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Review

Materials, Structures, and Applications of iTENGs

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Abstract: Implantable triboelectric nanogenerators (iTENG) have emerged as a promising technology for self-powered biomedical devices. This review explores the key aspects of materials, structures, and representative applications of iTENGs. The materials section discusses the core triboelectric layer, electrode layer, and encapsulation layer, emphasizing the importance of biocompatibility and mechanical flexibility. The structural design section delves into three common modes: contact–separation mode, single-electrode mode, and free-standing mode, highlighting their working principles and advantages. The application section covers diverse areas such as cardiac devices, sterilization processes, and anticancer therapies, showcasing the potential of iTENGs to revolutionize healthcare. Moreover, it discusses the challenges and future directions for material development, structural design optimization, conformal matching, and practical implementation of iTENGs. This comprehensive review provides valuable insights into the materials, structures, and applications of iTENGs, serving as a resource for researchers and engineers in the field.

Keywords: iTENGs; materials; structures; applications

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1. Introduction

A triboelectric nanogenerator (TENG) can convert mechanical energy into electricity/electrical signal based on the triboelectric effect and electrostatic induction [1–6]. In detail, after two different materials rub against each other, due to the difference in their ability to adsorb electrons, one material will carry a positive charge, while the other material will carry a negative charge. At the same time, induced charges will be generated on the back electrode of the two materials. When two materials are separated, positive and negative charges separate, and this separation of positive and negative charges creates a potential difference between the upper and lower electrodes of the material. As the distance between the two materials changes, the potential also undergoes periodic changes. Similar to piezoelectric nanogenerators, connecting the outer sides of two materials through external circuits or loads can generate alternating induced currents [7–10]. As shown in Figure 1, TENG harnesses electricity generation through multiple distinct working modes, each offering unique mechanisms for energy harvesting [11]. The vertical contact–separation mode involves two dissimilar materials making contact and then separating vertically. During contact, electron transfer occurs, leading to charge accumulation and subsequent potential difference upon separation, resulting in electricity generation. The single-electrode mode is a variation of the vertical contact–separation mode, where only one triboelectric material is used, and the other material is replaced with an electrode or a conductive surface. The single material is mechanically moved or flexed to induce contact and separation with the electrode, generating electricity through the triboelectric effect. The lateral sliding mode relies on two triboelectric materials in direct contact, which are laterally slid against each other. TENGs operating in the freestanding mode comprise a charged moving object and two stationary triboelectric layers. Electrodes positioned near these triboelectric layers are externally connected to a load. The reciprocating movement of the charged object between the two friction layers induces a potential difference between the two electrodes, initiating electron flow back and forth within the external circuit loop. As a result, electricity is generated, harnessing the triboelectric effect and transforming mechanical energy into a usable electrical output. TENGs provide a sustainable and renewable energy-harvesting solution that directly converts mechanical energy into electricity without relying on fossil fuels. They offer a cleaner and greener alternative to traditional power generation methods, contributing to reduced greenhouse gas emissions and environmental impact [12–14].

Compared to solar power, TENGs can generate electricity from various mechanical sources, making them suitable for both indoor and outdoor applications. They are not dependent on sunlight, making them viable for use in low-light or nighttime scenarios. TENGs and piezoelectric generators share similarities as both convert mechanical energy into electricity. However, TENGs offer advantages like higher power density and the ability to harvest energy from a broader range of mechanical movements, including sliding and rotational motion. Compared to the batteries, TENGs can serve as self-powered devices, eliminating the need for frequent battery replacements and reducing electronic waste. They offer sustainable power generation without relying on external energy storage. TENG technology has been widely researched and applied, including wearable electronics, smart sensors, biomedical devices, self-powered systems, and other fields [7,15–19].

With the development of TENG technology, implantable TENG (iTENG) has also received more and more attention and research [20–23]. The biggest advantage of this technology is that it can use the mechanical energy generated by the body's own movement to generate electricity in vivo, so there is no need to use an external power source or battery [11,24,25]. iTENGs can be used to prepare implantable medical devices, such as implantable cardiac pacemakers, EEG monitors, drug pumps, etc., thereby reducing the frequency of battery replacement and the risk of surgery [26,27]. iTENGs can not only reduce the volume and weight of the implant but also improve the service life of the implant, reducing the frequency of battery replacement and the risk of surgery [15,28,29].

Materials and structures play a crucial role in the design and application of iTENGs [30,31]. The choice of materials and structures is tailored to the specific requirements and constraints of each application [32]. By carefully selecting materials and optimizing structural designs, iTENGs can be customized to meet the requirements of various applications, including biomedical sensing, power supply, and other specific uses [33]. This approach ensures the functionality, biocompatibility, and efficiency of the iTENGs in their respective applications, leading to advancements in the field of implantable medical devices [34].

Biocompatibility, mechanical stability, and flexibility are three essential requirements for iTENGs [35,36]. These characteristics are crucial to ensure the safe and reliable operation of the devices within the human body. First of all, biocompatibility means that the material will not cause immune reaction and rejection when it comes into contact with human tissue and will not cause damage to human tissue and organs [37]. Therefore, in the preparation process of iTENG, it is necessary to select materials with good biocompatibility and conduct strict biocompatibility tests to ensure that it is harmless to the human body after implantation. Second, mechanical stability means that the material will not fail or be damaged due to mechanical stress, wear, or other factors during the implantation process [38]. Therefore, in the preparation of iTENG, it is necessary to select materials with good mechanical stability and conduct strict mechanical performance tests to ensure that its performance and stability can be maintained for a long time after implantation [39]. Flexibility is also a key consideration for iTENG as they need to conform to the shape and movement of the human body. Flexible materials and structural designs allow the devices to adapt and integrate seamlessly with the surrounding tissues or organs. This flexibility ensures patient comfort, minimizes the risk of damage to surrounding tissues, and enables unhindered bodily movements [40].

The iTENGs can be traced back to the development of triboelectric nanogenerators in the early 2010s [41–44]. As the field progressed, researchers also explored the use of flexible conductive polymers and carbon-based materials, such as graphene and carbon nanotubes, to achieve better compatibility with the human body [30,32,45]. As the field advanced, researchers focused on developing advanced encapsulation strategies, such as thin film coatings or biodegradable materials, to minimize device size, improve biocompatibility, and enable localized drug release [46]. Throughout the history of iTENGs, there has been a continuous effort to refine the materials and structures used in these devices [47]. The evolution of materials and structures has paved the way for the development of more advanced and functional iTENGs with the potential to power a wide range of biomedical devices and enable innovative healthcare solutions [48–50].

iTENG, as an emerging technology for energy harvesting and conversion, has broad application prospects. Although there are still some challenges, such as durability and stability, with the continuous advancement and improvement in technology, it is believed that iTENGs will be used in the future medical. As shown in Figure 1 and Table 1, this review explores the materials and structures used to create iTENGs and their potential applications. The potential for iTENGs to revolutionize the field of biomedicine and wearable electronics is significant, and ongoing research in this area is likely to lead to exciting new developments in the future [32,51,52].

The review article places a specific emphasis on iTENGs, a relatively new and emerging class of nanogenerators. The review takes a comprehensive and systematic approach, providing an in-depth analysis of various aspects related to iTENGs. This includes the exploration of materials, device structures, and diverse applications. The review not only examines the materials used in iTENGs but also pays particular attention to their encapsulation layer. This approach is essential as the combination of specific materials and structures greatly influences the performance and applicability of iTENGs. This review takes a specific and targeted approach by focusing on degradable materials. By honing in on this specific category, the review offers a specialized perspective that was not explored before, making it a novel and valuable contribution to the field. This aspect is crucial as it addresses environmental concerns and potential applications in biodegradable electronics or medical devices. As shown in Figure S1 (see Supplementary Materials), it can be seen that the attention of iTENG has been increasing year by year, indicating that iTENG has good development prospects and research value.

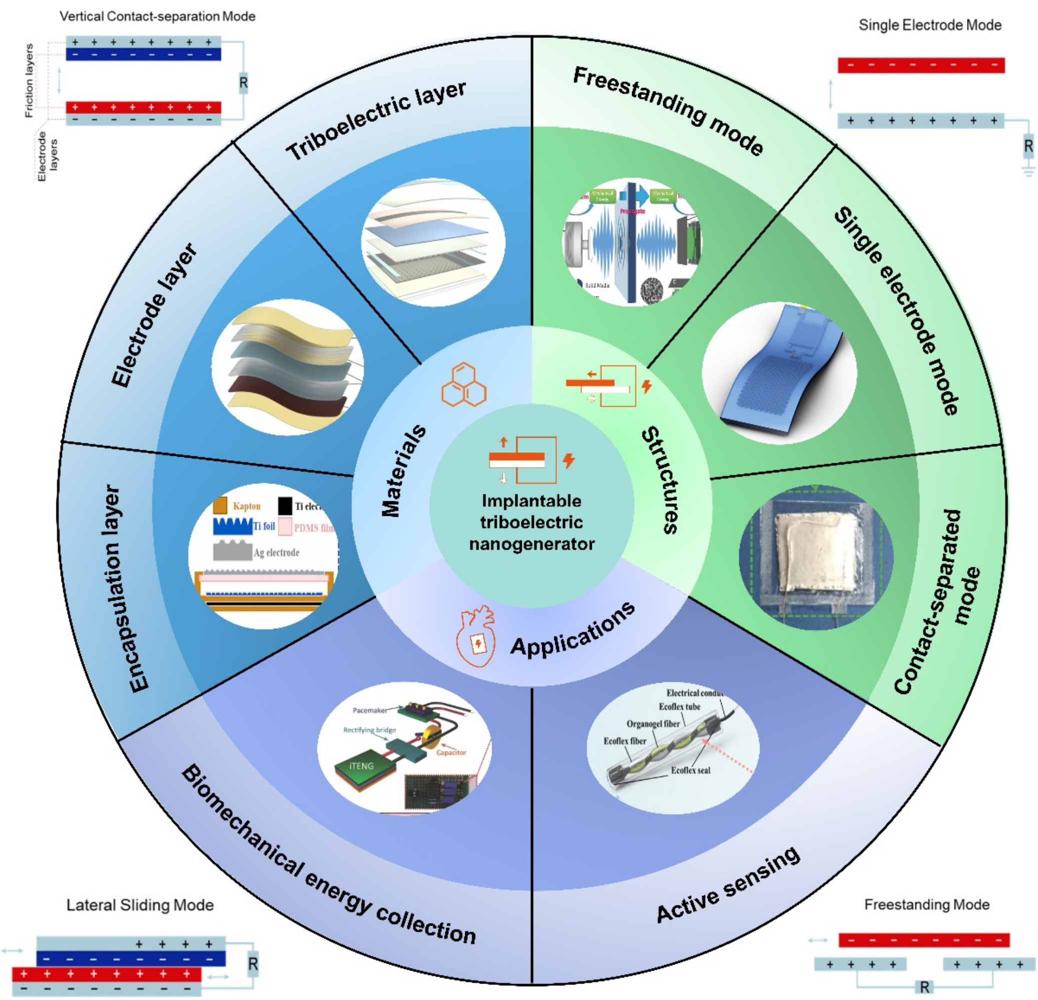


Figure 1. Materials, structures, and applications of iTENG. Materials, structures, and applications of iTENG. Four working modes on the edge [11]. Contact-separated mode. Reprinted with permission from Ref. [30]. Copyright 2016, AAAS. Single electrode mode. Reprinted with permission from Ref. [32]. Copyright 2018, Elsevier Ltd. Freestanding mode. Reprinted with permission from Ref. [53]. Copyright 2018, John Wiley & Sons, Inc. Triboelectric layer. Reprinted with permission from Ref. [54]. Copyright 2023, Elsevier. Electrode layer. Reprinted with permission from Ref. [55]. Copyright 2022, AAAS. Encapsulation layer. Reprinted with permission from Ref. [56]. Copyright 2023, Springer Nature Limited. Active sensing. Reprinted with permission from Ref. [57]. Copyright 2022, American Chemical Society. Biomechanical energy collection. Reprinted with permission from Ref. [58]. Copyright 2014, John Wiley & Sons, Inc.

Table 1. Materials, performance, working mode, and applications of iTENG. (Xiao et al. [59]. Sun, Y et al. [60]. Kang et al. [61]. Sheng et al. [57]. Iman, M et al. [62]. Zhao et al. [63]. Ouyang et al. [56]. Zheng et al. [30]. Jiang et al. [32]. Liu et al. [64]. Li et al. [65]. Liu et al. [66]. Shi et al. [67]. Ryu et al. [68]. Jin et al. [69]. Zheng et al. [70]. Yao et al. [71]. Zheng et al. [72]. Chen et al. [73]).

Core Triboelectric Layer	Electrode Layer	Encapsulation Layer	Operating Voltage	Power Density	Flexibility	Decomposable	Working Mode	Working Position	References
PLA, Mg	Mg	PCL	356.8 mV	-	Inflexible	Biodegradable	Contact-separation	Wound	Xiao et al. [59].
PTFE, Ag	Ag	PDMS	16.7 V	-	Flexible	Non-biodegradable	Free-standing	Vagus nerve	Sun, Y et al. [60].
ϰC-Agar, PCL	Mg	ϰC-Agar	~30 V	0.15 mW·m^{-2}	Inflexible	Biodegradable	Contact-separation	Subcutaneous tissue	Kang et al. [61].

