ISSN 2959-6157

Innovations in Biodegradable Batteries: A Sustainable Future

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Abstract:

The increasing demand for batteries in several industries such as medical and electric car (EV) Industry has led to significant environmental challenges due to the production and disposal of traditional batteries, which are non-biodegradable and pose risks to ecosystems. This report investigates the potential of biodegradable batteries as a sustainable alternative to traditional batteries, aiming to minimize environmental impact. This study analyzing and comparing the fiber batteries, zinc-molybdenum batteries, plant-based batteries (Flower battery), crab shell battery as well as algal biopolymers battery. It also highlights the key materials, methods for manufacture, and performance characteristics (biodegradability, energy capacity, degradation time) of each type of biodegradable batteries. The findings suggest that biodegradable batteries offer promising solutions for specific applications, such as in biomedical devices, wearable electronics, and precision agriculture, where their biocompatibility and environmental safety are crucial. Future development should focus on enhancing energy density, optimizing degradation timelines, and reducing costs to make these batteries more competitive with traditional options.

Keywords: Biodegradable batteries; Sustainable material; Environment.

1. Introduction

The rapid advancement of technology and the growing demand for portable and renewable energy sources have led to the widespread use of various types of batteries. Traditional batteries such as Lithium-Ion (Li-Ion) [1], Nickel-Metal Hydride (NiMH), Lead-Acid, Solid-State (an emerging technology), and Nickel-Cadmium (NiCd) batteries have been at the forefront of this energy revolution. These batteries have enabled significant progress in numerous applications, like in the power equipment, portable gadgets and EV industry [1,2].

However, these batteries pose substantial environmental concerns. The production of lithium-ion batteries is highly energy-intensive and contributes significantly to carbon emissions. Extracting lithium requires large quantities of water and involves the use of toxic chemicals [3]. Improper disposal of batteries further exacerbates environmental pollution. When batteries corrode, their chemicals leach into soil and water, contaminating ecosystems. Lithium batteries can cause landfill fires, releasing harmful gases into the atmosphere [4,5]. The disposal of electric vehicle batteries is particularly challenging due to their size and complexity, often resulting in hazardous materials being released if not dismantled correctly. Although some of the companies such as Volkswagen and Renault have designed the recycling plan for these batteries, only around 5% of batteries in the world are recycled [6].

As the waste batteries become one of the challenges in the world, recycling is not enough to tackle the waste batteries. One of the advanced solutions is by using biodegradable batteries and decrease the demand of traditional batteries. Biodegradable batteries are designed to address these environmental issues by utilizing materials that can naturally decompose without harming the environment [7]. The theoretical foundation of biodegradable batteries lies in the use of organic or bio-based materials for the anode, cathode, and electrolyte such as carbon, cellulose, glycerin, and table salt. These materials can break down into non-toxic byproducts, significantly reducing the ecological footprint of battery disposal [8]. Biodegradable batteries offer a promising solution by combining the principles of sustainability with the demands for efficient energy storage.

This work aims to explore the advancements in biodegradable batteries, focusing on the materials, synthesis methods, and performance characteristics based on existing literature and data. It will also discuss the environmental benefits and challenges associated with biodegradable batteries and their potential applications in various fields, such as medical devices and environmental sensors. Through case studies and a comprehensive review of current research, the report will provide insights into the future directions and broader adoption of biodegradable battery technology.

2. Biodegradable materials and properties for batteries

The advancement of biodegradable batteries hinges on the innovative use of environmentally friendly materials that offer both functional performance and the ability to degrade naturally. This section delves into the specific materials that form the backbone of biodegradable batteries, focusing on their unique properties that make them suitable for sustainable energy storage solutions. These materials, including biopolymers, natural fibers, and organic compounds, are selected not only for their biodegradability but also for their compatibility with various battery components such as electrolytes, electrodes, and separators.

