International Journal of Science Academic Research
Vol. 06, Issue 04, pp.9684-9687, April, 2025
Available online at http://www.scienceijsar.com

ISSN: 2582-6425

Research Article

BIORESORBABLE MATERIALS FOR FULLY-DEGRADABLE IMPLANT SYSTEMS

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Received 09th February 2025; **Accepted** 05th March 2025; **Published online** 14th April 2025

Abstract

The development of fully degradable implant systems has garnered significant attention as a promising approach to minimizing long-term complications associated with permanent implants. To enhance patient care and reduce the need for invasive post-surgical procedures, bioresorbable systems have been extensively researched. These systems eliminate the necessity for device retrieval, thereby improving patient outcomes and reducing healthcare burdens. At the core of this advancement lies the development of bioresorbable materials, including polymers, metals, and ceramics, which enable transient medical devices by offering controlled degradation and excellent biocompatibility. This review explores the fundamental properties of bioresorbable materials, their integration into implantable electronic and structural devices, and recent advancements in biomedical applications. Notable progress in cardiovascular stents, neural interfaces, orthopedic scaffolds, and drug delivery systems highlights the transformative potential of bioresorbable implants in clinical practice. Addressing key challenges such as degradation kinetics, mechanical stability, and functional performance will be essential for advancing the efficacy and applicability of these next-generation medical technologies.

Keywords: Bioresorbable, Systems.

INTRODUCTION

The field of biomedical engineering has made significant strides in recent decades, particularly in the development of implantable medical devices. Traditional implants, such as metal screws, plates, and prosthetics, have played a crucial role in modern medicine, providing structural support and aiding in the healing of various injuries and conditions. However, these permanent implants often present challenges, including long-term complications, the need for secondary surgical removal, and potential adverse immune responses. In response to these challenges, bioresorbable materials have emerged as a promising alternative, offering a fully degradable solution that can enhance patient outcomes while minimizing surgical interventions. Bioresorbable materials are specifically designed to provide temporary mechanical support and degrade over time through natural metabolic processes, ultimately being absorbed or excreted by the body. These materials are commonly used in various biomedical applications, including orthopedic fixation devices, cardiovascular stents, tissue engineering scaffolds, and drug delivery systems. The integration of bioresorbable materials into fully degradable implant systems represents a transformative shift in medical device design, aligning with the growing demand for patient-friendly, minimally invasive treatments. One of the primary advantages of bioresorbable implants is their ability to eliminate the need for follow-up surgical procedures to remove the device once healing is complete. This reduces the risk of complications such as infection, implant migration, and chronic inflammation. Additionally, bioresorbable materials can be engineered to match the mechanical properties of native tissues, ensuring optimal performance while gradually transferring load-bearing responsibilities back to the body as healing progresses.

Several classes of bioresorbable materials have been explored for use in fully degradable implant systems, including polymers, ceramics, and metallic alloys. Polymers such as polylactic acid (PLA), polyglycolic acid (PGA), and polycaprolactone (PCL) are widely utilized due to their tunable degradation rates and biocompatibility (1-3). These materials degrade via hydrolysis, breaking down into biocompatible byproducts that are safely metabolized or excreted. Ceramics like calcium phosphate and bioactive glass have also demonstrated potential in orthopedic and dental applications due to their bioactivity and ability to promote bone regeneration. In recent years, bioresorbable metallic alloys, such as magnesium and zinc-based materials, have gained attention for their combination of strength, biocompatibility, and controlled degradation behavior (4,5). Despite the promising advantages of bioresorbable materials, several challenges remain in their widespread clinical adoption. One major concern is the precise control of degradation rates to match the specific healing timeline of different tissues. Premature degradation can lead to loss of mechanical integrity before tissue healing is complete, while excessively slow degradation may result in prolonged foreign body reactions. Researchers are actively investigating ways to tailor degradation kinetics through material modifications, surface treatments, and composite formulations to achieve optimal performance. Another critical challenge is ensuring the mechanical strength of bioresorbable implants, particularly in load-bearing applications. Traditional metal implants, such as titanium and stainless steel, provide superior strength compared to bioresorbable alternatives. Therefore, the development of reinforced bioresorbable composites and hybrid materials is a key area of research to enhance mechanical properties without compromising degradability (6). Furthermore, biocompatibility remains a crucial consideration in the design of bioresorbable implants. While most bioresorbable polymers, ceramics, and metals have demonstrated good biocompatibility, individual patient responses can vary. The presence of degradation byproducts,

