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Advances in Biodegradable Electronic Materials for Wearable Devices

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ABSTRACT

The rapid expansion of wearable electronics has brought significant benefits to healthcare, fitness, and human–machine interaction, but it has also intensified concerns about sustainability and electronic waste. Biodegradable solutions have been an evolutionary concept whereby biodegradable devices can allow reliable functionality over their life cycle and then break down into non-toxic byproducts. This review features a survey of recent developments in three backbones of biodegradable wearable electronics, including conductive conveyance, ephemeral circuits, and environmentally friendly power sources. Conductive polymers, such as modified polyaniline, polypyrrole, or PEDOT-based polymer composites, have been optimized for both conductivity and controlled degradation, proving useful in flexible electronics and bioelectronic interfaces. Transient circuits have demonstrated the potential of functional systems designed to dissolve after use. They are relevant to medical implants and disposable environmental sensors, constructed from dissolvable substrates, biodegradable conductive materials, and resorbable encapsulants. In the meantime, advances in green power sources, such as biodegradable batteries, supercapacitors, and energy scavengers, have made it possible to develop autonomous wearable platforms. Despite these developments, issues of performance and degradation balance, system-level integration, and commercial viability at production scale persist. Moving forward,

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it will be essential that interdisciplinary research combines materials science, device engineering, environmental sustainability analysis, and regulatory models to achieve a truly visionary scenario of fully transient, green wearable electronics that foster technical innovation in line with environmental accountability.

Keywords: Biodegradable Electronics; Conductive Polymers; Transient Circuits; Green Power Sources; Wearable Devices

1. Introduction

The last twenty years have seen extraordinary inventions in wearable electronics, which is a result of the merger between materials science, microelectronics, and biomedical engineering. Wearable technologies have emerged at the core of health monitoring, personalized medicine applications, fitness and communications technology, and human-machine interaction. However, the increased and fast spread of such devices has also led to another daunting issue, the creation of electronic waste (e-waste). The conventional electronic parts are usually manufactured using non-biodegradable metals, plastic materials, and non-natural polymers that last for centuries in the environment. With the growing popularity of wearable electronics worldwide, the sustainability of both the device's design and the materials used becomes a more pressing concern [1,2].

Biodegradable electronics have offered hope to reduce the harm caused by wearables to the environment, and in the other way round, to provide temporary, biocompatible, and resorbable biomedical applications. The concept is based on the creation of functional materials and systems, which can safely fail to degrade or dissolve in the environment, or, in the case of human bodies, degrade and dissolve. Biodegradable devices do not aim for the high degree of durability and permanence that conventional electronics do, but instead value the idea of transience. Such devices may have very large benefits in medical applications (e.g., post-surgery monitoring implants that will safely depose) as in consumer electronics, where the rapidly growing product lifecycle leads to increased battles of products, a problem that can be compounded if fewer products are recycled because they use more looming substances [3,4].

The biodegradable wearable electronic items are currently supported by three pillars: conductive polymers, transient electronic circuits, and green power sources. In conductive polymers, electrical performance is achieved that is sufficient to support signal transmission and sensing, and the organic, tunable platforms also promise to improve biocompatibility and even eventual degradation. Transient electronic circuits constructed of degradable substrates, interconnects, and encapsulation layers provide the foundation to construct fully functional systems which may later dissolve or break down under controlled conditions. To add to this is the third pillar, which encompasses biodegradable power sources, which consist of biofriendly batteries, supercapacitors, and energy harvesters. Collectively, these innovations are inaugurating the path toward self-contained, sustainable, and wearable platforms. **Table 1** presents a summary of the three pillars of the biodegradable wearable electronics with their role and material innovation in the eco-friendly wearable platforms [4,5].

Table 1. Pillars of biodegradable wearable electronics.

Pillar	Key Components	Function	Sustainability Advantage
Conductive Polymers	Organic, tunable polymers	Signal transmission, sensing	Biocompatible; designed for controlled breakdown
Transient Electronic Circuits	Degradable substrates, interconnects, encapsulation	Full-system functionality with programmable disintegration	Minimizes e-waste through complete dissolution
Biodegradable Power Sources	Eco-friendly batteries, supercapacitors, energy harvesters	On-board energy supply	Renewable materials; non-toxic decomposition

Biodegradable conducting polymers are an active research field in the development. Traditional conductive polymers, including polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), have attempted to investigate flexible and stretchable electronics. New studies, however, have aimed to alter these polymers by coupling biodegradable backbones, natural fillers, or enzymatically break downable branched chains to these polymers to increase environmental friendliness and still maintain the same electrical characteristics in them. These materials are promising in terms of flexible sensors, bioelectronic interfaces, and temporary communication devices [6].

Other than conductivity materials, the concept of transient circuits is another revolutionary invention. Through the use of water-soluble metals, e.g., magnesium, zinc; bio-degradable substrates, e.g., cellulose, silk fibroin, poly (lactic acid); bio-resorbable encapsulation layers, researchers have shown integrated systems that perform the intended task throughout their operation but can be broken apart into harmless byproducts when the environmental triggers are present e.g., moisture or heat. This is made more useful in the case of biomedical implants, where the need to surgically retrieve is removed (thus putting a patient at risk) and disposable electronics, where e-waste could otherwise be generated on a large scale [7].

There are challenges in powering these devices. Conventional lithium-ion batteries cannot be freely disposed of because they do not break down and will harm the environment. Green and biodegradable sources of power would thus be important in achieving the completely green wearable vision. Development has occurred on zinc- and magnesium-based biodegradable batteries, organic electrode material, and transient electrolytes. Similar advances in energy harvesting, including biofuel cells with body fluid energy sources, piezoelectric energy harvesters, and biodegradable triboelectric nanogenerators, contribute to the dream of creating self-sustaining systems that are biodegradable. Collectively, these strategies will provide wearable systems capable of autonomously operating and biologically degrading after use [8,9].