2.1 Biodegradable fiber battery with body fluid

Fiber batteries are ultra-thin batteries, measuring just a few millimeters in thickness, and are constructed using fiber materials with layer-by-layer coating processes. These batteries can be seamlessly integrated into fabrics, making them suitable for incorporation into clothing or the creation of highly flexible, wearable electronic devices [9]. With the utilize of biodegradable material and solvent, the biodegradable fiber batteries can be formed. This type of battery is the advanced and environmentally friendly battery due to their biodegradability and these materials decompose easily in the environment, reducing waste.

2.1.1 Materials and basic component

One of the biodegradable fiber batteries use body fluid as an electrolyte in biodegradable fiber batteries. This innovative approach ensures biocompatibility and integration with biological tissues, eliminating the risk of immune responses.

In term of the electrodes of this type of battery, the polydopamine and polypyrene composite as the anode material. This composite is chosen for its biocompatibility and electrical conductivity. Manganese Dioxide (MnO_2) is used for the cathode, offering good electrochemical performance and the ability to decompose into non-toxic byproducts. In addition, $Na_4Fe_3(PO_4)_2(P_2O_7)$ (NFP) is another electrode material highlighted for its environmental compatibility and effective performance in biodegradable applications [10].

There is other basic component for most of the biodegradable fiber batteries, chitosan. Chitosan is a type of fiber derived from the exoskeletons of insects and the shells of crustaceans, such as shrimp, clams, and lobsters [11]. Thus, it is easily extracted from the daily life or the environment. Chitosan is utilized as the separator in these batteries due to its biodegradability and decent ionic conductivity [12], which helps prevent short circuits. Polyglycolic Acid Yarn serves as the structural base for the fiber electrodes, providing flexibility and biodegradability, essential for minimally invasive medical applications [13].

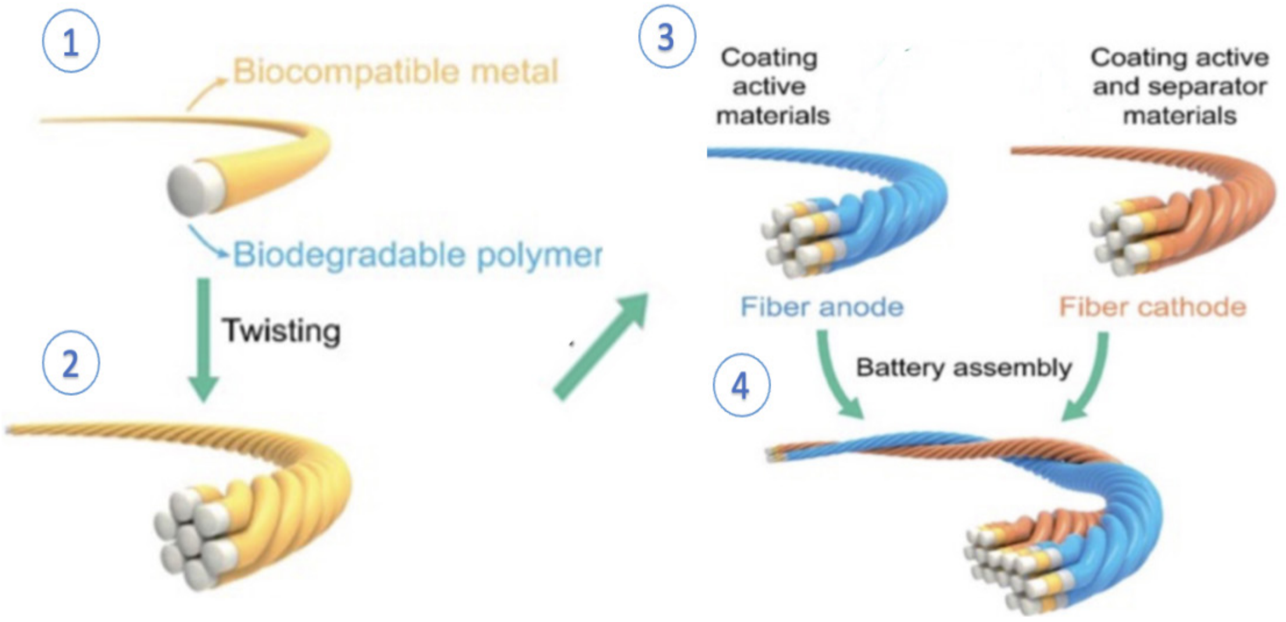

Fig. 1 The manufacture process of biodegradable fiber battery with body fluid [10]