Table 1. *Cont.*

Core Triboelectric Layer	Electrode Layer	Encapsulation Layer	Operating Voltage	Power Density	Flexibility	Decomposable	Working Mode	Working Position	References
Cu, Rubber	Cu	Rubber	3.67 V	-	Flexible	Non-biodegradable	Contact-separation	Patellar ligament of knee	Sheng et al. [57].
PVA, PHBV	Mg	PHBV	~4.1 V	-	Flexible	Biodegradable	Contact-separation	Subcutaneous	Iman, M et al. [62].
PTFE, Al	Cu, Al	PDMS	~20 V	-	Flexible	Non-biodegradable	Contact-separation	Heart	Zhao et al. [63].
PTFE, Al	Au, Al	PDMS, Teflon	65.2 V	-	Flexible	Non-biodegradable	Contact-separation	Heart	Ouyang et al. [56].
PLGA, PVA, PCL, PHB/V	Mg	PLGA	~40 V	-	Inflexible	Biodegradable	Contact-separation	Pleural	Zheng et al. [30].
MXene-based MSC	carbon-fiber-embedded	Silicone	~50 V	7.8 μW/cm^2	Inflexible	Non-biodegradable	Single-electrode	Skin	Jiang et al. [32].
PE	Ni	Steel	98 V	-	Inflexible	Non-biodegradable	Free-standing	Artificial joint	Liu et al. [64].
PTFE/PET	Cu/Cr	Silicone elastomer	2.2 V	-	Flexible	Non-biodegradable	Free-standing	Diaphragm	Li et al. [65].
PTFE/Ag	Ag	Acrylic plate	~0.5 V	-	Inflexible	Non-biodegradable	Single-electrode	Cochlea	Liu et al. [66].
$BaTiO_3$ doped PDMS, Al	Au/Al	PDMS	~40 V	97.41 mW·m^{-2}	Flexible	Non-biodegradable	Contact-separation	Subcutaneous	Shi et al. [67].
PFA, PVA-NH_2	Cu/Au	Liquid Silicone Rubber	136 V	4.9 μW$_{RMS}$/cm^3	Inflexible	Non-biodegradable	Contact-separation	Heart	Ryu et al. [68].
ZnO/CNT	CNT	PDMS	4.9 V	-	Flexible	Non-biodegradable	Contact-separation	Heart	Jin et al. [69].
$BaTiO_3$/PVDF-TrFE	steel	steel	15.24 V	-	Inflexible	Non-biodegradable	Contact-separation	Cochlea	Zheng et al. [70].
PLGA/P-PLGA	Mg	PLGA	6.8 V	-	Flexible	Non-biodegradable	Contact-separation	Bone	Yao et al. [71].
TiO_2/PDMS/Nitrile	Al	Kapton	~40 V	-	Inflexible	Non-biodegradable	Contact-separation	Cancer	Zheng et al. [72,73].
Al/PDMS	hydrogel	hydrogel	~10 V	-	Inflexible	Non-biodegradable	Single-electrode	Nerve	Chen et al. [74].

2. Materials

The material of the iTENG is mainly divided into three parts, which are the core triboelectric layer, the electrode layer, and the encapsulation layer [49,74]. The core triboelectric layer is the most important layer of the iTENGs, as it is responsible for generating electrical energy through the triboelectric effect. This layer is typically made of a material with high triboelectric properties, such as PTFE [75]. When the friction layer comes into contact with another surface, it generates an electrical charge through the transfer of electrons [76]. The choice of material for the core triboelectric layer is critical to the performance of the iTENGs, and ongoing research is focused on developing new materials with even higher triboelectric properties [46]. The electrode layer serves as a conductor to collect and transport the generated electrical energy. It is usually made of a conductive material such as silver, magnesium, or copper. The electrode layer is important for ensuring that the electrical energy generated by the iTENGs can be effectively collected and used to power external devices [33]. The encapsulation layer serves to protect the iTENGs from external influences and provide biocompatibility if it is intended for implantation in the human body. Biocompatible materials such as silicone or polyurethane are typically used for this layer, as they are non-toxic and do not elicit an immune response in the body [34]. The encapsulation layer is critical to the long-term functionality of the iTENGs, as it protects the device from degradation and wears over time [77]. As shown in Figure 2, the table displays the core friction layer, electrode layer, packaging layer, working voltage, flexibility, biodegradability, working mode, and working position of multiple representative articles.

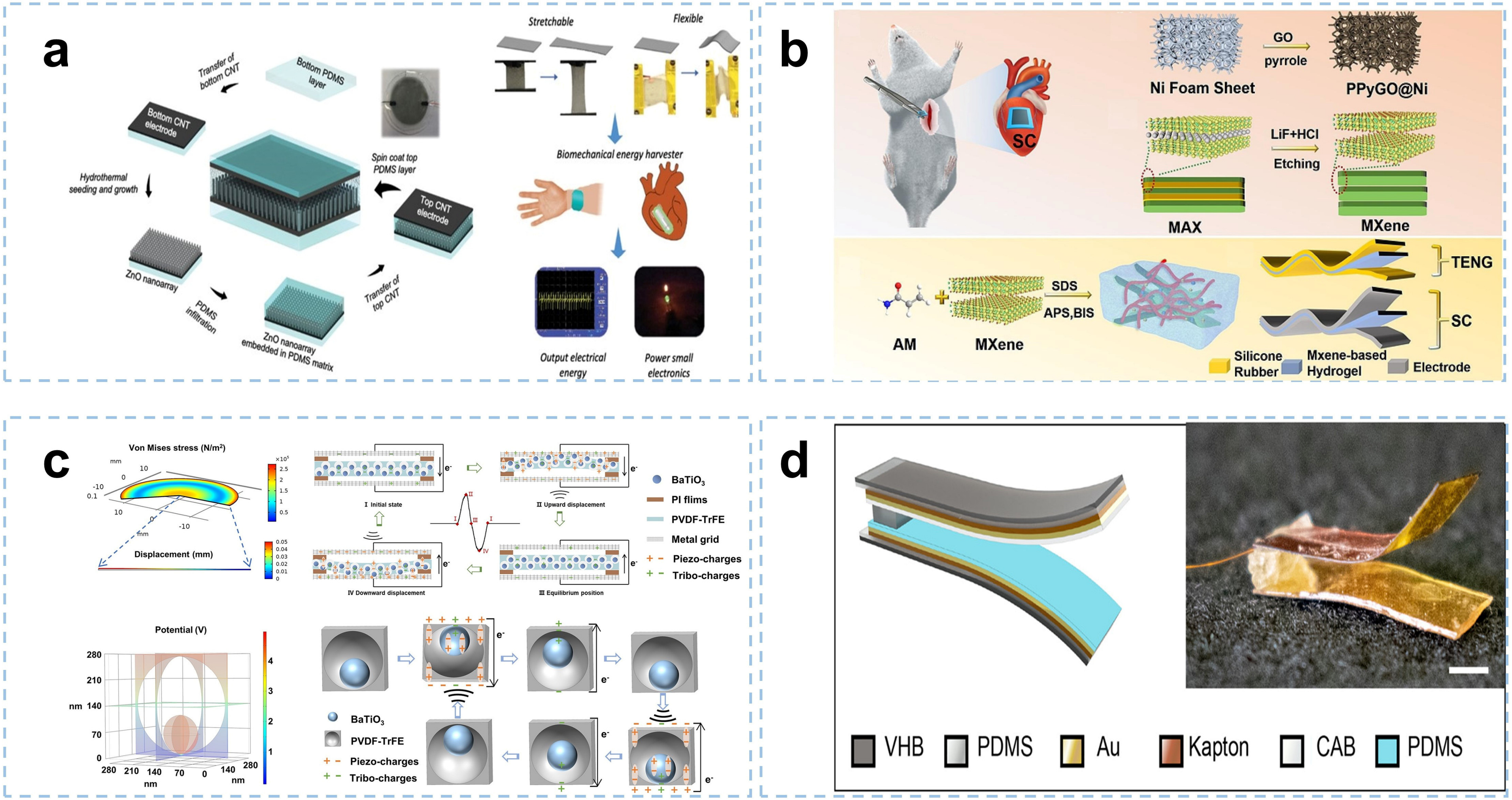


Figure 2. *Cont*.

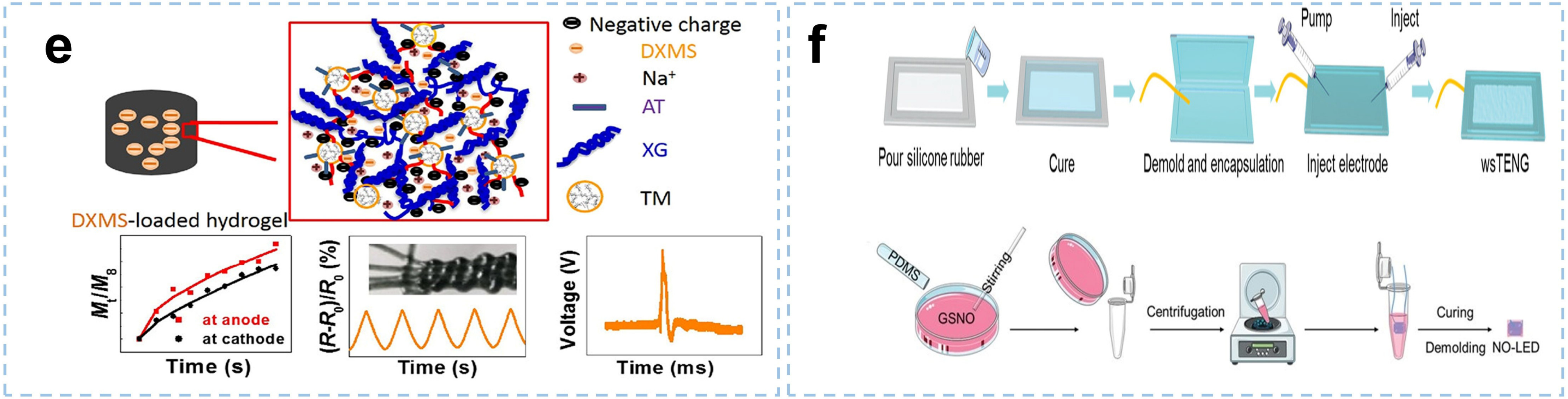


Figure 2. Materials of iTENG. (**a**) PDMS. Reprinted with permission from Ref. [69]. Copyright 2021, John Wiley & Sons, Inc. (**b**) Hydrogel. Reprinted with permission from Ref. [78]. Copyright 2023, Elsevier B.V. (**c**) $BaTiO_3$/PVDF-TrFE composite membranes. Reprinted with permission from Ref. [70]. Copyright 2021, American Chemical Society. (**d**) PDMS. Reprinted with permission from Ref. [79]. Copyright 2023, American Chemical Society (**e**) Conductive hydrogel. Reprinted with permission from Ref. [80]. Copyright 2022, American Chemical Society. (**f**) Conductive LiCl solution liquid electrode. Reprinted with permission from Ref. [81]. Copyright 2022, John Wiley & Sons, Inc.

Prolonged contact of iTENGs with human tissue can lead to biofouling, which refers to the accumulation and growth of biological substances on the surface of materials [82,83]. Biofouling can occur when iTENGs are exposed to bodily fluids and tissues, resulting in the adsorption of proteins, attachment of cells, and formation of biofilms [84]. This biofouling can negatively impact the performance and functionality of iTENGs in several ways. Firstly, the presence of biofilms and accumulated biological substances can interfere with the frictional properties of the device, hindering the effective contact and separation between materials required for energy conversion [85]. Secondly, biofouling can alter the electrical properties of electrode materials, leading to decreased energy generation efficiency. Additionally, the presence of biofilms and accumulated substances can trigger an inflammatory response in the body, compromising the biocompatibility of the device and potentially causing tissue damage [86]. Moreover, biofouling increases the risk of infection as biofilms provide a suitable environment for bacterial colonization and persistence [87]. Therefore, addressing biofouling is crucial to maintaining the performance, biocompatibility, and long-term functionality of iTENGs. Prolonged contact of iTENGs with human tissue can also lead to corrosion, which is the degradation of materials due to chemical reactions with their surrounding environment [88]. In the case of iTENGs, corrosion can occur when the device is exposed to bodily fluids and electrolytes, causing the material to undergo oxidation or other corrosive processes. Corrosion can have detrimental effects on the performance and structural integrity of iTENGs. It can result in the degradation of electrode materials, leading to reduced conductivity and energy generation efficiency [68]. Corrosion can also cause the release of metal ions or other corrosive byproducts, which may trigger inflammatory responses, tissue damage, and even systemic toxicity. Furthermore, corrosion-induced structural damage can compromise the mechanical stability of the device, increasing the risk of device failure or dislodgement [89]. To mitigate corrosion in iTENGs, the selection of corrosion-resistant materials, protective coatings, and appropriate device design is crucial. Adequate biocompatibility and long-term stability of iTENGs can be achieved by addressing the corrosion challenges and ensuring the durability and reliability of the device within the biological environment [90].

