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Sustainable Biopolymers in Eco-Friendly Triboelectric Energy Harvesting

Zekun Li, Aifang Yu, Junyi Zhai, and Zhong Lin Wang**

Biopolymer-based triboelectric nanogenerators (B-TENGs) represent an innovative fusion of eco-friendly, sustainable energy-harvesting technology with renewable and environmentally benign biopolymer material. This integration not only introduces novel pathways for advancing green energy solutions but also offers a critical approach to addressing contemporary environmental challenges and fostering sustainable progress. Over the past few years, B-TENGs have seen rapid and remarkable growth in the realm of biopolymers, device architecture, and their applications (e.g., implantable power source, electronic medicine, human anatomical and physiological movements monitoring sensors, etc.). In this review article, the promising developments in harnessing triboelectric biopolymers are encapsulated, enumerate their representative applications, evaluate the pros and cons of these biopolymers, highlight key challenges for future research, and offer strategic recommendations for innovating and realizing advanced B-TENGs.

1. Introduction

With the growth of the global population and economic development, how to achieve sustainable utilization of energy and environmental protection will always be the core issue of human society.[1] Energy and environmental issues have driven the transition from traditional fossil fuels to low-carbon energy, accelerating the development of environmentally friendly, stable, and sustainable energy resources.[2,3]

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The triboelectric nanogenerators (TENGs), invented by Zhong Lin Wang's group in 2012,[4] utilize the contact electrification and electrostatic induction coupling effects between two materials, effectively converting irregular, low-frequency, and distributed mechanical energy from nature and living organisms into electrical energy in the form of Maxwell's displacement current.[5–7] To date, TENGs have been used to harvest wind energy,[8–11] vibration energy,[12–15] water wave energy,[16–21] etc., to provide electrical power or serve as a self-powered sensor. **Figure 1a** depicts the operating principle of TENGs, where the contact and separation of friction layers induced by an external force create a variable electric field, facilitating charge flow in an external circuit. Meanwhile, as shown in Figure 1b, an electron-cloud-potential-well model is also provided to explain and visualize the charge transfer mechanism at the atomic scale when the positive and negative friction layers come into contact. The output electrical energy is proportional to the square of the charge generated by friction. Therefore, the triboelectric materials, as the core element of TENGs, not only determine the output power of TENGs but also dictate their green and sustainable development direction. The triboelectric layers of conventional TENGs are mostly derived from petroleum-based fossil fuels, such as polyvinylidene difluoride (PVDF),[22–25] polytetrafluoroethylene (PTFE),[26–28] polytetrafluoroethylene (PDMS),[29–32] polyimide (PI),[33–36] eco-flex,[37] etc, and thus do not possess environmental friendliness and sustainability, which is contrary to the goals of TENGs for environmental friendliness and sustainable development.

The application of biopolymers as friction layers has completely addressed the aforementioned issues and has opened up the use of TENGs in living organisms. Since the first poly-3-hydroxybutyrate (PHB)-based triboelectric nanogenerators were reported,[38] biopolymer-based triboelectric nanogenerators (B-TENGs) have undergone rapid and impressive development in recent years, as shown in **Figure 2**. Similar to common TENGs, B-TENGs also operate in four different fundamental working modes. In practical applications, a spectrum of B-TENGs architectures can be engineered by synthesizing these four modes. Based on the working mode of B-TENGs, a myriad of B-TENGs trigger sources have been documented, encompassing wind,[39,40] human motion,[41] ultrasonic waves,[42] and so on. The material sources for B-TENGs are quite diverse, encompassing: plants, animals, microbes, and so on. These biopolymers bestow

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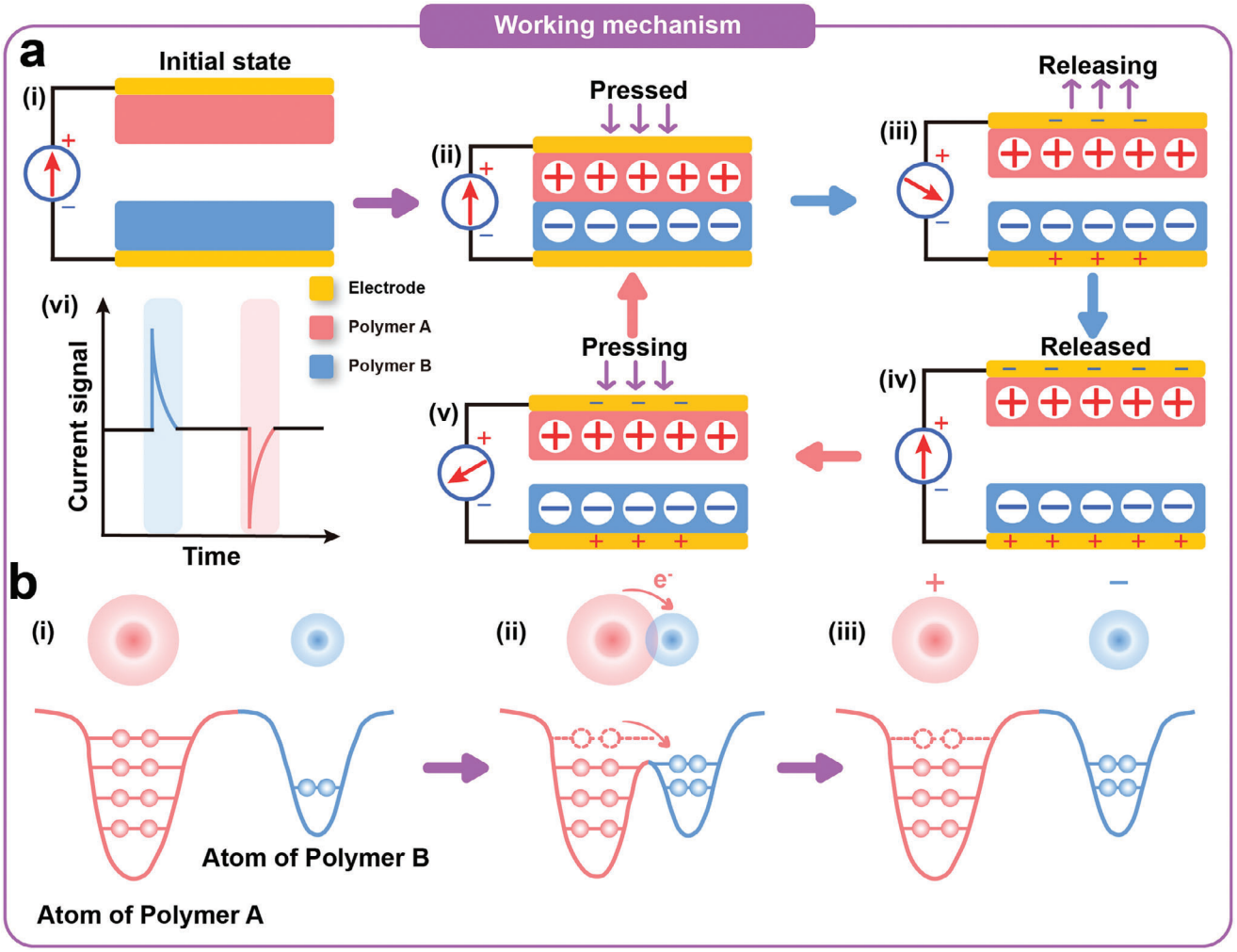

Figure 1. a) Working principle of TENGs. b) An electron-cloud–potential-well model for explaining contact electrification between two different polymers.