2.1.2 Synthesis techniques

The biodegradable fiber batteries are manufactured by sputtering, dip-coating as well as assembly step by step, as showed in the figure 1. Regarding sputtering, a thin layer of gold (~80 nm) [10] is sputtered onto polyglycolic acid yarn to create a conductive fiber, which is then twisted into a bundle. This process is essential for ensuring the conductivity of the fiber electrodes. Followed by the Dip-Coating as the fiber cathode is dip-coated with a chitosan layer to provide insulation and ionic conductivity. This technique ensures a uniform and thin coating, which is crucial for the battery's performance. Finally, is the assembly. The anode and cathode fibers are twisted together to form the complete fiber battery, featuring a multi-layered coaxial structure that enhances mechanical properties and flexibility. This assembly process ensures that the battery remains robust and flexible, suitable for integration with biological tissues.

2.1.3 Electrical performance, biodegradability and application

However, this type of battery only sufficient for powering low-power biomedical devices. Its electrical capacity is $24.4\text{mA}hg^{-1}$ at a current density of $1000\text{mA}g^{-1}$, maintaining a capacity retention of 89.1% after 1000 cycles retaining 69.1% of its capacity after 200 cycles [10], showcasing good cycle stability and ensuring reliable long-term operation. Its electrical capacity is $24.4\text{mA}hg^{-1}\left(24.4Ahkg^{-1}\right)$ 10and the energy capacity formula is:

$$\text{EnergyCapcity}\left(\text{Whkg}^{-1}\right)=\text{ElectricCapacity}\left(\text{Ahkg}^{-1}\right)\times\text{Voltage}\left(\text{V}\right) \quad (14)$$

If considering the battery operates within a voltage $3.7\,V$, the average energy capacity of the biodegradable fiber batteries should be 90.28Whkg^{-1}.

Furthermore, the result showed that the biodegradable fiber battery is not appropriate to use in the industries with larger electrical output and capacity demand such as electrical car, but can be used in implantable medical devices. Compare to a single lithium-ion cell used for the electric car with common voltage $3.7V$,the whole lithium-ion batteries have energy capacity around $260-270\text{Whkg}^{-1}$ for an electrical car [15]. The biodegradable fiber batteries are not appropriate to use in the electrical vehicle. However, it is suitable to use in the implantable medical devices, like pacemakers or drug delivery systems, which operating on very low power. The longevity and biocompatibility of this type of Biodegradable fiber batteries is more significant than high energy density in these devices. For example, a traditional implantable device needs a communication amplifier consuming $25mW$ and a sensor amplifier which need another $5mW$ from the batteries [16], the huge energy capacity of biodegradable fiber batteries can be used in the device for long time with non-toxic nature and compatibility with sensitive biological environments. In term of its biodegradability, the time of the biodegradable fiber battery begins to degrade into fragments after two weeks and is almost fully degraded by twelve weeks in phosphate-buffered saline at $37°C$. The components of the biodegradable battery, such as polyglycolic acid, polydopamine, polypyrene, chitosan, and MnO_2, degrade into non-toxic substances [10]. This minimizes environmental pollution and the need for hazardous waste disposal. Hence, it is not very useful for the electric car industry to replacing the traditional batteries. But the biocompatibility of these materials ensures safe integration with biological tissues, it can be used in the medical applications without causing adverse effects.

