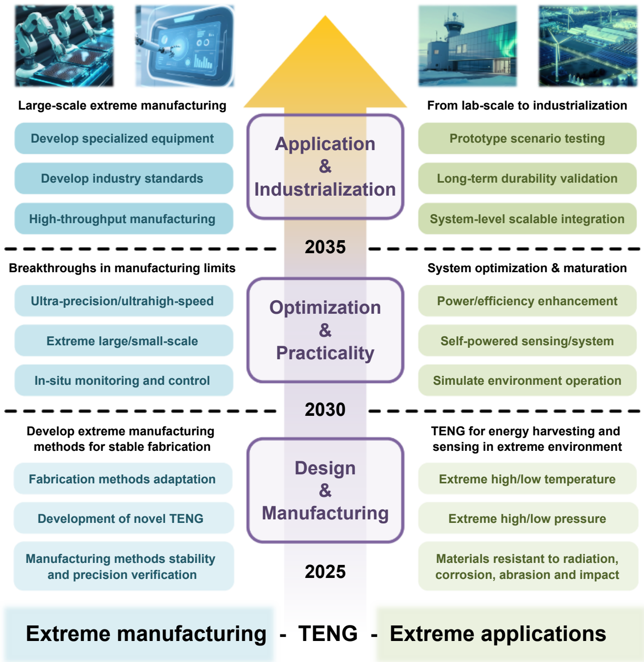

Figure 3. The road map starting from 2025 for TENG's extreme manufacturing technology and extreme environmental applications.

the power supply system, reduced maintenance costs, and achieved considerable economic benefits.

Based on a systematic review of extreme manufacturing methods and environmental applications for TENGs, a holistic roadmap has been proposed that outlines key research directions and major challenges across these two interrelated domains (Figure 3). Although developmental trajectories may differ between the domains, both are anticipated to evolve through three distinct dimensions:

(i) Synergistic process-structure-performance relationship
For extreme manufacturing methods, the primary objective involves establishing robust fabrication processes. This necessitates: (a) methodical screening and adaptation of manufacturing techniques for diverse TENG architectures, and (b) process innovations to develop devices with novel structural configurations or enhanced performance metrics, while maintaining strict process stability and performance consistency. Concurrently, for extreme environmental applications, research efforts should prioritize the development of environment-adaptive TENGs, with particular emphasis on underexplored directions such as radiation-resistant systems.

(ii) Optimization of process and performance
For extreme manufacturing technologies, this phase targets fundamental breakthroughs in processing limits—including ultimate precision thresholds, processing velocity, and dimensional extremes—while incorporating in situ, real-time monitoring and control. Regarding extreme environment applications, the focus transitions to system-level optimization based on high-performance TENG devices, encompassing: (a) power output and conversion efficiency enhancement, (b) self-powered system integration, and (c) simulated extreme environment validation testing.

(iii) Application and industrialization
The ultimate objective of extreme manufacturing on TENG is to realize scalable fabrication process and practical implementation of both the self-powered sensing technology and resultant products. Within the domain of extreme manufacturing

technology, research priorities include: (1) developing specialized equipment tailored for high-performance TENG production; (2) formulating stringent industrial manufacturing protocols; and (3) realizing high-throughput mass production capacity. The formulation of the industrialization path for TENG must fully consider the diverse characteristics of its technological routes. Different categories of TENG exhibit significant differences in material systems, structural design, and application scenarios, which necessitates the adoption of differentiated development strategies for their industrialization processes. Specifically, the industrialization of flexible TENG requires a primary focus on addressing the large-scale preparation of stretchable electrodes and packaging materials. The industrialization of structural TENG, on the other hand, demands breakthroughs in key technologies such as batch processing of weather-resistant materials and reliability testing. Meanwhile, the industrialization of micro/nanoscale TENG imposes unique requirements for precision manufacturing processes. These differentiated technological needs imply that, in terms of equipment development, specialized devices must be developed according to the characteristics of different types of TENG; in terms of standard formulation, a classified and guided testing and evaluation system must be established; and in terms of mass production processes, modular manufacturing solutions need to be developed. Regarding extreme-environment applications, three pivotal tasks emerge: first, conducting exhaustive field trials to authenticate prototype efficacy under real-world operating parameters; second, performing systematic longevity evaluations to substantiate operational stability; third, achieving complete system-level integration for scaled deployment scenarios.

This triphasic framework provides a structured transition pathway from fundamental research to industrial implementation. Successful execution will establish TENG technology as a transformative energy harvesting solution for extreme environments, effectively bridging the innovation-commercialization gap. Sustained interdisciplinary collaboration and strategic investment will prove critical to overcoming persisting technical barriers and accelerating market adoption.

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