B-TENGs with advanced properties, such as biodegradability, nontoxic, and biocompatibility, which significantly broaden and enhance the application spectrum of B-TENGs. A profusion of B-TENG applications has been reported, primarily encompassing energy harvesting,[43,44] self-powered sensing,[45,46] and electronic medicine.[47,48] The distinctive attribute of utilizing B-TENGs for energy harvesting and self-powered sensing lies in its ability to seamlessly integrate with the environment, facilitating unobtrusive collection and sensing. B-TENGs are currently a focal point of research within the domain of electronic medicine, including serving as a power source,[47] vascular monitoring,[49] electrostimulation for antibacterial purposes,[50] electrostimulation for wound healing,[51] and physiological signal monitoring.[52]

In this work, we highlight the most promising advancements in the exploitation of triboelectric biopolymers, discuss strategies for boosting the triboelectric output of these biopolymers, and illustrate representative applications of B-TENGs. Furthermore, key challenges for future research are delineated and methodological recommendations aiming at the innovation and realization of B-TENG technologies are provided.

2. Overview of Biopolymers Implemented in B-TENGs

Biopolymers are commonly characterized as polymers composed of repeating units such as sugars, amino acids, or hydroxy fatty acids, which are produced by living beings.[53] Many ways of classifying biopolymers exist.[54,55] For instance, biopolymers can be dichotomized as either biodegradable or non-biodegradable based on their degradation properties. Additionally, biopolymers can be distinguished into elastomers, thermoset plastics, and thermoplastic plastics based on their different behaviors when subjected to heat. These diverse categorizations reflect the intricacy and diversity of biopolymers, as well as their applications across various fields. Within the field of TENGs, natural and biodegradable biopolymers are of paramount interest to researchers. **Figure 3** elucidates the categorization of natural biopolymers that can be employed for the fabrication of biodegradable B-TENGs. According to the chemical structure of natural biopolymers, they can be classified into polysaccharides, aliphatic polyester, polyamides, isoprene, etc.

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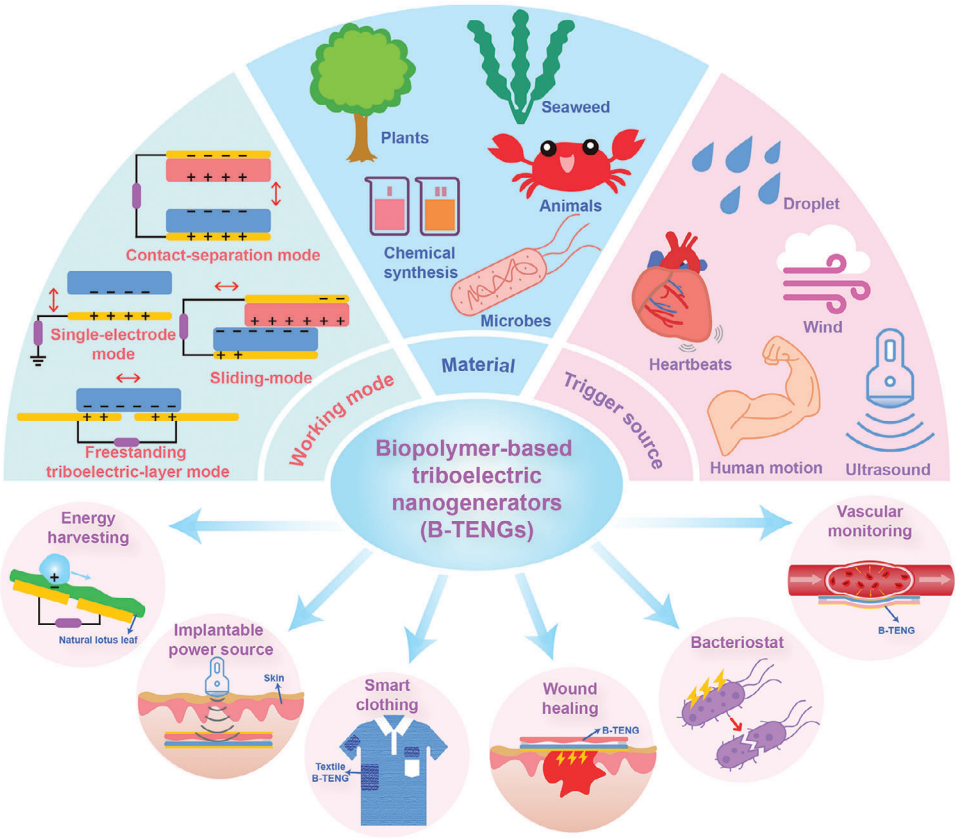

Figure 2. An overall view of the working modes, material sources, energy sources, and application scope of B-TENGs.

Although the biopolymers depicted in Figure 3 can all function as the triboelectric layer in B-TENG for the collection of mechanical energy, cellulose has emerged as the most extensively investigated triboelectric biopolymer owing to its superior film-forming ability and potential for modification, as well as its outstanding mechanical strength and considerable output performance.[56–60] Research has reported that the B-TENG based on cellulose has achieved an output power density of 300 W m^{-2} and maintained cycle stability for 30000 cycles.[56] Concurrently, cellulose has been extensively studied for self-powered sensing devices based on B-TENGs. For instance, smart floors,[57,58] smart fabrics,[59] and filtering masks[60] based on cellulose triboelectric materials have been widely reported. Another biopolymer frequently employed in triboelectric energy harvesting and self-powered sensing is chitosan, which possesses both antimicrobial properties and bioactivity.[61–63] The research into utilizing chitosan as the triboelectric layer for B-TENGs began with an exploration of the effects of varying the types and concentrations of additives within the chitosan matrix on the triboelectric output.[61] Beyond the enhancement of the output, triboelectric visual sensors[62] and motion signal monitoring sensors[63] based on chitosan films have also been developed in recent studies. With the rise of self-powered medical implants, an increasing number of biopolymers, including polylactic acid (PLA), silk fibroin, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), PHB, and polycaprolactone (PCL) have found expanded applications.[64–67] Among these, PCL and PHB were the first biopolymers reported for use as the triboelectric layer in implantable B-TENGs.[38] Silk fibroin and PLA can serve as both the triboelectric layer and the protective layer of implantable B-TENGs.[68] In summary, when fabricating self-powered medical implants, various biopolymers are often combined to achieve devices with balanced performance in various aspects. **Table 1** summarizes the triboelectric performance of unmodified biopolymers.

3. Materials-Related Strategies for Output Amelioration

In general, biopolymers endowed with triboelectric effects can serve as triboelectric layers for B-TENGs. Nevertheless, a haphazard assembly of biopolymers into a triboelectric pair will not yield high-output B-TENGs. To commence, it is essential to discern the triboelectric polarities of diverse biopolymers. **Figure 4** delineates the triboelectric series of various biopolymers (experimental data referenced for constructing these sequences can be found in Meng et al.[77]). The predominant factors contributing to the positive polarity (electron-donating) or negative polarity (electron-withdrawing) of biopolymers lie in the divergent chemical compositions of their main and side chains. For instance, chitin and chitosan share a consistent main chain chemical structure, but chitin's side chain groups encompass N-acetyl amide groups, whereas chitosan's side chain groups incorporate amino groups ($-NH_2$). The amino group exhibits a more pronounced electron-

