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Academic Progress Report

Engineering High-Performance Bioelectronic Triboelectric Nanogenerators via Innovative Material Synthesis and Structural Design for Extreme Biomedical Environments

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Abstract: The mounting demand for sustainable, self-powered biomedical devices, particularly those engineered for extreme environments, has established triboelectric nanogenerators (TENGs) as a prominent technology in energy harvesting research. This review examines state-of-the-art biomaterial synthesis strategies essential for developing high-performance bioelectronic TENGs that can operate reliably under harsh conditions, including elevated temperatures, extreme humidity, and mechanical strain. It begins with a comprehensive overview of the fundamental principles of triboelectricity and subsequently addresses the pivotal challenges associated with efficient charge generation and retention in such challenging settings. The content places particular emphasis on recent advancements in composite material engineering and structure design for high-efficiency mechanisms, with a particular focus on biocompatible and environmentally resilient materials. The integration of TENGs into wearable sensors, implantable devices, and self-powered monitoring systems is also investigated, demonstrating their transformative potential for bioelectronic applications. Our goal subsequently underscores persistent limitations to overcome, including those pertaining to fabrication scalability and long-term operational stability, while concurrently proposing prospective research directions. Consequently, this work underscores how innovative biomaterial synthesis and bioelectronic devices can enable the development of next-generation, high-performance, self-powered devices suited for extreme biomedical environments.

Keywords: Bioelectronic TENG, Biocompatibility, Biomaterial synthesis, Advanced mechanism, Biomedical devices

1. INTRODUCTION

In recent years, the convergence of energy harvesting technologies and biomedical device engineering has emerged as a powerful driving force of innovation, responding to the growing demand for sustainable, self-powered systems. Among various energy harvesting mechanisms, triboelectric nanogenerators (TENGs) have generated significant attention owing to their distinct advantages, including high mechanical flexibility, lightweight structure, and seamless compatibility with a broad range of biotechnological platforms [1-5]. These characteristics are especially valuable in extreme biomedical environments, where traditional power sources often fall short due to limitations in reliability, biocompatibility, and long-term operational stability.

Triboelectric nanogenerators (TENGs) have emerged as a highly promising technology for converting ambient mechanical energy into electrical energy by combining the principles of triboelectric effect and electrostatic induction. Since its introduction in 2012, TENGs have demonstrated high

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energy conversion efficiency, low cost, material versatility, and compatibility with microfabrication techniques [6-9]. These features make them ideal candidates for powering next-generation self-sustaining electronic systems, particularly in portable, wearable, and biomedical platforms [10-15]. The operation of TENGs is fundamentally based on contact electrification, where charge transfer occurs when two different materials come into contact and then separate. This process generates a potential difference that drives electron flow in an external circuit. The exact charge transfer pathways involve a combination of electron transfer, ion transfer, and even material transfer, depending on the nature of the materials involved [16,17,59]. To optimize performance, material selection is of critical importance. Moreover, biocompatible and environmentally resilient materials such as hydrogel, silk fibroin, and biodegradable polymer are increasingly utilized for implantable and wearable TENGs, facilitating their application in medical diagnostics, therapeutic patches, and wireless biosensing systems [18-23]. Through continued innovation in materials engineering, TENGs are expected to play a key role in the realization of next-generation self-powered bioelectronic devices.

Currently, bioelectronic TENGs have emerged as core technology revolutionizing medical diagnostics and treatment by precisely detecting biological signals and converting or modulating them into electrical signals [62,63]. These devices have advanced in various forms, including wearable sensors, neural interfaces, electrical stimulators, and implantable systems, forming the foundation of precision medicine through applications such as cardiovascular monitoring and accelerated wound healing. The integration of low-power consumption, high-sensitivity sensors, flexible and biocompatible materials, and wireless communication technologies is accelerating, with self-powered systems playing a key role in enabling long-term and implantable bioelectronic devices [64,65]. Furthermore, the incorporation of artificial intelligence (AI) and machine learning–based data analysis is opening new possibilities for predictive and personalized healthcare. In the future, bioelectronic TENG devices are expected to evolve into intelligent bio-interfaces and real-time feedback therapy platforms. As technologies such as self-healing materials, biodegradable electronics, and multifunctional integrated platforms mature, high-efficiency wireless bioelectronic devices are anticipated to be widely implemented in clinical settings. These developments will significantly transform the healthcare paradigm by advancing personalization, automation, and overall efficiency in medical technology.

This review critically examines recent advancements of bioelectronic TENGs in material-driven and structure-driven performance aimed at enhancing TENG performance in biomedical applications. Key focus areas include material engineering and advanced structure design approaches that collectively enable efficient energy conversion and prolonged device stability. The integration of biocompatible and environmentally resilient materials is also highlighted, as it not only ensures safety in vivo and wearable applications but also broadens the scope of TENG deployment in complex physiological environments. Furthermore, exploring the current applications of TENGs in the biomedical field, encompassing wearable health monitors, implantable therapeutic devices, and self-sustaining diagnostic systems. Despite the promising progress, persistent challenges remain such as the scalability of fabrication processes, material degradation over time, and inconsistent performance under dynamic environmental conditions. Addressing these issues through continued innovation in material synthesis and advanced structure design will be essential for realizing the full potential of TENGs as a transformative power solution for extreme biomedical environments.