Although biodegradable electronics are promising, there are issues concerning the achievement of a balance between performance, stability, and programmed degradation. Electrical, mechanical, and chemical stability must be maintained in devices to survive through the anticipated functional life with unambiguous degradation thereafter. Also, the barriers are large-scale manufacturing, cost-efficiency, and regulatory clearance to commercialization. These challenges can be solved with the help of an interdisciplinary approach to combine the efforts of materials science, chemistry, electronics, and environmental engineering [2,10–12].

In this review, we provide a detailed discussion of the progress in biodegradable materials and systems for wearable electronics, specifically focusing on conductive polymers, transient circuits, and green power sources. We describe some recent developments, the current issues, and examine future trends to scalable, safe, and environmentally responsible wearable technologies. It is hoped that this review, through the consideration of the above three pillars of innovation, will provide some light as to how biodegradable electronics could be translated out of the laboratories to the real world where they would be functional in the context of functionality, comfort of the user, and sustainability regarding the environment.

2. Biodegradable Conductive Polymers

Due to their intrinsic electrical conductivity, mechanical compliance, and variable chemical characteristics, conductive polymers (CPs) have gained enormous attention as the basis of flexible and stretchable electronics. They play a pivotal role in the biodegradable wearable devices, as they not only provide essential electrical conductivity in the sensory and communication framework but can also be chemically modified to degrade in biological environments or other biological settings. More traditional electronic conductors like metals have high-conductivity properties yet are flexible, dense, and therefore not bio-breakable, constraining usage in sustainable or temporary systems. In comparison, with polymers, electrical performance, mechanical flexibility, and degradation pathways can be tailored at the molecular level.

2.1. Fundamentals of Conductive Polymers in Wearables

The conductive polymers possess 1D-chain structures that involve the delocalization of 1D-conjugated 1-electrons polymer. The best-known examples are polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), which have received much attention in relation to electronic applications, including antistatic coatings up to bioelectronic interfaces. Their conductivities, in particular when doped with appropriate counterions, lie within the realm of interest needed in wearable sensing, low-power circuits, and soft electrodes. Such materials, however, are not inherently biodegradable in their natural form and tend to persist in the environment. The features required of conductive polymers for wearables that are temporary or environmentally benign differ from the electrical requirements. They must be able to store conductivity and biocompatibility, reliably break down into non-toxic products, and maintain mechanical flexibility to be subjected to bending, stretching, or flexible attachment to the skin and fabrics [13,14].

2.2. Strategies to Impart Biodegradability

Since the majority of conventional conductive polymers are not degradable, one approach was to introduce controlled degradation through a number of strategies developed by researchers. Probably the most popular method is a change in the polymer structure by the introduction of ester, amide, or carbonate bonds, which can be broken by either hydrolytic or enzymatic processes. Copolymerization is another crucial approach in which conductive domains will be assembled with biodegradable blocks of poly (lactic acid), polycaprolactone, or polypeptides. This enables the material to be conductive, yet the polymer chain will be broken down in the end in physiological or environmental conditions. Mixing with non-synthetic polymers like chitosan, silk fibroin, cellulose, or starch is also very common. Not only do such mixtures enhance biocompatibility, but they also provide natural routes of degradation by enzymatic or microbial attack. Moreover, degradability may be drastically affected by the selection of a dopant. The biodegradable organic acids or bio-derived anions may be used instead of persistent synthetic dopants in order to increase environmental compatibility. Lastly, nano-structuring of polymers to compositions with porous or ultrahin or fibrous morphologies can provide a faster degradation time and still retain an electrical connecting nature throughout the lifespan of the device [15].

2.3. Representative Biodegradable Conductive Polymers

One of the initial conductive polymers studied in biodegradable systems has been polyaniline. It is easily synthesized, and the oxidation states are controllable and therefore of interest, yet the backbone of this material is typically stable and not susceptible to degradation. Scientists have solved this by subjecting aniline to copolymerization with biodegradable material such as polylactic acid, or with plant-derived conductive dopants such as phytic acid, both of which increase conductivity and add biodegradability. The altered polyaniline systems have actually been applied in flexible sensors, temporary skin patches, and temporary electrochemical devices [16].

Polypyrrole has been the other one that has been widely examined as a transient electronics. It has lower conductivity than polyaniline and can undergo direct electro-polymerization on various biodegradable formats. Tests to improve its degradability include incorporating (in scaffolds made of collagen, gelatin, or chitosan, which are naturally degradable) polypyrrole so that these scaffold materials are enhanced in degradability. In other words, degradable side chains of polypyrrole derivatives have been worked out in a few cases, and these side chains can be hydrolyzed in water. Examples of biodegradable applications of polypyrrole as strain sensors include temporary neural probes and electroactive tissue engineering scaffolds. PEDOT, especially in the commercial form of PEDOT: PSS, is one of the most widely used conductive polymers in wearable devices because of its high conductivity and processability. However, the poly (styrene sulfonate) component is non-degradable and persists in the environment. To address this, researchers have begun replacing PSS with biodegradable polyanions such as poly (aspartic acid) or alginate. PEDOT has also been successfully blended with cellulose nanofibers, silk fibroin, and other biodegradable supports, producing flexible and biocompatible composites. These modified PEDOT materials have been applied in skin-compatible electrodes for ECG and EEG monitoring, in biodegradable circuits, and in short-term biosensors [17].