2.1. Core Triboelectric Layer

The core friction layer is a critical component of iTENGs because it is responsible for generating electrical energy through the triboelectric effect [13,17,91]. This layer is typically made of a material with high triboelectric properties, which means that it is capable of generating a large amount of electrical charge through contact with another surface [10,35,92].

There are several materials that are commonly used for the core friction layer in iTENGs [93,94]. Polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE), for example, are two materials that have high triboelectric properties and are frequently used in iTENG applications [37,95]. As shown in Figure 2a, Jin, C. et al., report a facile method to fabricate substrate-free energy harvesters with ZnO nanoarrays directly and fully embedded in a PDMS elastomer matrix, which has similar mechanical properties to human skin [69]. The device can harvest energy from finger movements and heartbeats using in vitro and in vivo testing. PDMS is a common choice for the core tribological layer because it has high triboelectric properties and can generate a large amount of charge through contact with another surface. Furthermore, PDMS can be easily patterned into various shapes and sizes using techniques such as soft lithography, allowing complex device structures to be fabricated. One of the challenges of using PDMS as a core friction layer is optimizing the surface roughness of the material. The triboelectric effect is highly dependent on the surface topography of the material, and the performance of PDMS-based iTENGs can be enhanced by controlling the surface roughness of the material to increase the contact area with other surfaces.

In addition to this, some other materials are used for the friction core layer [37,96]. Hydrogels have been investigated as potential materials for the core friction layer in iTENGs [97]. Hydrogels are a class of materials that are composed of a network of crosslinked polymer chains that can absorb and retain large amounts of water. One advantage of using hydrogels in iTENGs is their high biocompatibility, which makes them well-suited for use in biomedical applications [39,40]. Hydrogels can be made from a variety of materials, including natural polymers such as collagen and chitosan, as well as synthetic polymers such as polyethylene glycol (PEG) and polyacrylamide (PAA) [57]. Some hydrogels can also exhibit high triboelectric properties, which makes them a potentially attractive material for use in the core friction layer [98]. In Figure 2b, Wang, Z. et al., reported a new MXene-based polyacrylamide (PAM) hydrogel with high mechanical stretchability and excellent ionic conductivity [78]. The hydrogel has good biocompatibility, high capacitance, high flexibility, and long-term stability and is suitable for wearable energy storage devices and implanted electronic devices. The hydrogel can be implanted in rats as an implantable generator. However, there are also some challenges associated with using hydrogels as the core friction layer in iTENGs. One issue is that hydrogels can be relatively soft and may not exhibit the mechanical durability required for long-term use in implantable devices. Additionally, the performance of hydrogel-based iTENGs can be influenced by factors such as the water content of the hydrogel, the composition of the hydrogel, and the surface roughness of the other material in contact with the hydrogel. Overall, while hydrogels hold promise as a potential material for the core friction layer in iTENGs, further research is needed to fully understand their properties and optimize their performance for use in practical devices [36,78].

2.2. Electrode Layer

The electrode layer is an important component of iTENGs. It is responsible for collecting and transmitting the electrical charges generated by the core friction layer to an external device or storage device [99]. The electrode layer is typically composed of a conductive material that can provide a low resistance path for the flow of electrical charge [96]. There are different materials that can be used as the electrode layer in iTENGs, including metals such as gold, silver, and platinum, as well as conductive polymers [97]. These materials have good electrical conductivity and can be deposited on the surface of the core friction layer using a variety of techniques, such as physical vapor deposition, chemical vapor deposition, or solution-based methods. One important consideration for the electrode layer in iTENGs is its biocompatibility [100]. As shown in Figure 2c, Zheng, J. et al., prepared core–shell $BaTiO_3$/PVDF-TrFE composite membranes. Then, the metal mesh was covered on the composite film as an electrode [70]. A composite film with well-organized nanostructures and interconnecting pores was thus manufactured. Since the device is intended for implantation into the human body, it is essential that the materials used do not cause any harm to the surrounding tissue.

Another important factor to consider for the electrode layer is its mechanical flexibility [101,102]. Since iTENGs are intended for use in flexible and dynamic environments, the electrode layer must be able to withstand repeated bending and stretching without losing its electrical conductivity [103,104]. As shown in Figure 2d, Shlomy, I. et al., will implant an integrated tactile TENG (TENG-IT) device under the skin and convert tactile pressure into electrical potential, which is transmitted to healthy sensory nerves using cuff electrodes to stimulate them and mimic touch [79]. A system for providing tactile sensation to rats was implemented using in vivo testing. By ensuring the mechanical flexibility of the electrode layer, iTENGs can be more comfortable for the wearer and better accommodate the natural movements of the human body. This flexibility is particularly important for implantable devices, as it allows the device to conform to the curved and dynamic surfaces within the body without causing discomfort or tissue damage. Moreover, the mechanical flexibility of the electrode layer also influences the overall durability and longevity of the iTENG device. A flexible electrode layer is more resistant to cracking or delamination, ensuring the stable performance of the device over time and under various mechanical stresses. Continued research efforts are focused on developing electrode materials and substrates with enhanced mechanical flexibility, stretchability, and durability, which will contribute to the advancement and practical implementation of iTENGs in various biomedical and wearable electronics applications [105–107].

Overall, the electrode layer is a critical component of iTENGs, and the selection of the appropriate material is essential for achieving optimal performance and biocompatibility of the device [38,108]. By developing new electrode materials and deposition techniques, it is likely that the performance and functionality of iTENGs will continue to improve in the future [109–111].

2.3. Encapsulation Layer

The encapsulation layer in an iTENG serves as a protective barrier, shielding the device's internal components from external influences and providing biocompatibility if the device is intended for implantation in the human body [110]. The encapsulation layer ensures the longevity and functionality of the iTENG by preventing moisture ingress, physical damage, and degradation of the device [71,112,113].

When selecting a material for the encapsulation layer, considerations such as biocompatibility, mechanical properties, and barrier performance are essential [114,115]. Biocompatible materials are crucial to avoid adverse reactions or tissue responses when the iTENG is implanted in the body. Commonly used biocompatible materials for the encapsulation layer include medical-grade silicone, polyurethane, or other polymers that have been approved for implantation. As shown in Figure 2e, Zhang, Y. et al., prepared conductive and injectable XG-TMAT-STMP hydrogels. Additionally, TENG was prepared as a self-powered power source for triggering on-demand drug release [80]. The PDMS used has good biocompatibility and can be used for in vivo implantation [116]. The mechanical properties of the encapsulation layer are important to ensure the device can withstand external stresses, such as bending or stretching, without compromising its functionality. The encapsulation layer should possess adequate flexibility and elasticity to accommodate the natural movements of the surrounding tissues or wearable applications [117].

In addition to biocompatibility and mechanical properties, the encapsulation layer must provide an effective barrier against moisture, gases, and other potentially harmful substances. It should prevent water vapor, oxygen, or contaminants from reaching the sensitive components of the iTENG, as these can cause performance degradation or damage over time. The encapsulation layer's barrier properties can be enhanced by selecting materials with low permeability to moisture and gas or by employing additional coatings or barriers on the surface [118–120].

To ensure proper encapsulation, the layer is typically applied using techniques such as coating, spraying, or encapsulation molds during the fabrication process of the iTENG. The encapsulation layer is designed to fully cover and protect the core friction layer and electrode layer, forming a robust and reliable barrier against external elements [121]. As shown in Figure 2f, Yao, S. et al., prepared a self-powered, wearable, and stretchable single-electrode TENG by injecting a conductive LiCl solution as a liquid electrode into a sealed silicone rubber capsule [81]. The self-powered TENG combined with an implantable nitric oxide release device can be used for the treatment of intracranial gliomas [122].

By providing a protective and biocompatible encapsulation layer, the iTENG can maintain its performance, reliability, and longevity during long-term implantation or wearable use. Ongoing research in encapsulation materials and techniques aims to improve the durability, biocompatibility, and overall performance of iTENG devices in various applications [123,124].

2.4. Degradable Material

Degradable materials are an intriguing area of research for iTENGs because they offer unique advantages in certain applications. Degradable materials have the ability to break down over time, either using chemical reactions or biological processes, into smaller components that can be naturally absorbed or eliminated from the body. This property allows for temporary use of the device without the need for surgical removal [21]. The degradable material used in iTENGs can be categorized into two main types, which are spontaneous degradable materials and controllably degradable materials [125–128].

Spontaneous degradable materials, also known as inherently degradable materials, refer to those that naturally degrade over time without external control or stimuli. These materials undergo degradation using natural processes such as hydrolysis, enzymatic breakdown, or metabolic reactions [129–132]. Spontaneous degradable materials are particularly valuable for applications where long-term implantation is not required or where the device's function is intended to be temporary. By utilizing these materials, iTENGs can degrade naturally and be absorbed by the body, eliminating the need for surgical removal. Biodegradable polymers can degrade through natural biological processes [133,134]. Common examples include polylactic acid (PLA), polyglycolic acid (PGA), and their copolymer poly (lactic-co-glycolic acid) (PLGA). These polymers have been extensively investigated for medical applications due to their biocompatibility and controllable degradation rates. Hydrolytically degradable polymers undergo degradation in the presence of water. Polyesters like poly(caprolactone) (PCL) and poly (lactic acid) (PLA) are examples of hydrolytically degradable materials that have been used in various biomedical devices. These materials can be tailored to degrade over specific timeframes, allowing for temporary use of iTENGs. Some naturally derived materials, such as silk fibroin and cellulose, possess inherent biodegradability. These materials offer advantages like biocompatibility, mechanical strength, and tunable degradation rates, making them attractive for use in iTENGs. As shown in Figure 3a, Zheng, Q. et al., reported a biodegradable triboelectric nanogenerator for the collection of biomechanical energy in vivo, which can be degraded and reabsorbed in animals after completing the work cycle without any adverse long-term effects [30]. It generates a DC pulse electric field and successfully directs the growth of nerve cells, indicating its feasibility in the process of neuronal repair. As shown in Figure 3b, Xiao, X et al., developed an ultrasound-driven, biodegradable, and injectable TENG [59]. It can reduce the risk of implant-related damage and infection. Its main structure decomposes in about 15 days. As shown in Figure 3c, Kang, M. et al., studied a naturally sourced chi arrageenan agar composite material as a high-performance friction and electric friction material that can be biodegradable TENG [61]. They found that the chi arrageenan agar complex has high biocompatibility because it exhibits high cell viability in MTT analysis, and the subdermal implant hardly causes significant inflammation.

Controllable degradable materials refer to those that can be designed to degrade at a controlled rate or in response to specific stimuli. These materials allow researchers to precisely tune the degradation properties of the iTENG to meet specific application requirements. By blending different polymers or incorporating degradable fillers, researchers can create composite materials with tailored degradation rates. pH-responsive polymers can degrade in response to changes in pH levels. These materials are particularly useful for applications in the body, where pH variations can trigger controlled degradation. pH-responsive polymers can be designed to degrade gradually or rapidly, depending on the desired timeline for device degradation. Light-sensitive or photosensitive materials can be employed as degradable components in iTENGs. These materials degrade upon exposure to specific wavelengths of light, providing a means for on-demand degradation. For instance, materials that undergo photodegradation upon exposure to ultraviolet (UV) light can be used to achieve controlled degradation of the iTENG. As shown in Figure 3d, Niu, Q. et al., have prepared a new type of wire with excellent conductivity, bioabsorbability, biocompatibility, and low weight [37]. Compared to traditional metal wires, this type of wire has higher transmission efficiency, biodegradability, better biocompatibility, and is lighter. The wire and the integrated fully bioabsorbable energy generation device can be used in the field of wearable electronics and implantable bioelectronics. As shown in Figure 3e, Niu, Q. et al., prepared biological TENG based on silk nanoribbons using newly formed silk nanoribbons and regenerated silk fibroin membranes [135]. In order to maintain the original mesoscale/nanoscale structure of silk, a silk nanotape film with a thickness of

0.38 nm was directly peeled off from natural silk. The degradation rate of TENG depends on the post-treatment of encapsulation. As shown in Figure 3f, Li, Z. et al., prepared a series of biodegradable TENGs and effectively regulated their degradation process in vivo by using Au nanorods sensitive to near-infrared light [136]. The degradation processes in the body can be triggered and quickly take effect.

The incorporation of degradable materials in iTENGs opens up opportunities for applications where long-term implantation is not required or where the device's function is time-limited [30]. For example, in temporary biomedical implants like drug delivery systems or tissue scaffolds, degradable iTENGs can provide self-sustaining power during the desired timeframe before naturally degrading and being absorbed by the body. The degradation characteristics of these materials can be tailored by adjusting parameters such as molecular weight, polymer composition, and crosslinking density. The degradation kinetics can be influenced to match specific application requirements, ensuring that the device remains functional for the desired duration [137]. However, it's important to note that the use of degradable materials in iTENGs also presents challenges. Controlling the degradation rate and maintaining stable device performance during the degradation process are key considerations. Additionally, the byproducts of degradation should be non-toxic and easily eliminated by the body. By harnessing the benefits of degradable materials, iTENGs have the potential to enable new applications in temporary biomedical implants and environmental monitoring systems [100,138].

