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Research Article

ECO-FRIENDLY BIODEGRADABLE MATERIALS FOR WEARABLE DEVICE APPLICATIONS

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Abstract

The increasing demand for wearable devices has amplified the need for sustainable materials that balance functionality with environmental responsibility. Eco-friendly biodegradable materials have emerged as a promising solution, offering a sustainable alternative to conventional materials that contribute to electronic waste. These materials, derived from natural sources such as cellulose, chitosan, polylactic acid (PLA), and silk, or synthesized through green processes, possess unique properties like flexibility, biocompatibility, and degradability, making them ideal for wearable applications. This article explores the design, development, and integration of biodegradable materials into wearable devices, focusing on their mechanical, electrical, and environmental performance. Key applications include wearable sensors for health monitoring, flexible electronics, and transient devices designed to degrade after use, minimizing ecological impact. Advances in material science have further enabled the incorporation of functional additives, such as conductive polymers, carbon-based fillers, and bio-inks, to enhance the electrical and mechanical properties of these materials. Despite their potential, challenges remain in optimizing the durability, scalability, and cost-effectiveness of biodegradable materials for widespread use. This article highlights recent progress, discusses limitations, and outlines future directions in developing eco-friendly biodegradable materials, emphasizing their transformative role in creating sustainable wearable technologies that align with global efforts to reduce electronic waste and environmental pollution.

Keywords: Materials, Device.

INTRODUCTION

In recent years, the growing concern for environmental sustainability has spurred significant research into eco-friendly materials across various industries. Wearable devices, which encompass applications ranging from fitness tracking and health monitoring to advanced prosthetics and electronic skins, represent a rapidly growing sector of consumer and medical technology (1-3). However, the environmental implications of these devices have become an area of increasing scrutiny. Conventional materials used in wearable devices such as non-degradable plastics, heavy metals, and synthetic polymers contribute to mounting electronic waste (e-waste) that poses long-term challenges to ecosystems (Figure1) (4). These materials are often non-biodegradable, toxic, and energy-intensive to produce and recycle, exacerbating environmental issues. The shift toward developing biodegradable materials for wearable devices addresses these concerns while paving the way for a new generation of sustainable, high-performance technologies. Biodegradable materials offer a promising solution by ensuring that worn-out or obsolete devices can decompose naturally without harming the environment. These materials are derived from renewable sources such as plant-based polymers, proteins, and bio-composites, or are engineered to break down under specific environmental conditions. The use of biodegradable materials aligns with global initiatives to reduce carbon footprints, promote circular economies, and create safer alternatives to traditional electronic components. Moreover, the integration of such materials into wearable devices opens doors to novel design approaches, including transient electronics systems designed to perform a specific function for a limited time before harmlessly disintegrating.

Figure 1.

These innovations have the potential to redefine the lifecycle of electronic devices, ensuring minimal ecological impact while maintaining functionality and performance. The field of biodegradable materials is particularly relevant to wearable devices, as these devices often come into direct and prolonged contact with the human body. This unique interaction requires materials that are not only eco-friendly but also biocompatible, flexible, and durable under dynamic conditions. Biodegradable polymers such as polylactic acid (PLA), polycaprolactone (PCL), and polyhydroxyalkanoates (PHAs) have emerged as frontrunners due to their excellent mechanical properties, environmental degradability, and safety for human contact (5,6). Likewise, naturally derived materials such as silk fibroin,