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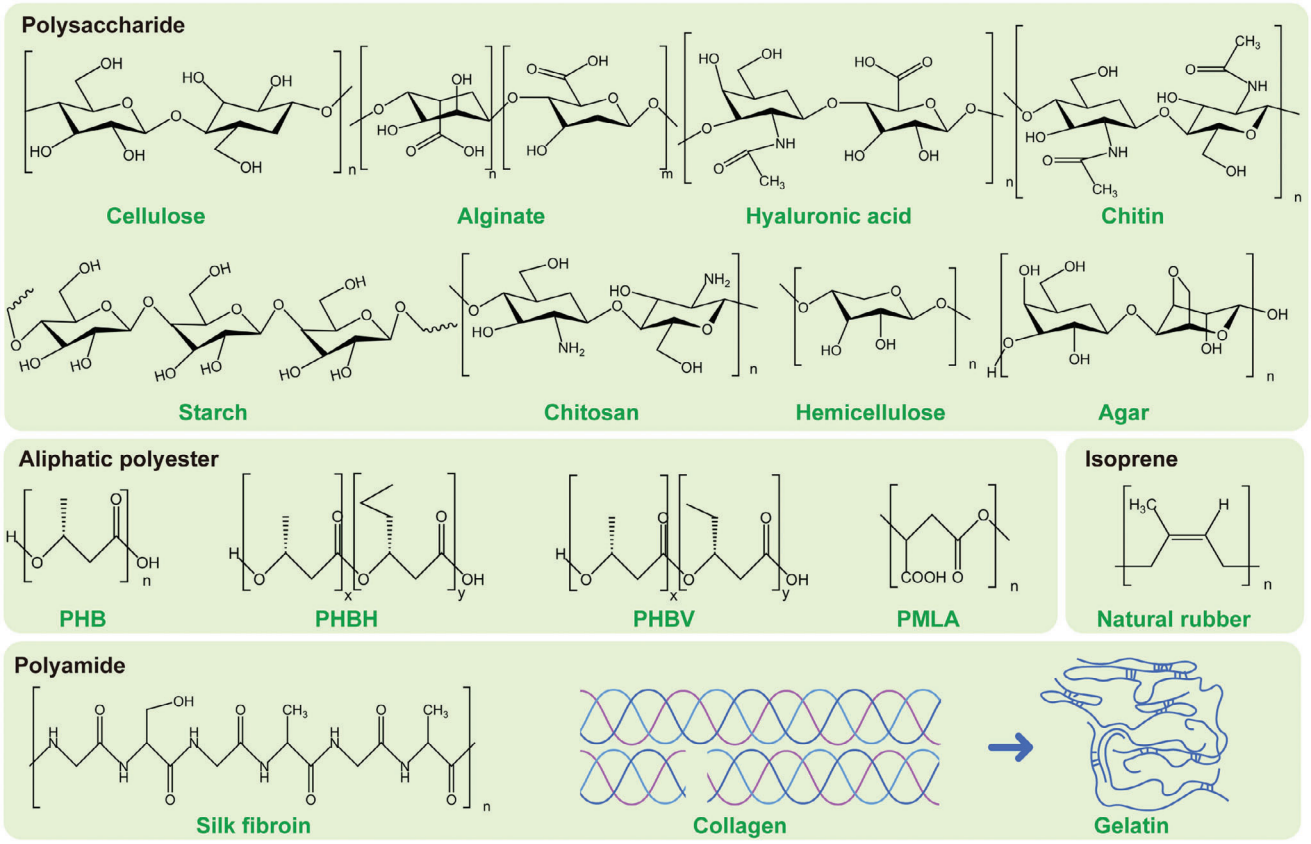

Figure 3. Classification of natural biopolymers for the manufacture of B-TENGs.

donating (ED) capability, thereby rendering chitosan more prone to exhibit positive polarity than chitin. The primary constitution of poly(butylene succinate) (PBS) and poly(butylene adipate-co-terephthalate) (PBAT)'s main chains comprise repetitive units of alkanes and esters, yet PBAT's main chain also harbors a benzene ring, conferring it with a more robust electron-donating (EW) capability and subsequently manifesting a more pronounced triboelectric positivity. In the general context, the presence of ester and amide functionalities qualifies biopolymers as potential candidates for the negative triboelectric layer. Conversely, the incorporation of carboxyl, hydroxyl, and amino groups positions biopolymers as potential choices for the positive triboelectric layer.[77]

Table 1. The triboelectric output of unmodified biopolymers.

Biopolymers	Positive friction layer	Negative friction layer	Voltage [V]	Current density [mA m^{-2}]	Charge density [μC m^{-2}]	Power density [mW m^{-2}]	Stability [cycles]	Refs.
Alginate	Al	Calcium alginate	33	0.17	10	10.5	3000	[69]
PLA	PLA film	Reed film	368	2.1	–	256	10000	[70]
Chitosan	Chitosan film	Fluorinated ethylene propylene (FEP)	19.32	2.2	16.7	–	–	[71]
Silk fibroin	Silk fibroin film	Polyethylene glycol terephthalate	268	2.4	19.2	1936	18000	[72]
Starch	Starch film	PTFE	0.4	0.5	–	–	–	[73]
Gelatin	PLA	Gelatin film	16	0.3	–	–	–	[74]
PCL	PLGA	PCL	40	1.7	–	32.6	–	[38]
Bacterial cellulose	Bacterial cellulose film	Cu	13	6.9	–	4.8	–	[75]
Cellulose	Cellulose membrane	FEP	21.9	1.2	13.8	76.8	–	[76]

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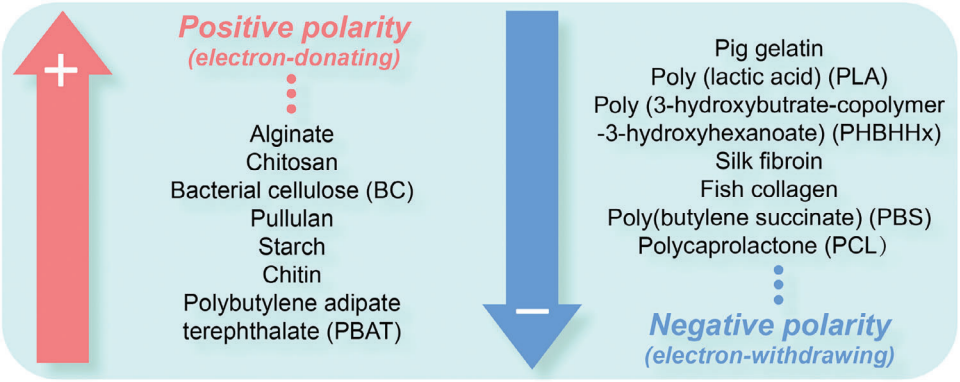

Figure 4. Triboelectric series of biodegradable biopolymers.

The triboelectric polarity induced by different main or side chain groups varies significantly and can substantially influence the charge transfer of the triboelectric material during the operation of the TENG. Therefore, in the actual construction of B-TENGs, the selection of triboelectric biopolymer pairs with markedly divergent polarities can yield favorable performance.

The dynamic behavior of triboelectric charges, encompassing their generation and storage, exerts a substantial influence on the induced output charge density of TENGs.[78] Consequently, the endeavors to augment the generating capacity of biopolymers are predominantly directed toward the optimization of triboelectric charge generation and storage. Various factors affect the generation of triboelectric charges, such as the surface structure of the polymer, the surface functional groups of the polymer, and so on. Accordingly, as depicted in **Figure** 5a, the strategies for enhancing the triboelectric charge generation of biopolymers primarily involve the manipulation of surface roughness,[79] surface chemical treatment,[80] and chemical structure modification.[81] During the operation of TENGs, the dissipation of triboelectric charges severely curtails the charge output induced by electrostatic induction. Consequently, another strategy to bolster the triboelectric performance of B-TENGs is to enhance the charge storage capacity of the biopolymers. Presently, there are two methodologies to enhance charge storage capacity: one is to increase the dielectric constant,[82] and the other is to enhance the storage of triboelectric charge.[83] As illustrated in Figure 5b, coating the surface of biopolymers with high-k polymers and incorporating high-k nanomaterials and functional nanomaterials with large surface areas within them are the predominant methods for enhancing the dielectric constant of biopolymers. In addition, under the in-