Beyond synthetic polymers, there has been increasing interest in conductive biomaterials derived from nature. Melanin and eumelanin, for instance, are naturally conductive pigments that offer both biocompatibility and biodegradability. Chitosan and cellulose, when doped or partially carbonized, can also achieve functional conductivity. Silk fibroin, when combined with conductive fillers, has been employed as a transient bioelectronic material. These natural systems are especially attractive for medical applications since their degradation products are benign and often already present in the body. Beyond synthetic and protein-based polymers, wood-derived materials have emerged as a novel platform for biodegradable electronics. **Figure 1** illustrates the processing of wood into transparent films and conductive inks. Delignification and pressing yield flexible cellulose substrates (**Figure 1a**), while carbonized lignin nanofibers (LCF) serve as sustainable printed conductors. Though less conductive than synthetic polymers, these systems offer mechanical robustness and industrial scalability, particularly for disposable sensors or eco-friendly substrates in transient electronics. **Table 2** summarizes key biodegradable conductive polymers, their modifications for enhanced degradability, and their applications in transient electronics. These material innovations demonstrate the progress in developing functional yet environmentally benign conductive systems for wearable devices [18,19].

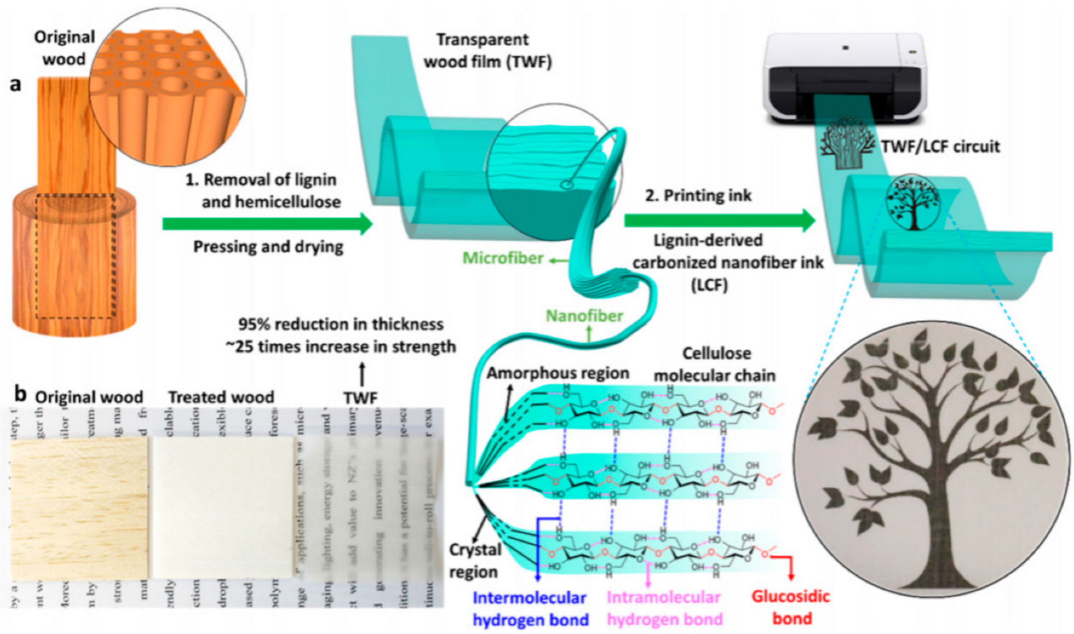

Figure 1. Wood processing for flexible electronics. (**a**) Hierarchical structure of delignified wood films. (**b**) Visual transformation from raw wood to transparent film. LCF ink enables printed circuits on biodegradable substrates.

Table 2. Representative biodegradable conductive polymers for transient electronics: compositions, modifications, and applications [19].

Polymer	Degradability Modifications	Conductivity Enhancement	Applications	Degradation Mechanism
Polyaniline	Copolymerization with PLA; plant-derived dopants	Phytic acid doping	Flexible sensors, skin patches, electrochemical devices	Enzymatic/hydrolytic breakdown
Polypyrrole	Embedded in collagen/chitosan scaffolds; degradable side chains	Electro polymerization on biodegradable substrates	Neural probes, strain sensors, tissue engineering scaffolds	Hydrolysis of side chains/scaffolds
PEDOT	Replacement of PSS with poly (aspartic acid) or alginate	Blending with cellulose/ silk nanofibers	Skin electrodes (ECG/EEG), biosensors, transient circuits	Polyanion degradation
Natural Polymers (Melanin, Chitosan, Silk)	Native biodegradability; conductive filler integration	Carbonization or doping	Medical bioelectronics, implantable sensors	Natural enzymatic degradation

2.4. Device Applications in Wearables

Various wearable devices that integrate conductive polymers are made using biodegradable ones. An important area of use is in transient sensors. Examples include polyaniline-PLA composites and polypyrrole-chitosan films, which are used as strain and pressure sensors. They can last from several days to several weeks in operation before breaking down naturally. PEDOT-cellulose films have also been used as temporary skin electrodes in electrophysiological monitoring, with the merits of being comfortable, electrically stable, and degradable. Short-term health tracking is also done through biodegradable CPs, such as biochemical sensors detecting analytes, including glucose or lactate. Other notable uses are in flexible circuits and interconnects. Transient electronic circuits can be printed on biodegradable base materials, such as cellulose or silk, using conductive polymer ink. These circuits can continue to work throughout their operational life and thereafter dissolve in conditions present in the environment. Another area of use is biomedical implants. Conductive polymer composite biodegradable neural probes, cardiac patches, and electrostimulation scaffolds have demonstrated functionality as therapeutic aids or monitoring devices. They have subsequently degraded, allowing the body to reabsorb and eliminate them, obviating the surgical removal procedure [20].