2. MATERIAL-DRIVEN PERFORMANCE ENHANCEMENTS

The selection of biocompatible and environmentally resilient materials is paramount for developing triboelectric nanogenerators (TENGs) intended for biomedical applications. The selection of appropriate materials is a critical factor in the development of bio-integrated devices, as the chosen materials can directly influence the health and safety of both animal models and the human body [24-28]. As illustrated in Fig. 1, four essential characteristics must be satisfied for high-performance bioelectronic systems. First and foremost, materials must be biocompatible and biodegradable, especially in applications involving direct interaction with living organisms. Any material that induces toxicity or elicits adverse biological responses could result in severe complications during vivo experiments or clinical use. The second key requirement is a mechanism capable of generating high electrical output with minimal mechanical input. Unlike external mechanical sources, internal biological environments provide only limited motion, typically from organ activity or muscle contractions. Therefore, materials must be engineered to harvest energy efficiently from these small-scale biomechanical movements, ensuring continuous and stable power generation. Additionally, implantable devices must be designed for long-term operation without the need for repeated removal or replacement. The materials used should provide stable energy conversion under various physiological and environmental conditions. Finally, since many target organs or tissues are confined in size, the system must be miniaturized to fit within limited anatomical spaces without compromising function or integration. It will sufficiently conduct outstanding research for future bioelectronic devices based on the above conditions.

Generally, materials such as polydimethylsiloxane (PDMS), silk fibroin, hydrogel, and biodegradable polymers offer essential properties including mechanical flexibility, non-toxicity, and adaptability to moist and dynamic biological environments [29-35]. PDMS, a widely used elastomer, provides excellent flexibility and processability while maintaining chemical stability. Silk fibroin, derived from natural protein sources, offers inherent biocompatibility and tunable mechanical properties. Hydrogels mimic the viscoelastic properties of human tissue, making them ideal for soft tissue interfacing. Additionally, biodegradable polymers such as poly (lactic-co-glycolic acid) (PLGA) and polylactic acid (PLA) enable the development of transient or resorbable TENGs suitable for implantable applications. Integrating these materials into device design not only addresses safety requirements for biomedical use but also enhances environmental robustness under challenging physiological conditions, such as high humidity, body fluids, and temperature variations [60].

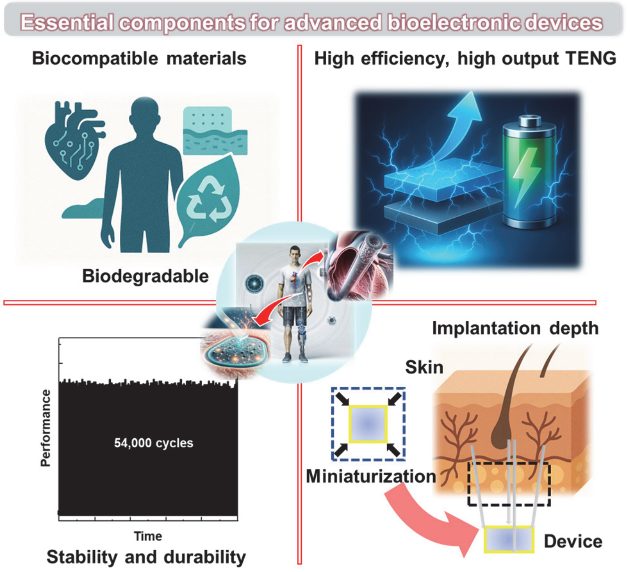

Fig. 1. Schematic illustration of the essential material requirements such as biocompatibility, biodegradability, high efficiency, stability, and miniaturization for the fabrication of advanced bioelectronic devices.

2.1 Natural Materials for Advanced Bioelectronic Devices

Natural materials have long been utilized in biomedical applications due to their intrinsic biocompatibility, degradability, and similarity to biological tissues [36-38]. Substances such as silk fibroin, cellulose, chitosan, collagen, and bacterial nanocellulose (BNC) are commonly derived from biological sources and offer excellent integration with living systems. These materials are often favored for applications where tissue compatibility and minimal immune response are critical, such as wound dressings, scaffolds for tissue regeneration, and soft interfaces in implantable devices. Additionally, many natural polymers possess functional groups (e.g., hydroxyl, amino, or carboxyl groups) that allow for easy surface modification and drug loading. Their inherent softness, moisture retention, and adaptability to physiological conditions make them particularly suitable for devices interfacing with skin, mucosa, or internal organs.

In the development of advanced biomedical devices, the integration of natural biomaterials offers a compelling route to achieving biocompatibility, biodegradability, and long-term physiological stability. In this context, silk fibroin, a protein derived from natural silk, has emerged as a versatile substrate material due to its excellent air and moisture permeability, skin compliance, and mechanical flexibility. As shown in Fig. 2(a), a silk fibroin-based triboelectric nanogenerator (SFB-TENG) is a self-powered electrical stimulation system to promote tissue regeneration [39]. This study exemplifies how the thoughtful incorporation of natural materials can significantly enhance device functionality and clinical safety in bioelectronic applications. The SFB-TENG is designed as a multilayered structure composed of a silk fibroin substrate, PDMS friction layer, silver nanowire electrodes, and a titanium foil counter electrode [Fig. 2(b)]. The schematic highlights the operational mechanism of the device, which relies on the contact-separation triboelectric effect between silk fibroin acting as the positively charged material, and PDMS which is the negative counterpart. Electrical charges are generated and transferred during mechanical deformations such as skin bending or contact with clothing. Furthermore, the integration of an Ecoflex micropillar array on the surface amplifies low-level mechanical inputs, making the system highly sensitive to subtle biomechanical stimuli commonly encountered in daily human motion. This bioelectronic device can safely generate electrical signals capable of stimulating key cell types involved in wound healing, including endothelial cells, fibroblasts, and Schwann cells. Importantly, the study identifies the optimal electrical stimulation range to enhance cell proliferation and migration without triggering apoptosis, particularly under low-voltage (10 V) and low-frequency (1–2 Hz) conditions [Fig. 2(c)]. This led to the design of a highly efficient wound-healing device. These findings emphasize the potential of natural biomaterials, silk fibroin, not only to serve as passive structural components but also to actively participate in therapeutic functions, paving the way for next-generation bioelectronic systems that are both effective and biologically harmonious.