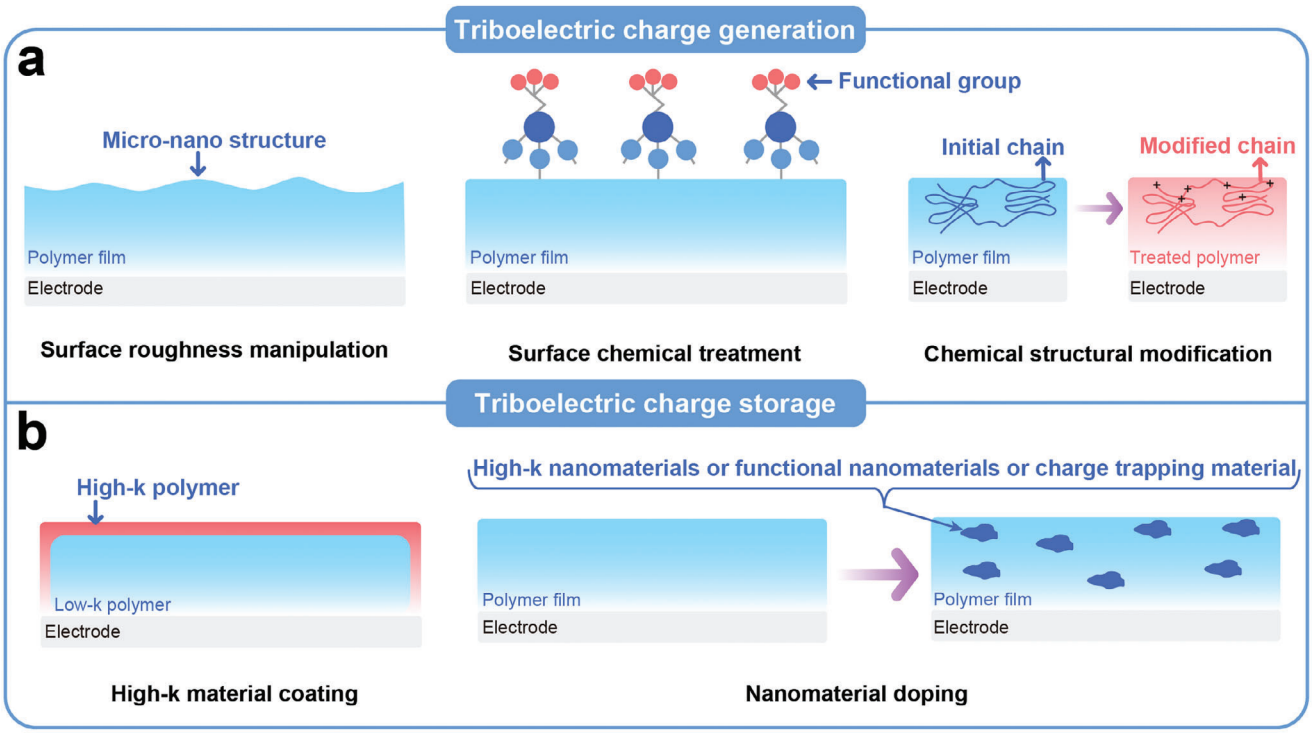

Figure 5. Output enhancement strategies for triboelectric biopolymers.

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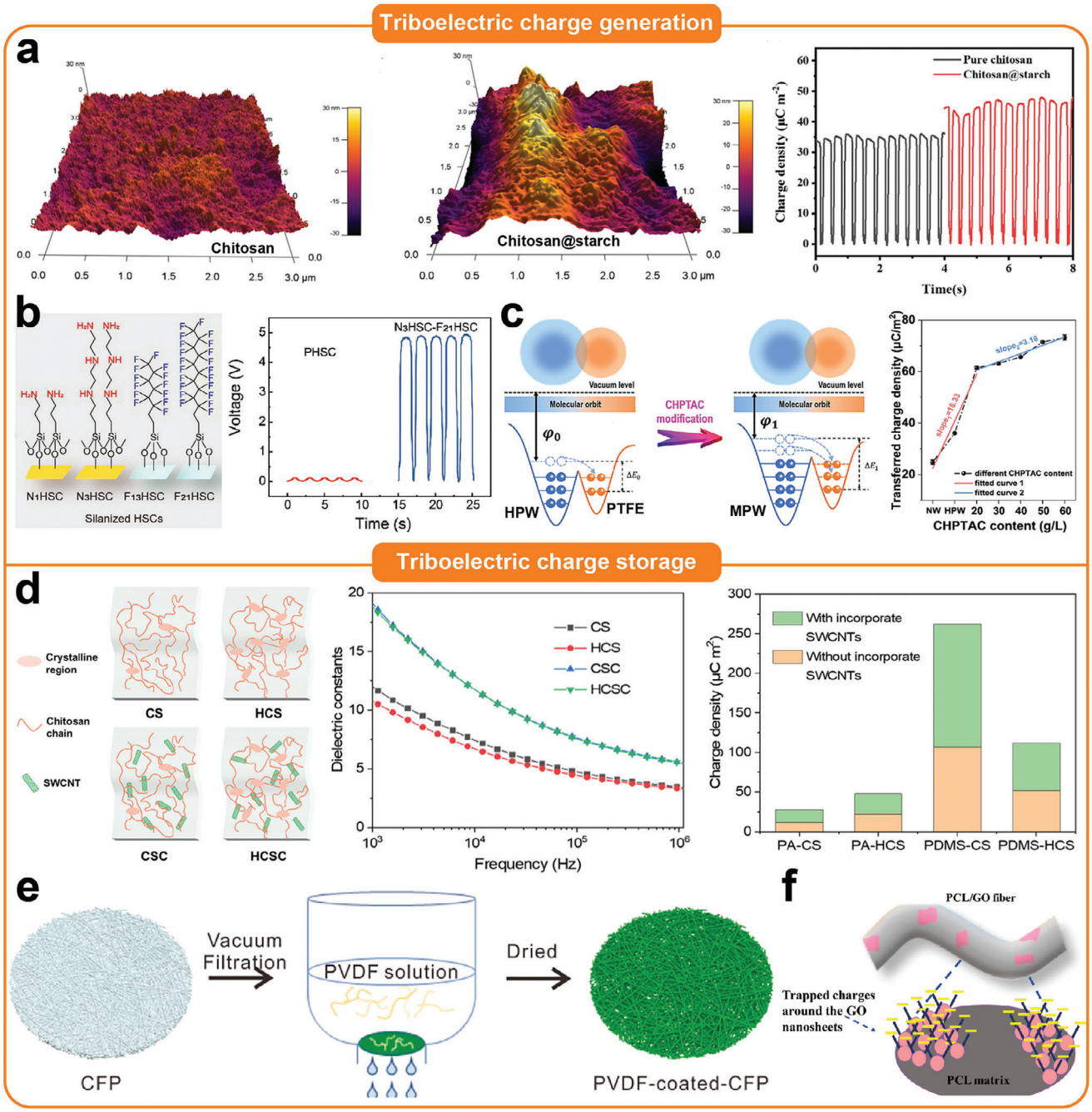

Figure 6. a) The surface atomic force microscope (AFM) images of chitosan@starch composite film. Reproduced with permission.[79] Copyright 2022, Elsevier. b) HSC membranes modified with different functional groups. Reproduced with permission.[80] Copyright 2023, John Wiley & Sons. c) The electronic tunneling model of HPW before and after CHPTAC modification. Reproduced with permission.[81] Copyright 2022, American Chemical Society. d) The dielectric constant and output charge density of unmodified chitosan films and chitosan films modified with SWCNTs. Reproduced with permission.[82] Copyright 2023, Elsevier. e) Structural schematic diagram of CFP and PVDF/CFP composite materials. Reproduced with permission.[85] Copyright 2022, Elsevier. f) The structure schematic of the PCL/GO composite materials. Reproduced with permission.[83] Copyright 2019, Elsevier.

fluence of the triboelectric field, triboelectric charges migrate into the bulk material. Therefore, introducing charge-trapping nanomaterials into biopolymers can effectively capture triboelectric charges and enhance the storage of triboelectric charges.

