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Biodegradable power sources for transient bioelectronics

Li Dong [1], Liangjie Shan [1], Yafei Wang, Ji Liu [*]

Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

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ABSTRACT

The development of biodegradable power sources has opened new avenues for transient bioelectronics, offering temporary energy solutions for implantable medical devices. This review presents a systematic overview on the design, materials, and functionalities of biodegradable devices for energy storage, harvesting, and transfer. Biodegradable batteries and supercapacitors provide reliable, short-term energy for implantable devices, while triboelectric and piezoelectric nanogenerators enable continuous energy harvesting from biomechanical sources. Additionally, wireless energy transfer systems enable safe power delivery without direct contact with biological tissues, broadening the scope of implantable bioelectronics. Future research should prioritize enhancing biocompatibility, increasing energy density, and refining degradation control to extend the practical applications of biodegradable power sources in bioelectronics.

1. Introduction

Transient bioelectronics is a rapidly emerging field focused on creating electronic devices that self-degrade after completing specific tasks within the human body [1–3]. These devices hold significant potential for applications in medical diagnosis, tissue rehabilitation, and therapeutic interventions (Fig. 1) [4–7]. As a crucial component of transient bioelectronic devices, the power supply must provide stable energy throughout the device operation and degrade safely at the end of its lifecycle. Therefore, designing biodegradable power supplies that fulfill these requirements is vital for advancing the application of transient bioelectronic devices. Currently, biodegradable power sources include three main categories: biodegradable energy storage devices, biodegradable energy harvesting devices, and biodegradable energy transmission devices (Fig. 1) [8,9]. Each type of system features unique design strategies and functional advantages, offering effective energy solutions across various application scenarios. This review will provide an overview of these three types of biodegradable power sources and their development, along with an exploration of their potential applications in transient bioelectronic devices.

Biodegradable energy storage devices, such as biodegradable batteries and supercapacitors, serve as essential components in transient bioelectronics. Biodegradable batteries produce electrical energy through chemical reactions, providing continuous and stable power for implantable medical devices, including drug delivery systems, sensors, and neurostimulators. These batteries are particularly well-suited for applications requiring a medium- to long-term power supply [10]. Biodegradable supercapacitors possess high power density and fast charge/discharge capabilities, making them ideal for transient devices with short-term, high-power demands [11,12]. Unlike traditional batteries and supercapacitors, these biodegradable energy storage devices can break down into non-toxic byproducts within living organisms while supplying electrical energy, thus minimizing the risk of long-term tissue irritation.

To further boost the autonomy of transient bioelectronic devices, biodegradable energy harvesting systems offer long-term power by capturing energy from the environment. These devices primarily consist of biodegradable triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs). They utilize mechanical energy (e.g., human movement, heartbeat, etc.) to be converted into electrical energy with efficient energy conversion capability for transient devices in dynamic environments [13]. Biodegradable energy transfer systems wirelessly power transient bioelectronic devices, overcoming the limitations and drawbacks of wired connections while enhancing the flexibility and comfort of the device. The main types include wireless electromagnetic induction devices, radio frequency (RF) energy harvesters, and ultrasonic and optical energy transmission devices [14–16]. Metals (e.g., magnesium, zinc, and molybdenum) and natural polymers

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* Corresponding author.
E-mail address: liuj9@sustech.edu.cn (J. Liu).
[1] These two authors contributed equally to this work.

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(e.g., silk proteins and collagen), known for their excellent biocompatibility and degradability, are commonly used to manufacture key components (e.g., inductors, coils, and RF antennas). These materials not only transmit energy efficiently but also degrade in the body, thereby reducing the health risks associated with long-term implantation. The versatility of biodegradable power sources enables a broad spectrum of applications for transient bioelectronic devices. With optimized material selection and structural design, these power sources can deliver stable electrical support during use and gradually degrade after completing their task, ensuring both biosafety and environmental sustainability [17,18]. Future research should aim to enhance the biocompatibility, energy density, and integrative capabilities of these power sources to provide more robust energy solutions for advancing transient bioelectronics.

2. Biodegradable energy storage devices

Biodegradable energy storage devices are vital components of transient bioelectronic systems, storing and releasing electrical energy to maintain stable operation during their functional tasks. These devices primarily consist of biodegradable batteries and supercapacitors. Despite notable differences in their operating principles and material choices, all the considerations in design and fabrication of biodegradable energy storage devices both are aiming to enhance their energy density, stability, and degradability.

2.1. Biodegradable batteries

Batteries are composed of a cathode, an anode, and an electrolyte. Its operation relies on redox reactions between the electrodes, converting chemical energy into electrical energy (Fig. 2**a**) [19,20]. During the discharge process, the anode material undergoes oxidation to release electrons, while the cathode material undergoes reduction to accept electrons, resulting in electric current.

Electrode materials and electrolytes must possess high electrical conductivity, biocompatibility, and degradability. Representative anode materials include magnesium, zinc, iron, and their alloys, which exhibit high theoretical specific capacities (e.g., magnesium: ∼2200 mAh··g-^{1}; zinc: ∼820 mAh··g-^{1}; iron: ∼960 mAh·g-^{1}) and can gradually degrade through dissolution or oxidation within biological tissues [22,23]. Cathode materials are usually selected from conductive polymers (e.g., polypyrrole, polyaniline) or inorganic materials (e.g., lithium iron phosphate, manganese oxide) (Fig. 2**b**) [3]. Electrolytes typically include polyethylene glycol, polylactic acid, and their derivatives, ensuring both ionic conductivity and biosafety [24].

Biodegradable batteries can be designed in stacked, microstructured, or fiber configurations to suit various applications (Fig. 2**c-e**) [25–29]. Stacked configurations can increase the specific capacity and energy density by stacking multiple layers of electrodes and electrolytes. Microstructured designs boost reaction rates and power density by utilizing electrodes with micrometer-scale dimensions. Fiber-based designs provide flexibility and mechanical compliance to the battery. To enhance the performance of biodegradable batteries, structural engineering, such as surface modification of the electrodes, utilizing nanoscale materials or porous materials for electrode fabrication, could be applied [23,30,25].

2.2. Biodegradable supercapacitors

Supercapacitors store energy through charge adsorption on the electrode surface, providing high power density, quick charge/discharge capabilities, and a prolonged cycle life [31,32]. They are composed of two electrodes and an electrolyte. Capacitance mainly arises from the double-layer capacitance and Faradaic pseudocapacitance of the electrodes, where charges are adsorbed on the electrode surface or embedded in ions, enabling energy storage and release during the charging and discharging processes (Fig. 2**f**) [33].