Chitosan, a biopolymer derived from chitin, has attracted increasing attention in the field of TENGs due to its intrinsic biocompatibility, biodegradability, and eco-friendly processing. However, its conventional role as a positively charged

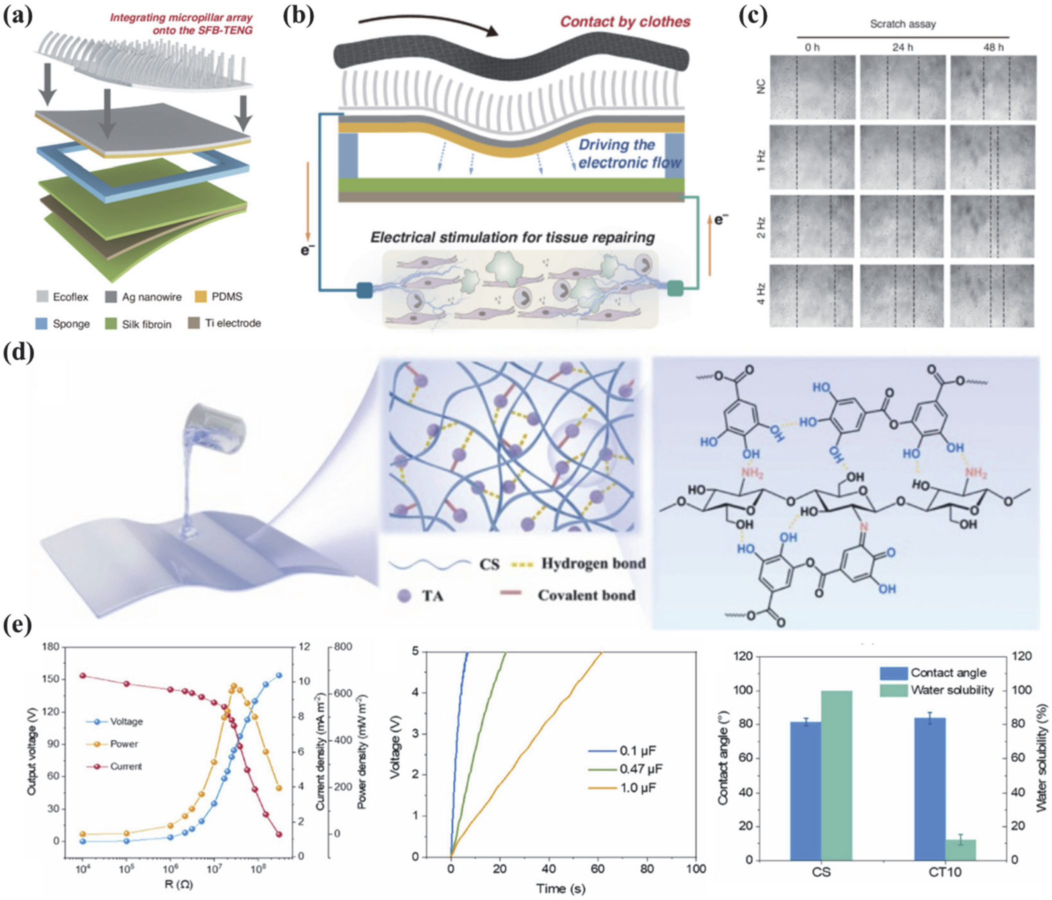

Fig. 2. Natural materials for advanced bioelectronic devices. (a) Schematic images of silk fibroin-based TENG. (b) Schematic illustration of the silk fibroin-based triboelectric nanogenerator (SFB-TENG) with a micropillar array. (c) The migration properties of the hy926 cells treated with different frequencies (1 Hz, 2 Hz, 4 Hz) were determined. Magnification: ×100 (Reprinted with permission from Ref. [39]. Copyright 2024, Springer Nature). (d) Schematic illustration of the formation process of chitosan films (CT10). (e) The output performance of CT10-TENG (current, voltage, instant peak power density, and charging curve of 0.1, 0.47 μF, and 1.0 μF capacitor). Water contact angle and water solubility of CS and CT10 films (Reprinted with permission from Ref. [40]. Copyright 2025, Elsevier).

triboelectric material limits its pairing options and performance tuning. This study presents a novel strategy to modulate the triboelectric charging behavior of chitosan (CT) through a natural polyphenol, tannic acid (TA) surface modification, achieving a remarkable shift in triboelectric polarity from positive to negative [40]. As illustrated in Fig. 2(d), CT films were chemically modified with various concentrations of tannic acid, resulting in covalent crosslinking via Schiff base reactions and enhanced surface roughness. This chemical interaction not only increased the mechanical strength up to 55.8 MPa but also induced significant changes in surface potential and electronic structure. Specifically, the introduction of TA lowered the LUMO energy level and increased electron-withdrawing capability through π-conjugation effects, as confirmed via DFT and XPS analysis. These alterations translated into a shift in triboelectric polarity and an optimized output charge density of 182 $\mu C/m^2$ for chitosan films (CT10) when paired with polyamide (PA), a typical positive triboelectric material [Fig. 2(e)]. Beyond electrical performance, the modified film of CT10 exhibited outstanding moisture resistance, retaining structural integrity with only 12.8% water solubility, and antibacterial efficiency of up to 96.5%. The authors further demonstrated a practical application of CT10-based TENGs in enhancing the fluffiness of down materials in textiles via electrostatic repulsion, highlighting the versatility of this natural-material approach. Ultimately, this work expands the utility of natural polymers like chitosan for TENG applications by unlocking polarity tunability, mechanical robustness, and functional integration, all achieved through a green and sustainable fabrication process.