Ion etching and template-based methods are commonly employed techniques for fabricating triboelectric biopolymers with surface micro- and nano-structures.[84] Recently, as depicted in **Figure 6a**, it has been reported that the introduction of starch into chitosan films results in a significant increase in the surface root mean square roughness of the chitosan@starch composite films, rising from 3.42 to 14.39 nm.[79] Correspondingly, the transfer charge density of the

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composite films also increases, from 35.0 μC m^{-2} for pure chitosan films to 45.8 μC m^{-2}. Clearly, this increase in surface roughness aids in enhancing the contact area between triboelectric materials, thereby promoting the generation of triboelectric charges and subsequently enhancing the output performance of the TENG. Additionally, as mentioned earlier, the manipulation of surface functional groups and the chemical structure of biopolymer films through chemical modification can also effectively improve their triboelectric performance. As shown in Figure 6b, (3-aminopropyl)triethoxysilane/3-[2-(2-aminoethylamino)ethylamino]propyl-trimethoxysilane (APTES /DETAS) and trichloro(1H,1H,2H,2H-perfluorooctyl)silane/1H, 1H,2H,2H-perfluorododecyltrichlorosilane (FOTS/FTCS) are utilized to enhance the charge donating and drawing capabilities of hollow stellate cellulose (HSC) films.[80] In this case, the triboelectric pair composed of N_3HSC (DETAS modified HSC) and F_{21}HSC (FTCS modified HSC) achieved the highest open-circuit voltage, reaching 4.86 V, which is 28 times higher than that of the triboelectric pair composed of two unmodified HSC films. Furthermore, the triboelectric devices fabricated using these biopolymer films treated through chemical modification exhibit stability exceeding 10000 cycles.[80] Figure 6c demonstrates the changes in the electron tunneling model of a hot-pressed wood (HPW)-based TENG before and after 3-chloro-2-hydroxypropyltrimethylammonium chloride (CHPTAC) modification.[81] During the modification process, cationic groups are introduced into the cellulose backbone, thereby reducing the work function of HPW. Consequently, the energy difference (ΔE) between the positive and negative triboelectric layers increases, thereby promoting the flow of static charge. Furthermore, as the CHPTAC content increases, the increment of the transfer charge density of modified hot-pressed wood (MPW) gradually slows down, which can be attributed to the existence of a saturation value for the number of loadable cationic groups on MPW. Overall, manipulating the physicochemical state of the biopolymer surface can effectively control the amount of triboelectric charge generated and transferred during the contact process, thereby enhancing the output performance of materials.

As shown in Figure 6d, single-walled carbon nanotubes (SWCNTs) with high specific surface area can form interface polarization regions within chitosan films,[82] resulting in an increase in the dielectric constant over a wide frequency range for both low-crystallinity chitosan films (CS) and high-crystallinity chitosan films (HCS) after the addition of SWCNTs. Consequently, the triboelectric charge density of chitosan films modified with SWCNTs (CSC) and high-crystallinity chitosan films modified with SWCNTs (HCSC) is enhanced by 2 times and 2.45 times, respectively, compared to pure CS and pure HCS. It has been found that coating a layer of high dielectric constant polyvinylidene difluoride (PVDF) on the surface of biopolymer films, such as a cellulose filter paper (CFP), can significantly enhance its dielectric constant,[85] as illustrated in Figure 6e. Compared to pure CFP, the dielectric constant of the PVDF-coated CFP composite is increased from 2.37 to 15.65. Correspondingly, the output voltage of the PVDF-coated CFP composite is also increased from ≈30 to 192 V, a 6.2-fold increase. It has been reported that graphene oxide (GO) nanosheets can form charge-trapping sites within PCL, effectively capturing triboelectric charges,[83] as illustrated in Figure 6f. When the GO content is 4 wt%, the open-circuit voltage of the TENG reaches 22.73 V, ≈48 times higher than that of the pure PCL layer. In summary, the addition of modifiers to the polymer matrix can effectively reduce the loss of triboelectric charges and enhance the storage of triboelectric charges, thereby improving the triboelectric output of biopolymers. **Table 2** summarizes the triboelectric output of modified biopolymers.

4. Application Scenarios of B-TENGs

Biopolymers are ubiquitous in our daily lives, being extensively utilized in a plethora of products and playing a pivotal role, such as in wooden furniture, packaging materials, and cotton textiles. Consequently, self-powered sensors based on B-TENGs can be seamlessly integrated into our living and working environments for signal monitoring and control. **Figure 7a** depicts a smart ping-pong table equipped with a flexible wood-based triboelectric nanogenerator (W-TENG) array.[98] The fabrication of the W-TENG comprises two key steps: i) natural wood is submerged in a NaOH/Na_2SO_3 solution to remove most of the lignin and hemicellulose, then thermally pressed to enhance its strength and flexibility. ii) The processed flexible wood is shaped and fitted with electrodes to form a single-electrode W-TENG, which is then arrayed on the ping-pong table surface for tracking the path and location of the ball's trajectory. The information on the ball's falling point is collected and processed through multiple channels, which can be utilized to analyze an athlete's training habits and provide training guidance. Figure 7b presents a schematic illustration of the structural configuration and working principle of a waterproof fabric TENG (RF-TENG) fabricated from cotton fabric that has been subjected to silane coupling agent treatment.[99] The hierarchical construction of this device, from top to bottom, comprises a waterproof fabric embroidered protective layer, a top electrode made of Ag nanoflakes (AgNFs), a waterproof cotton fabric positive friction layer, a spin-coated PTFE negative friction layer, a bottom electrode made of Ag nanoflakes (AgNFs), and a waterproof fabric protective layer. Under pressure, the positive and negative friction layers come into contact and become electrically charged. After the external force is released, electrons flow from the back electrode of the negative triboelectric layer to the back electrode of the positive triboelectric layer. The RF-TENG can not only serve as a power source to drive LEDs but can also be integrated into the collar position of a polo shirt as a self-powered sensing interface. The self-powered sensing interface, stitched with different colored threads, serves distinct functions, such as altering volume, pausing, and resuming the music played by the integrated music player within the fabric.

The biodegradability and biocompatibility of triboelectric biopolymers afford B-TENGs the unique capability of being integrated within the biological environment for physiological signal monitoring and electrostimulation therapy. This characteristic not only facilitates seamless integration within the body but also obviates the requirement for subsequent invasive surgical procedures to remove the device, thereby enhancing patient comfort and minimizing the risk associated with repeated surgical interventions. **Figure 8a** presents a bioresorbable triboelectric sensor (BTS) for cardiovascular postoperative care.[100] The BTS has adhered to the vascular walls of large animals (dogs) to monitor the mechanical movements of the vascular walls and convert them into electrical signals for the

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Table 2. The triboelectric output of modified biopolymers.