3. Transient Electronics and Circuits

The idea of shifting towards transient electronics has changed the way researchers perceive the life of an electronic device. In contrast to permanent implementations, where the goal in electronics experiments is to achieve long-term stability, transient electronics are designed to last only a specified time before decomposing into nonhazardous products in an environmental/physiological context. This paradigm is particularly applicable to wearable technology, where devices are disposable and may have a short product life cycle, as well as disposable medical products, or life-cycle monitoring. Transient circuits are functional processing cores of such systems, conforming to degradable substrates, conductors, semi-conductors, and encapsulation materials that collectively provide functionality and controlled degradation [21].

3.1. Principles of Transient Electronics

Transient electronics are based on the impermanence of materials. Each of the components—the substrate, the conductor, and the encapsulation layer—is designed to degrade typically by hydrolysis, enzymatic digestion, oxidation, or dissolution. With the delicate choice and combination of these materials, one can create a circuit that works perfectly during its lifespan while breaking up when triggered by some environmental influence. This controlled transience can be useful in biomedical implants that are bioresorbable and tooth braces that can be used temporarily to minimize electronic waste, or in wearables intended for temporary consumer use. The technical issue is the necessity to synchronize the degradation of various components, so the performance can be predicted during exploitation [22].

3.2. Materials for Transient Substrates

The substrate forms the physical support for electronic circuits, and in transient systems, it must be flexible, biocompatible, and degradable. A wide range of natural and synthetic polymers has been investigated for this purpose. Silk fibroin, a protein derived from silkworm cocoons, has emerged as a particularly versatile candidate because of its mechanical strength, conformability, and controlled dissolution rates in aqueous environments. Cellulose and its derivatives are also widely used, offering renewable, biodegradable, and low-cost platforms for printed electronics. **Figure 2** demonstrates advanced processing of cellulose nanocomposites for transparent substrates. The etherification and blending with tunicate cellulose nanocrystals (TCNCs) yield papers (P10) with tunable optical properties (**Figure 2e**), while maintaining biodegradability. Such materials could serve as eco-friendly alternatives to plastic substrates in wearable sensors, though their electronic functionality would require additional conductive modifications [4,22].

Other options include poly (lactic acid), polycaprolactone, and poly (glycolic acid), all of which hydrolyze into benign monomers under physiological conditions. By tuning crystallinity, molecular weight, and blending ratios, the degradation time of these substrates can be adjusted from days to months, making them suitable for applications ranging from short-term diagnostic patches to medium-term implants [23,24].

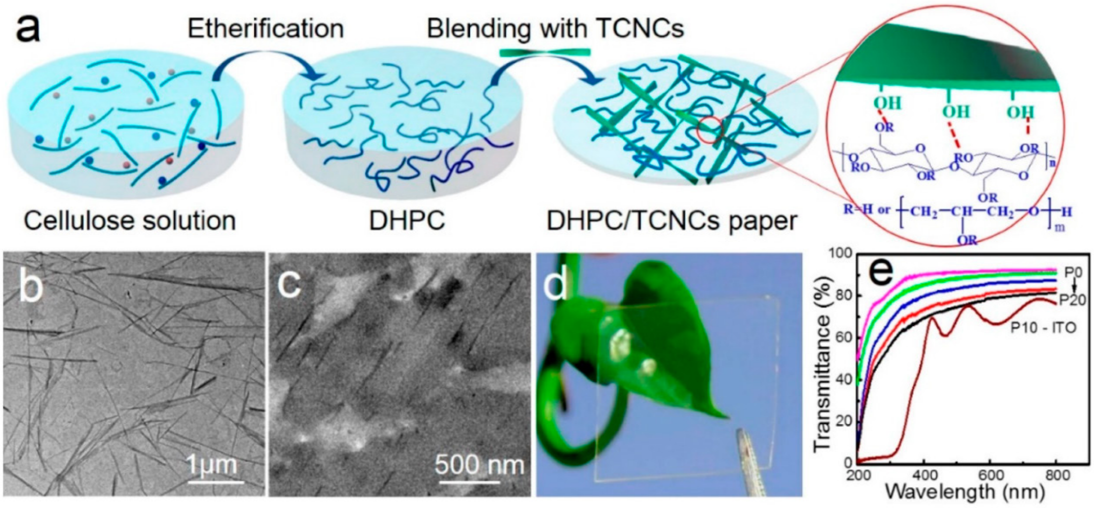

Figure 2. Cellulose nano composite fabrication. (**a**) Process flow: etherification (DHPC) and TCNC blending. (**b**–**c**) TEM images of nanocrystals. (**d**) Photograph and (**e**) UV-vis transmittance of resulting paper substrates [23].

3.3. Biodegradable Conductors and Interconnects

Conductors are essential for circuit functionality, but traditional metals such as copper or gold do not degrade safely in the environment or body. To address this, biodegradable metals, including magnesium, zinc, iron, tungsten, and molybdenum, have been extensively explored. These metals dissolve in aqueous media through corrosion, producing ions that are either biocompatible or naturally metabolized in the body. Magnesium and zinc, in particular, are promising because they degrade relatively quickly and are already used in medical implants such as biodegradable stents. **Figure 3** exemplifies this principle, showcasing a transient n-MOSFET array fabricated on biodegradable iron (Fe) foil. The process leverages Fe as a substrate and magnesium (Mg) electrodes—both metals that corrode harmlessly in physiological environments—while incorporating silicon nanomembranes (Si NMs) and spin-on glass (SiO_2) as semiconductor and dielectric layers. This system demonstrates how conventional materials can be adapted for transience without sacrificing performance, offering a scalable template for integrated biodegradable electronics [25].