Electrode materials for biodegradable supercapacitors primarily consist of conductive polymers, carbon-based materials, and bio-based nanomaterials (Fig. 2**g**). For example, conductive polymers like polypyrrole and polyaniline exhibit high electrical conductivity (e.g., ∼10–100 S·cm^{-1}) and can be degraded into non-toxic byproducts in vivo [34]. Conversely, carbon-based materials such as carbon nanotubes and

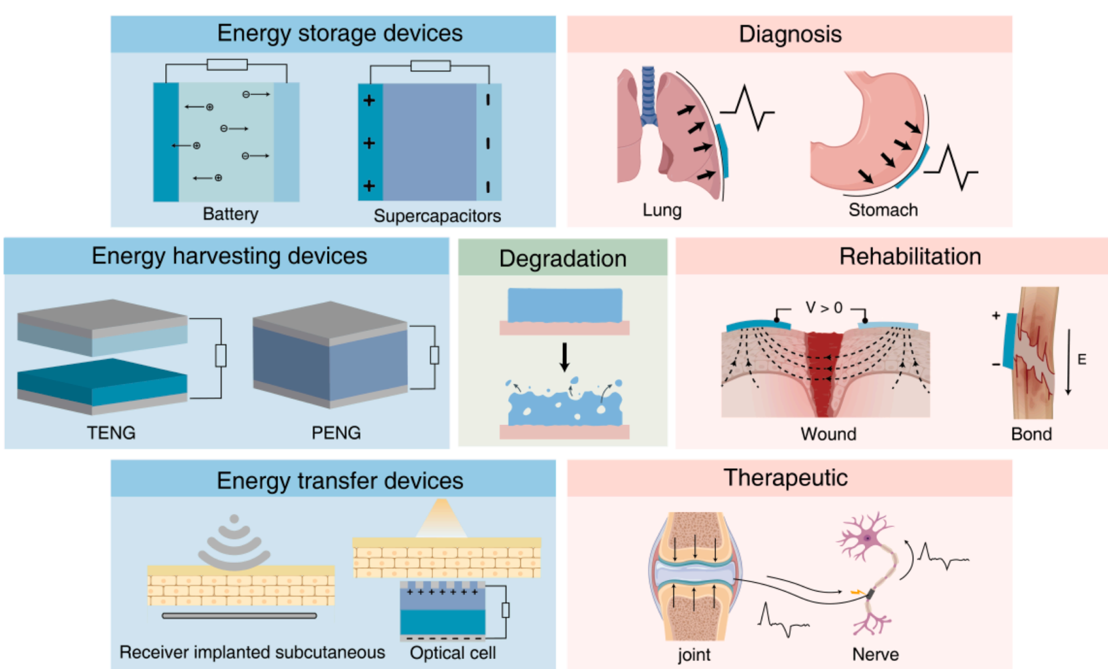

Fig. 1. Overview of different types of biodegradable power sources for transient bioelectronics. Transient bioelectronics are electronic devices capable of self-degradation after completing specific tasks within the human body. Their power sources include energy storage devices (such as batteries and supercapacitors), energy harvesting devices (e.g., TENG and PENG), and energy transfer devices (e.g., inductive coupling/RF, ultrasonic, and photovoltaic energy harvesters), offering broad application potential in medical diagnosis, tissue repair, and therapeutic interventions.

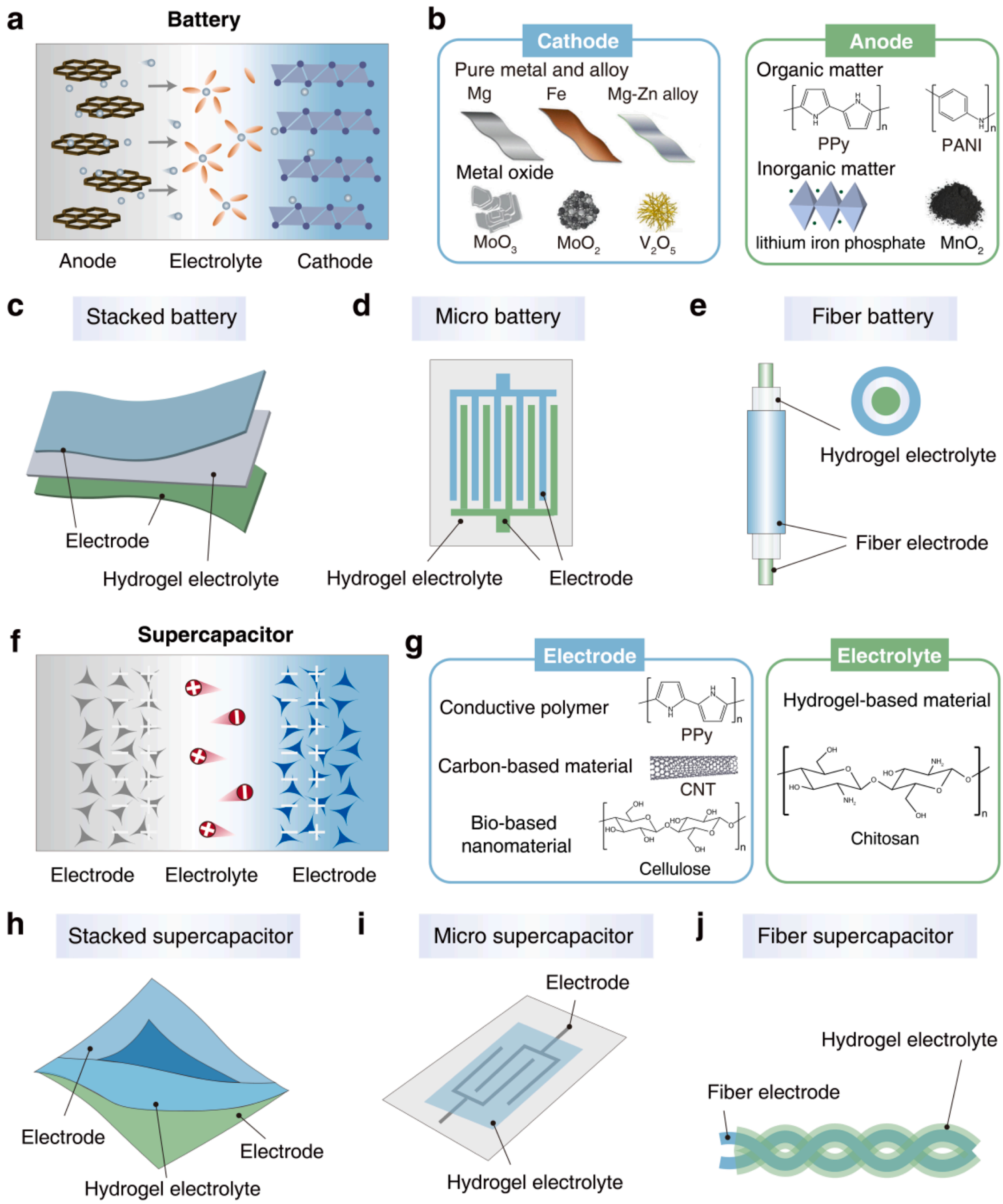

Fig. 2. Biodegradable energy storage devices. (**a**) Battery structure and power supply mechanisms. (**b**) Classification of representative biodegradable materials in cathode and anode materials for biodegradable batteries. Reproduced with permission [21]. Copyright 2021, Wiley-VCH. Structural schematic of a stacked battery (**c**), microbattery (**d**), and fiber battery (**e**). (**f**) Structure and power supply mechanism of supercapacitors. (**g**) Classification of representative biodegradable materials in electrode and electrolyte materials for biodegradable supercapacitors. Structural schematic of a stacked supercapacitor (**h**), microsupercapacitor (**i**), and fiber supercapacitor (**j**).

graphene offer high specific surface area and excellent electrical conductivity, making them ideal for efficient charge storage [35,36]. Bio-based nanomaterials, including nanofibrillar cellulose and chitosan nanosheets, are emerging as ideal biodegradable electrode materials. Electrolytes are typically composed of hydrogel-based materials like chitosan or polyvinyl alcohol hydrogels, offering superior ionic conductivity, along with excellent biocompatibility and degradability (Fig. 2**g**).