2.2 Synthetic Materials for Advanced Bioelectronic Devices

Synthetic materials refer to synthetically designed or structurally modified materials that are tailored to meet specific functional, mechanical, and environmental requirements in biomedical devices [41-44]. Unlike natural materials, synthetic materials offer precise control over properties such as electrical conductivity, mechanical strength, degradation rate, and surface energy. This makes them highly suitable for advanced applications including implantable sensors, neural interfaces, energy harvesting devices, and drug delivery platforms. These materials often incorporate nanostructures, surface functionalization, or composite architectures to enhance performance. Examples include core-shell nanoparticles, polymer–inorganic hybrids, and conductive polymers (e.g., polyaniline, PEDOT:PSS). Synthetic materials can also be designed to respond to external stimuli such as pH, temperature, or electrical signals, enabling smart, adaptive therapeutic systems. Their compatibility with microfabrication and 3D printing technologies further allows for miniaturization and integration into complex bioelectronic systems. As bioelectronic devices evolve toward multifunctionality and autonomous operation, synthetic materials play a pivotal role in bridging the gap between biology and electronics.

The integration of synthetic materials into biomedical devices has enabled multifunctional systems capable of real-time monitoring, therapeutic delivery, and autonomous operation. As shown in Fig. 3(a), presents a smart bandage platform with leverages the unique properties of zeolite imidazolate framework (ZIF-8) nanoparticles, a synthetic metal-organic framework (MOF), as a functional component within a TENG architecture [45]. This work highlights the power of synthetic material engineering in overcoming traditional limitations in wound care, particularly in achieving self-powered operation, wireless communication, and dynamic feedback for drug delivery. As described in the study, ZIF-8 was utilized to functionalize the surface of a nanofiber membrane, effectively enhancing its triboelectric performance through increased surface roughness and electron-withdrawing capability. When embedded into a multilayer smart dressing, the ZIF-8-modified membrane served as a negative triboelectric layer, this is PCL/ZIF-8@GS fiber based on TENG (PZ-TENG) enabling the generation of stable output signals under minimal mechanical motion such as skin movement Fig. 3(b). These signals were used not only to wirelessly monitor pressure and bandage-skin interaction but also to track drug release kinetics via integrated fluorescent and electrochemical sensors. The choice of synthetic materials, ZIF-8 and polyvinylidene fluoride (PVDF) nanofibers was critical in achieving the necessary mechanical durability, chemical stability, and tunable electronic properties. These engineered components provide long-term operation and repeatable output performance under physiological conditions. Moreover, the modular device structure allows for the integration of wireless data transmission modules, demonstrating the scalability of synthetic-material-based designs toward practical clinical translation. Ultimately, this study exemplifies how rationally designed synthetic materials can elevate the functionality of biomedical devices, transforming passive wound dressings into intelligent, responsive platforms capable of sensing, reporting, and adapting to the biological environment in real-time.

The advancement of wearable biomedical devices depends heavily on synthetic materials that can be engineered to deliver both mechanical adaptability and high energy conversion efficiency. Addressing this challenge by developing a stretchable triboelectric nanogenerator (TENG) using a molybdenum disulfide (MoS_2)-based nanocomposite film, a synthetic system that exemplifies the fusion of material functionality and biomechanical conformity [46]. The core of TENG is composed of a MoS_2–PDMS composite, where MoS_2 nanosheets are uniformly dispersed within a flexible PDMS elastomer. This synthetic combination enables a dual advantage, MoS_2 enhances the surface charge density and dielectric properties, while PDMS contributes stretchability, biocompatibility, and durability—all of which are essential for skin-contact bioelectronic devices Fig. 3(c). The material design allows the device to be highly deformable up to 100% strain without significant performance degradation, which is crucial for capturing biomechanical energy from various human motions such as walking, bending, or stretching. With a peak output power of 30.6 μW and voltage responses directly