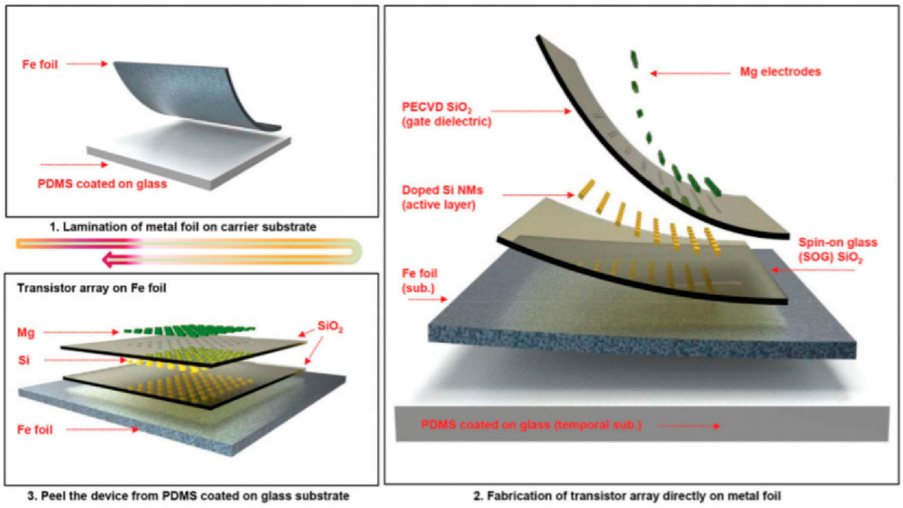

Figure 3. Fabrication of transient n-MOSFET arrays on Fe foil. (Top) Process flow: lamination on PDMS/glass, transistor fabrication, and detachment. (Bottom) Exploded view of MOSFET layers (Si NMs, Mg, SiO_2, Fe). All materials degrade in physiological conditions [19].

In addition to metals, conductive polymers, carbon-based materials, and transient inks have been studied for interconnects and electrodes. By employing composites of conductive fillers with biodegradable binders, researchers have fabricated flexible, transient wiring and interconnect networks that maintain conductivity during operation but break down after disposal [19].

3.4. Semiconductors and Active Devices

Developing biodegradable semiconductors has proven more challenging, yet several promising strategies have emerged. Organic semiconductors, such as polylactide-based conjugated polymers, offer partial biodegradability while retaining charge transport properties suitable for low-power devices. Silicon, though traditionally non-degradable, can be engineered in ultrathin, nanomembrane form to gradually dissolve into non-toxic silicic acid in aqueous environments. This property has been exploited to fabricate transient transistors, diodes, and sensors capable of operating in physiological fluids before dissolving over a controlled timeframe. The integration of such semiconductors enables the realization of fully transient integrated circuits, albeit with performance limitations compared to conventional silicon-based systems [26].

3.5. Encapsulation and Packaging Layers

Encapsulation plays a critical role in defining the operational lifetime of transient electronics. Packaging layers protect the active components from premature degradation while also controlling the exposure to triggers such as water, enzymes, or temperature. Biodegradable encapsulants, including silk fibroin, polycaprolactone, and bioresorbable waxes, have been employed to delay degradation until the desired functional period is completed. **Figure 4** illustrates two scalable fabrication approaches for transient devices. **Figure 4a** shows additive manufacturing of liquid metal circuits with selective activation, while **Figure 4b** demonstrates transfer printing from silicon to biodegradable PLGA substrates—a key technique for integrating conventional fabrication methods with degradable materials. These processes highlight how encapsulation layers (e.g., the top elastomer in a-IV) can be combined with sacrificial layers (**Figure 4b**) to control device lifetime while maintaining manufacturing compatibility [27]. By adjusting encapsulation thickness and composition, the lifetime of transient circuits can be tuned from hours to several months. In wearable applications, this allows for precise tailoring of device durability, whether for short-term physiological monitoring or longer-term therapeutic support [28].

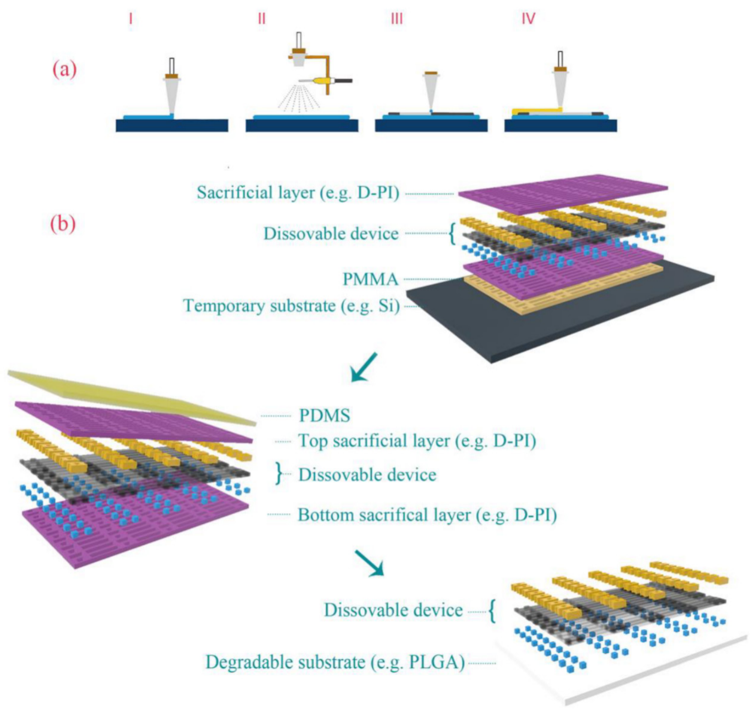

Figure 4. Fabrication of transient electronics. (**a**) Additive manufacturing: (I-IV) Layer-by-layer printing of elastomers and selectively activated liquid metal circuits. (**b**) Transfer printing from silicon to PLGA using sacrificial layers (D-PI: degradable polyimide) [28].