2.2 High ionic conductivity biodegradable fiber battery (zinc-based fiber batteries)

2.2.1 Materials and basic component

The biodegradable fiber batterie can be improved by using various electrolytes like $ZnSO_4$ and NiO. For the zinc-based fiber batteries, MnO_2, NiO, and air electrodes act as the cathode while Zinc metal is commonly used as the anode. The $ZnSO_4$ or $MnSO_4$ will be used as electrolytes [17]. These materials are chosen for their high electrochemical performance and compatibility with flexible substrates. With the additional component such as polyvinyl alcohol (PVA) gel is used as a separator (flexibility, high ionic conductivity, and ability to form a stable gel electrolyte), the zinc-based fiber battery is formed.

2.2.2 Synthesis and Fabrication Techniques

Materials like MnO_2 and NiO are coated onto flexible substrates to form the cathode. This process involves the use of conductive polymers and nanomaterials to enhance the electrochemical performance and flexibility of the electrodes. Zinc metal is processed into flexible forms and integrated with the cathode using a variety of techniques, including sputtering and electrospinning.

2.2.3 Electrical Performance, biodegradability and application

This type of battery shows a relatively higher capacity as the electrolytes ($ZnSO_4$ and $MnSO_4$) have the high capacity. A lithium sulfur fiber battery produced with these hybrids fibrous cathode improves its mechanical robustness and even have capacity $335\text{mA}hg^{-1}$ and current density of $167.5\text{mA}g^{-1}$. The biodegradable fiber batteries, maintain good cycle stability. Some prototypes exhibited capacity retention of over 90% after several hundred cycles, indicating their potential for long-term use in wearable electronics [17].

In term of biodegradability, the materials used in these fiber batteries are designed to degrade safely over time. For instance, PVA gel electrolytes and MnO_2 cathodes decompose into non-toxic byproducts [17], $ZnSO_4$ are chosen for their non-toxicity and ability to degrade into harmless substances to minimizing environmental impact.

This type of biodegradable fiber battery with a capacity of $335\text{mA}hg^{-1}$ ($1.2395Whg^{-1}$ for $3.7V$ battery) and a current density of $167.5\text{mA}g^{-1}$, shows promise for powering low-power devices due to its relatively high capacity [17]. When considering the energy requirements of common wearable electronics, such as wireless earbuds or smartwatches that typically use batteries with capacities ranging from 0.3 to $1.5Wh$, the battery can be used in these devices. Furthermore, as the low-power microcontrollers for wearable sensors generally require between 1 to 100 mW of power, the high capacity and current density of this fiber battery make it an excellent candidate for powering low-power biomedical devices, where consistent and reliable energy delivery is crucial but the overall power demand is modest. These characteristics suggest that the battery could efficiently support the operation of such biomedical devices, offering both flexibility and adequate energy storage [18].

2.3 The biodegradable primary zinc-molybdenum battery

Although the biodegradable fiber batteries are innovative and flexible, it may not fully meet the demands of certain low-power biomedical applications, one of the robust alternatives: the biodegradable primary zinc-molybdenum battery. Compare to the earlier fiber batteries, this zinc-molybdenum battery offers significantly stable voltage, better biodegradable and biocompatibility, making it exceptionally well-suited for biomedical devices that require a more substantial and sustained power supply. Its enhanced performance ensures that it can reliably meet the energy needs of even the most demanding low-power biomedical applications.

2.3.1 Materials and basic component

The electrodes in biodegradable primary zinc-molybdenum battery are different to that in the previous biodegradable fiber battery. Zinc is chosen for anode material as its biocompatibility, environmental safety, and ability to provide high energy density. The zinc anode is prepared by sintering zinc nanoparticles, which enhances the specific surface area and improves the electrical conductivity of the electrode. While Molybdenum (Mo) act as the cathode. Molybdenum is used as the cathode material due to its desirable degradation rates, excellent electrical conductivity, and biocompatibility. The Mo cathode is treated with hydrochloric acid to remove surface oxides and is combined with a biodegradable polymer, poly(lactic-co-glycolic) acid (PLGA), to form the electrode [19].

In term of electrolyte, the batteries use either normal saline ($0.9wt\%$ NaCl [19]) or a gelatin hydrogel with NaCl as the electrolyte. These materials are selected for their biocompatibility and ability to support the electrochemical reactions within the battery while also being biodegradable.