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cellulose, and chitosan have gained attention for their unique properties and adaptability to wearable applications. These materials can be engineered to meet the specific needs of wearables, such as stretcha bility for motion sensors, thermal stability for on-skin applications, and electrical conductivity for biosensing (7-9) .However, despite their potential, biodegradable materials for wearable devices still face several challenges. One of the most pressing issues is achieving the balance between biodegradability and functionality. Wearable devices often demand high-performance components, including sensors, batteries, and interconnects, which require materials with robust mechanical strength, electrical conductivity, and chemical stability. Biodegradable materials must meet these performance requirements while maintaining their ability to decompose under appropriate conditions. Another critical challenge is the controlled degradation rate of these materials. While some applications may benefit from rapid degradation, such as disposable health-monitoring patches, others require materials to remain functional for extended periods, as seen in prosthetics or implantable devices. Developing materials with tunable degradation properties is thus essential to their successful integration into wearable technologies. The adoption of biodegradable materials in wearable devices also holds significant implications for healthcare, where wearables are increasingly used for patient monitoring, drug delivery, and rehabilitation. Biodegradable materials enable the creation of temporary medical devices, such as transient implants or sensors, that dissolve safely within the body, eliminating the need for surgical removal (10). This capability is particularly valuable for applications in remote or resource-limited settings, where access to medical infrastructure is constrained. Moreover, eco-friendly wearables can support broader public health initiatives by reducing the environmental impact of medical waste, aligning healthcare with sustainability goals. This article explores the state of the art in biodegradable materials for wearable device applications, addressing their potential, challenges, and future directions. It begins by reviewing the key categories of biodegradable materials, highlighting their properties, degradable mechanism and compatibility with wearable technologies. The subsequent sections delve into recent advancements in integrating biodegradable materials into functional components, such as memory, sensors and wireless systems. The discussion also emphasizes the critical role of interdisciplinary research and sustainable design principles in overcoming the challenges associated with these materials. By fostering a deeper understanding of eco-friendly biodegradable materials, this article aims to contribute to the development of innovative solutions for a sustainable future in wearable technology.

Increase demand of eco-friendly materials

The demand for eco-friendly materials has seen a significant surge in recent years, driven by the global push for sustainability and the urgent need to address environmental challenges such as climate change, resource depletion, and waste management (11). Industries across various sectors, including consumer electronics, healthcare, packaging, and fashion, are increasingly adopting sustainable practices, fueled by consumer awareness and regulatory pressures. Governments and organizations worldwide have implemented stringent environmental policies and initiatives, such as carbon taxes, bans on single-use plastics, and incentives for green technologies, which further encourage the use of eco-friendly materials. Consumers, particularly younger generations, are demanding products that align with their values, favoring brands and innovations that prioritize environmental stewardship. This shift has compelled companies to rethink their material choices, leading to the development and adoption of biodegradable polymers, bio-based composites, and recycled materials. The rise of the circular economy has also emphasized the importance of designing materials and products that can be reused, recycled, or safely returned to the environment at the end of their lifecycle, creating a paradigm shift in material science and product design. In the electronics industry, the increase in electronic waste (e-waste) has highlighted the environmental impact of non-biodegradable components, leading to growing interest in materials that decompose or are easier to recycle. Similarly, in the field of wearable devices, there is an escalating demand for eco-friendly materials that are not only biodegradable but also biocompatible, durable, and capable of meeting the performance requirements of modern technology. Beyond consumer-driven trends, industries also recognize the financial benefits of sustainable materials, as they help reduce energy consumption, lower raw material costs, and foster innovation in product development. Advancements in biotechnology, nanotechnology, and material processing have further accelerated the availability and feasibility of eco-friendly materials, making them more accessible for large-scale manufacturing. The combination of societal, regulatory, and technological factors underscores a transformative era where eco-friendly materials are no longer a niche option but a vital cornerstone for achieving a sustainable future across industries.

Biodegradable materials

Biodegradable plastics can be categorized into two types: natural polymers and synthetic polymers. Bio-based biodegradable polymers are derived from renewable sources such as cellulose, silk fibroin, and starch, making them environmentally friendly alternatives to conventional petroleum-based plastics (12). These materials are gaining increasing attention due to their potential to address plastic waste accumulation, reduce carbon footprints, and promote sustainability across various industries, including electronics, healthcare, and packaging. Among natural polymers, cellulose is one of the most widely used due to its abundance, cost-effectiveness, and excellent environmental compatibility. As a polysaccharide found in plant cell walls, cellulose is naturally biodegradable and exhibits unique physicochemical properties, including high mechanical strength, flexibility, and water absorption capacity. These properties have made cellulose-based materials essential in numerous applications, from textiles and paper production to advanced bioelectronics. One promising area where cellulose is playing a transformative role is in paper-based electronics, where it serves as a biodegradable substrate for sensors, transistors, and energy storage devices. Cellulose-based paper electronics are lightweight, low-cost, and environmentally friendly, offering a sustainable alternative to conventional electronic components that contribute to e-waste accumulation. Furthermore, modifications of cellulose, such as nanocellulose and cellulose derivatives, have expanded its applications in flexible electronics, biomedicine (13,14), and food packaging. Starch-based plastics, another important category of bio-based biodegradable materials, are widely recognized for their low cost and ease of production. Derived from renewable sources such as corn, potatoes, and cassava, starch-based polymers provide an economically viable alternative to petroleumderived plastics, especially in single-use applications. These biodegradable plastics have been utilized in packaging, disposable cutlery, agricultural films, and increasingly, in transient electronics. One key advantage of starch-based materials is their ability to decompose into harmless byproducts, such as carbon dioxide and water, through microbial activity. However, to enhance their mechanical properties and water resistance, starch is often blended with other biopolymers or biodegradable synthetic polymers, such as poly(lactic acid) (PLA) or polycaprolactone (PCL). PLA is widely used biodegradable materials with hydrolysis (Figure 2). The application of starch-based polymers in electronics is an emerging field with significant potential. With the growing concern over electronic waste (e-waste), researchers are exploring starch-based biodegradable substrates for flexible circuits, sensors, and energy storage devices. Disposable electronics, such as biosensors for environmental monitoring and medical diagnostics, benefit from starch's natural degradation, ensuring that the materials do not persist in the environment after their intended use. Additionally, advances in biopolymer engineering have led to the development of starch-based composites with improved conductivity, flexibility, and mechanical stability, making them more suitable for next-generation electronic applications.