3.6. Device Demonstrations and Applications

Transient circuits have been successfully demonstrated in a range of wearable systems. In medical applications, temporary implants such as neural probes, cardiac monitors, and wound-healing stimulators have been fabricated from fully biodegradable circuits that dissolve naturally after completing their task, thereby eliminating the need for surgical retrieval. For skin-mounted wearables, transient circuits printed on silk or cellulose substrates have been used for short-term biosensing, motion monitoring, and communication modules. Environmental monitoring has also benefited from transient circuits, with disposable sensors designed to track pollution or detect pathogens before safely degrading without adding to waste streams. These applications underscore the versatility of transient electronics in bridging performance with sustainability.

4. Green and Biodegradable Power Sources

The power supply is a critical element in wearable electronic systems that keep sensors, circuits, and communications modules running 24 hours a day and at acceptable reliability levels. Lithium-ion batteries and nickel-cadmium cells are widespread traditional energy storage and retrieval technologies, but biodegradable electronics are inapplicable due to their use of harmful substances, their rigid form, and lasting elements, which remain in the earth. Due to the growing need for sustainable wearable devices, the building of green and biodegradable sources of power has developed to be a critical frontier. The field of power sources is particularly focused not only on providing reasonable performance in the electrical state when in use but also on breaking down safely in the post-use environment, leaving only non-reactive byproducts or being directly attenuated by the environment or the human body [29].

4.1. Principles of Biodegradable Power Systems

Design strategies aim to manage two competing needs: reliable in-service functionality for its intended purposes and ecological acceptability, in terms of its eventual biodegradation under environmental conditions. Over the life span of their operation, they should be able to offer adequate voltage, current, and energy density powering low-power circuits, sensors, or communication modules. After use, they have to break down in a predictable manner, such as by hydrolysis, by enzyme attack, rain and wind, or by dissolution. Ideally, the products of the degradation process must be biocompatible ions, naturally occurring biomolecules, or other environmentally harmless substances. The main difference between biodegradable power systems and conventional batteries and capacitors is that the former consider environmental needs in addition to performance requirements [30].

4.2. Biodegradable Batteries

Among power sources, biodegradable batteries have received the most attention. These devices typically employ biodegradable metals such as magnesium, zinc, or iron as anodes, paired with cathode materials and electrolytes that can safely decompose. Magnesium and zinc are especially attractive because they dissolve in aqueous environments into ions that are already present in biological systems and play essential metabolic roles. Researchers have demonstrated biodegradable magnesium–air and zinc–air batteries capable of powering transient sensors and medical implants for days to weeks. Cathode materials in such batteries often include manganese oxides, molybdenum oxides, or organic compounds that degrade without releasing harmful byproducts. Electrolytes are another critical component, and biodegradable alternatives such as gelatin, agarose, chitosan, and silk fibroin hydrogels have been developed. These materials not only conduct ions effectively but also degrade into biocompatible products. The integration of biodegradable current collectors and packaging materials ensures that the entire battery system is transient. Despite their promise, challenges remain in achieving energy densities comparable to conventional batteries, and in extending operational lifetimes for longer-term applications [31].

4.3. Biodegradable Supercapacitors

Another type of energy storage device used in biodegradable wearables is supercapacitors, which have been modified to work in this sector. They are charged by the separation of charges at electrode/electrolyte interfaces and are valued for their high-charging and high-discharging capabilities as storage devices. The biodegradable supercapacitors are mostly based on the use of the carbon-based electrodes obtained as a result of biomass conversion (activated carbon made of coconut shells, carbonized cellulose, or lignin). Electrodes have also been made of conductive polymers such as polyaniline and PEDOT, together with biodegradable dopants. They are usually conditioned on the biodegradable hydrogels or ionic solutions and are environmentally safe. The systems are capable of achieving respectably high capacitance values and maintaining cycle stability over hundreds of cycles, allowing tasks with intermittent use of wearable sensors or communication modules to be electronically powered by these systems. Notably, they are lightweight and flexible in nature, which makes them suitable to be incorporated into skin-mounted or cloth-based devices. Current work in this field focuses on increasing energy density, improving resistance to mechanical fatigue, and ensuring reliable degradation [32].

4.4. Energy Harvesting Approaches

Besides storage devices, there are also energy harvesting mechanisms under consideration to allow self-powered biodegradable wearables. The biodegradable biofuel cell is one potential solution providing a way to harness energy by using body fluids that are classified as biological, as sweat, saliva, or interstitial fluid. These instruments use fixed enzymes or biocatalysts on biodegradable electrodes to oxidize metabolites viz. glucose or lactate, and they generate electricity through the process. Healthcare settings are gorgeous applications of biofuel cells because they have the ability to produce power based on the physiology of the wearer.

Another example of common biodegradable energy harvesters is triboelectric nanogenerators (TENGs) and piezoelectric harvesters. TENGs utilize the triboelectric effect, or creation of electricity by contact and separation of different materials. With compliance to the requirements of biodegradable layers made of polymers like silk fibroin, polylactic acid, or chitosan, hence being triboelectric layers, researchers have designed transient TENGs that can harness energy during body movement. Likewise, piezoelectric harvesters can convert mechanical deformation into electrical energy and, in the case of biodegradable materials, such as poly(L-lactic acid) and some amino acid crystals, these can again serve as a route to powering transient devices. These are lightweight, conformal harvesters that can run continuously without any other recharging [33].

4.5. Fully Biodegradable Self-Powered Systems

It has been shown that the combination of transient circuits with biodegradable batteries, supercapacitors, and energy harvesters allows the demonstration of fully self-powering, biodegradable platforms. Examples include skin-mounted sensors worn temporarily and powered by a dissolvable zinc-air battery, biodegradable supercapacitors connected to transient circuits for motion detection, and implants powered by biofuel cells that self-dissolve after providing temporary therapeutic benefits. These combined systems are an important step on the way to achieve the vision of sustainable electronics, which finally disappear after functioning as intended [34].