2.5. Common Materials

The common materials used in iTENGs include PTFE, PDMS, and PVA. PTFE is often used as the core friction layer due to its low friction coefficient and excellent triboelectric properties [73]. PDMS is utilized as the encapsulation layer, offering biocompatibility, transparency, and electrical insulation [139]. PVA finds applications in both the core friction layer and encapsulation layer, providing triboelectric properties, flexibility, biocompatibility, and processability [140]. These materials contribute to the development of iTENGs with enhanced energy harvesting capabilities, biocompatibility, and durability, enabling their seamless integration with biological systems [141].

As shown in Figure 4a–c, PTFE (Polytetrafluoroethylene) is a commonly used material in the development of iTENGs [60,65]. As the core friction layer or encapsulation layer, PTFE offers several advantages that make it suitable for biomedical applications. One of the key features of PTFE is its excellent biocompatibility. It has a low reactivity with biological tissues, minimizing the risk of adverse reactions or inflammation when in contact with the human body. This biocompatibility is crucial for ensuring the long-term functionality and safety of implantable devices [142]. PTFE can also be used for efficient energy conversion in iTENGs. When in contact with other materials, such as silicone or metals, PTFE can generate significant triboelectric charges using frictional forces. This enables the conversion of mechanical energy into electrical energy, which can be utilized to power biomedical devices or sensors. Furthermore, PTFE possesses excellent chemical and thermal stability. It is resistant to degradation from exposure to bodily fluids or harsh environments, ensuring the durability and longevity of iTENGs. This stability is particularly important for implantable devices that need to maintain their performance over an extended period. In summary, PTFE is a promising material for iTENGs due to its biocompatibility, low friction coefficient, and chemical stability. By incorporating PTFE into the design of iTENGs, researchers and engineers can develop self-powered biomedical devices that are reliable, efficient, and compatible with the human body [39].

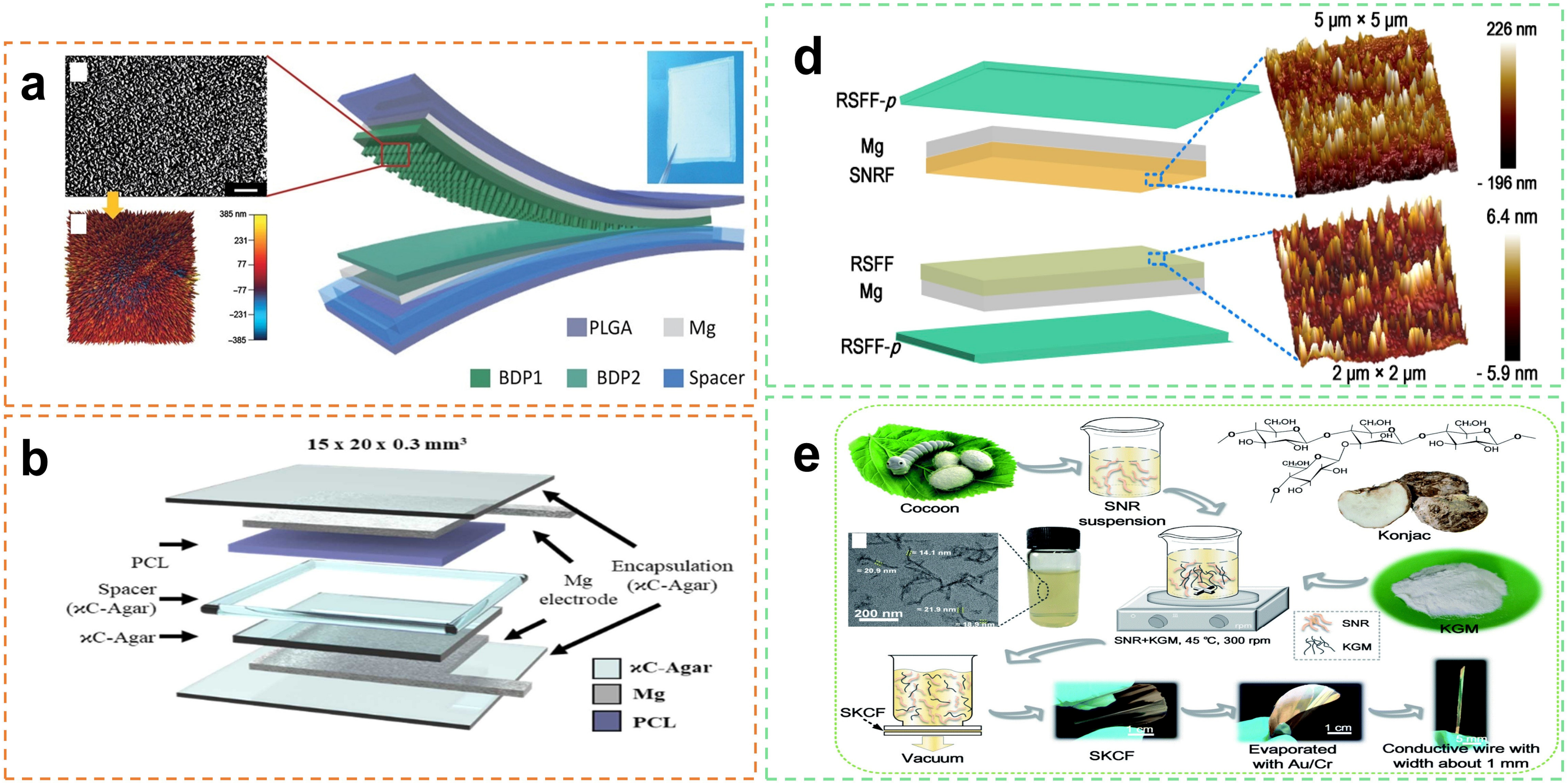


Figure 3. *Cont.*

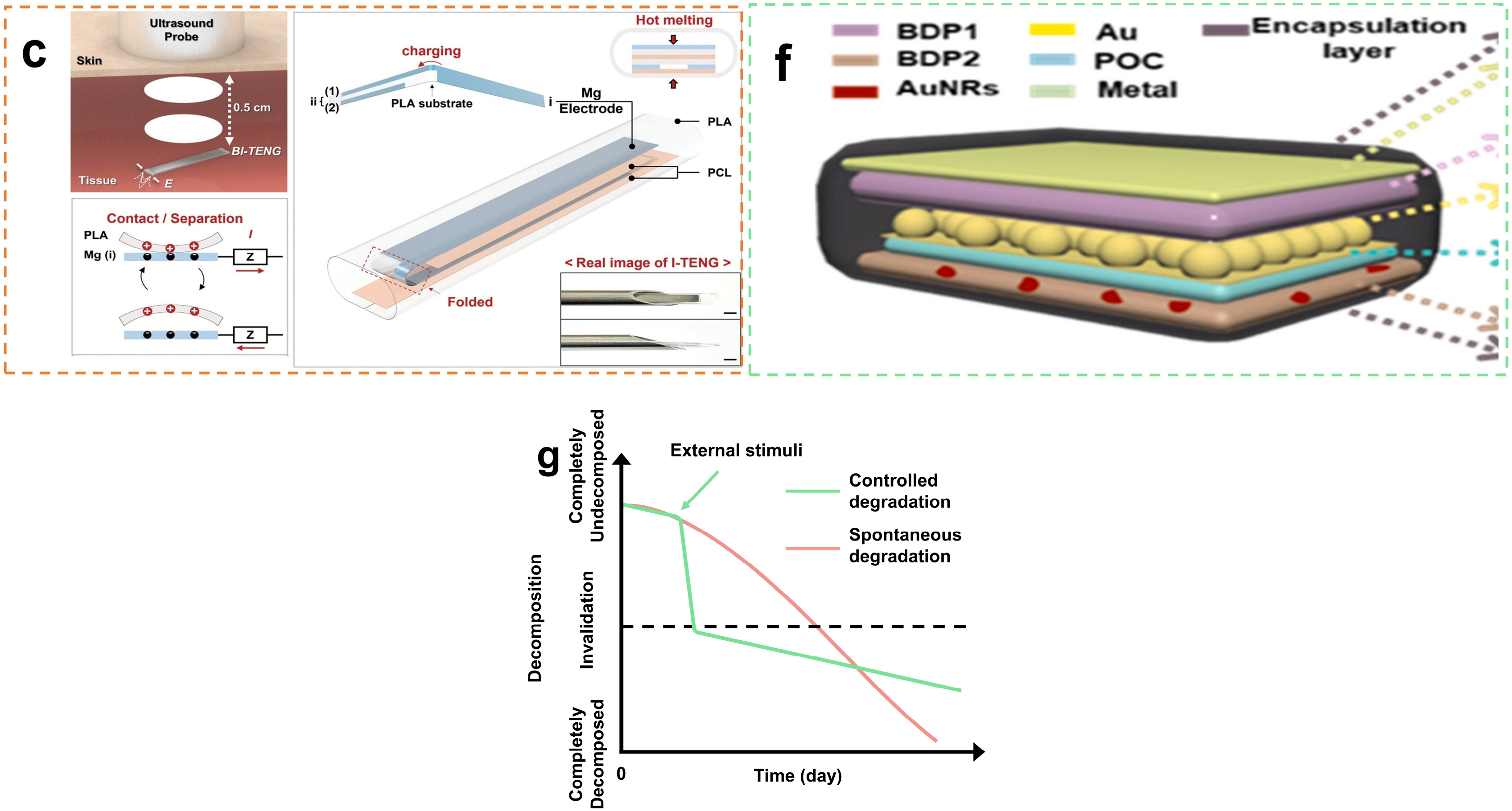


Figure 3. (**a**) Spontaneous degradable materials. Reprinted with permission from Ref. [30]. Copyright 2016, AAAS. (**b**) Spontaneous degradable materials. Reprinted with permission from Ref. [61]. Copyright 2022, Elsevier B.V. (**c**) Spontaneous degradable materials. Reprinted with permission from Ref. [59]. Copyright 2023, John Wiley & Sons, Inc. (**d**) Controllable degradable materials. Reprinted with permission from Ref. [37]. Copyright 2020, Elsevier B.V. (**e**) Controllable degradable materials. Reprinted with permission from Ref. [135]. Copyright 2023, AIP Publishing. (**f**) Controllable degradable materials. Reprinted with permission from Ref. [136]. Copyright 2018, Elsevier B.V. (**g**) Comparison of degradation rates among different degradation modes. Green curve represents a controlled degradation mode, while red curve represents a spontaneous degradation mode. After being stimulated by external stimuli, the controlled degradation mode will exhibit significant degradation acceleration.

As shown in Figure 4d–f, PDMS (Polydimethylsiloxane) is a versatile material that finds applications in various fields, including the development of iTENGs [63,67]. In the context of iTENGs, PDMS is primarily used in the core friction layer, encapsulation layer, or as a substrate for electrode deposition. PDMS offers several advantageous properties that make it suitable for implantable devices. Firstly, it exhibits excellent biocompatibility, meaning it is well-tolerated by living tissues and does not cause adverse reactions or inflammation. This biocompatibility is crucial for the long-term performance and safety of implantable devices, ensuring their compatibility with the human body. Another important characteristic of PDMS is its flexibility and elasticity. It is a soft and stretchable material that can conform to irregular shapes and withstand mechanical deformations without losing its functionality. This flexibility is particularly beneficial for implantable devices as it allows for comfortable integration with the surrounding tissue, minimizing discomfort or interference [143]. PDMS is also optically transparent, allowing for easy monitoring and visualization of the underlying tissues or structures. This property is advantageous for applications where real-time imaging or monitoring is necessary, such as in biomedical sensors or diagnostic devices. Additionally, PDMS exhibits good chemical resistance, protecting the underlying components of iTENGs from potential damage caused by bodily fluids or environmental factors [144]. It is also relatively easy to process and fabricate, enabling the production of complex device structures or customized designs. In summary, PDMS is a versatile material that offers excellent biocompatibility, flexibility, transparency, and chemical resistance, making it a suitable choice for various components in iTENGs. By utilizing PDMS in the design and fabrication of iTENGs, researchers and engineers can develop implantable devices that are reliable, biocompatible, and capable of generating electrical energy for self-powered biomedical applications [67].

PVA (Polyvinyl Alcohol) is a promising material used in the development of iTENGs, as shown in Figure 4g–i [30,62]. It offers unique properties that make it suitable for various components within these devices. In the iTENGs, PVA is commonly utilized as the core friction layer. The core friction layer is responsible for generating triboelectric charges through contact and separation movements. PVA possesses excellent triboelectric properties, allowing it to efficiently generate static charges when in contact with other materials. This characteristic is essential for the effective functioning of the iTENG, as it enables the conversion of mechanical energy into electrical energy. Furthermore, PVA exhibits exceptional mechanical properties, including high tensile strength and flexibility. These properties are crucial for the core friction layer, as it undergoes repeated cycles of contact and separation during device operation [145]. The mechanical robustness of PVA ensures that the core friction layer can withstand these movements without significant degradation or failure. Another advantage of PVA is its biocompatibility. PVA is a biocompatible polymer that is widely used in medical and biomedical applications. When used in implantable devices, PVA shows compatibility with living tissues, minimizing adverse reactions and inflammation. This biocompatibility is essential for the long-term functionality and safety of implantable devices, allowing them to interact harmoniously with the surrounding biological environment. Additionally, PVA can be easily processed and fabricated into various shapes and forms, enabling the design of customized iTENG structures. It is soluble in water, allowing for straightforward casting or deposition techniques to create the desired device configuration. This flexibility in fabrication techniques facilitates the integration of PVA-based iTENGs into different biomedical applications. In summary, PVA is a versatile material for the development of iTENGs. Its exceptional triboelectric properties, mechanical robustness, biocompatibility, and ease of processing make it an attractive choice for the core friction layer in iTENGs. By leveraging the unique properties of PVA, researchers can design and create implantable devices capable of generating electrical energy from mechanical movements, opening up new possibilities for self-powered biomedical applications [78].