Biopolymers	Positive friction layer	Negative friction layer	Voltage [V]	Current density [mA m^{-2}]	Charge density [μC m^{-2}]	Power density [W m^{-2}]	Stability [cycles]	Refs.
Chitosan	$BaTiO_3$-Nanorods/Chitosan	PTFE	111.4	216	–	7.56	3000	[86]
	Nanostructured chitosan	FEP	74.1	4.3	51.3	0.15	1000	[71]
	PEI-GO /Chitosan	PTFE	222	1.8	41.6	0.4	3600	[87]
	Chitosan/ kaolin	Silicone	963	22.5	–	22.8	–	[88]
Natural rubber	Natural rubber/TiO_2	PTFE	110	8.1	–	0.24	–	[89]
Silk fibroin	PEO-Silk-NFs	PVBVA-NFs	2100	65	–	1960	4000	[90]
	Nylon 66-Silk	PVDF	100	24.5	68.8	0.28	12000	[91]
Starch	$CaCl_2$/starch film	PTFE	1.2	1.5	–	0.17	5000	[73]
Cellulose	BC/AgNWs/BTO	PDMS	87	17.8	87.5	0.75	3000	[92]
	CNF-PEI-Ag	FEP	100	1.8	50	0.43	10000	[93]
	Regenerated cellulose	Cellophane	300	1040	–	307	30900	[56]
	AgNP/Cellulose	PTFE	142.6	16.4	25	87.3	10000	[94]
Cyclo-phenylalanine peptide	Cyclo-phenylalanine peptide nanowire	PTFE	350	8.3	–	0.07	–	[95]
Fish gelatin	Nanostructured gelatin film	PTFE	130	0.14	–	0.46	10000	[96]
Lignin	Lignin/starch composite	Kapton	1.04	0.0396	–	–	1800	[97]

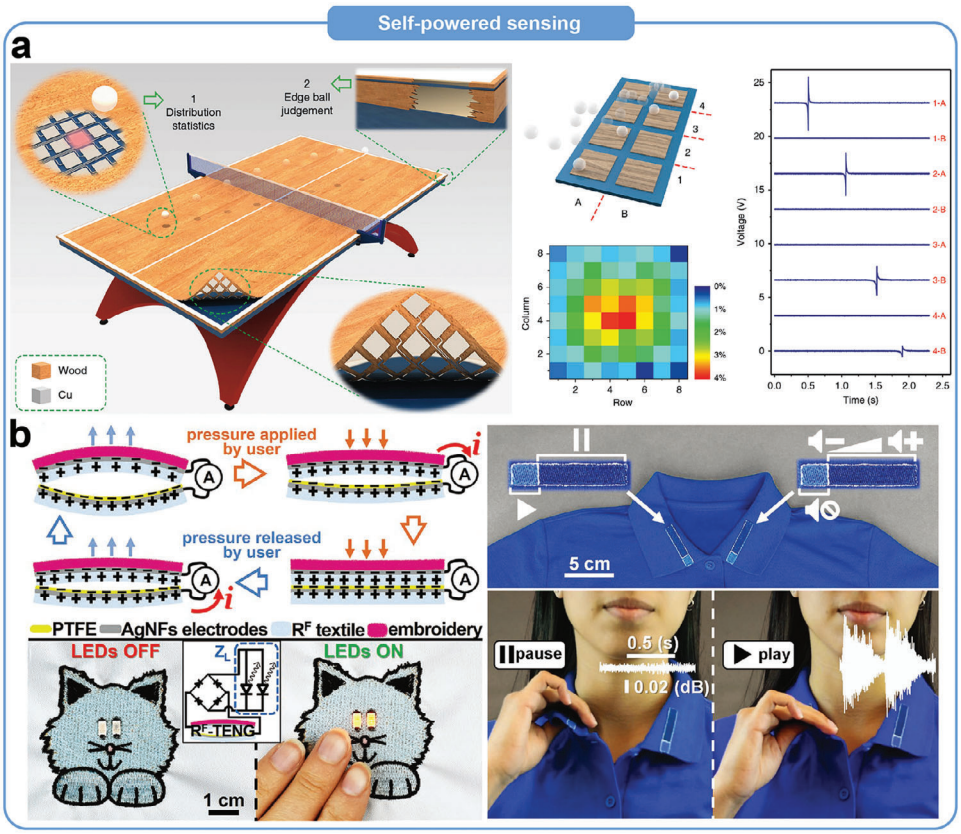

Figure 7. a) Schematic of smart ping-pong table based on W-TENG; table tennis movement signal obtained by W-TENG array. Reproduced under the terms of the CC-BY 4.0 license.[98] Copyright 2019, Springer Nature. b) Smart shirt based on waterproof cotton fabric TENG. Reproduced with permission.[99] Copyright 2019, John Wiley & Sons.

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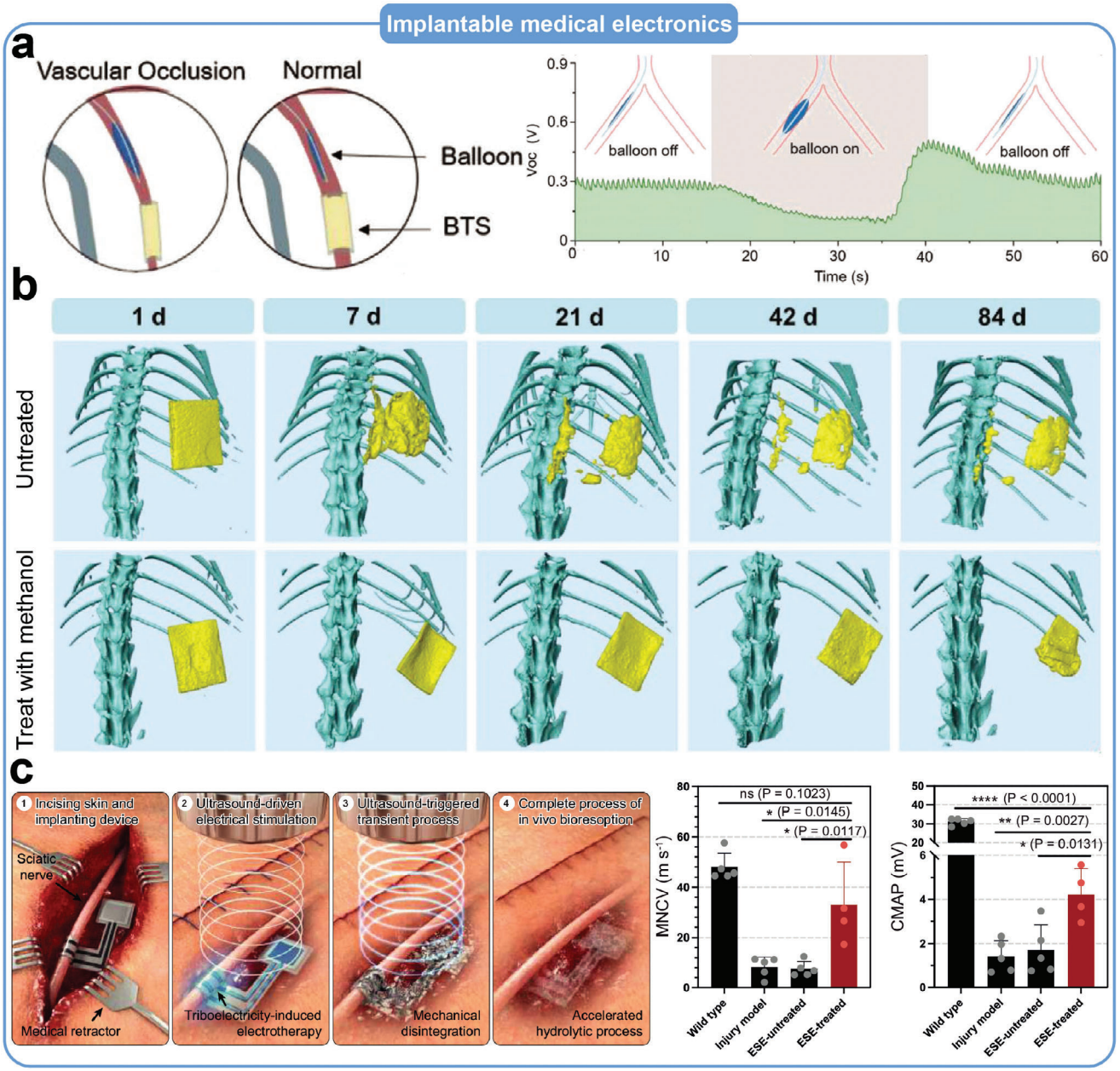