5. Integration and System-Level Considerations

While material innovations in biodegradable conductive polymers, transient circuits, and green power sources have been remarkable on their own, the true test is long-term successful integration of these technologies into functional, unified, and scalable wearable systems. A wearable device is seldom a single material or component; it is a network of cooperating parts that should work in unison. There is a need to interface conductive materials with substrates and power supplies, use transient circuits to communicate reliably as they degrade predictably, and power systems to provide adequate energy throughout the life of the device. Attaining this type of integration will necessitate the system-level design where mechanical, biocompatibility, safety, and sustainability factors will be as important as the electrical characteristics [35].

5.1. Mechanical Flexibility and Wearability

In wearable systems, mechanical performance is at least as important as electronic performance. Parts need to be able to resist bending, stretching, twisting, and compression as the wearer moves, and still retain electrical integrity. In biodegradable substrates like silk fibroin, cellulose, and poly (lactic acid), there is flexibility and conformability, but brittle metals or rigid polymer layers result in embrittlement and may also result in the occurrence of cracks and failure due to mechanical mismatch. As a way of addressing this, methods like nano-structuring, mesh designs, and addition of elastomeric biodegradable polymers have been incorporated. System-level: The key to remaining comfortable and functional in an actual wearable situation is to guarantee the ability to attain uniform flexibility across the entire circuitry, interconnects, and power sources [36].

5.2. Biocompatibility and User Safety

When applied to wearables, the integration of biodegradable electronics frequently means they are in contact with the human body, such as through patches held to the skin or implants. This renders biocompatibility a high-level system consideration. The substances in the materials themselves must be non-toxic; in addition to that the products of their degradation process must be safe in contact with or absorption into the body in the long-term or used in the future. As an example, magnesium/zinc ions released by transient conductors are usually compatible, although at higher doses they can create a local increase in pH or inflammation. Likewise, the degradation products of the synthetic polymers have to be well defined in order to eliminate the chances of cytotoxicity. System integration, hence, should involve a strict biological testing, *in vitro* and *in vivo*, to ascertain users' safety upon usage and even after degradation of the system [29].

5.3. Electrical and Functional Integration

Increasingly, functionalization challenges arise under a functional approach of incorporating conductive polymers, transient circuits, and biodegradable power sources. Conductive polymers used have to be compatible with metallic interconnects or electrodes without solution to delamination during mechanical deformation. Transient circuits need component lifetimes well synchronized; failure to conduct a lifetime shorter than the substrate lifetime or the power source will result in premature failure of a device. Power sources such as biodegradable batteries or harvesters need to meet electrical requirements, such as circuit voltage and current requirements, and degrade predictably. To attain this functional compatibility, co-optimization of the material selection, device design, and encapsulation strategy needs to be achieved.

5.4. Encapsulation and Lifetime Control

The biodegradable wearable systems have protective captures and act as timers, serving as encapsulation layers. The encapsulation technique can also prevent early degradation by controlling the permeability of moisture, oxygen, or enzymes, and might delay the onset of degradation until the desired operating period of a device has elapsed. This has often been done by materials like silk fibroin, polycaprolactone, or bioresorbable waxes. At a system level, integration demands that encapsulation must protect not only individual components but also the device itself, ensuring that the degradation of individual components is mutually consistent. Biomedical implants prone to premature failure due to lifetime control are of particular interest; environmental sensors, which need to remain functional long enough to complete monitoring before safely decomposing, are another example of this need [37].

5.5. Life-Cycle Analysis and Environmental Sustainability

One of the driving factors of biodegradable wearables is environmental sustainability. Nevertheless, system-level life-cycle analysis is needed to make sure that devices are indeed environmentally friendly. This concerns the raw materials used, the way they are manufactured, their operational efficiency, and their degradation at the end of their life. As an example, a biodegradable device based on polymers derived from reneawble resources might be more sustainable than one based on non-renewable petrochemical-derived synthetic monomers. In the same way, manufacturing processes that reduce the use of toxic solvents or are energy-intensive add to sustainability.

Disposal at the end of their lifecycle, devices need to break down into environmentally neutral products, preferably nutrients to either soil or aquatic habitat. Life-cycle analyses should be rigorous and would help design next-generation biodegradable wearables that keep environmental impact at a minimum.

5.6. Regulatory and Ethical Considerations

The use of biodegradable wearable electronics also raises regulatory and ethical concerns. In regulated usage such as medical applications, regulatory approvals involve long-term testing of safety, efficacy, and reliability, and long-term degradation product toxicity. The ethical issues arise when it comes to different uses of transient electronics in health, especially data security. As an example, a temporary implant that is used to monitor the health of a patient should still have secure transmission and storage of patient data despite the degradation of the device itself. There is also the consideration of environmental ethics, whereby the designer may need to make sure that biodegradability claims are backed and that the parts do not create microplastic pollution or biofilms that are toxic. On the system level, these issues are of high concernregarding acquiring people's trust and regulatory establishment [38].

5.7. Pathways to Commercialization

To move beyond the laboratory prototypes in biodegradable wearables into commercial production, manufacturing needs to be scaled, and economical designs will be necessary. The output of screen printing and biodegradable inkjet has the potential for mass production. Scalability could also be increased by roll-to-roll processing on biodegradable substrates. Nevertheless, to achieve integration at scale, standardization of material properties, predictable patterns of degradation, and a predictable supply of bio-derived raw materials will be needed. Testing standards and speed certification, and removing the boundaries to commercialization will be needed, and cross-sector collaboration between industry and regulators, researchers, and scholars will be required. Also, interdisciplinary work will be essential in terms of filling in the gap between basic materials science and product-level engineering [39].