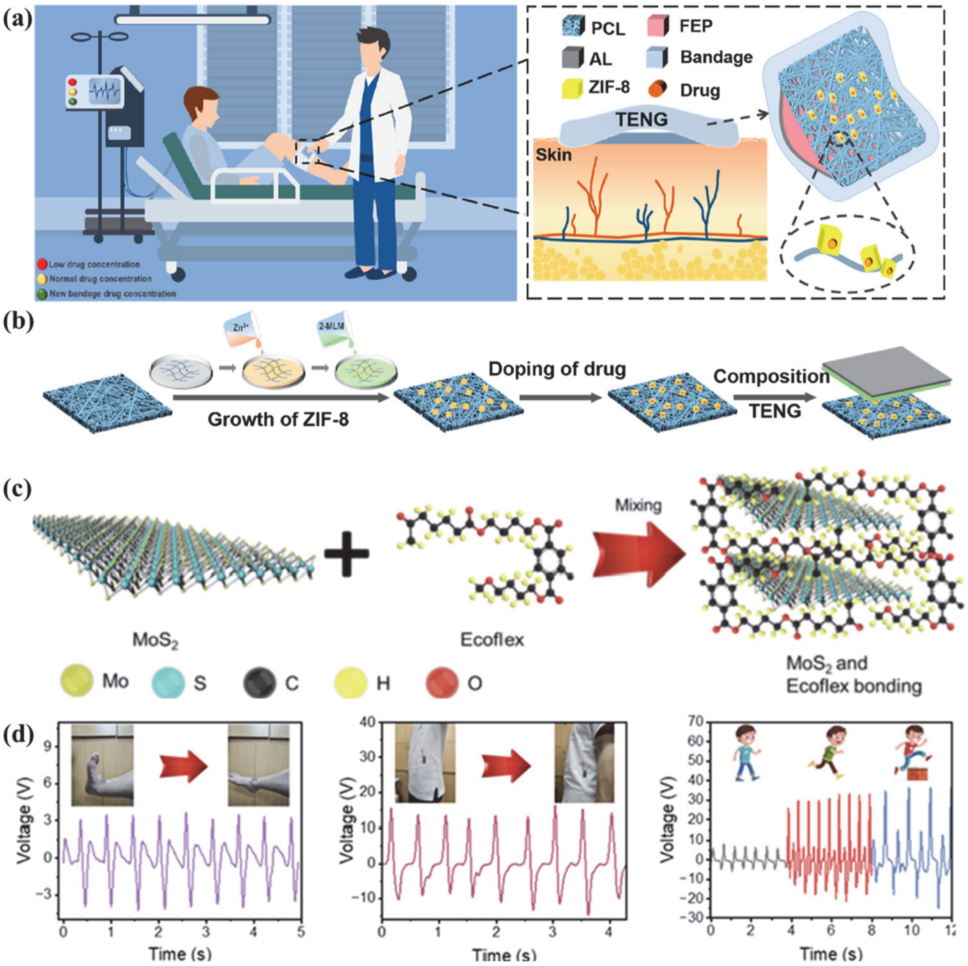

Fig. 3. Synthetic materials for advanced bioelectronic devices. (a) Schematic illustration of smart bandage application scenarios, simulation, and composition of smart bandage based on PCL/ZIF-8@GS-TENG (PZ-TENG). (b) The assembly process of PZ-TENG (Reprinted with permission from Ref. [45]. Copyright 2024, American Chemical Society). (c) Atomic structure of the Ecoflex/MoS_2 composite. (d) Images of biomotion monitoring using a manufactured flexible stretchable TENG (S-TENG). The output voltage of the S-TENG is generated by ankle bending, clothing of a human, and human motion monitoring (Reprinted with permission from Ref. [46]. Copyright 2024, Elsevier).

correlated with limb movements, this stretchable TENG (S-TENG) is well-suited for self-powered motion sensing and real-time health monitoring Fig. 3(d). The use of synthetic 2D materials like MoS_2 also contributes to interface stability, chemical robustness, and long-term operational reliability under repeated dynamic loading—characteristics often lacking in naturally derived systems. This work clearly illustrates how rationally engineered synthetic nanomaterials, when combined with elastomeric matrices, can be customized to meet the mechanical and electrical demands of advanced bioelectronic platforms. Moreover, the fabrication process solution casting and curing is compatible with scalable, low-cost production, enhancing its potential for commercial and clinical deployment in wearable healthcare electronics.

2.3 Composite Materials for Advanced Bioelectronic Devices

Composite materials have emerged as a cornerstone in the development of advanced biomedical devices due to their ability to synergistically combine the desirable properties of multiple constituents such as mechanical flexibility, electrical conductivity, biocompatibility, and environmental stability [47-50]. By integrating functional fillers (e.g., carbon nanotubes, metal oxides, piezoelectric or ferroelectric particles) into polymeric matrices, these composites enable precise tuning of surface charge behavior, durability, and device responsiveness to biomechanical stimuli. Nanostructured composites offer improved triboelectric performance, long-term operational stability, and scalable fabrication pathways, making them ideal for wearable or implantable applications. This strategic material design not only enhances the efficiency of energy harvesting and sensing but also broadens the functional scope of biomedical platforms toward smart, self-powered, and adaptive healthcare systems [61].

In the design of high-performance biomedical devices, composite materials play a central role in balancing biocompatibility, energy conversion efficiency, and mechanical adaptability. As illustrated in Fig. 4(a), propose a poly (lactic acid) (PLA)-based triboelectric nanogenerator (TENG), where the primary innovation lies in the controlled construction of a secondary electron path using functionalized layers, rather than relying on multilayered or metallic composites [51]. The contact-separation mode TENG (CS-TENG) is composed of a biocompatible PLA substrate, modified via oxygen plasma treatment to introduce surface functional groups, enhancing the charge-trapping capability of the polymer. To further optimize electron transfer pathways, the authors apply a layer of amino-functionalized polydopamine (PDA-NH_2), which serves as a secondary charge transport interface. This engineered electron path amplifies triboelectric output by facilitating interfacial charge separation and retention while maintaining the inherent flexibility and biodegradability of PLA. Unlike traditional composite structures that require embedded fillers like Ag nanowires or nanocellulose, this approach achieves high electrical performance approximately 124 V and 3.6 μA with a chemically tailored interface, which significantly simplifies fabrication and enhances environmental sustainability Fig. 4(b). The device's ability to power LEDs and respond to low-frequency mechanical stimuli such as human motion makes it a strong candidate for wearable or implantable bioelectronic energy systems. The device's thin, flexible form composite material design also supports its use in conformal, lightweight, and eco-friendly skin-integrated devices that require reliable performance under repeated deformation. Furthermore, its fabrication from a biodegradable substrate aligns with modern priorities in eco-safe medical electronics, particularly in single-use or implantable systems, where post-use environmental impact must be minimized. Overall, the device exemplifies how bio-derived, environmentally conscious materials can be engineered for robust functionality in energy-autonomous medical and wearable technologies, opening the door to more sustainable and patient-friendly healthcare solutions.