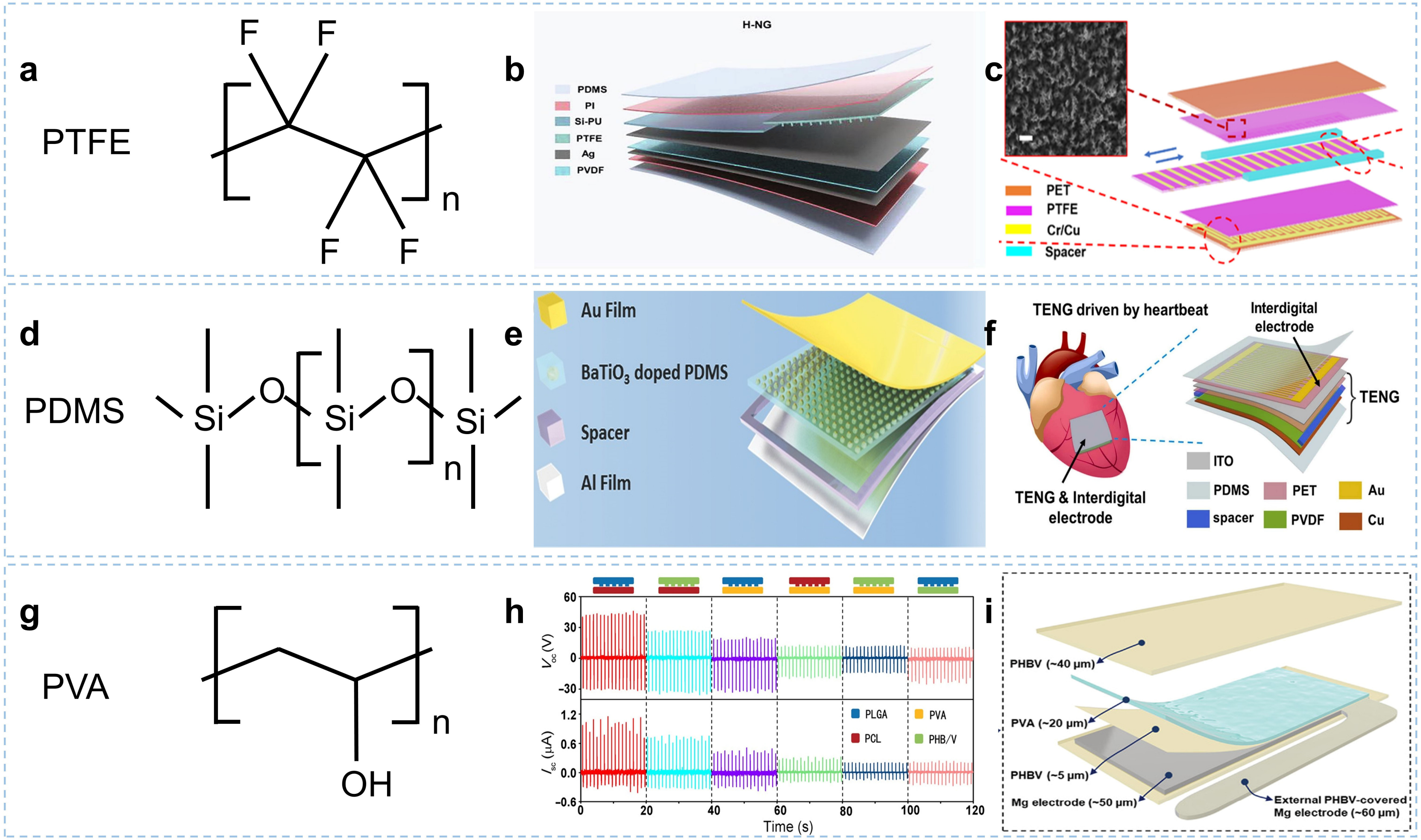


Figure 4. Common materials of iTENG. (**a**) PTFE. (**b**) PTFE. Reprinted with permission from Ref. [60]. Copyright 2022, Elsevier B.V. (**c**) PTFE. Reprinted with permission from Ref. [65]. Copyright 2018, American Chemical Society. (**d**) PDMS. (**e**) PDMS. Reprinted with permission from Ref. [65]. Copyright 2016, John Wiley & Sons, Inc. (**f**) PDMS. Reprinted with permission from Ref. [63]. Copyright 2022, Elsevier B.V. (**g**) PVA. (**h**) PVA. Reprinted with permission from Ref. [30]. Copyright 2016, AAAS. (**i**) PVA. Reprinted with permission from Ref. [62]. Copyright 2022, John Wiley & Sons, Inc.

The chapter focuses on the materials used in iTENGs, exploring the core triboelectric layer, electrode layer, encapsulation layer, and degradable materials. The core triboelectric layer plays a vital role in generating electricity through frictional interactions. Various materials, such as hydrogels and PDMS, are commonly used in this layer due to their excellent mechanical flexibility, biocompatibility, and triboelectric properties [146]. The electrode layer, responsible for collecting and transferring the generated charges, requires materials with high electrical conductivity and mechanical flexibility. Materials like metals, conductive polymers, and carbon-based materials are often employed in this layer. The encapsulation layer serves to protect the internal components of the iTENG, and materials with good biocompatibility, mechanical strength, and barrier properties are preferred [22]. Furthermore, the chapter discusses the use of degradable materials in iTENGs, which can undergo controlled degradation over time, making them suitable for transient or temporary applications. The development of such materials allows for the design of implantable devices that can degrade safely within the body without causing long-term complications. Overall, the chapter highlights the significance of material selection and design considerations in iTENGs, aiming to enhance their performance, biocompatibility, and potential applications in various healthcare and biomedical fields [24,40].

3. Structures

The four power generation modes of the triboelectric nanogenerator are as follows: contact–separation mode, horizontal sliding mode, single-electrode mode, and independent layer mode [106,147–150]. In the contact–separation mode, the contact and separation between two materials is achieved by vertical motion. When two materials are in contact, charges are transferred from one material to another due to the contact electrification effect, causing equal but opposite charges to be generated on the surfaces of the two materials. Then, when the two materials separate, the potential difference drives charge back and forth between the electrodes using an external circuit due to electrostatic induction, generating electricity [151–153]. The triboelectric nanogenerator in horizontal sliding mode has a slidable upper plate. Initially, the two materials overlap completely and are in close contact, so the surface charge is evenly distributed. However, when the upper plate slides, the reduced contact area causes charge separation, causing a potential difference between the surfaces of the two materials. This potential difference drives electrons to flow between the upper and lower electrodes, generating electricity. The triboelectric nanogenerator in single-electrode mode has only one main electrode, and the other electrode is the ground electrode. This mode is different from others because the triboelectric nanogenerator works through the combined effect of triboelectrification and electrostatic induction rather than through the contact and separation between the two materials. In this mode, the reference electrode acts to guide the charge transfer while the main electrode collects and outputs the generated electrical energy. The independent layer mode is a special triboelectric nanogenerator structure consisting of a movable dielectric layer and a pair of fixed electrodes. The key in this pattern is the movement of the dielectric layer, which causes charges to be unevenly distributed between the materials, creating a potential difference. This potential difference drives electrons to move between the two stationary electrodes, thereby generating electrical energy [14,154,155].

For iTENGs, commonly used power generation modes include vertical contact–separation mode, single-electrode mode, and free-standing mode [40,53,76,145,156]. These patterns have certain advantages and applicability in implantable applications. In the vertical contact–separation mode, the contact and separation between two materials is achieved by vertical motion [157,158]. This mode is suitable for the movement process of implantable devices, such as joint movement, breathing, etc. Through the combination of contact electrification and electrostatic induction effects, implantable devices can generate electrical energy during motion and provide continuous electrical support for organisms. The single-electrode mode has the advantages of certain flexibility and simplified structure in implantable applications. In this mode, only one main electrode and one ground electrode are required, simplifying the device fabrication and implantation process. The main electrode is in contact with the implantable tissue and guides charge transfer through the reference electrode to realize energy conversion and power generation. This mode is suitable for applications requiring long-term implantation in biological tissues. The free-standing mode is a flexible and diverse power generation mode for iTENGs. The non-uniform distribution of charge and the generation of potential difference can be achieved through the moving dielectric layer and fixed electrodes. This mode can be applied to different implant structures, such as implantable catheters, implantable sensors, etc., to achieve energy harvesting and utilization. The choice of these power generation modes depends on the specific implant application requirements, including implant location, motion mode, material selection, etc. By rationally designing and optimizing the power generation mode, iTENGs can provide a long-lasting and reliable energy supply for medical devices, biosensors, and other implanted electronic devices.

3.1. Contact–Separation Mode

The vertical contact–separation mode is one of the commonly used power generation modes in iTENGs and has broad application prospects [112,157,159]. In this mode, using the combination of contact electrification and electrostatic induction, the triboelectric nanogenerator can utilize the motion of the implanted site or the effect of the external environment to generate a continuous power supply [160–162]. This model is suitable for a variety of implantable medical devices, sensors, and biological implants. For implantable medical devices such as pacemakers and neurostimulators, the vertical contact–separation mode can provide the energy needed to ensure the normal operation of the device. For implantable sensors, triboelectric nanogenerators can collect environmental parameters and physiological signals using the movement of human joints or external pressure and provide power and signal transmission for sensors. In addition, for various bio-implanted devices, such as implantable heart assist devices and electronic drug delivery systems, the vertical contact–separation mode can use the motion of the device or the dynamics inside the organism as the energy source to meet the energy demand of the device. As shown in Figure 5a, Yao, G. et al., proposed a self-powered implantable and bioabsorbable fracture electrical stimulation device, which consists of a friction electric nanogenerator for power generation and a pair of dressing electrodes for directly applying electrical stimulation to fractures [71]. They designed highly flexible and sharp micro cones, which can be activated by many types of body movements, such as muscle stretching and knee bending, for generating electrical pulses through contact separation movements. As shown in Figure 5b, Zhao, L. et al., proposed a TENG-based flexible self-powered implantable electrostimulator that induces myocardial cell maturation by generating an electric field on the interdigital electrode [63]. Various nano/micron patterns were prepared on the friction surface of TENG, using a vertical contact separation mode as an implantable medical electronic device. Overall, the vertical contact-separation mode brings great potential to iTENGs, promotes the development of implantable medical technology and bio-implantable devices, and provides better biomedical applications for new possibilities [70].