2.3.2 Synthesis and Fabrication Techniques

The manufacture process of biodegradable primary zinc-molybdenum battery includes sintering of zinc nanoparticles, acid treatment of Molybdenum and encapsulation [19], as showed in the figure 2. The sintering process aim to sintering zinc nanoparticles using acetic acid at room temperature. This process increases the specific surface area and forms a porous structure, improving the electrode's performance by enhancing conductivity and providing more active sites for electrochemical reactions. Then, the molybdenum particles are treated with hydrochloric acid to remove any surface oxides, which increases the effectiveness of the material as a cathode. The particles are then mixed with PLGA to create a stable and flexible electrode. Finally, the entire battery module is encapsulated with PLGA, which provides structural stability and controls the degradation rate of the battery when implanted in biological environments.

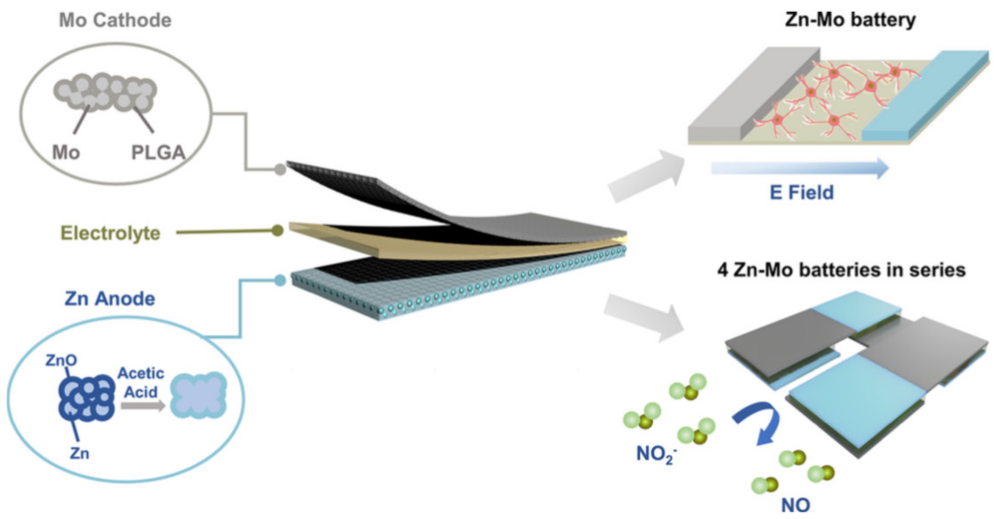

Fig. 2 The manufacture process of biodegradable primary zinc-molybdenum battery [19]

2.3.3 Electrical Performance, biodegradability and application

The Zn-Mo battery achieves an output voltage of approximately $0.6-0.7V$. The battery also demonstrates a prolonged operational lifetime of up to 19 days. The energy capacity is reported to exceed $1500\mu\text{Wh}$, making it suitable for low-power biomedical applications [19]. The use of zinc oxide and hydroxide as byproducts helps form a protective layer that prolongs the battery's operational life by reducing side reaction.

This type of battery required longer Biodegradable time, complete degradation timeline of approximately 85 days when immersed in phosphate-buffered saline (PBS) $at 37°C$ [19]. But the researchers found that the battery has been shown to promote the proliferation of Schwann cells and axonal growth of dorsal root ganglia (DRG), indicating that it not only degrades safely but also supports tissue regeneration.

Furthermore, regarding electronic medicine, the Zn-Mo battery module is capable of driving electrochemical reactions to produce nitric oxide (NO), a signaling molecule that can modulate cellular behavior. This capability suggests that the battery could be used in therapeutic applications where controlled NO release is needed, such as in the treatment of nervous system disorders [19].

2.4 Plant-like battery (Flower battery)

It's important to explore another promising frontier in sustainable energy storage: biodegradable batteries made from plant-based polymers. These plant-derived batteries not only offer the same benefits of biodegradability and environmental safety but also harness the abundant, renewable resources provided by nature. As polymers, these plant-based materials can be engineered to decompose harmlessly after use, making them an ideal candidate for various eco-friendly applications, particularly in low-power devices and biomedical applications where sustainability and biocompatibility are crucial.