Device forms of capacitors likewise include stacked structures, microstructures, and fiber structures (Fig. 2**h-j**) [37–39]. Stacked configurations enhance capacitance and energy density through parallel and series connection of multiple layers of electrodes. Microstructured designs boost charge transfer rates and power density by arranging nanoelectrodes. Fiber-based designs enhance the flexibility and stretchability of capacitors by utilizing flexible fiber electrodes. Strategies to enhance capacitor performance focus on optimizing the porous structure of electrode materials, increasing the active sites of the electrode surface, and improving the ionic conductivity of the electrolytes [40–43]. Biodegradable batteries and supercapacitors serve as essential energy storage components in transient bioelectronic systems. By optimizing material selection and structural design, these devices deliver efficient and stable energy output while naturally degrading into non-toxic byproducts after use. Future research should aim to improve the energy density, power density, and cycling stability of these energy storage devices, while ensuring controlled degradability and biosafety in vivo and in the environment, to advance biodegradable energy storage technologies in transient electronics.

3. Biodegradable energy harvesting devices

Biodegradable energy harvesting devices provide continuous energy for transient bioelectronic devices by converting environmental mechanical energy into electrical energy. TENGs and PENGs are two pivotal energy harvesting technologies, which have emerged as major research focuses in transient bioelectronics, owing to their simple design, high efficiency, versatile materials, and broad adaptability [44–47]. The features of these two devices will be explored in detail across four aspects: structure, operating principles, material selection, and performance optimization.

3.1. Biodegradable triboelectric nanogenerators

TENGs operate on frictional initiation and electrostatic induction principles, converting mechanical energy to electrical energy through the periodic contact and separation of two different material surfaces (Fig. 3a) [48,49]. A typical TENGs structure is consisted of two friction layers, which are made of different materials, a flexible substrate, and an electrode layer [50,51]. During the contact-separation process, electric charge accumulates through friction at the interface and is transferred through the electrodes to form an electric current when the materials are separated [52]. TENGs are available in contact-separation, sliding, and free-vibration configurations to adapt to various mechanical energy sources, including heartbeat, respiration, muscle contraction, and external vibration [53].

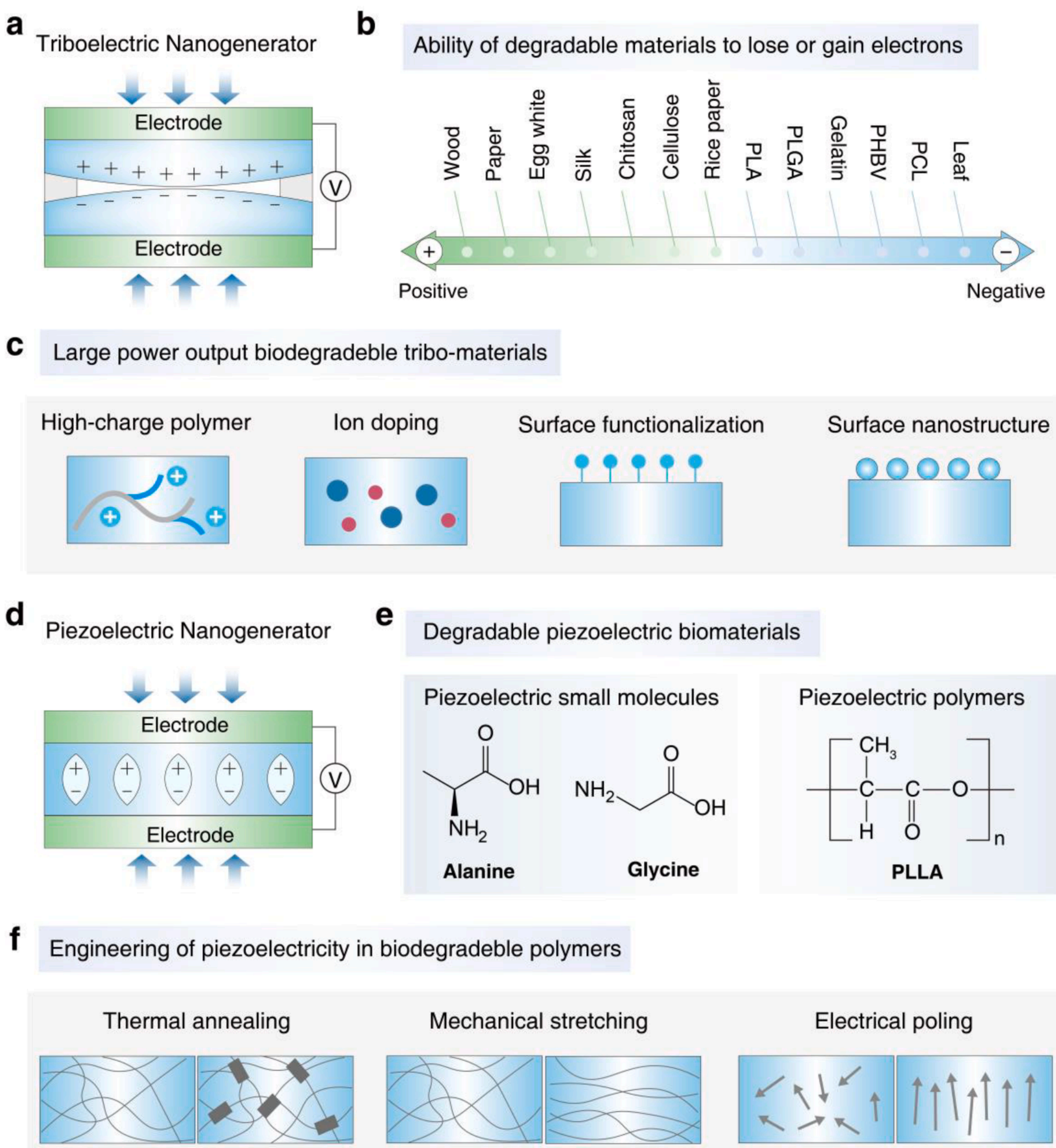

Fig. 3. Biodegradable energy harvesting devices. (**a**) Schematic illustration of the TENG structure and its working mechanism. (**b**) Representative biodegradable triboelectric biomaterials. (**c**) Strategies for developing high-performance biodegradable triboelectric materials and devices. (**d**) Schematic illustration of the structure and operating mechanism of a PENG. (**e**) Representative biodegradable piezoelectric biomaterials. (**f**) Strategies for achieving high-performance biodegradable piezoelectric materials and devices.