3. STRUCTURE-DRIVEN PERFORMANCE ENHANCEMENTS

The development of advanced biomedical devices increasingly relies on innovative mechanisms and structural designs that maximize functionality, adaptability, and biocompatibility [52-55]. By incorporating features such as micropatterned surfaces, hierarchical porous architectures, and sandwich-layered configurations, these devices can efficiently interact with biological systems while maintaining mechanical resilience and signal fidelity. Structural innovations enable enhanced energy harvesting, sensing accuracy, and

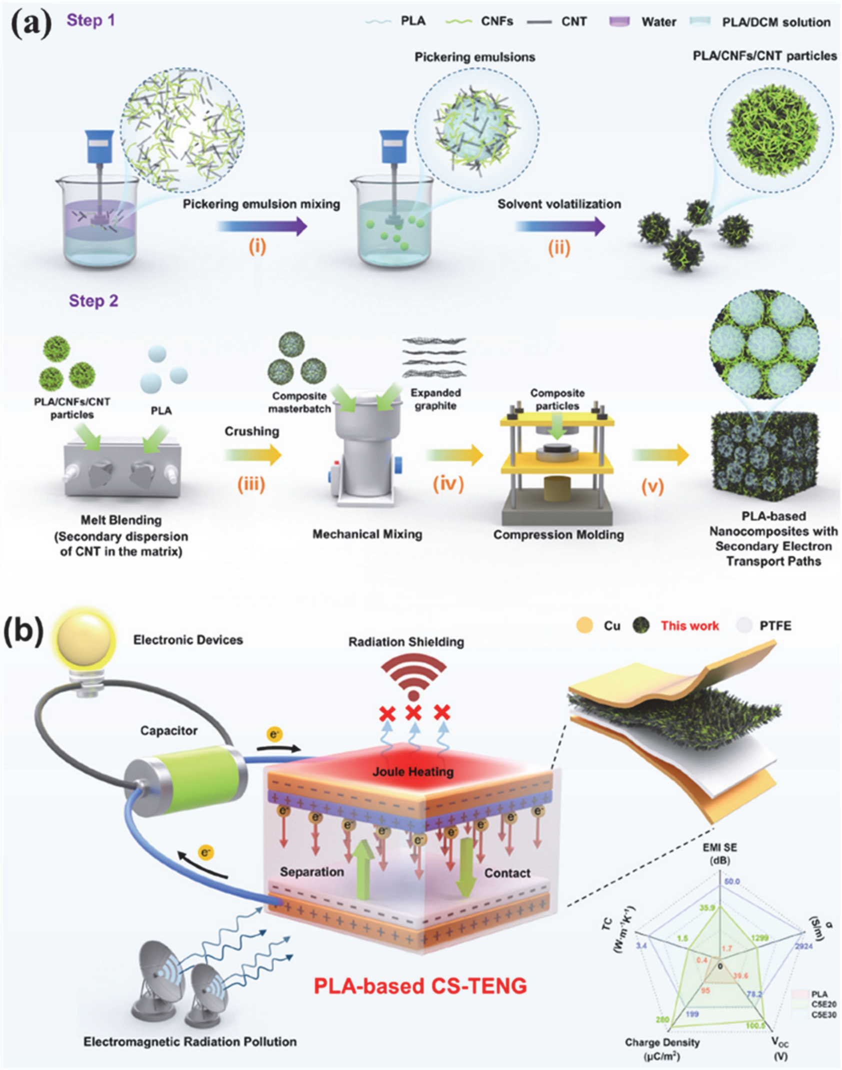

Fig. 4. Composite materials for advanced bioelectronic devices. (a) Descriptions of the C5Ex nanocomposite films and PLA-based TENG device. (b) Schematic illustration of a biopolymer PLA-based CS-TENG featuring integrated EMI shielding and joule heating capabilities (Reprinted with permission from Ref. [51]. Copyright 2024, Elsevier).

stimulus responsiveness, especially under dynamic physiological conditions. For instance, devices engineered with flexible multilayered geometries or mechanically tunable frames can conform to irregular tissue surfaces, accommodate body motion, and maintain stable performance over long-term use. These advanced structural strategies, when integrated with suitable functional materials, lay the foundation for next-generation biomedical platforms that are not only high-performing but also minimally invasive and personalized for patient-specific needs.

3.1 Wound Healing with Advanced System

The convergence of structural innovation and intelligent mechanism design is redefining the functionality of biomedical devices, particularly in the field of wound healing and real-time health monitoring. As shown in Fig. 5(a), introduces an integrated bilayer microneedle (MN) dressing coupled with a triboelectric nanogenerator (TENG), the entire set of flatform is called the MN-TENG, a sophisticated device that exemplifies how advanced structures can simultaneously serve therapeutic technologies and diagnostic roles in clinical

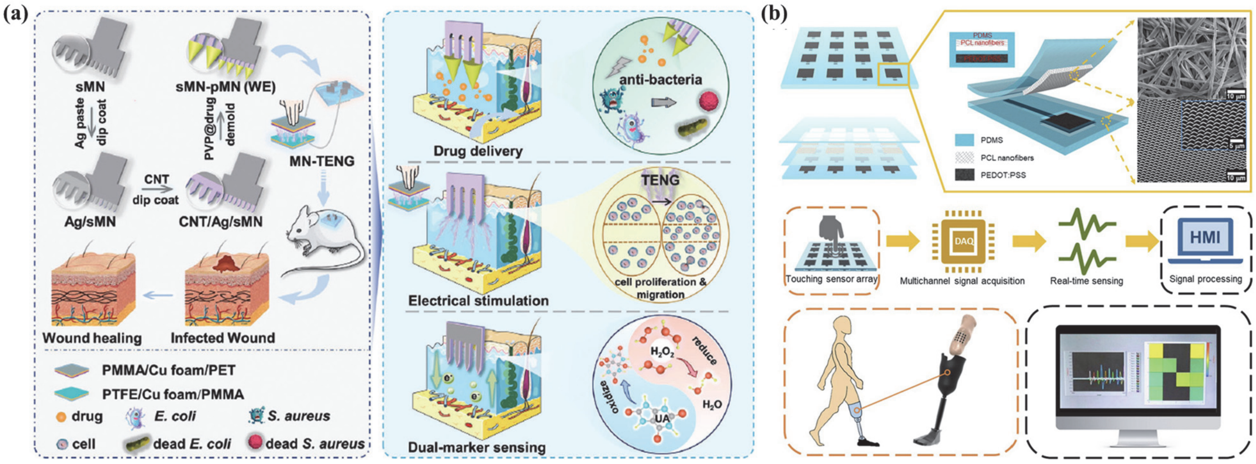

Fig. 5. Advanced mechanism and new structure. (a) The microneedle-triboelectric nanogenerator (MN-TENG) therapeutic platform combines coated microneedles and electrodes into a resin-encapsulated device for antibiotic delivery, electrical stimulation, and real-time wound monitoring through redox-based sensing (Reprinted with permission from Ref. [56]. Copyright 2024, Wiley). (b) Schematic of a TENG-based tactile sensor for monitoring pressure in a prosthetic limb. It features layered materials (PDMS, PCL nanofiber, PEDOT:PSS) and uses a multichannel system to display pressure distribution in real-time via an HMI interface (Reprinted with permission from Ref. [57]. Copyright 2023, Elsevier).