6. Limitations and Future Outlook

Despite significant improvements in biodegradable wearable electronics over the last few years, there are a number of deficiencies still limit their effective usage. At the materials level, biodegradable conductors, semiconductors, and substrates tend to have electrical and/or mechanical properties worse than their conventional counterparts. Although conductive polymers have the advantages of malleability and adjustability, they tend to offer conductivity values that are lower than those of metals and are also subject to degradation under humid and/or physiological conditions. Bioweight power sources, like magnesium-air batteries or hydrogel supercapacitors, have low energy densities and short life spans in relation to lithium-ion cells, and are thus limited to less demanding devices.

On the device and system integration levels, integration is one of the key issues. Biodegradable circuits are assembled from components of different degradation rates. One of the constituents may not dissolve before another becomes degraded. For example, a substrate may not erode before a conductor erodes, or vice versa, resulting in unreliable device performance or sensor failure. It is not technically easy to achieve synchronized degradation of all components to ensure reliable performance. Lifetime can be controlled in part through encapsulation schemes, but even these are still lacking to provide desirable and repeatable degradation kinetics. Scalability and manufacturing also pose significant obstacles. Many biodegradable materials are synthesized through complex laboratory procedures or rely on scarce bio-derived feedstocks. Current fabrication techniques, such as electropolymerization of conductive polymers or printing of transient inks, are often limited in throughput and reproducibility. Transitioning from proof-of-concept devices to commercially viable products will require the development of standardized, cost-effective, and environmentally benign processing methods that are compatible with large-scale manufacturing.

From a biomedical perspective, safety and regulatory considerations cannot be overlooked. Even when base materials are biocompatible, their degradation products may accumulate locally or systemically, raising concerns about long-term safety. Comprehensive toxicological studies, coupled with regulatory approval processes, will be necessary before biodegradable electronics can be widely applied in clinical practice. In consumer and environmental applications, public trust depends on a transparent demonstration that devices truly degrade without leaving behind microplastics or harmful residues.

Looking toward the future, several promising directions may help overcome these limitations. First, the rational design of new polymer backbones and hybrid nanocomposites could lead to materials with improved conductivity, stability, and tunable degradation rates. Advances in bio-derived nanomaterials, such as cellulose nanofibers, lignin derivatives, or carbon dots, may provide sustainable fillers that enhance both performance and biodegradability. Second, hybrid energy systems that combine biodegradable batteries with energy harvesters could reduce reliance on storage capacity alone, enabling longer-lasting self-sustained devices. Third, innovations in additive manufacturing, including roll-to-roll printing of transient inks and 3D printing of bioresorbable scaffolds, could enable scalable production of complex biodegradable systems.

Lastly, interdisciplinary work will also play a key role. The work of materials scientists, electronic engineers, biomedical researchers, and environmental scientists will need to collaborate to develop devices that not only perform their functions but are also safe and sustainable throughout their lifetime. By including an analysis of the life cycle, in situ supervision of degradation, and defined testing methods, more transparent paths to commercialization will be open. Finally, the future of wearable electronic devices in clothing will be sustainable, to design wearable methods and devices that could match the technological attributes with eco-friendliness.

7. Conclusions

The sudden increase of wearable electronics has provided unprecedented potential in tailored healthcare, fitness tracking, and human-machine interface, as well as unparalleled challenges in terms of sustainability and device-generated waste. Conventional materials and power systems are very effective but are not suited for applications that are disposable, biocompatible, and environmentally friendly. The research on biodegradable electronic materials presents an attractive alternative, because such materials could be used to create electronic devices that can be used reliably in their intended usage and then reliably break down into benign compounds. This review has discussed recent advances in three of the most important pillars of biodegradable wearable electronics: conducting polymers, transient circuitry, and renewable power. There have been conductive-polymer-based advances, such as modified polyaniline, polypyrene, and PEDOT derivatives, that have been bioengineered to be both conductive and biodegradable, introducing the potential for flexible sensors, electrodes, and bio interfaces. Transient circuits use transient substrates based on dissolving biomaterials and biodegradable conductors, combined with resolvable insulation layers, to exhibit controllable degradation. This process switches off their electronic functionality, allowing them to be released into the environment or in the body with applications in medical implants, disposable wearables, and environmental monitors. To complement these breakthroughs are green energy sources that include biodegradable batteries, supercapacitors, and energy harvesters, which offer the much-needed backbone to self-cleaning, eco-friendly devices.

Although this has improved, there are still major challenges that exist. The electrical performance of eco-friendly materials can typically benefit compared with conventional equivalents, and preventing unpredictable premature degradation remains a focal point. Combining this in many components, getting conductors, substrates, circuits, and power resources to degrade at the same time, introduces further challenges. In addition, matters of feasibility, economic efficiency, and regulatory acceptability must be resolved before biodegradable wearables can demonstrate that laboratory findings can be scaled to broad commercial usage.

In the future, it is expected that interdisciplinary innovation will be the future of biodegradable wearable electronics. Innovations in materials chemistry and device engineering, along with bio interface research and development, must be integrated with life-cycle analysis, safety and bio interface testing, and sustainable manufacturing. The end game is intelligent, self-contained wearable systems capable of becoming fully invisible after performing their essential tasks, whether in healthcare, environmental monitoring, or consumer electronics. Pursuing this cause will not only change the paradigm of how electronic gadgets are built and utilized, but also serve as a milestone in the move towards ensuring that benevolent mark advancements are made with respect to the environment.

Author Contributions

All authors contributed equally to the conception, design, data collection, analysis, and writing of this study. All authors have read and agreed to the published version of the manuscript.

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