The performance of biodegradable TENGs is influenced by both the triboelectric properties and the degradability of the materials employed. Material selection has primarily concentrated on naturally biodegradable substances (e.g., chitosan, silk, and gelatin) and synthetic biodegradable polymers (e.g., poly (lactic acid) (PLA) and polycaprolactone (PCL)) (Fig. 3**b**) [54,55]. These materials possess good biocompatibility and degradability, but their triboelectric output is usually low, mainly due to limited charge trapping and transport capabilities. Therefore, material modification becomes a key strategy to improve the performance of biodegradable TENG [56]. Common modification techniques include the use of high charge density polymers, ion doping, surface functionalization, and the design of surface nanostructures (Fig. 3**c**) [6, 57,44]. For instance, doping biodegradable polymers with high dielectric constant polymers (e.g., PEDOT: PSS) increases their dielectric constant and enhances charge trapping and transport between biodegradable TENG surfaces, thereby amplifying the triboelectric output [58]. Introducing ions into polymers can elevate the surface potential and enhance the triboelectric properties by facilitating more efficient charge transfer [57]. Additionally, functionalizing materials with groups can enhance the triboelectric effect by increasing the electron affinity of the polymer surface [59]. Increasing the surface area through techniques can significantly enhance the triboelectric charge density, thereby boosting the output voltage and current [60]. Through the combined application of these strategies, the challenge of low output power in biodegradable TENG can be effectively overcome, allowing it to demonstrate greater potential for application in transient bioelectronics.

3.2. Biodegradable piezoelectric nanogenerators

The PENGs operate according to the piezoelectric effect. When piezoelectric materials experience mechanical deformation (e.g., bending, compression or tension), their internal electric dipole moments reorient, causing charge accumulation and enabling the conversion of mechanical energy into electrical energy (Fig. 3**d**) [61,62]. Typical PENG structures include a piezoelectric membrane, a flexible substrate, and electrode layer. The piezoelectric membrane, in the form of a thin film, is attached to a flexible substrate, in respond to mechanical deformation. PENGs provide unique advantages in capturing and converting low-frequency mechanical energy, making them particularly well-suited for energy harvesting from physiological activities such as heartbeat, respiration, and vasovagal pulsation [63,64].

Material selection for biodegradable PENGs has centered on biodegradable small molecules and polymers with piezoelectric properties, including piezoelectric small molecules such as alanine and glycine, and piezoelectric polymers like proteins, cellulose, and poly(L-lactic acid) (PLLA) (Fig. 3**e**) [65–67]. Despite significant progress in biodegradable PENG material systems, their output performance remains limited by the low piezoelectric coefficient of these materials, resulting in insufficient energy output. Material modification has been employed to enhance the piezoelectric performance of biodegradable PENGs [6]. For material modification, the introduction of inorganic nanoparticles, such as barium titanate ($BaTiO_3$), into the substrate material can substantially improve the piezoelectric response and charge transfer efficiency. For instance, incorporating 20 % of $BaTiO_3$ nanoparticles into a PLLA substrate can increase the piezoelectric coefficient by about 15 times and significantly improve the charge transfer efficiency [68]. Thermal annealing can adjust polymer chain alignment, enhancing material crystallinity and polarization direction, which in turn contributes to improved piezoelectric properties (Fig. 3**f**) [69]. Mechanical stretching and electric field polarization align molecular chains or electric dipoles in a specific direction, significantly boosting piezoelectric output (Fig. 3**f**) [70,71]. These material optimization strategies have significantly expanded the potential of biodegradable PENGs for transient bioelectronics applications.

The energy-harvesting capabilities of biodegradable TENGs and PENGs in transient bioelectronic devices have been extensively studied, demonstrating promising application prospects [46,5,72]. Through optimized material selection and structural design, these devices effectively convert mechanical energy and gradually degrade into non-toxic byproducts post-use [6]. Future advancements in biodegradable TENGs and PENGs for transient bioelectronics should focus on enhancing energy conversion efficiency, achieving precise control over degradation rates, and ensuring mechanical stability under physiological conditions. Furthermore, progress in multifunctional integration with other bioelectronic components and scalable manufacturing techniques will be critical to fully realize their biomedical applications.

4. Biodegradable energy transfer devices

Traditional implantable devices, such as pacemakers and neurostimulators, remain bulky due to power limitations. Although energy storage technology has made significant advancements, battery miniaturization remains to be challenging. In addition to energy-harvesting technologies such as triboelectric and piezoelectric systems, wireless power transfer (WPT) offers an alternative solution to these long-lasting challenges. Compared to other strategies, WPT offers higher power transfer efficiency (PTE) and increased design flexibility, while its wireless nature reduces operational complexity and minimizes potential tissue damages. WPT-based power devices eliminate the need for bulky batteries by utilizing energy receivers, thereby extending battery life and reducing the overall size of the devices. This approach enables the development of smaller, simpler, and safer implantable device designs. Common WPT strategies for bioelectronic implants include inductive coupling, RF, ultrasound, and photovoltaic technologies [73]. The following sections will provide a detailed overview of these strategies.

4.1. Inductive coupling/RF energy harvesters

Inductive coupling is one of the earliest and most widely used wireless power transfer strategies, primarily due to its low attenuation of RF microwaves in near-field regions [74]. As shown in the circuit diagram (Fig. 4**a**), this power source functions through electromagnetic induction, transferring energy via magnetic coupling between transmitting (TX) and receiving (RX) coils. Based on Faraday's law, the magnetic field interacting with the circuit produces electromotive force (EMF). The alternating voltage in the TX coil induces a change in magnetic flux in the RX coil, thereby generating EMF in the implanted device [75]. Typically, the operating frequency falls within the kilohertz (kHz) range, enabling efficient power transfer over short distances (less than a few centimeters). Inductive coupling systems commonly employ conductive metals, such as copper and silver; however, these materials cannot undergo complete degradation within the in vivo environment. To address this issue, Song et al. developed a miniaturized electrotherapy device based on bioabsorbable Mo metal. This device utilizes magnetic induction at 13.56 MHz to provide wireless power, eliminating the need for physical battery components (Fig. 4**b**) [76]. In the uniform electromagnetic field generated by an inductive power transmitter coil, this device achieves a stable output voltage of 1.1 V (Fig. 4**c**). The Mo device implanted in the mouse's body maintains its original shape over the 13-week healing period, and subsequently, it is completely absorbed and disappears from the body after approximately 35 weeks. This bioabsorbable wireless system reduces the need for secondary surgeries to remove power and data transmission components from experimental animals, thereby minimizing unnecessary stress on the subjects.

