GLOBAL MULTIDISCIPLINARY PERSPECTIVES JOURNAL

Biodegradable Electronics: Combining Materials Science, Engineering, and Sustainability for Eco-Friendly Devices

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Article Info

ISSN (online): xxxx-xxxx
Volume: 02
Issue: 02
March-April 2025
Received: 05-12-2024
Accepted: 07-01-2025
Page No: 01-02

Abstract
The rapid advancement of electronic devices has led to increasing environmental concerns due to the accumulation of electronic waste (e-waste). Biodegradable electronics present a promising solution by integrating sustainable materials with innovative engineering to create devices that decompose naturally after their functional lifespan. This review explores the latest developments in biodegradable materials, fabrication techniques, and applications in transient electronics. We discuss organic and inorganic substrates, conductive polymers, and biodegradable semiconductors, along with their degradation mechanisms. Furthermore, we evaluate the performance and environmental impact of these devices, highlighting their potential in medical implants, environmental sensors, and consumer electronics. The challenges of scalability, stability, and cost-effectiveness are also addressed, emphasizing the need for interdisciplinary collaboration to advance this field.

Keywords: Biodegradable electronics, transient electronics, sustainable materials, e-waste, green technology, biodegradable polymers, eco-friendly devices

1. Introduction

Electronic waste (e-waste) is one of the fastest-growing waste streams globally, with over 53.6 million metric tons generated in 2019 alone, and projections suggesting an increase to 74 million tons by 2030 (Forti *et al*., 2020). Conventional electronics contain hazardous materials such as lead, mercury, and cadmium, which pose significant environmental and health risks when improperly disposed of. To mitigate this issue, researchers have turned to biodegradable electronics—devices designed to decompose into non-toxic byproducts after use.

Biodegradable electronics leverage advances in materials science, nanotechnology, and sustainable engineering to create functional yet environmentally benign devices. These systems can be used in medical implants, environmental monitoring, and disposable consumer electronics, where their transient nature is advantageous. This review examines:

- Key biodegradable materials (polymers, metals, semiconductors)
- Fabrication techniques for eco-friendly electronics
- Performance and degradation characteristics
- Current applications and future prospects

By integrating sustainability with cutting-edge technology, biodegradable electronics offer a pathway toward reducing e-waste and promoting a circular economy.

2. Materials and Methods

2.1 Biodegradable Substrates

The foundation of biodegradable electronics lies in substrates that provide mechanical support while being environmentally benign. Common materials include:

- **Natural polymers**
- **Silk fibroin:** Biocompatible, tunable degradation (Huang *et al*., 2021).
- **Cellulose:** Abundant, flexible, and compostable (Zhu *et al*., 2022).
- **Chitosan:** Derived from crustacean shells, antimicrobial properties (Kumar *et al*., 2020).

- **Synthetic biodegradable polymers**
  - **Polylactic acid (PLA)**: Derived from corn starch, widely used in 3D printing (Gonzalez-Henriquez *et al*., 2019).
  - **Polycaprolactone (PCL)**: Slow degradation, suitable for long-term implants (Woodruff & Hutmacher, 2010).

2.2 Conductive and Semiconductor Materials

- **Conductive polymers**
  - **PEDOT: PSS**: Water-soluble, used in flexible circuits (Li *et al*., 2021).
  - **Polyaniline (PANI)**: Degrades under oxidative conditions (Bober *et al*., 2020).

- **Biodegradable metals**
  - **Magnesium (Mg)**: Degrades into non-toxic $Mg(OH)_2$ (Zheng *et al*., 2020).
  - **Zinc (Zn)**: Biocompatible, used in transient batteries (Huang *et al*., 2022).

- **Semiconductors**
  - **Silicon nanowires**: Ultrathin layers dissolve in water (Hwang *et al*., 2021).
  - **Organic semiconductors**: e.g., Pentacene-based transistors (Irimia-Vladu *et al*., 2020).

2.3 Fabrication Techniques

- **Inkjet printing**: Low-waste deposition of biodegradable inks (Khan *et al*., 2021).
- **3D printing**: Customizable structures using PLA/PCL blends (Gao *et al*., 2022).
- **Vacuum deposition**: Thin-film semiconductors on biodegradable substrates (Yu *et al*., 2020).

2.4 Degradation Testing

- **Hydrolytic degradation**: Simulated body fluid (SBF) for medical devices (Wang *et al*., 2021).
- **Enzymatic degradation**: Protease for protein-based materials (Bai *et al*., 2020).
- **Soil/compost testing**: ASTM D6400 standards for biodegradability (ASTM International, 2019).

3. Results

3.1 Performance of Biodegradable Electronics

- **Flexible electronics**: Silk-based circuits exhibit high flexibility ($\leq$ 5% resistance change after 1000 bends) (Zhang *et al*., 2021).
- **Transient batteries**: Mg-Zn batteries achieve 15 mAh/cm^2 before dissolving (Yin *et al*., 2022).
- **Biodegradable sensors:** pH sensors degrade within 30 days in soil (Park *et al*., 2021).

Table 1: Degradation Profiles

Material	Degradation Time	Conditions
Silk fibroin	2-4 weeks	Aqueous
Mg alloy	4-8 weeks	SBF
PLA	6-12 months	Compost

4. Discussion

4.1 Advantages

- **Reduced e-waste**: Complete decomposition minimizes landfill burden.
- **Biocompatibility**: Ideal for medical implants (e.g., transient pacemakers).
- **Sustainable sourcing**: Renewable materials decrease reliance on rare metals.

4.2 Challenges

- **Limited operational lifetime**: Balancing functionality and degradation rate.
- **Manufacturing costs**: Higher than conventional electronics.
- **Standardization**: Lack of universal biodegradability certifications.

4.3 Future Directions

- **Hybrid materials**: Combining biodegradability with self-healing properties.
- **Scalable production**: Roll-to-roll printing for mass adoption.
- **AI-driven design**: Machine learning for optimizing material combinations.

5. Conclusion

Biodegradable electronics represent a transformative approach to sustainable technology, merging materials science with environmental stewardship. While challenges remain in durability and cost, ongoing research is paving the way for scalable, high-performance eco-friendly devices. Interdisciplinary efforts among chemists, engineers, and policymakers will be crucial in realizing the full potential of this technology.

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