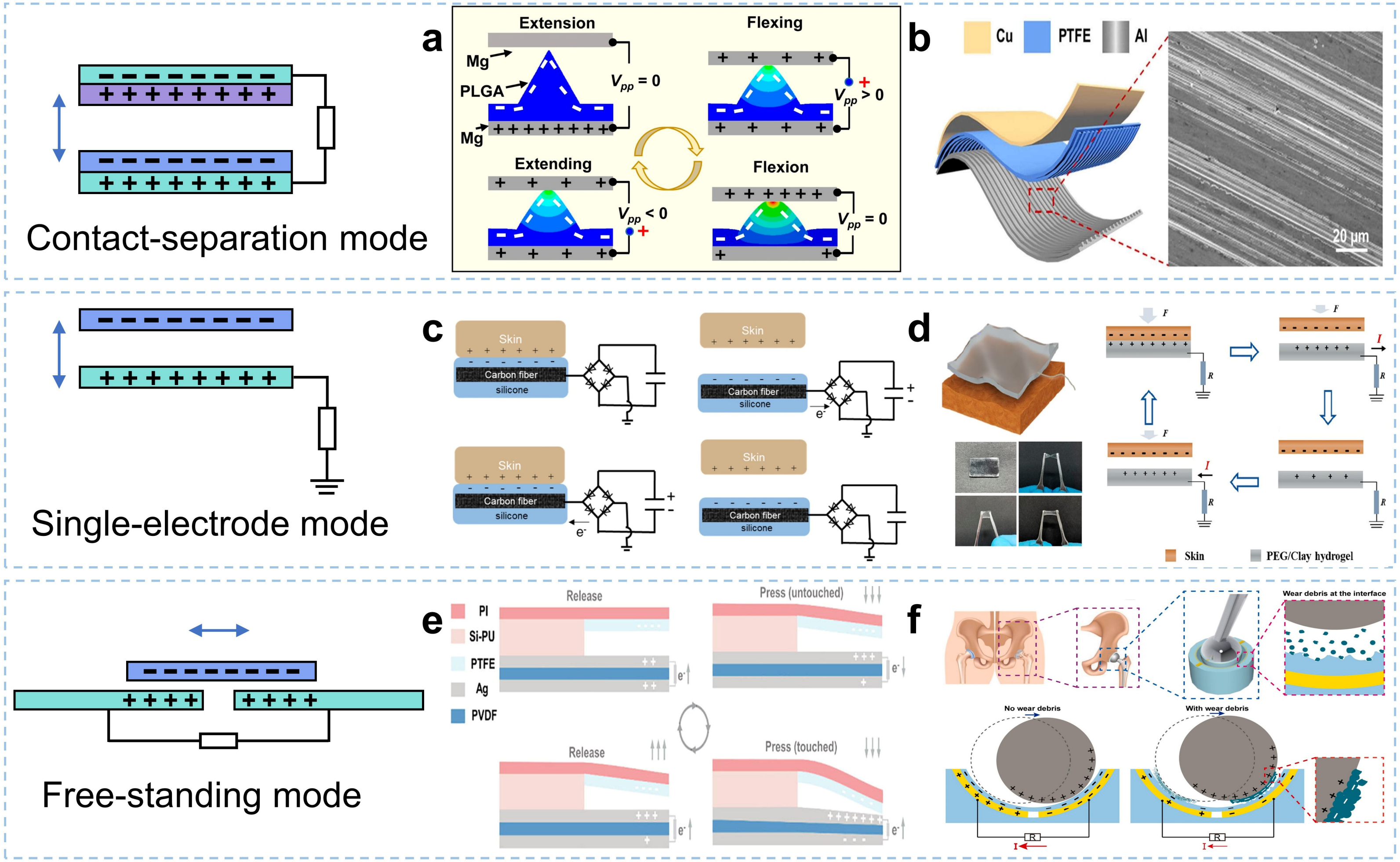


Figure 5. Structures of iTENG. (**a**) Contact–separation mode. Reprinted with permission from Ref. [63]. Copyright 2022, Elsevier B.V. (**b**) Contact–separation mode. Reprinted with permission from Ref. [71]. Copyright 2021, National Academy of Science. (**c**) Single-electrode mode. Reprinted with permission from Ref. [32]. Copyright 2018, Elsevier B.V. (**d**) Single-electrode mode. Reprinted with permission from Ref. [36]. Copyright 2023, American Chemical Society. (**e**) Free-standing mode. Reprinted with permission from Ref. [60]. Copyright 2022, Elsevier B.V. (**f**) Free-standing mode. Reprinted with permission from Ref. [64]. Copyright 2021, Elsevier B.V.

3.2. Single-Electrode Mode

The single-electrode mode is one of the commonly used power generation modes in iTENGs [64,163]. In this mode, the generator consists of only one main electrode, usually fixed in position, while the other electrode is directly grounded. The single-electrode mode achieves charge transfer and power generation using the combined effects of triboelectrification and electrostatic induction. In iTENGs, the single-electrode mode has a wide range of applications [11]. First, it is suitable for implantable medical devices such as pacemakers and neurostimulators. These devices require a steady supply of energy to maintain their proper function. Using a triboelectric nanogenerator in single-electrode mode, movement within the device or external stimulation can trigger charge transfer and potential difference generation to provide the desired electrical energy. Second, the single-electrode mode can be used for implantable biosensors. These sensors are used to monitor information such as physiological parameters and disease states. Using the single-electrode mode of the triboelectric nanogenerator, the sensor can be powered by the energy generated by the motion of the organism or external stimuli to realize real-time data acquisition and transmission. In addition, the single-electrode mode is also suitable for implantable drug delivery systems. In this system, triboelectric nanogenerators generate electrical energy through the movement of the implanted device or friction with surrounding tissue to provide the required energy for the drug delivery system. In this way, the release rate and timing of the drug can be precisely controlled, enabling customized drug delivery. The single-electrode model has the advantages of simplicity and flexibility. Since only one main electrode is needed, its design and manufacture are relatively simple, and it can meet the needs of various implantable devices. In addition, the single-electrode mode reduces system complexity and size, improving the reliability and durability of implanted devices. As shown in Figure 5c, Jiang, Q. et al., designed a single electrode TENG based on carbon fiber embedded in silicone resin [32]. When human skin comes into contact with silicone, its surfaces generate positive and negative charges. Generate a potential difference between the two input terminals of the bridge rectifier. This device can utilize and store random energy from human activities in standby mode. As shown in Figure 5d, Li, Z. et al., prepared PEGDA/Lap nanocomposite hydrogel based on biocompatible polyethylene glycol diacrylate and laponite and constructed biodegradable single electrode TENG [36]. Use a single electrode mode to come into contact with the skin to collect energy. In summary, the single-electrode mode has broad application potential in iTENGs. It provides reliable and sustainable energy solutions for implantable medical devices, biosensors, drug release systems, etc., promotes the development of implantable medical technology, and provides a new way to achieve higher-level biomedical applications.

3.3. Free-Standing Mode

The free-standing mode is one of the commonly used power generation modes in iTENGs [125,164]. It consists of a movable dielectric layer and a pair of fixed electrodes. In this mode, the movement of free-standings leads to non-uniform charge distribution, which drives electrons to move between two fixed electrodes, generating electrical energy. The free-standing mode has broad applications in iTENGs. First, it could be used to harvest the kinetic energy of living organisms around implants [37]. When the human body moves, the friction between the implant and the surrounding tissue generates mechanical energy, which can be converted into electrical energy through the triboelectric nanogenerator in the free-standing mode to provide continuous energy for the implanted device. Second, the free-standing model is suitable for implantable medical devices such as pacemakers and neurostimulators [165]. These devices require a reliable energy supply to keep them running. Using the triboelectric nanogenerator in the free-standing mode, the friction or movement of the device with the surrounding tissue can generate electrical energy to provide the required power for the medical device. Furthermore, the layer-independent paradigm is also suitable for implantable biosensors for monitoring physiological parameters and disease states [166]. Using the triboelectric nanogenerator in the free-standing mode, the sensor can be powered by the energy generated by the motion of the organism or external stimuli to realize real-time data acquisition and transmission [167]. In addition, the free-standing mode can be applied to implantable drug release systems, which can be used to provide energy to control the release rate and time of drugs. When the implant rubs or moves with the surrounding tissue, the triboelectric nanogenerator in the free-standing mode generates electricity to provide the required power for the drug release system to achieve precise drug delivery [160]. As shown in Figure 5e, Sun, Y. et al., designed a closed-loop self-powered LL-VNS system that can monitor the patient's pulse wave status in real-time and automatically transmit stimulus pulses during the development of atrial fibrillation [60]. The implant is a hybrid nanogenerator, which uses piezoelectric friction electricity for hybrid power generation. As shown in Figure 5f, Liu, Y. et al., have developed a TENG-based self-powered sensor for detecting wear debris generated in artificial joints [64]. Generate communication signals using the reciprocating motion of steel balls. As the reciprocating motion continues, more wear debris will adhere to the steel ball, resulting in a decrease in TENG's electrical output and monitoring of wear.

Overall, the free-standing mode has broad applications in iTENGs. It can collect the motion energy of living organisms, provide reliable energy solutions for implantable medical devices, biosensors, and drug release systems, promote the development of implantable medical technology, and achieve a higher level [168].

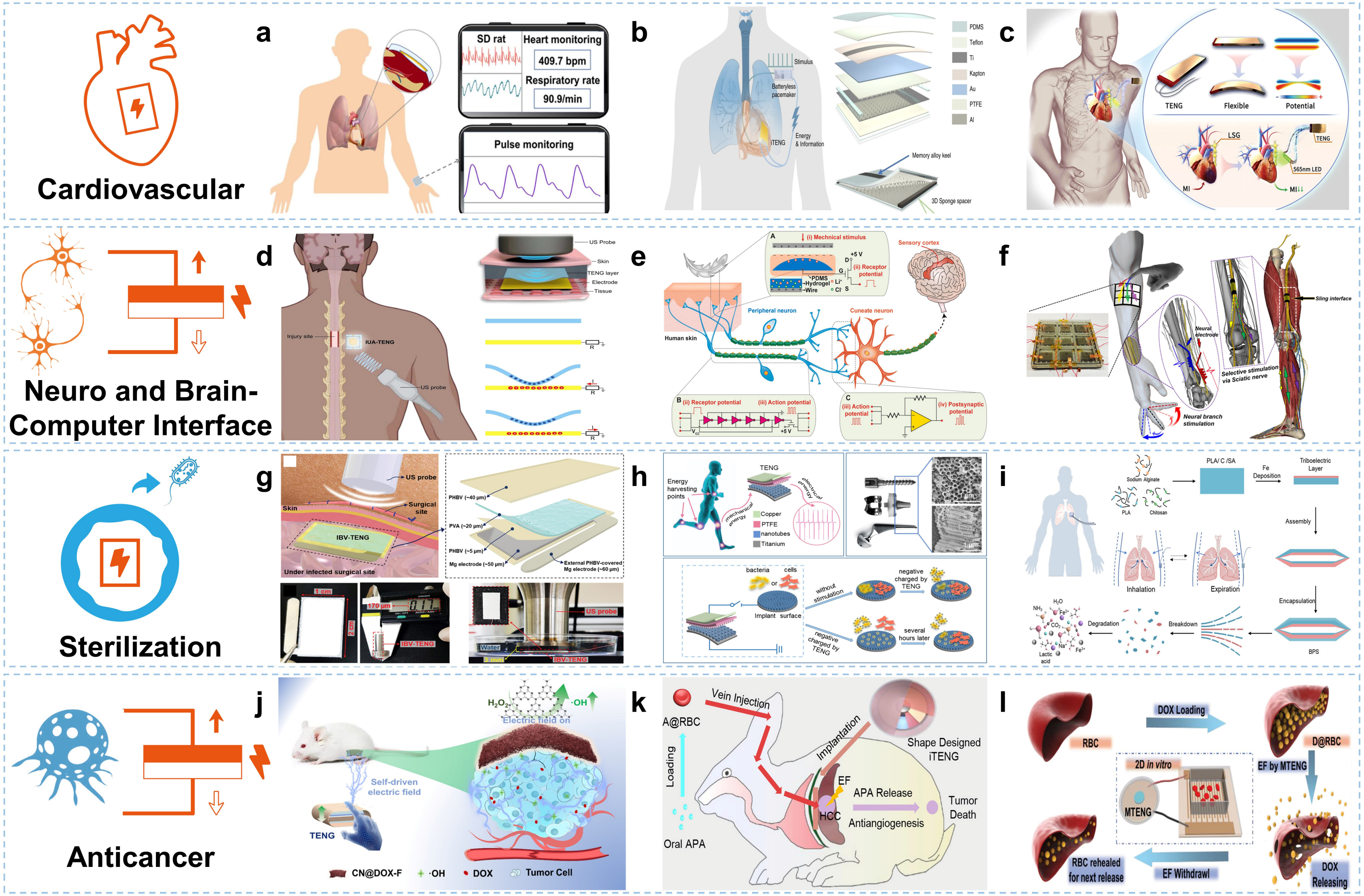
The chapter focuses on the structural design aspects of iTENGs, exploring three key modes of operation: contact–separation mode, single-electrode mode, and free-standing mode [26,69,169]. The contact–separation mode involves the generation of electricity using the combined effects of contact electrification and electrostatic induction. When two materials in contact experience relative motion, charge transfer occurs, resulting in the generation of opposite charges on their surfaces. The resulting potential difference drives charge flow through an external circuit. The single-electrode mode differs from the other modes as it employs only one main electrode, while a reference electrode is grounded [170]. Charge transfer between the reference and main electrodes occurs using a movable charging surface driven by friction and electrostatic induction. The free-standing mode utilizes a movable dielectric layer between two fixed electrodes. As the dielectric layer moves, it induces an uneven charge distribution, leading to charge flow between the electrodes to balance the potential distribution. These structural designs allow for versatile applications of iTENGs, enabling their integration into various biomedical devices and systems. The chapter emphasizes the importance of structural optimization for maximizing energy generation efficiency, improving device flexibility and conformability, and ensuring compatibility with different operating conditions. By understanding and harnessing the unique features of each structural mode, researchers can advance the development and implementation of iTENGs in diverse healthcare and wearable technology applications.