Although inductive coupling can power implantable electronic devices, its effectiveness is limited by transmission distance, leading to low efficiency for devices implanted deeper within tissues. In contrast, RF energy transfer offers the advantage of covering longer distances. RF typically operates in the MHz to GHz range, transmitting energy through electromagnetic waves propagating through air and other media. When applied in biological systems, the frequency of RF can be adjusted to

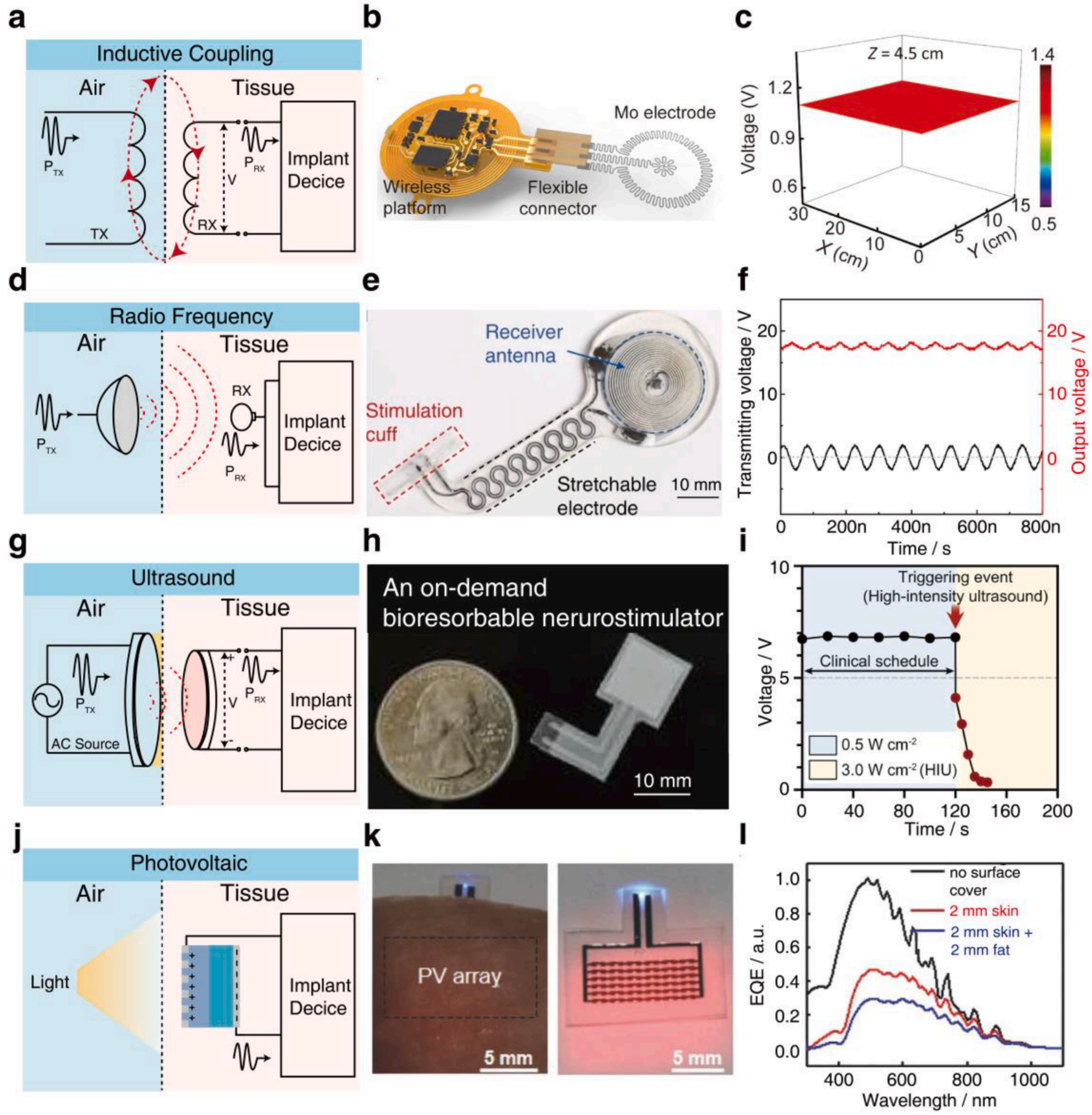

Fig. 4. Biodegradable energy transfer devices. (**a**) Schematic of inductive coupling. (**b**) Image of a transient, wireless, and battery-free system. (**c**) Stimulation voltage across the cage was measured at a height of 4.5 cm. Reproduced with permission [76]. Copyright 2023, American Association for the Advancement of Science. (**d**) Schematic of radio frequency. (**e**) Bioresorbable wireless electronic stimulator [14]. (**f**) Example output waveform of the stimulator (red) generated wirelessly by applying an alternating current (sine wave) to the transmission coil (transmitter, black).Reproduced with permission [14]. Copyright 2020, Springer Nature. (**g**) Schematic of ultrasound. (**h**) The overall structure of the on-demand bioresorbable neurostimulator [77]. (**i**) Demonstration of on-demand transience with long-term electrical characterization of the ACT-TENG output. Reproduced with permission [77]. Copyright 2023, Springer Nature. (**j**) Schematic illustration of photovoltaic technology. (**k**) A fully biodegradable monocrystalline Si-based PV platform [78]. (**l**) Normalized external quantum efficiency (EQE) spectra of a microcell measured in three scenarios. Reproduced with permission [78]. Copyright 2018, Wiley-VCH.

precisely control its penetration depth in different biological tissues. (Fig. 4**d**) [75,79]. Specifically, the receiver coil captures RF radiation from the transmitter coil and converts it into DC power through a rectifier circuit, providing sufficient power for various implants. Based on this principle, Choi et al. developed a wireless electrostimulation device for neural tissue stimulation, which is powered by wireless RF energy transmission, thereby eliminating the need for batteries (Fig. 4**e**) [14]. By adjusting the transmission power and the distance between the transmitter and receiver coils, the output voltage range (2–17 V) can be controlled. The device is constructed from bioabsorbable dynamic covalent polyurethane (b-DCPU) material, providing mechanical stretchability, and features a serpentine Mo metal strip. This design ensures that the output voltage remains stable under 30 % elongation and 360° torsion (Fig. 4**f**).