settings [56]. The core structural advancement lies in the bilayer architecture, which combines a drug-loaded microneedle array with a porous triboelectric layer to achieve dual functionality, localized drug delivery, and energy harvesting from skin motion. The microneedles are engineered to painlessly penetrate the stratum corneum, enabling efficient transdermal drug administration while also serving as a stable interface for bioelectronic sensing. Meanwhile, the triboelectric layer, comprising a flexible substrate and patterned electrode structure, transduces biomechanical movements such as joint flexing or skin deformation into electrical signals. These signals are used to monitor wound status, enabling real-time tracking of motion, temperature, and humidity at the wound site. The synergy between microscale geometry, skin-conformal materials, and self-powered operation exemplifies an advanced mechanism that goes beyond passive therapy. The device's structure is also optimized for biomechanical adaptability, ensuring continuous contact with the skin surface and consistent signal output, even under dynamic physiological conditions. Furthermore, the integration of wireless data transmission modules allows for remote monitoring, making the system suitable for next-generation telemedicine and closed-loop wound management. This work demonstrates that by combining hierarchical microstructures with multifunctional layers, bioelectronic devices can evolve into intelligent platforms that seamlessly integrate sensing, therapy, and energy autonomy, all within a single wearable or implantable interface.

3.2 Wearable Health Monitoring Devices

Advances in biomedical engineering demand sensor systems that are not only sensitive and responsive but also structurally adaptive to complex human-machine interfaces. As shown in Fig. 5(b), a triboelectric nanogenerator (TENG)-based tactile sensor array is specifically engineered to monitor pressure distribution inside a prosthetic limb, a setting that requires both precision sensing and mechanical compatibility [57]. The structural innovation centers around a flexible multilayer architecture, where Ecoflex and conductive textiles are layered to form a sandwich-type TENG sensor unit. This design enables real-time pressure mapping by converting mechanical deformation into electrical signals with high sensitivity and spatial resolution. The array configuration consists of 4×4 sensor units that can detect localized pressure variations, offering valuable feedback for adjusting prosthetic socket fit and preventing pressure ulcers in amputees. What distinguishes this system is its biomechanical adaptability, the soft, stretchable materials conform to the curved surfaces of the residual limb, maintaining stable contact and signal accuracy during movement. Additionally, the integration of a wireless data acquisition and visualization system allows for remote and continuous monitoring, a critical feature for clinical rehabilitation and long-term patient care. By merging modular sensor design, conformal material integration, and self-powered functionality, this work showcases how advanced structural strategies can lead to smart, responsive, and patient-centric bioelectronic systems. It underscores the potential of TENG-based tactile platforms in enhancing prosthetic feedback, ultimately contributing to more natural and safer prosthetic control.

3.3 Magnetically Coupled Architecture

The integration of wireless energy transfer mechanisms into biomedical systems represents a critical leap toward fully autonomous and minimally invasive healthcare devices. As illustrated in Fig. 6(a), propose a magnetically actuated-triboelectric nanogenerator (MA-TENG) that offers a wireless and non-contact energy transfer solution, made possible through a sophisticated interplay of magnetic actuation, mechanical resonance, and structural optimization [58]. At the core of the system lies a vibration-coupled architecture, where a magnetic oscillator induces resonance in a freestanding TENG unit without physical contact. This design enables efficient power generation and transmission across air gaps or encapsulated environmental conditions highly relevant for implantable and hard-to-access bioelectronic devices. The structural innovation includes mechanically tuned elastomeric supports, spiral spring elements, and a non-contact rotary module, all engineered for high-frequency responsiveness and precise displacement control Fig. 6(b). This mechanism eliminates many limitations of conventional contact-based TENGs, including wear, frictional degradation, and limited