4. Application

4.1. Different Scope of Application

iTENGs have emerged as versatile devices with diverse applications across various organs in the human body [171]. They can be utilized in cardiovascular, nervous, gastrointestinal, musculoskeletal, respiratory, genitourinary, and ophthalmic systems, among others. By harnessing the mechanical energy generated by the body's movements and processes, iTENGs provide sustainable and self-powered solutions for a wide range of medical devices, including pacemakers, neural interfaces, gastrointestinal monitors, orthopedic implants, respiratory aids, urological devices, and ophthalmic implants. The integration of iTENGs in these organs and systems holds great potential for advancing implantable medical technologies and improving patient outcomes [172].

iTENGs can be utilized in cardiac devices such as pacemakers and implantable cardioverter-defibrillators [57,173–175]. These devices require a reliable power source to maintain optimal heart function. By harvesting energy from the mechanical motions of the heart, iTENGs can provide a self-sustaining power supply, reducing the need for frequent battery replacements and ensuring the continuous operation of cardiac devices. As shown in Figure 6a, Zhao, D. et al., have developed a kind of nanogenerator that can be manufactured by evaporating distilled water [158]. By installing it on the heart of rats, it can monitor normal heart movement with a heart rate accuracy of up to 99.73%. It can also monitor abnormal heart movements and detect subtle heart movements that cannot be captured by the electrocardiogram. As shown in Figure 6b, Ouyang, H. et al., demonstrated a fully implantable symbiotic pacemaker based on an implantable triboelectric nanogenerator, which can achieve energy collection and storage and cardiac pacing on a large animal scale [56]. It can successfully correct sinus arrhythmias and prevent the condition from worsening. It is expected to become a research on heart pacemakers that do not require battery replacement. As shown in Figure 6c, Zhou, L. et al., introduced a wireless self-powered optical gene modulation system that can achieve long-term precise cardiac nerve regulation in dynamic dogs [176]. The wireless self-powered optical system based on the triboelectric nanogenerator is driven by the energy obtained by human movement, which realizes the effective light illumination required by the optogenetic neural regulation (on). It can improve ventricular dysfunction, reduce infarct size, and increase electrophysiological stability.



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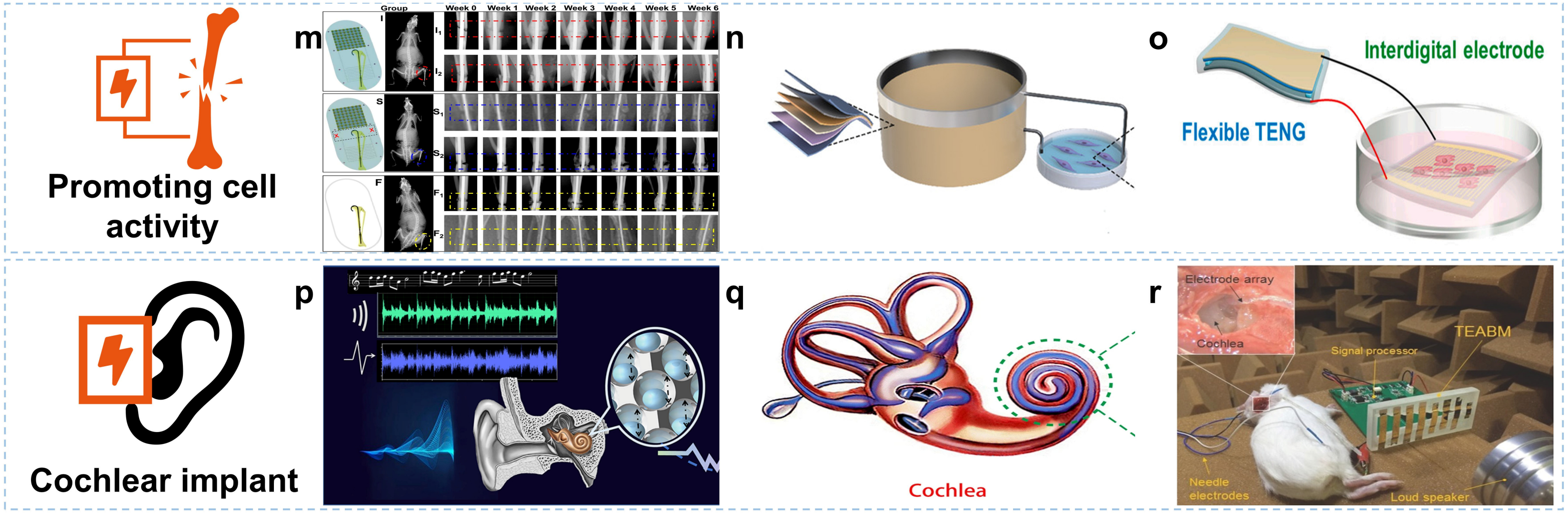

Figure 6. Application of iTENG. (**a**) Cardiac devices. Reprinted with permission from Ref. [158]. Copyright 2021, Elsevier B.V. (**b**) Cardiac devices. Reprinted with permission from Ref. [56]. Copyright 2023, Springer Nature Limited. (**c**) Cardiac devices. Reprinted with permission from Ref. [176]. Copyright 2023, John Wiley & Sons, Inc. (**d**) Neural interfaces and Brain–computer Interface. Reprinted with permission from Ref. [168]. Copyright 2021, Elsevier Ltd. (**e**) Neural interfaces and Brain–computer Interface. Reprinted with permission from Ref. [73]. Copyright 2021, Elsevier B.V. (**f**) Neural interfaces and Brain–computer Interface. Reprinted with permission from Ref. [177]. Copyright 2018, Elsevier B.V. (**g**) Sterilization systems. Reprinted with permission from Ref. [62]. Copyright 2022, John Wiley & Sons, Inc. (**h**) Sterilization systems. Reprinted with permission from Ref. [122]. Copyright 2020, Elsevier B.V. (**i**) Sterilization systems. Reprinted with permission from Ref. [178]. Copyright 2023, American Chemical Society. (**j**) Anticancer. Reprinted with permission from Ref. [179]. 2023, American Chemical Society. (**k**) Anticancer. Reprinted with permission from Ref. [180]. Copyright 2022, American Chemical Society. (**l**) Anticancer. Reprinted with permission from Ref. [181]. Copyright 2019, John Wiley & Sons, Inc. (**m**) Promoting cell maturation. Reprinted with permission from Ref. [71]. Copyright 2021, National Academy of Science. (**n**) Promoting cell maturation. Reprinted with permission from Ref. [182]. Copyright 2022, John Wiley & Sons, Inc. (**o**) Promoting cell maturation. Reprinted with permission from Ref. [63]. Copyright 2022, Elsevier B.V. (**p**) Cochlear implant. Reprinted with permission from Ref. [70]. Copyright 2022, American Chemical Society. (**q**) Cochlear implant. Reprinted with permission from Ref. [66]. Copyright 2018, Springer Nature. (**r**) Cochlear implant. Reprinted with permission from Ref. [183]. Copyright 2016, John Wiley & Sons, Inc.

iTENGs hold promise for neural interfaces and brain–computer interfaces. They can be integrated into implantable devices used for deep brain stimulation, neuroprosthetics, and brain-controlled interfaces [98,177,184,185]. The mechanical energy generated by movements within the body can be converted into electrical power by iTENGs, enabling the long-term and self-powered functionality of these devices. As shown in Figure 6d, Chen, L. et al., reported an ultra-sensitive artificial slow adaptation tactile afferent nervous system based on the triboelectric nanogenerator technology [73]. It has the inherent ability to process neural morphological signals, providing a minimum distinguishable dimension that is twice as small as the distance between receptors. As shown in Figure 6e, Deng, W. et al., designed a calculation model to study the optimal ultrasonic irradiation conditions of the triboelectric nanogenerator, including frequency, probe distance, size, and design [168]. Its use can immediately convert ultrasound into electrical energy using simple ultrasonic irradiation. As shown in Figure 6f, Lee, S. et al., introduced a new type of water/air hybrid triboelectric nanogenerator to overcome the shortcomings of current liquid-based TENG and achieve effective nerve stimulation [177]. By combining this device with a neural interface, selective and force-controlled regulation of rat leg muscles can be achieved.

iTENGs also find diverse applications in sterilization processes. With their unique ability to convert mechanical energy into electrical power, iTENGs can be utilized in sterilization systems to provide self-sustaining energy for various sterilization methods [27,81,161]. They can be integrated into implantable devices such as catheters, implants, or wound dressings, where the generated electrical power can be used to activate antimicrobial agents or facilitate localized heat generation for sterilization purposes. Additionally, iTENGs can be employed in wearable or implantable devices used in healthcare settings to power UV light-emitting diodes (LEDs) or other disinfection mechanisms, enabling effective sterilization of medical equipment, surfaces, or even body tissues. As shown in Figure 6g, Imani, I. et al., proposed a new strategy, an implantable and biodegradable triboelectric nanogenerator driven by ultrasound [62]. It can eliminate microorganisms in deep tissues using electrical stimulation. The device implanted under pig tissue successfully inactivated bacteria. The use of iTENGs in sterilization applications holds promise for enhancing infection control measures and reducing the risk of healthcare-associated infections. As shown in Figure 6h, Shi, R. et al., proposed a self-powered method using a triboelectric nanogenerator to load and accumulate negative charges on the surface of titanium anode oxide implants [122]. It can construct stable and long-term effective negatively charged implant surfaces, effectively inhibiting bacterial adhesion, reducing bacterial count, and reducing the live/dead bacterial ratio during biofilm formation and maturation. As shown in Figure 6i, Li, Z. et al., reported a bioabsorbable pressure sensor based on a triboelectric nanogenerator [178]. It can achieve a bactericidal effect of 99.99% on both Gram-positive and Gram-negative bacteria. The device can successfully identify abnormal breathing in small animals and completely degrade after 21 days.

iTENGs have diverse applications in anticancer research and treatment [186,187]. They can be utilized for targeted drug delivery, allowing the controlled release of therapeutic agents directly to tumor sites, minimizing side effects. iTENGs also enable real-time monitoring of tumor growth and treatment response through energy harvesting from physiological movements [8,55,188]. Additionally, their electrical output can be combined with other modalities for enhanced cancer therapies, such as electrochemical treatment or bioelectric stimulation. The potential of iTENGs in anticancer applications offers promising advancements in personalized cancer treatment and improved patient outcomes. As shown in Figure 6j, Zheng, M. et al., reported a self-powered electrical stimulation promoting cancer catalytic therapy and chemotherapy method by integrating TENG with implantable biodegradable nanofiber patches [72]. The results of in vitro and in vivo experiments indicate that it has a good tumor inhibitory effect. As shown in Figure 6k, Zhao, C. et al., have established an intelligent drug delivery system based on implanting TENG and red blood cells [180]. As an oral anti-tumor drug, afatinib is loaded into red blood cells, realizing the transformation from oral APA release preparation to injection preparation. It has significant therapeutic effects on experimental rabbits and is expected to be applied in clinical medicine. As shown in Figure 6l, Zhao, C. et al., have successfully established a nanogenerator control drug delivery system for cancer treatment [181]. Under the electrical stimulation of the magneto triboelectric nanogenerator, the release of doxorubicin increased significantly and returned to normal again after stimulation. Thus, a controllable DDS was established. It can achieve effective killing of cancer cells.

It is a very effective method to use electrical signals to promote cell proliferation and differentiation to repair damaged tissues or organs. The specific electrical signals generated by TENG can promote cell maturation and repair damaged tissues and organs. It activates bone cells and aids in the formation of new bone tissue and the healing of fractured sites. As shown in Figure 6m, Yao, G. et al., proposed a self-powered implantable and bioabsorbable fracture electrical stimulation device [71]. The operation of the device was demonstrated in rats, and effective fracture healing was achieved within 6 weeks, while the control group achieved the same healing results over 10 weeks. This work provides an effective implantable fracture treatment device that does not require batteries and is biodegradable. As shown in Figure 6n, Wang, B. et al., have developed a pulse triboelectric nanogenerator [182]. It has the effect of restoring the vitality of aging bone marrow mesenchymal stem cells, enhancing their osteogenic differentiation, and promoting the formation of Human umbilical vein endothelial cell tubes. Additionally, it provides a potential signal transduction mechanism for the regeneration of aging bone marrow mesenchymal stem cells. As shown in Figure 6o, Zhao, L. et al., proposed a flexible, self-powered implantable electric stimulator based on TENG, which can induce cardiomyocyte maturation by generating an electric field on the interdigital electrode [63]. It can significantly promote the maturation of neonatal rat cardiomyocytes in vitro. The device can be driven by the breathing of rats and the heartbeat of rabbits.

The plane is an electronic device that directly excites the nerves by implanting electrode systems in the body to restore or rebuild the auditory function of deaf people. Teng has a sensitive sensing ability and self -powered nature, which is a feasible technology for cochlear implants. As shown in Figure 6p, Zheng, J. et al., reported a kind of acoustic core–shell resonance collector based on piezoelectric triboelectric effect for the application of cochlear implants [70]. A clever acoustic acquisition device with a core–shell structure was designed by using dispersed $BaTiO_3$ particles as the core and porous PVDF-TrFE as the shell. It shows admirable feasibility and sensitivity in recording and shows potential application prospects in Cochlear implants. As shown in Figure 6q, Liu, Y. et al., proposed a bionic cochlear Basement membrane acoustic sensor combined with TENG [66]. By trapezoidally distributing nine silver electrodes on two polytetrafluoroethylene membranes, the device achieves high-frequency selection from 20 to 3000Hz. The device can self-power to a certain extent by absorbing the vibration energy carried by sound. As shown in Figure 6r, Jang, J. et al., designed an A triboelectric-based artificial basic membrane that can simulate the cochlea [183]. Additionally, animal model testing was conducted to verify the self-powered acoustic sensor.

In conclusion, iTENGs have a wide range of applications across various organs. By harnessing the mechanical energy within the body, iTENGs provide self-sustained power sources for cardiac devices, neural interfaces, gastrointestinal devices, orthopedic implants, respiratory devices, urological systems, and ophthalmic devices. These advancements contribute to the development of more efficient and long-lasting implantable medical devices, improving patient outcomes and quality of life [63,189].