4.2. Ultrasonic energy harvesters

Ultrasound-induced wireless energy harvesting (UWEH) technology converts mechanical energy from sound waves into electrical energy. (Fig. 4**g**). Unlike electromagnetic waves, ultrasound with frequencies above 20 kHz has a stronger penetration capability, enabling effective energy transfer through skin, muscle, and other soft tissues [80]. In addition, compared to traditional transient bioelectronic devices, the lifespan of these devices is typically determined by the size and degradation characteristics of the materials, which degrade gradually over time. By increasing the intensity of the ultrasound, localized acoustic pressure is generated within the device, causing structural vibrations and friction, thereby accelerating the degradation of the materials [81]. Based on this principle, Lee et al. developed a controllably biodegradable neurostimulator that generates power through an ultrasound-driven triboelectric mechanism, enabling neural stimulation therapy at a kilohertz frequency under low-intensity ultrasound (≤1.0 W·cm^{-2}) (Fig. 4**h**) [77]. Under high-intensity ultrasound (≥3.0 W·cm^{-2}), the device rapidly decomposes without requiring surgical removal and leaves no residue (Fig. 4**i**). This on-demand degradation design enhances clinical safety and flexibility and optimizes therapeutic outcomes by reducing the risk of inflammation or tissue reactions caused by residual materials, ultimately promoting better recovery for patients.

4.3. Photovoltaic devices

Photovoltaic (PV) devices are technologies that directly convert light into electricity and are widely used in implantable devices powered by external light sources (Fig. 4**j**) [82]. PV devices capture photons and convert them into electrical energy via a photodiode. Traditional photovoltaic cells operate under environmental conditions, collecting solar energy without the need for additional optical modules. In biomedical applications, PV devices are typically encapsulated within the skin, fat, muscle, or deeper soft tissues. Lu et al. developed a biodegradable photovoltaic system based on single-crystal silicon microbatteries, where all components, including the active layer, electrodes, interconnections, and encapsulation layers, are made from fully biocompatible and biodegradable materials (such as Mo, PLGA, etc.). This system efficiently converts light energy into electrical energy (Fig. 4**k**) [78]. These microbatteries exhibit high external quantum efficiency in the 500–700 nm wavelength range and continuously generate 25 μW of power under absorption by skin and fat tissues, which is sufficient to power subcutaneous devices such as LEDs (Fig. 4**l**). Table 1 summarizes the key characteristics of various types of biodegradable power sources.

5. Application in biomedical fields

Implantable transient bioelectronic devices utilize bioabsorbable materials, allowing them to perform diagnostic or therapeutic functions during specific biological processes and then naturally degrade within the body once their tasks are completed. This design eliminates the risks, tissue damage, and financial burden associated with secondary surgeries required to remove conventional implants, significantly enhancing the safety and convenience of clinical applications [83–85]. Due to these advantages, implantable transient bioelectronics exhibit broad potential in the medical field.

Table 1
Summary of key characteristics of different types of biodegradable power sources for transient bioelectronics.

Type of power source	Energy type	Key features	Challenges
Biodegradable Batteries	Chemical	- High energy density [23]	- Limited cycle life -Corrosion management
Biodegradable supercapacitors	Electrochemical	- Rapid charge/ discharge [32] - Long cycle life	-Stability in wet environments
Biodegradable TENGs	Mechanical	- Harvests low-grade mechanical energy [53] - Lightweight	- Low power output
Biodegradable PENGs	Mechanical	- Converts small mechanical stresses [64] - High sensitivity	- Material degradation
Inductive coupling/RF energy harvesters	Electromagnetic Radio frequency	- Remote power delivery - No need for onboard energy storage [71]	- Limited power range - Complex receiver design [73,74]
Ultrasonic energy harvesters	Acoustic	- High penetration in tissue[75] - Controlled degradability [79]	- Attenuation in tissue [79] - Precision alignment required
Photovoltaic devices	Photovoltaic	- Sustainable - Energy conversion under light exposure [82]	- Dependency on light [78] - Efficiency trade-offs

Implantable bioelectronic devices enable precise monitoring of essential physiological parameters, including pressure, temperature, and bioelectrical signals, due to their high sensitivity, rapid response, and miniaturized design [86]. These devices play a vital role in the diagnosis and management of chronic diseases. Curry et al. developed a biodegradable piezoelectric sensor based on PLLA nanofibers, capable of monitoring abdominal pressure changes during cyclic contraction and relaxation of mouse peritoneal muscles and transmitting real-time data wirelessly (Fig. 5**a**) [87]. This sensor shows promising potential for applications in intra-abdominal pressure monitoring (Fig. 5**b**). However, periodic tissue movements during long-term monitoring can lead to sensor detachment from target tissues, compromising device stability. To address this challenge, Lin et al. designed a wireless pressure sensor with a mechanically flexible hydrogel biointerface, constructed using a poly(HEMA-NVP) hydrogel substrate and an adhesive (AA-NHS) polymer brush. Through a mature, dry crosslinking mechanism, the sensor forms an instant and robust bioadhesive interface, ensuring tight tissue adhesion even in dynamic environments, thus enabling stable intracranial pressure monitoring (Fig. 5**c**) [6,88,29]. Their results showed that variations in resonant frequency (f_o) detected by a vector network analyzer (VNA) closely correlated with applied pressure, enhancing monitoring precision while reducing foreign body reactions and mechanical mismatches at the interface (Fig. 5**d**).

Electrical stimulation, a precise, non-pharmacological intervention, has been shown to effectively regulate biological processes at the molecular, cellular, tissue, and organ levels [91–93]. It is especially effective in promoting cell proliferation and tissue healing. In recent years, increasing efforts have focused on employing electrical stimulation to treat chronic wounds, especially diabetic wounds, which are regarded as refractory due to their slow healing and susceptibility to infection (Fig. 5**e**). To address this challenge, Song et al. developed a wirelessly powered miniature electrical therapy device that accelerates wound healing by simulating endogenous electric fields and monitors the healing process in real-time. Experiments on a diabetic mouse model demonstrated that electrical stimulation significantly accelerated wound healing. On day 15, the wound closure rate in the electrostimulation group was 86.0 ± 10 %, compared to 62.6 ± 11 % in the untreated group and 66.4 ± 12 % in the control group. Most mice in the control and untreated groups required >4 weeks to achieve full wound closure. In contrast, the treatment group achieved wound closure in <3 weeks. (Fig. 5**f**) [89].

In recent years, electric field-controlled drug delivery systems have advanced significantly, demonstrating their potential across various tissue environments. By precisely controlling drug release through electric fields, these systems offer on-demand drug delivery tailored to various physiological and pathological conditions, including subcutaneous, muscular, vascular, and neural tissues, thereby meeting the needs of personalized therapies (Fig. 5**g**). Sheng et al. developed an implantable system that integrates a wireless charging module and a biodegradable zinc-ion hybrid supercapacitor. This system utilizes electric fields to trigger the release of ibuprofen (IBU) anions, effectively treating fever in a rat model. Experimental results indicated that the rectal temperature in the electro-stimulated group (E-DG) was significantly lower than that in the non-stimulated group (NG), confirming the advantages of electric field control in precise drug delivery (Fig. 5**h**). The integration of the wireless charging module further enhances the flexibility and adjustability of the system design. In addition to inductive coupling, photovoltaic and radiofrequency power sources are also