Flower battery, a biodegradable, plant-inspired power source designed specifically for precision agriculture (PA) applications [20]. The Flower battery mimics natural processes, such as transpiration in plants, to generate and sustain electrical power over extended periods. The design and materials used in the battery are focused on minimizing environmental impact while meeting the power requirements of PA systems.

2.4.1 Materials and basic component

The majority system for the flower battery is called Paper-Based Fluidic System [20]. The core structure of the Flower battery is made from paper materials, specifically cellulose, chosen for its biodegradability and ability to facilitate fluid transport through capillary action. The paper serves as both the structural material and the medium for fluid flow, analogous to the xylem in plants.

The electrodes are mainly formed by porous carbon. The battery uses porous carbon electrodes, which are hydrophilic and allow for efficient electrochemical reactions as the fluid flows through them. These electrodes are key components in creating the membrane-less galvanic cell that drives the battery's operation.

Furthermore, there are some redox species inside the batteries to produce the electricity. The battery uses quinone-based organic species, such as p-benzoquinone and hydroquinone sulfonic acid potassium salt, as the redox couple. These species are chosen for their ability to undergo redox reactions that generate electrical power, and their degradation products are non-toxic.

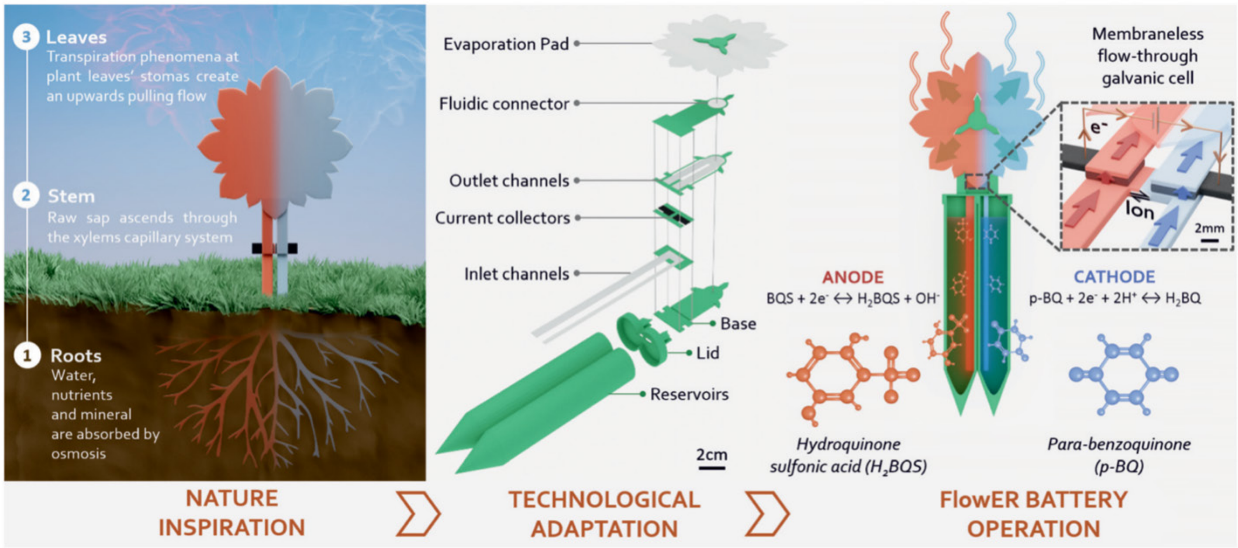

Fig. 3 shows the flower battery produced from the environment [20]

2.4.2 Synthesis and Fabrication Techniques

The battery's components are fabricated using a combination of 3D printing (for the compostable casing) and laser cutting (for the paper components). This approach allows for precise control over the design and ensures that all parts fit together to create a robust and functional device. The figure 3 illustrates the materials obtained from environment and the formation of flower battery.