Figure 8. a) Self-powered blood pressure sensor based on a B-TENG. Reproduced with permission.[100] Copyright 2021, John Wiley & Sons. b) The degradation process of B-TENG encapsulated within treated and untreated silk fibroin films in vivo. Reproduced with permission.[68] Copyright 2018, John Wiley & Sons. c) On-demand degradation neurostimulator based on a B-TENG. Reproduced under the terms of the CC-BY 4.0 license.[101] Copyright 2023, Springer Nature.

acquisition of blood pressure information. When compared to commercial blood pressure sensors, the BTS demonstrates good consistency in the acquired dynamic blood pressure signals and can identify arrhythmias. Especially, the BTS can identify abnormal vascular occlusion events; when the implantation balloon is inflated, vascular blockage occurs, leading to a rapid decrease in blood pressure; upon deflation, blood pressure recovers. Despite the absorption or natural degradation of bio-polymers within the body, the complex polymer degradation kinetics can impact device lifespan and functionality. To tackle this challenge, several methodologies have been reported. Figure 8b displays the degradation process of B-TENGs encapsulated within treated and untreated silk fibroin films in vivo.[68] It can be observed that the B-TENG shielded by the treated silk fibroin film maintained structural integrity for up to 42 days, whereas the B-TENGs encapsulated by the untreated silk fibroin film began to decompose by day 21. Figure 8c illustrates an on-demand neurostimulator (ACT-TENG) based on a B-TENG for electrical therapy of nerve injuries and neuropathies.[101] During electrical stimulation therapy, low-intensity ultrasound waves ($\leq$1.0 W cm^{-2}) propagate

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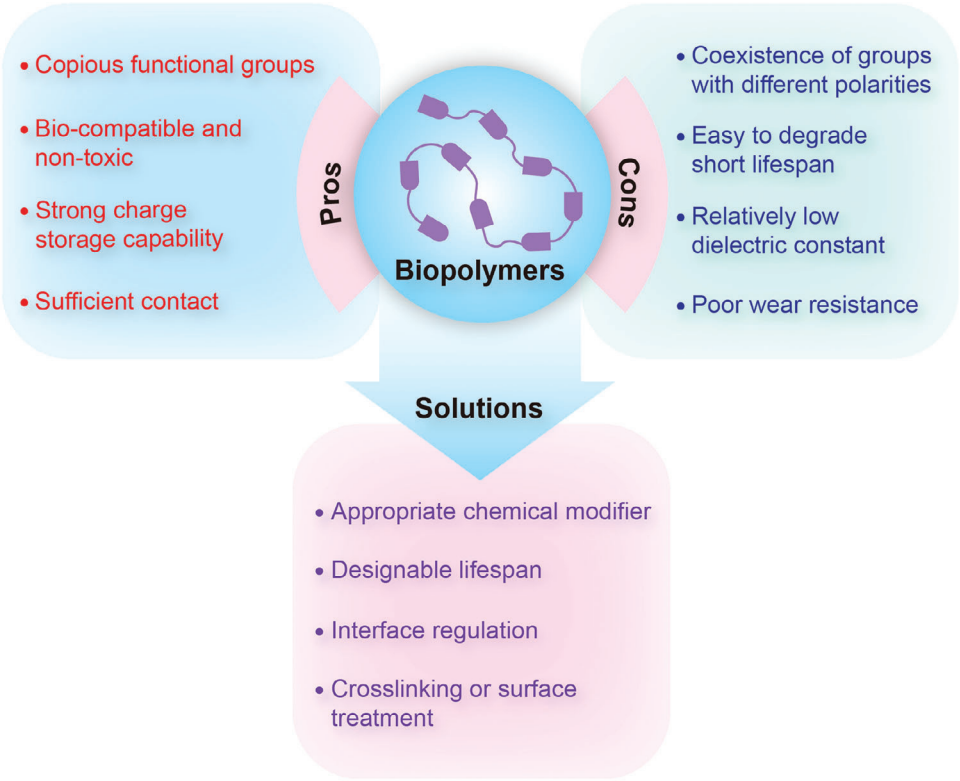

Figure 9. The pros and cons of triboelectric biopolymers, along with corresponding solutions.

through deep tissues to reach the ACT-TENG. The ACT-TENG converts the energy of the ultrasound waves into triboelectric pulses, which are then transmitted through Mg electrodes to the treated nerves. After electrical stimulation therapy, high-intensity ultrasound waves (≥3.0 W cm^{-2}) mechanically decompose the ACT-TENG, followed by complete biodegradation and absorption by the body. This device achieves on-demand, controllable therapy while ensuring device biosafety and demonstrating significant therapeutic effects. For instance, as illustrated in Figure 8c, after 5 days of electrical stimulation therapy applied to the injured sciatic nerve of mice, there was a noticeable enhancement in both the motor nerve conduction velocity (MNCV) and the compound muscle action potential (CMAP).

5. Pros and Cons of Triboelectric Biopolymers

The excellent properties of biopolymers not only enrich the application scenarios of TENGs but also expand the material library of TENGs. However, biopolymers also have some drawbacks that need to be improved, as shown in **Figure 9**. This section provides a succinct account of the pros and cons of biopolymers, alongside corresponding improvement strategies.

1) It has been found that the polarity of functional groups significantly influences the output performance of triboelectric materials. The chemical structures of biopolymers are often complex, containing a plethora of diverse functional groups. In this case, the coexistence of functional groups with different triboelectric polarities influences the triboelectric charge of biopolymers. Nevertheless, the presence of these functional groups renders biopolymers susceptible to chemical modification. Therefore, the judicious selection of modifiers to suppress the impact of functional groups that weaken triboelectric output performance is a potential solution.
2) The preeminent advantage of biopolymers lies in their exceptional biocompatibility, non-toxicity, and biodegradability. The functional groups contained within biopolymers, such as hydroxyl, carboxyl, and amino groups, are capable of reacting with water molecules, thereby leading to the rupture and degradation of biopolymers. Nevertheless, this facilely degradable attribute may abbreviate the operational lifespan of B-TENG devices. Therefore, it is necessary to manufacture biopolymers with designable lifespans by considering the perspectives of molecular structure design and material synthesis.
3) Some biopolymers exhibit a lower degree of crystalline state, which implies the presence of a significant number of grain boundaries. The presence of these grain boundaries facilitates the material's ability to store triboelectric charges. Nevertheless, the permittivity of biopolymers is generally low (permittivity < 5), which results in weak induced charges on the attached electrodes. Hence, concurrently augmenting the charge storage capability and dielectric constant of biopolymers is pivotal for the attainment of B-TENGs with satisfactory output performance. Recently reported interface regulation methods represent a potential solution to this conundrum.[24]