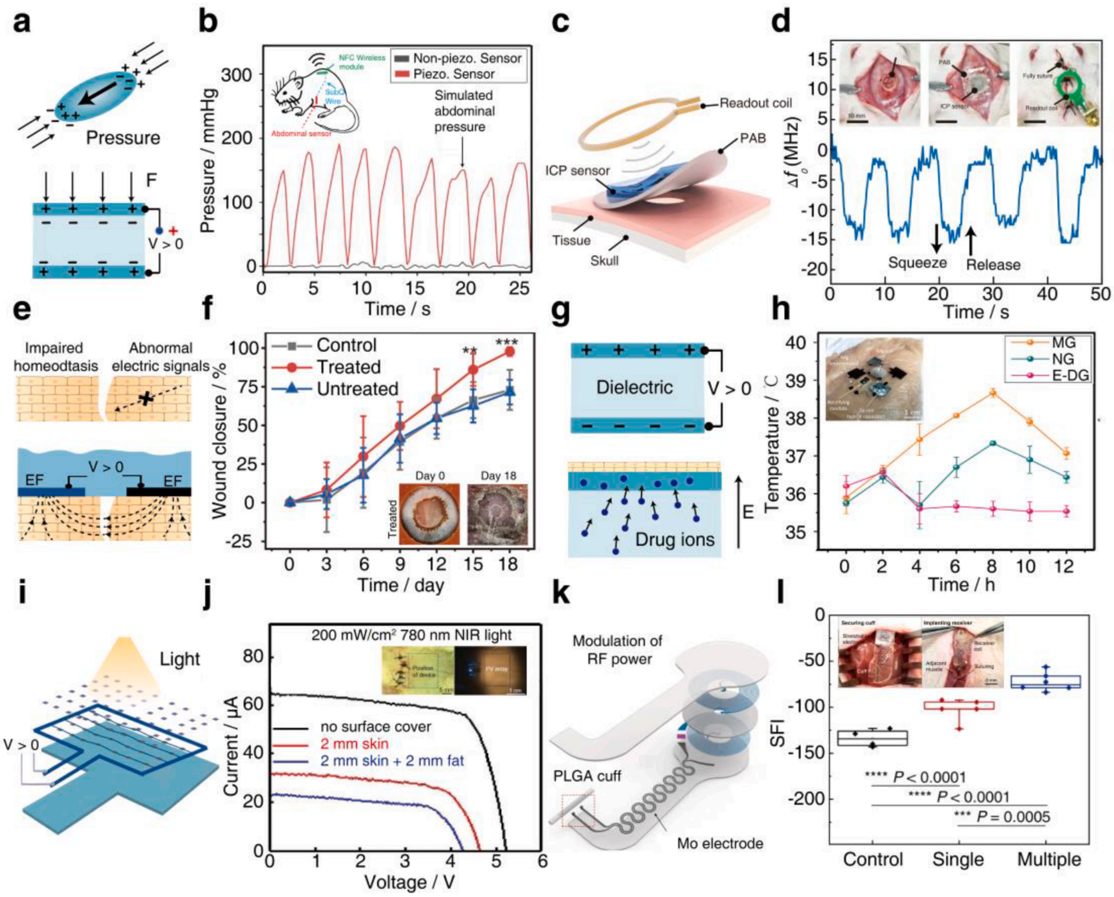

Fig. 5. Applications of biodegradable power sources in bioelectronics. (**a**) Schematic showing the operating principle of transient piezoelectric devices. (**b**) The application of piezoelectric materials in abdominal pressure signal acquisition, with the illustration showing a simplified schematic of an implanted wireless pressure sensor inside a rat. Reproduced with permission [87]. Copyright 2020, National Academy of Sciences of the United States of America (**c**) Schematic of the implanted ICP sensor with hydrogel biointerface. (**d**) Measurements of f_0 while squeezing and releasing the flank of a rat with the illustration presented as images of the device implantation. Reproduced with permission [6]. Copyright 2018, Wiley-VCH. (**e**) Schematic illustration of transient batteries applied in wound healing. (**f**) Quantification of wound closure for day 18 after wounding with the illustration presented as images of the wound healing process. Reproduced with permission [89]. Copyright 2023, American Association for the Advancement of Science. (**g**) Schematic of transient supercapacitors applied in drug delivery. (**h**) Rectal temperatures change value after administration with the illustration presented as images of the device implantation. Reproduced with permission [90]. Copyright 2023, American Association for the Advancement of Science. (**i**) Schematic illustration of the energy conversion process in transient photovoltaic devices. (**j**) Current/voltage curves of an array measured with different materials on its surface with the illustration presented as images of the device implantation Reproduced with permission [78]. Copyright 2018, Wiley-VCH. (**k**) Schematic illustration of the energy conversion process in transient RF devices. (**l**) Dynamic gait analysis confirms the enhanced sciatic function index (SFI) in the group undergoing repeated distal nerve stimulation. Reproduced with permission [14]. Copyright 2020, Springer Nature.

widely used in transient bioelectronics (Fig. 5**i**). These technologies provide various effective energy harvesting methods, significantly broadening the range of applications for implantable bioelectronic devices. In the field of photovoltaics, Lu et al. developed a single-crystal silicon photovoltaic platform. In in vivo experiments, the platform was able to generate approximately 60μW of power under 4 mm of pig skin and fat tissue, demonstrating its potential for wireless energy transmission in deep tissues (Fig. 5**j**) [78].

Neuromodulation, a precise intervention, regulates neuronal electrical activity to influence nervous system functions and promote nerve regeneration and recovery. This technology plays a vital role in treating nerve injuries, managing neurodegenerative diseases, and alleviating chronic pain [90,94]. Recent advances in implantable bioelectronic devices and RF power technology have significantly improved the flexibility and biocompatibility of neuromodulation systems (Fig. 5**k**). Choi et al. developed a biodegradable electrical stimulation device that promotes sciatic nerve regeneration and functional recovery through wireless radiofrequency energy harvesting [14]. The results showed that, compared to the single stimulation group (−103±12) and the control group (−134±9), repeated electrical stimulation significantly improved the sciatic functional index (SFI) (−73±10), highlighting the cumulative effect of distal electrical stimulation on neuromuscular regeneration and functional recovery (Fig. 5**l**). This technology shows promising potential for broad applications in treating neurological and muscular disorders.

6. Conclusion and perspectives

Biodegradable power sources offer short-term, stabilized power for various implantable electronic devices, holding significant potential for applications in transient bioelectronics. Despite considerable advancements in recent years, these power sources still encounter numerous challenges in practical applications. Further optimization in material design and device performance is required to enable the widespread application of transient bioelectronics. The following discussion will cover aspects such as enhancing biocompatibility and safety, increasing energy density and stability, achieving controlled degradation, optimizing implantation, improving mechanical compatibility with tissues, and enabling multifunctional integration to clarify future directions for biodegradable power supply development (Fig. 6).