2.4.3 Electrical Performance, biodegradability and application

On the one hand, The Flower battery achieves a maximum power density of $1.42 \mathrm{mWcm}^{-1}[20]$ at the start of operation, which decreases linearly over time. The battery is capable of continuous operation, providing stable power output for up to 8 hours at a time. As the battery can deliver $100\,\mathrm{mA}$ of current for 8 hours without significant voltage or power loss [20], delivering a total capacity of approximately $0.8\,\mathrm{mAh}$. The energy is estimated as $2.96\,\mathrm{mWh}$.

On the other hand, the battery components, particularly the cellulose-based materials, degrade efficiently under aerobic conditions, and the degradation products are non-toxic and beneficial for the soil. This compost generated from the degraded battery components was found to be nutritious and non-toxic, supporting healthy plant growth.

2.5 Others feasible biodegradable batteries

2.5.1 Biodegradable battery from crab shells

Researchers developed a gel electrolyte from chitosan, derived from chitin in crab shells, which is combined with a zinc anode and a biodegradable organic cathode. This battery is highly efficient, maintaining 99.7% efficiency over $1,000$ cycles. About two-thirds of the battery is biodegradable, and it degrades in soil within a few months. The remaining zinc can be easily recycled, making this battery both eco-friendly and sustainable [21].

2.5.2 Algal biopolymers in biodegradable battery

Algae-based biopolymers like alginates and cellulose are primarily used as separators in batteries. These materials offer high porosity, good thermal and chemical stability, and excellent electrolyte absorption properties, making them suitable for lithium-ion and other battery types. These biopolymers offer advantages like biodegradability, biocompatibility, and environmental sustainability, making them suitable alternatives to traditional oil-based polymers. Algal polysaccharides such as carrageenan are particularly highlighted for their use in energy storage devices due to their ability to form stable hydrogels and their high ionic conductivity [22].

Table 1. Comparison of 4 majority biodegradable batteries

Battery / Properties	Biodegradable Fiber Battery with Body Fluid [10]	Zinc-Based Fiber Batteries [17]	Biodegradable Primary Zinc-Molybdenum Battery [19]	Flower Battery [20]
Capacity at 3.7V / Wh	90.28 (per kg)	1240 (per kg)	0.0015	0.00296
Degradation Time	twelve weeks	over several weeks	Approximately 85 days in biological environments	Degrade efficiently under aerobic conditions
Sustainability	Uses materials like polyglycolic acid and chitosan, which are easily sourced and environmentally friendly	Utilizes zinc and biodegradable materials, making it an eco-friendly option	The use of zinc and molybdenum, combined with biodegradable polymers like PLGA, enhances sustainability	Highly sustainable, with cellulose-based materials and non-toxic byproducts beneficial for the soil
Cost	Moderate	Relatively low	Moderate to high	Low
Safety	High biocompatibility, making it safe for biomedical applications	High, especially suited for wearable electronics due to the non-toxic and flexible nature of the materials.	Excellent biocompatibility, supports tissue regeneration, making it ideal for electronic medicine.	High, with no toxic residues, making it suitable for agricultural applications.

3. Summary

Biodegradable batteries are emerging as a promising solution for various applications, particularly in biomedical devices, wearable electronics, and precision agriculture. These batteries offer distinct advantages, such as biocompatibility, sustainability, and the ability to safely degrade in the environment. Applications like the biodegradable fiber battery with body fluid are ideal for medical devices due to their integration with biological tissues. Zinc-based fiber batteries, with higher energy capacity, are well-suited for wearable electronics. The plant-inspired Flower battery, appropriately designed for agricultural use and low power equipment with relatively high sustainability and low cost.

The future development of biodegradable batteries will likely focus on enhancing energy density, improving degradation timelines, and reducing production costs to make these batteries more competitive with traditional energy storage solutions. Continued research into new materials and fabrication techniques will be essential in expanding their applicability across various industries, paving the way for a more sustainable and environmentally conscious future in energy storage

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