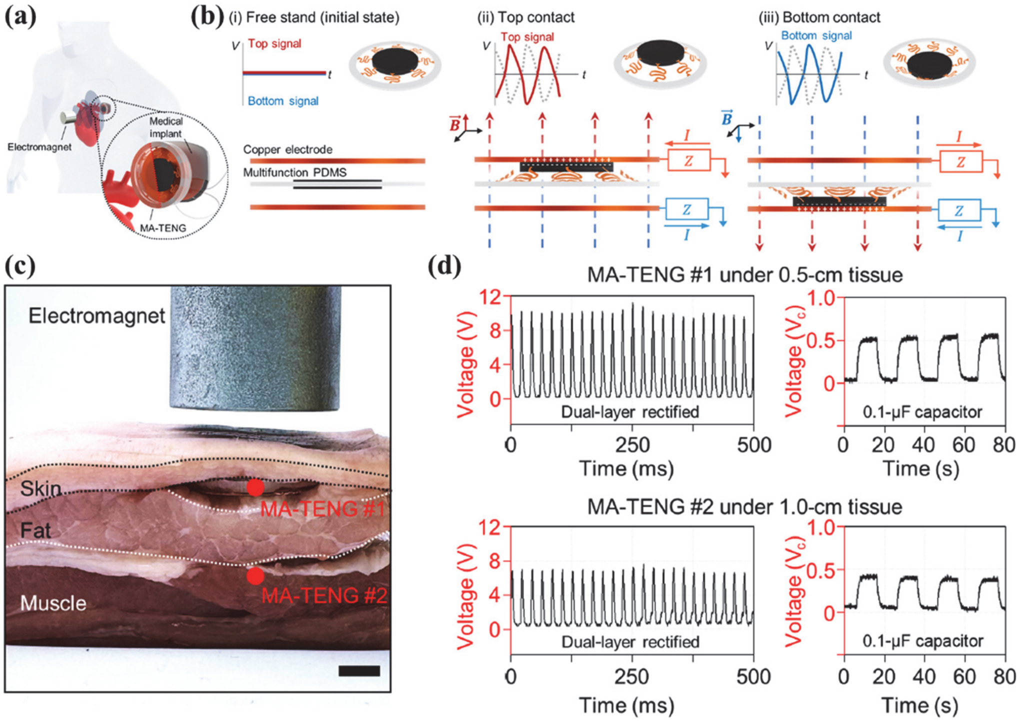

Fig. 6. Advanced magnetic mechanism and structure. (a) Concept and design of magnetically actuated-triboelectric nanogenerator (MA-TENG). Illustration of a medical implant with MA-TENG an electromagnet mounted on the chest. (b) MA-TENG operates by using magnetic fields to drive movement. When a magnetic field is applied, the structure moves to contact the top and bottom electrodes, generating triboelectric charges. (c) Photo of MA-TENG embedded in porcine tissue, where external magnetic fields were applied to generate output voltage and charge a capacitor. Scale bar, 10 mm. (d) Output voltage and capacitor charging/discharging of MA-TENG were measured under 0.5 cm and 1.0 cm porcine tissue (Reprinted with permission from Ref. [58]. Copyright 2025, American Association for the Advancement of Science).

placement flexibility. Moreover, the modularity of the system allows it to deliver consistent power output over variable distances, orientations, and barriers, opening new possibilities for wireless powering of biosensors, implantable pumps, or diagnostic implants. Fig. 6(c), shows MA-TENG tested in porcine tissue at depths of 5 mm and 10 mm to simulate implant conditions. MA-TENG #1 (5 mm) produced 11.2 V, while MA-TENG #2 (10 mm) produced 7.6 V, demonstrating that output voltage and capacitor charging efficiency decrease with greater tissue depth Fig. 6(d). Approaching exemplifies how advanced structural design, centered on magnetic-mechanical coupling and freestanding multilayer resonators can expand the operational landscape of triboelectric systems. By decoupling energy generation from direct physical interaction, the MA-TENG offers a scalable path forward for bioelectronics requiring untethered operation and robust long-term functionality.

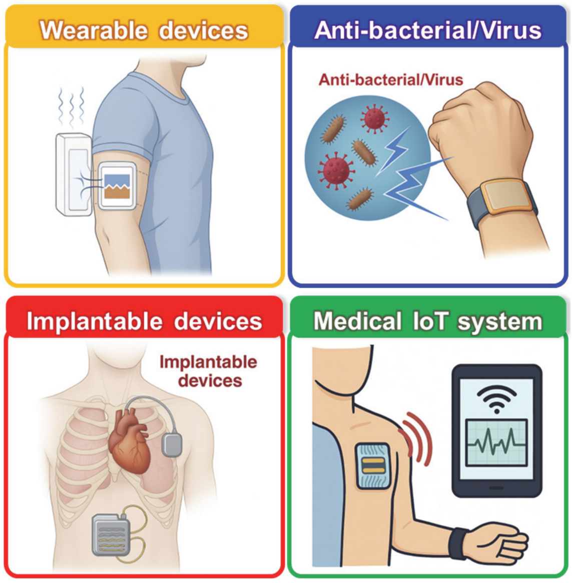

Fig. 7. High-performance bioelectronic-TENG based on advanced material and structural design for Extreme Biomedical Environments (wearable devices, anti-bacterial devices, implantable devices, and medical IoT systems).

4. CONCLUSION

Despite significant advancements in triboelectric nanogenerator (TENG) research, several fundamental challenges remain that hinder their seamless integration into biomedical systems, especially those intended for use in extreme environments. One of the most critical issues is material durability and long-term stability. TENGs used in implantable or wearable applications are frequently subjected to continuous mechanical deformation, high humidity, and exposure to biological fluids. These conditions can accelerate material degradation, leading to performance loss over time. Therefore, the development of self-healing, fatigue-resistant, and bio-inert materials is essential to ensure prolonged and reliable operation.

Another key challenge lies in the scalability and manufacturing compatibility of high-performance TENGs. Many current fabrication methods, such as spin-coating, photolithography, or vacuum deposition, are well-suited for laboratory research but are not easily scalable for industrial or clinical deployment. To bridge this gap, future work should focus on roll-to-roll printing, 3D printing, and solution-processable synthesis techniques that allow for large-area, flexible, and cost-effective production of Bio-TENG devices. In addition to material and manufacturing challenges, regulatory frameworks, standardization of performance testing, and clinical validation remain underdeveloped. Addressing these aspects is crucial for transitioning TENG-based systems from experimental devices to medically approved solutions. In the future, triboelectric nanogenerators with highly efficient materials and optimized structural designs will be widely applied to promote human health through various bioelectronic systems, including wearable devices, antibacterial platforms, implantable electronics, and IoT-enabled healthcare technologies Fig. 7. This paper aims to provide a comprehensive review of innovative material synthesis strategies that are redefining the capabilities of triboelectric generators. By linking fundamental triboelectric mechanisms with advanced material engineering, we highlight promising pathways for the development of next-generation biomedical devices capable of reliable operation in extreme conditions.

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