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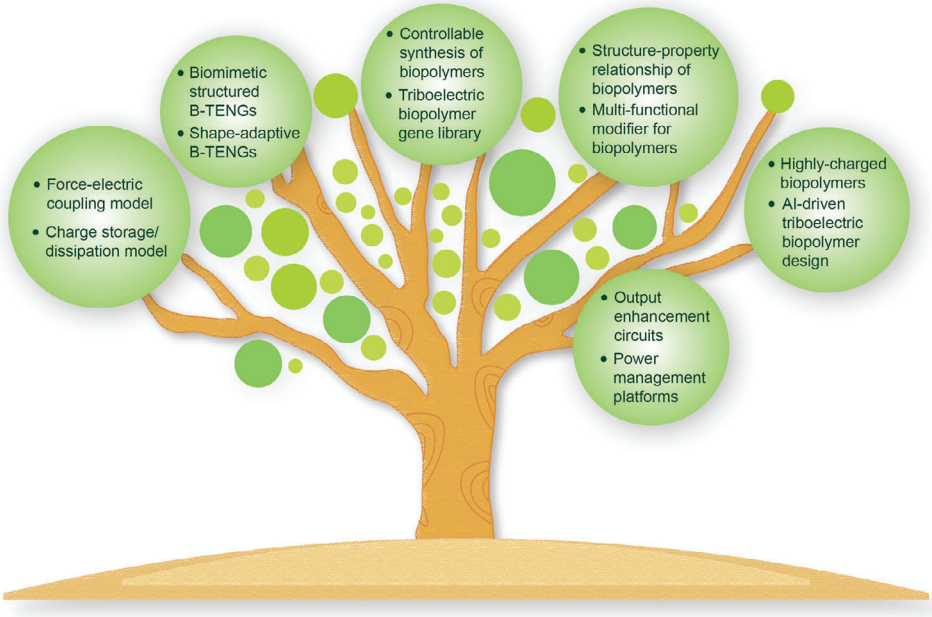

Figure 10. Prospects of triboelectric biopolymers and B-TENGs.

4) Some biopolymers are characterized by exceptional softness, a property that augments their contact efficiency with another friction layer during the contact-separation process. However, these materials are susceptible to wear and tear during service, which may compromise the stability of the device. Hence, it is important to employ strategies such as surface modification, crosslinking, or copolymerization to enhance the wear resistance of the material.

6. Future Perspectives

Indeed, substantial advancements have been achieved in the field of triboelectric biopolymers and B-TENGs in recent times. However, there remains scope for further exploration and optimization. This section and **Figure 10** delineate the prospects for triboelectric biopolymers and B-TENGs:

6.1. Fundamental Physical Models

The magnitude of impact forces and the modulus of the biopolymers exert a pronounced influence on the contact state of the triboelectric layers, which in turn affects the TENG's performance metrics. Hence, it is imperative to formulate force-electric coupling models that delineate the interplay and transformational relationship between the force field and the electric field. On this basis, the accuracy of the model will be ascertained through a comparative analysis with experimental data, and the model will be employed for simulative examinations under diverse operational scenarios to elaborate on the force-electric coupling effects and their implications for triboelectric characteristics. Existing research indicates that the storage and dissipation of triboelectric charge within the polymers have a marked influence on the induced electrode charge density. Therefore, a model that encapsulates the mechanisms of triboelectric charge dynamic behavior is essential for a systematic investigation of the physicochemical processes underlying charge storage and dissipation. Following this, the model will be refined by calibrating parameters in accordance with experimental data, thereby offering a theoretical substratum for the enhancement of the power-generating capabilities of triboelectric biopolymers.

6.2. Refinement of Triboelectric Biopolymers

6.2.1. Controllable Synthesis of Triboelectric Biopolymers

The chemical structure and composition of biopolymers markedly influence their properties, such as triboelectric performance, degradability, and so on. Consequently, it is essential to orchestrate the structural and compositional attributes of biopolymers through a meticulously controllable synthesis process. On one hand, the controllable synthesis of triboelectric biopolymers facilitates the fabrication of high-performance materials that are custom-designed to fulfill specific requirements. On the other hand, the intrinsic correlation between the molecular structure of biopolymers and their electrical properties can be methodically explored. Moreover, the controllable synthesis of triboelectric biopolymers guarantees the uniformity, yield rate, reliability, and reproducibility of the materials throughout industrial production, thereby laying the groundwork for the scalable manufacturing of biopolymer-based triboelectric devices.

6.2.2. Develop More Output Amplification Methods

A plethora of methods have been developed to augment the power generation capabilities of biopolymers. Among them,

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the utilization of polymer composites, especially those integrated with two or more materials including nanomaterial doping, emerges as a prevalent and effective modification approach that manifests considerable enhancements in output. Additional methods such as biomimetic material structure, sandwich composite structures, and core-shell fiber architectures deserve investigation to bolster the triboelectric output of biopolymers. In pursuit of a more streamlined fabrication process and to address a wide array of application needs, the exploration of multifunctional modifiers is merited. These multifunctional modifiers can elevate the triboelectric performance of biopolymers while endowing them with a suite of additional functionalities, including enhanced mechanical robustness, adhesiveness, biodegradability, and antimicrobial characteristics. In addition, the biocompatibility and biodegradability of the modifiers should also be taken into consideration when modifying biopolymers.

6.3. Investigation of Advanced Biopolymers

6.3.1. Exploring Novel Biopolymers

Within the array of triboelectric biopolymers reported, a significant proportion exhibits positive polarity. Therefore, the development of biopolymers characterized by negative polarity and endowed with superior electron-accepting capabilities, as well as biopolymers possessing elevated dielectric constants, is imperative. Additionally, the exploration of non-degradable yet biocompatible biopolymers that demonstrate excellent triboelectric output is of considerable interest for further study.

6.3.2. Establishment of Triboelectric Biopolymer Gene Libraries

Currently, the triboelectric series of some biopolymers have been delineated. It is essential to further refine and expand these series to construct a more comprehensive triboelectric biopolymer gene library. Additionally, machine learning (ML) algorithms can be employed to enhance the analysis and utilization of the ever-expanding triboelectric biopolymer database. For instance, ML can optimize the preparation of biopolymer blends or composites by analyzing existing data and proposing optimal material combination schemes, thereby improving their triboelectric output or other beneficial attributes. ML is also capable of predicting the triboelectric output of novel biopolymers based on their chemical structure or surface properties, enabling researchers to prioritize the most promising candidate materials for experimental testing. The application of these advanced tools not only accelerates the development of triboelectric biopolymers significantly but also reduces the time necessitated by trial-and-error methods.

6.4. Biomimetic Structure and Circuit Integration

6.4.1. Biomimetic Structured B-TENGs and Shape-Adaptive B-TENGs

Biological structures inherently boast superior efficiency and efficacy. Thus, by drawing upon inspiration from natural organisms, we can design and manufacture biomimetic architecture B-TENGs that not only exhibit enhanced performance but also superior biocompatibility. The monitoring of human anatomical and physiological motion signals represents a prevalent use case for B-TENGs. Therefore, the invention and manufacturing of shape-adaptive B-TENGs not only facilitates their accommodation to the dynamic contours of the human body form and ensures consistent performance under diverse environmental and conditional parameters, but it also affords a more seamless and agreeable experience for the users. Furthermore, when fabricating biomimetic structured B-TENGs and shape-adaptive B-TENGs as triboelectric sensors, it is beneficial to employ chemical modification techniques to enhance the properties (e.g., adhesion, bioactivity, output performance, etc.) of the biopolymer triboelectric layer to achieve a synergistic effect with the device structural design, thereby collectively improving the sensing characteristics of the B-TENGs.

6.4.2. Output Boosting Circuits and Power Management Platforms Designed for B-TENGs

The enhancement of the output charge density of TENG through the integration of functional circuits, such as the charge pumping circuit and the charge excitation circuit, has emerged as a focal point in recent research on TENGs with ultra-high transferred charge density. Thus, the integration of such performance enhancement circuits is an efficacious strategy in applications necessitating high-power B-TENGs. Additionally, the substantial impedance of TENGs restricts their practical application in driving low-impedance devices. Therefore, the design of appropriate power management platforms for the precise control, storage, and regulation of the electrical energy harnessed from B-TENGs is instrumental in broadening their applicability spectrum.

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Conflict of Interest

The authors declare no conflict of interest.

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