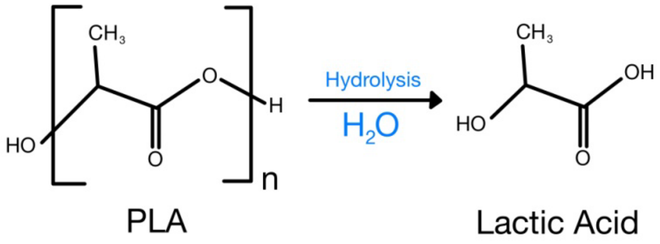

Figure 2.

Application to wearable electronics

Electronics are an essential part of daily life, used in applications ranging from communication and healthcare to entertainment and industrial automation. However, the rapid obsolescence of electronic devices and their reliance on non-degradable materials, such as plastics, heavy metals, and synthetic polymers, have led to a dramatic increase in e-waste. The application of biodegradable materials in electronics offers a solution that combines functionality with environmental stewardship, enabling the creation of devices that decompose naturally after their operational lifecycle. These materials, derived from renewable resources or engineered for environmental degradation, open new possibilities for sustainable electronics, particularly in wearable devices, transient electronics, and medical implants. One of the most promising applications of biodegradable materials in electronics is the development of transient electronic devices systems designed to perform a specific function for a finite period before disintegrating harmlessly. These devices are particularly valuable in medical and environmental applications. For instance, biodegradable sensors and circuits can be implanted in the body for post-surgical monitoring or drug delivery, eliminating the need for invasive removal procedures as the device dissolves once its purpose is fulfilled (15). Similarly, transient sensors for environmental monitoring can collect data on pollutants or weather conditions before breaking down in situ, reducing the ecological footprint associated with their deployment. This approach ensures that the devices serve their intended purpose without contributing to long-term waste accumulation. In wearable electronics, biodegradable materials are gaining traction for their ability to meet the unique requirements of devices that interact closely with the human body. Wearables often demand materials that are lightweight, flexible, and biocompatible while maintaining adequate electrical and mechanical performance. Biodegradable polymers, such as polylactic acid (PLA), polycaprolactone (PCL), and cellulose-based materials, have been utilized as substrates for wearable sensors and circuits. These materials provide the flexibility needed for conformal contact with skin while offering the advantage of environmental decomposition at the end of their use. Additionally, natural materials like silk fibroin and chitosan are increasingly used in wearable devices due to their excellent biocompatibility and degradability, making them ideal for applications in health monitoring, fitness tracking, and electronic skin (16). Energy storage systems, such as batteries and super capacitors, are another critical component of electronic devices where biodegradable materials have demonstrated potential. Traditional energy storage systems often rely on toxic metals and non-biodegradable components, raising concerns about their disposal. Researchers have developed biodegradable alternatives, including electrolyte systems derived from natural polymers and electrodes made from bio-based materials like carbon derived from biomass (17). These innovations have enabled the creation of fully biodegradable energy storage systems that can be safely discarded or composted without harming the environment. Such systems are particularly valuable for temporary electronic devices or applications in remote areas where proper e-waste management infrastructure is unavailable. The use of biodegradable materials in flexible and stretchable electronics is another area of active development. These devices, designed to maintain their functionality under mechanical deformation, are integral to next-generation applications such as foldable displays, stretchable sensors, and bioelectronics. Biodegradable elastomers, often made from plant-based or engineered polymers, have been developed to serve as substrates or encapsulating layers in flexible electronics. These materials not only provide mechanical durability but also ensure environmental safety through controlled degradation. Furthermore, biodegradable conductive materials, including metallic nanoparticles stabilized in biopolymers or conductive inks based on natural polymers, have been employed to fabricate stretchable circuits for wearable and implantable devices. Despite these advancements, the widespread adoption of biodegradable materials in electronics faces challenges that require further research and development. One of the primary hurdles is achieving a balance between biodegradability and performance. Many biodegradable materials struggle to match the electrical conductivity, thermal stability, and mechanical strength of traditional electronic materials, limiting their application in high-performance devices (Figure 3). Additionally, controlling the degradation rate of these materials remains a critical challenge, as different applications require materials to degrade at specific timescales. For example, a biodegradable sensor for environmental monitoring may need to last for several weeks, whereas a medical implant might need to dissolve within days. Another challenge lies in the scalability of biodegradable material production and their integration into existing manufacturing processes for electronics. Innovations in material synthesis, processing, and device design will be essential to overcoming these barriers and realizing the full potential of biodegradable electronics.