4.2. Sensing and Power Supply

iTENGs have diverse applications that can be broadly categorized into two main areas: sensing and power supply [190].

In terms of sensing, iTENGs can be used for various biomedical sensing applications. They can be integrated into implantable devices to monitor physiological parameters such as heart rate, blood pressure, glucose levels, and body temperature. The triboelectric effect allows iTENGs to convert mechanical energy from movements and vibrations within the body into electrical signals, enabling real-time monitoring and data collection. This capability opens up possibilities for applications in wearable healthcare devices, smart prosthetics, and biofeedback systems [191,192].

In the realm of power supply, iTENGs serve as self-sustaining energy sources for implantable medical devices [193]. These nanogenerators can harvest energy from the natural movements and mechanical forces occurring within the body, such as muscle contractions, heartbeat, or joint movements. The harvested energy can be used to power implantable devices, eliminating the need for external batteries or frequent replacements. This application is particularly beneficial for long-term implantable devices like pacemakers, neural stimulators, drug delivery systems, and biosensors, as it enhances device functionality, reduces the need for invasive surgeries, and improves patient comfort [28,194].

By combining sensing and power supply capabilities, iTENGs offer a unique platform for the development of self-powered biomedical devices. They enable continuous monitoring of physiological parameters while providing a sustainable power source, leading to advancements in personalized medicine, remote patient monitoring, and the development of more efficient and reliable implantable medical technologies [61].

Overall, this chapter highlights the diverse and promising applications of iTENGs in cardiac devices, sterilization processes, and anticancer therapies. These applications demonstrate the potential of iTENGs to revolutionize various aspects of healthcare, providing self-sustainability, improved functionality, and enhanced treatment options. With further research and development, iTENGs hold great promise for advancing medical technologies and improving patient outcomes [29,195].

5. Conclusions and Outlook

While iTENGs show great promise for various applications, there are still several challenges and limitations that need to be addressed [196]. One of the primary concerns with implantable devices is ensuring their compatibility with the human body [29]. The materials used in iTENGs need to be biocompatible, non-toxic, and non-allergenic to avoid any adverse reactions or tissue damage. Achieving long-term biocompatibility remains a challenge, especially considering the complex and dynamic nature of the human body. The long-term stability and durability of iTENGs need to be improved. Over time, the friction materials and electrode layers may experience wear and degradation, which can affect the performance and efficiency of the device. Ensuring the robustness of the device and optimizing the material selection and encapsulation techniques are crucial for enhancing the longevity of iTENGs. iTENGs typically generate low-power outputs compared to conventional energy sources. Improving the power output and efficiency of iTENGs is essential to meet the energy demands of various applications [197,198]. This involves optimizing the materials, structural design, and interface interactions to enhance energy conversion efficiency and maximize power generation. Miniaturization and Integration: Implantable devices require compact and miniaturized designs to fit within the limited space available in the body. Achieving miniaturization while maintaining the functionality and performance of iTENGs is a significant challenge [199]. Additionally, integrating iTENGs with other components, such as sensors, electronics, and wireless communication modules, adds complexity to the design and requires careful consideration. Biomechanical Compatibility: iTENGs should be able to harvest energy efficiently from the specific biomechanical movements or activities they are designed for. Designing iTENGs that can conform to the shape and movement of specific body parts or organs, while still maintaining optimal energy conversion is a complex task. Achieving good conformal matching and reliable energy harvesting from diverse human motions remains a challenge [200]. Scalability and Manufacturing: The scalability and cost-effective manufacturing of iTENGs are important factors for their widespread adoption. Developing scalable fabrication techniques that can produce iTENGs in large quantities with consistent performance is crucial for commercial viability. Additionally, cost-effective manufacturing processes need to be established to make iTENGs accessible and affordable for various applications. Addressing these challenges requires interdisciplinary research efforts in material science, engineering, biomedicine, and manufacturing. Overcoming these problems will contribute to the advancement and commercialization of iTENGs, enabling their seamless integration into various implantable devices and revolutionizing the fields of healthcare, energy harvesting, and human–machine interfaces [15,201,202].

Material development is a critical aspect of advancing iTENGs for practical applications. Researchers are actively exploring various materials to improve the performance, durability, and biocompatibility of these devices [78,203,204]. One area of focus is the development of high-performance triboelectric materials that exhibit strong triboelectric properties, such as large contact electrification and high charge density. Nanomaterials, including graphene, carbon nanotubes, and nanowires, are of particular interest due to their unique electrical and mechanical properties. These materials offer high surface-to-volume ratios, excellent conductivity, and the ability to withstand mechanical stress, making them suitable for use in iTENGs. In addition to triboelectric materials, the selection of substrate materials is crucial for achieving mechanical flexibility, conformability, and biocompatibility. Flexible polymers, such as polydimethylsiloxane, polyimide, and biodegradable polymers, are commonly used as substrate materials for iTENGs [59,136]. These materials can be fabricated into thin, flexible films or micro/nanostructures, allowing for conformal integration with biological tissues and organs. Biocompatibility is a fundamental requirement for implantable devices. Biocompatible materials that minimize adverse reactions and promote tissue integration are important. This includes the use of bioresorbable and biodegradable materials that can degrade over time, eliminating the need for device removal surgeries. Such materials can include polymers derived from natural sources, such as silk, chitosan, or collagen, which offer good biocompatibility and biodegradability. Furthermore, advances in material surface engineering techniques, such as surface modification, functionalization, and coating, are being explored to enhance biocompatibility and reduce inflammatory responses. These techniques can modify the surface properties of materials to promote cell adhesion, prevent bacterial colonization, and improve the overall biocompatibility of the iTENG devices. Overall, material development for iTENGs involves a multidisciplinary approach, combining expertise in materials science, nanotechnology, biomaterials, and engineering. By exploring and optimizing the properties of triboelectric materials, substrates, and surface coatings, researchers aim to develop materials that can withstand the physiological environment, facilitate efficient energy conversion, and promote long-term biocompatibility for the successful implementation of iTENGs in various biomedical applications [36,136].

Structural design plays a crucial role in the development of iTENGs to ensure their optimal performance, functionality, and integration within the human body [72]. The design considerations focus on flexibility, stretchability, conformability, and precision fabrication techniques. Flexibility and stretchability are key attributes in iTENG structural design to enable the devices to conform to the complex anatomical shapes and movements of organs and tissues [162,176]. Flexible substrates, such as polymeric films or elastomers, are commonly used to provide mechanical flexibility. Additionally, the integration of stretchable materials or structures, such as serpentine patterns, enables the devices to withstand stretching or bending without compromising their functionality or integrity. Conformability is another important aspect of structural design, aiming to ensure intimate contact between the iTENGs and biological tissues [62,205,206]. The devices should be capable of adapting to the curvatures and irregularities of the target organs. To achieve this, innovative design strategies such as serpentine structures, fractal patterns, or mesh-like configurations are employed. These designs enable the iTENGs to conform to the 3D shapes of tissues, ensuring efficient energy harvesting and minimizing mechanical mismatch or discomfort. Precision fabrication techniques are employed to create intricate and well-defined structures for iTENGs. Microfabrication, nanofabrication, and additive manufacturing methods, including photolithography, soft lithography, 3D printing, and electrospinning, are utilized to produce precise patterns, microstructures, or nanostructures. These techniques offer control over the dimensions, geometries, and features of the iTENG devices, allowing for customization and optimization based on specific organ requirements [80]. Moreover, the integration of multiple layers or components within the iTENGs is carefully designed to achieve efficient energy conversion and functional stability. The arrangement and alignment of the triboelectric layers, electrode layers, and insulating layers are strategically designed to maximize the contact area, enhance charge transfer, and minimize leakage or interference. This requires precise alignment, patterning, and bonding techniques to ensure reliable and robust device performance. Overall, the structural design of iTENGs needs to combine flexibility, stretchability, conformability, and precision fabrication techniques to create devices that can seamlessly integrate with biological tissues. These design considerations enable the development of iTENGs with improved energy harvesting efficiency, mechanical durability, and biocompatibility, paving the way for their successful implementation in various biomedical applications [207–209]. iTENGs, with their high voltage and low current characteristics, exhibit certain limitations in their suitability for all implantable medical environments. While they offer advantages in energy generation using the triboelectric effect, the specific requirements of some medical implants may not align perfectly with these characteristics. As a consequence, there remains ample opportunity for the development of power management miniaturization and circuits to address these challenges. To make iTENGs more compatible with various implantable medical devices, power management miniaturization is essential. By miniaturizing these power management components, the overall size and weight of the implant can be reduced, making it more comfortable and less invasive for patients. Additionally, the integration of specialized circuits can optimize the energy output from iTENGs. Customized circuitry can efficiently convert the high voltage, low current output of iTENGs into the appropriate form needed to power specific medical devices. They not only improve the efficiency and performance of implantable medical devices based on iTENG technology but also play a crucial role in enhancing safety. By aligning the power management miniaturization and circuit design with the specific requirements and characteristics of iTENG material structures, researchers and engineers can create safe, efficient, and reliable implantable medical devices that harness the full potential of iTENG technology while ensuring patient well-being.

Conformal matching is a critical concept in the design of iTENGs to ensure intimate contact and seamless integration with biological tissues or organs [26,54,210]. It refers to the ability of the device to conform to the specific shape, curvature, and irregularities of the target organ surface, ensuring maximum surface contact and optimal energy harvesting efficiency. The human body consists of complex and intricate anatomical structures, such as organs, blood vessels, or soft tissues, which exhibit diverse shapes and contours. Conformal matching addresses the challenge of developing iTENGs that can adapt to these anatomical features, allowing for efficient energy conversion and stable operation. To achieve conformal matching, several design strategies and considerations are employed. One approach is the use of flexible and stretchable materials in the construction of iTENGs. These materials, such as elastomers or polymer films, possess mechanical properties that enable them to deform and stretch, conforming to the surface of the target organ [211]. This flexibility allows the iTENGs to maintain intimate contact and conformal coverage, maximizing the contact area and improving energy harvesting efficiency. Another approach involves the use of specialized structural designs that facilitate conformal matching. For instance, serpentine patterns or mesh-like configurations are utilized to enhance the stretchability and flexibility of the device, enabling it to conform to irregular surfaces. Fractal patterns, which exhibit self-similarity across different scales, are also employed to achieve conformal matching by adapting to various surface curvatures. Furthermore, advances in fabrication techniques, such as 3D printing or lithography, enable the creation of customized and complex geometries that closely match the target organ's shape. This allows for precise tailoring of the iTENG device to conform to the specific contours and dimensions of the organ, ensuring optimal contact and energy harvesting performance. Conformal matching not only enhances energy conversion efficiency but also plays a crucial role in maintaining the long-term stability and functionality of the iTENGs within the body. It reduces the risk of device displacement, mechanical stress, or discomfort, thereby improving the overall biocompatibility and reliability of the implantable devices. In summary, conformal matching is an essential consideration in the design of iTENGs to ensure effective energy harvesting and integration with biological tissues or organs. By employing flexible materials, specialized structural designs, and precise fabrication techniques, researchers aim to achieve seamless conformal matching, enabling the successful implementation of iTENGs in various biomedical applications.

The application outlook of iTENGs is highly promising and encompasses a wide range of fields. As these devices continue to advance in terms of material development, structural design, and conformal matching, their practical applications are expected to expand. iTENGs have significant potential for powering biomedical implants, such as pacemakers, neurostimulators, and drug delivery systems. By harnessing the body's mechanical energy, these devices can provide sustainable power without the need for frequent battery replacements or external charging. Additionally, iTENGs can enhance the functionality of prosthetic limbs by powering sensors, actuators, and feedback systems, enabling more natural and intuitive movements. iTENGs can be integrated into wearable devices for continuous health monitoring and tracking. By converting body movements into electrical energy, these devices can power sensors that monitor vital signs, track physical activity, and collect physiological data. This can facilitate real-time health monitoring, disease management, and preventive healthcare. iTENGs can play a vital role in powering IoT devices and sensors. They can harvest energy from ambient vibrations, mechanical interactions, or human activities, providing a self-sustaining power source for remote or hard-to-access locations. This can enable the deployment of energy-efficient and environmentally friendly IoT networks for applications like environmental monitoring, structural health monitoring, and smart cities. Human–machine Interfaces and Interactive Systems: iTENGs can be utilized in human–machine interfaces and interactive systems, enabling self-powered touch-sensitive surfaces, gesture recognition interfaces, and wearable electronics. By capturing the energy generated from human touch or body motions, iTENGs can provide a reliable and sustainable power source for these systems, enhancing user experience and convenience. iTENGs have the potential to be integrated into orthopedic implants or assistive devices to harvest energy from human motion, such as walking or joint movements. This energy can be converted into electrical power to supplement the energy needs of the devices, reducing the reliance on external power sources and increasing their autonomy.

The application outlook for iTENGs is dynamic and continually evolving as research and development progress. With advancements in material science, device design, and integration techniques, the potential applications of iTENGs are expected to expand, revolutionizing fields such as healthcare, IoT, human–machine and interfaces. [179].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/coatings13081407/s1, Figure S1: Number of publications about iTENG over the years.

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