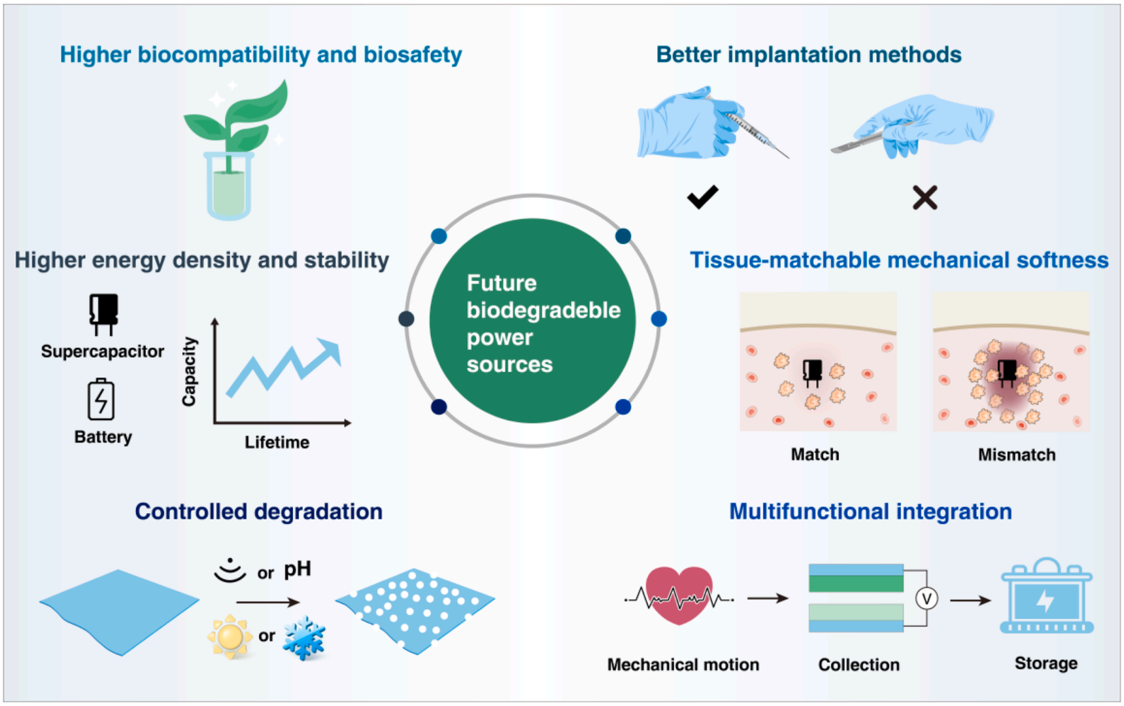

Fig. 6. Challenges and required properties of future biodegradable power sources for transient bioelectronics.

6.1. Improving biocompatibility and biosafety

Biocompatibility and safety are essential prerequisites for applying biodegradable power sources in bioelectronic devices. While some current biodegradable materials demonstrate good biocompatibility, they still pose risks of immune reactions and tissue irritation during long-term in vivo implantation. Future research should focus on optimizing the chemical composition and structure of these materials to minimize immune reactions and ensure that degradation products are non-toxic and harmless to the human body. Additionally, composite systems combining natural biomaterials and synthetic materials should be further explored to enhance biosafety by replicating the chemical environment and physical properties of biological tissues [95]. This approach will enhance the long-term stability of implanted devices and reduce the risk of biological rejection during both implantation and degradation.

6.2. Increased energy density and stability

The application of biodegradable power sources in transient bioelectronic devices is constrained by limitations in energy density and stability. Although current biodegradable power sources can provide short-term power, their energy output is often insufficient to support the long-term operation of high-power-consumption devices. Future research should prioritize developing high-energy-density electrode materials and optimizing electrolyte systems to enhance the energy output of batteries and supercapacitors [96,97]. Specifically, the electrodes' capacity can be increased by introducing nanomaterials and expanding surface area, while ion transfer efficiency can be enhanced using electrolytes with higher ionic conductivity, thereby improving overall energy density and stability. Additionally, material stability is essential for the long-term performance of power sources, so ensuring chemical stability in the design phase is crucial to prevent undesired degradation or performance loss in vivo.

6.3. Achieving controlled degradation rates

Controlled degradation rates are essential for the safety and functional efficacy of transient bioelectronic devices [98]. Different biological applications demand varying degradation rates; for instance, short-term diagnostic devices may require rapid degradation, whereas devices for long-term monitoring need slower degradation rates. Future designs of degradable power supplies should incorporate precise regulation of degradation rates through chemical material modification, structural adjustments, or multilayer composites. This approach will not only extend the device's effective operational period but also enhance its efficiency [95]. In addition, it enables flexible adjustment of the degradation process to meet specific application requirements.

6.4. Improved implantation methods

Currently, most biodegradable power sources require surgical implantation, which not only increases patient discomfort but also carries a risk of infection at the implantation site. Future research should therefore explore easier and safer implantation methods, such as minimally invasive techniques, needle-free injections, or other non-invasive approaches [29,99]. Such methods would not only reduce postoperative recovery time but also lower the risk of infection and other complications. Additionally, enhancements in implantation methods should be complemented by adjustments to the shape, size, and flexibility of the power source to achieve a better fit and stability within the tissue, thereby increasing the device's clinical feasibility and utility.

6.5. Tissue-matched mechanical compliance

The effectiveness and comfort of transient bioelectronic devices largely depend on matching their mechanical properties to those of biological tissues [100,97,101]. Current biodegradable power sources often differ significantly from soft tissues in stiffness and flexibility, which can lead to inflammatory reactions due to friction or stress concentration post-implantation [102]. Future designs should therefore aim to enhance the mechanical flexibility of materials and achieve tissue-matching mechanical properties by modulating molecular structure or incorporating a multilayer composite structure [103]. Such design improvements not only reduce interfacial stress between the device and tissue but also enhance device stability and signal transmission reliability.

6.6. Realization of multifunctional integration

As bioelectronic devices continue to diversify, biodegradable power supplies must integrate with other functional modules, such as sensors and data transmission systems [104]. Such multifunctional integration requires the power supply to possess strong compatibility and system integration capabilities, enabling synergy with other components without compromising power performance. Additionally, future biodegradable power sources should incorporate integrated designs for energy harvesting, storage, and transmission to enhance overall efficiency and stability [78,31]. Future research should investigate multi-material and multifunctional composite systems to achieve seamless integration of power supplies with other functional modules through structural design and material optimization. This multifunctional integration will not only improve the device's overall performance but also enhance greater efficiency and precision in medical diagnosis, monitoring, and treatment.

In conclusion, the development of biodegradable power supplies for diverse applications in transient bioelectronics requires optimization in several key areas, including biocompatibility, energy density, controlled degradation, implantation techniques, mechanical flexibility, and multifunctional integration. With advances in material research, engineering optimization, and system integration, future biodegradable power supplies will play a pivotal role in the biomedical field, providing stable and reliable energy support for sustainable transient electronic devices.

Declaration of competing interest

Ji Liu is a guest editor for Supramolecular Materials and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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Supplementary materials

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