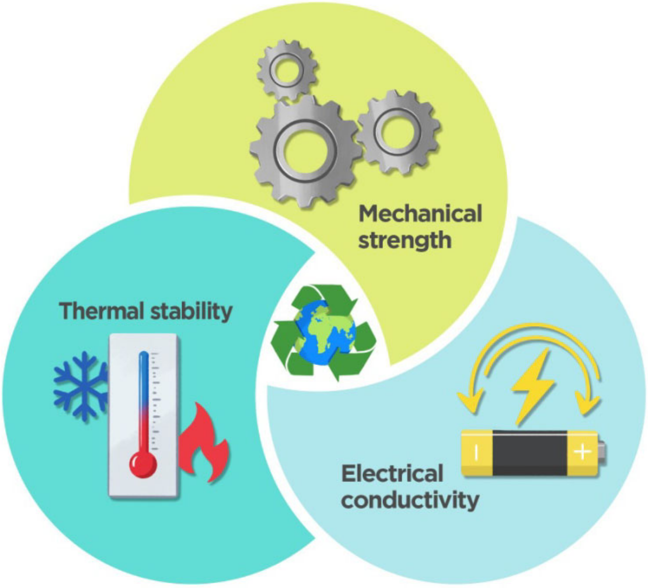

Figure 3.

The application of biodegradable materials to electronics not only addresses pressing environmental concerns but also expands the horizons of device functionality and design. By enabling the development of sustainable, transient, and biocompatible devices, these materials represent a crucial step toward a future where technology and environmental responsibility coexist harmoniously. As interdisciplinary efforts between material scientists, engineers, and environmentalists continue to advance, the integration of biodegradable materials into electronics promises to redefine the lifecycle of electronic devices, making sustainability an integral part of technological progress.

Conclusion

The increasing demand for sustainable solutions in wearable technologies has positioned eco-friendly biodegradable materials as a cornerstone of innovation. Derived from natural sources such as cellulose, chitosan, and silk, or developed through environmentally conscious synthesis methods, these materials offer a sustainable alternative to traditional counterparts that contribute to the growing problem of electronic waste. Their unique attributes flexibility, biocompatibility, and degradability make them exceptionally well-suited for wearable applications, including health-monitoring sensors, flexible electronics, and transient devices designed to naturally decompose after fulfilling their purpose. Despite remarkable advancements, challenges such as enhancing durability, achieving scalability, and reducing production costs continue to impede widespread adoption. Overcoming these obstacles will require sustained interdisciplinary collaboration among material scientists, engineers, and manufacturers, coupled with ongoing innovation in fabrication techniques and design strategies. Nevertheless, the transformative potential of biodegradable materials to mitigate environmental impact and contribute to global sustainability initiatives remains clear. As research and development in this field progress, eco-friendly biodegradable materials hold the promise of revolutionizing wearable technologies. By enabling devices that seamlessly blend functionality with environmental stewardship, these materials represent a pivotal step toward reducing electronic waste, fostering a circular economy, and building a more sustainable future for the electronics industry.

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