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local inflammatory responses, and immune reactions must be carefully studied to ensure safety and efficacy. Advances in biomaterial science, including bioactive coatings and drug-eluting implants, are being explored to mitigate potential adverse effects and enhance the therapeutic benefits of bioresorbable systems. The integration of bioresorbable materials in fully degradable implant systems is not only revolutionizing medical device technology but also opening new possibilities for personalized medicine. Customizable implants, 3D-printed bioresorbable scaffolds, and bioengineered tissue replacements are being developed to tailor treatments to individual patient needs. The convergence of bioresorbable materials with cutting-edge fabrication techniques, such as additive manufacturing and nanotechnology, is further expanding the potential applications of these materials in regenerative medicine and beyond. Looking ahead, the future of bioresorbable implants lies in continued material innovation, regulatory advancements, and clinical validation. Collaborative efforts between biomedical engineers, medical doctor, and electrical engineers are essential to translating laboratory discoveries into clinically viable solutions (Figure 1). As the demand for minimally invasive, patient-centric treatments grows, bioresorbable materials are poised to play an increasingly vital role in shaping the next generation of implantable medical devices. This article explores the latest advancements in bioresorbable materials, their integration into fully degradable implant devices and systems, and the challenges and opportunities associated with their clinical applications. By examining recent research developments, material properties, and emerging trends, we aim to provide a comprehensive overview of the transformative potential of bioresorbable materials in modern medicine.

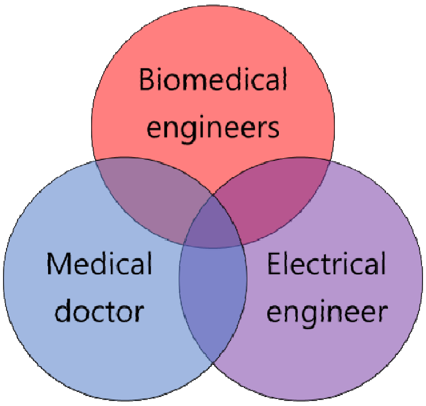

Figure 1. Bioresorbable medical research based on three main fields

Recent progresses in bioresorbable materials

Bioelectronics is emerging technology that involves development of medical system used for diagnosis of patients. Especially, implantable devices have been studied for many years to enhance both high quality functions and non-invasiveness for patients. The foundation of bioresorbable electronic systems lies in a comprehensive understanding of the chemistry and degradation kinetics of their constituent materials. These materials must balance operational stability and complete bio-absorption, ensuring functionality for the required clinical timeframe while avoiding long-term persistence in the body. Typically, the functional lifespan of these materials takes days to weeks, whereas full bio-absorption occurs over months. Achieving an optimal balance often involves precise material engineering or external triggers to accelerate degradation when necessary. Bioresorbable systems generally consist of three key components: functional materials, supporting substrates, and encapsulating layers. The outer encapsulation plays a critical role in controlling degradation by regulating the permeation of biofluids. Its breakdown initiates the dissolution of internal functional components, ultimately leading to the system's degradation. The rate of bio-absorption is largely dictated by the encapsulating layer's permeability and the substrate's structural integrity, making these factors crucial in determining the device's operational lifespan. A variety of bioresorbable materials have been explored for transient electronic applications. In inorganic materials, such as silicon (Si), magnesium (Mg), zinc (Zn), and molybdenum (Mo), have been widely used for transient electronics due to their controlled degradation and biocompatibility. Silicon, in particular, dissolves into silicic acid in biofluids at a tunable rate, while magnesium and zinc offer excellent electrical conductivity and structural support for bioresorbable circuits and sensors (7).The degradation of such metals follows from a series of anodic and cathodic reactions to produce general, a complex collection of products. Upon immersion in water/biofluids, these metals undergo electrochemical oxidation to generate metal cations and electrons as shown in below example and Figure 2.

$$Mg+2H_2O \rightarrow Mg(OH)_2+ H_2(Gas)$$

Previous research illustrates the dissolution behavior of patterned Mg (50 nm thick) and Zn (400 nm thick) traces immersed in phosphate-buffered saline (PBS) at physiological pH (~7.4) under both room and body temperature conditions (~37 °C) (8,9). Bioresorbable metal alloys are well-suited for developing structural implantable devices in orthopedic applications due to their adjustable mechanical properties and controlled degradation rates. For example, the incorporation of aluminum enhances mechanical strength and corrosion resistance. Such fabricated alloys generate insoluble aluminum oxide as a degradation byproduct, significantly slowing the degradation rate compared to pure magnesium (10).

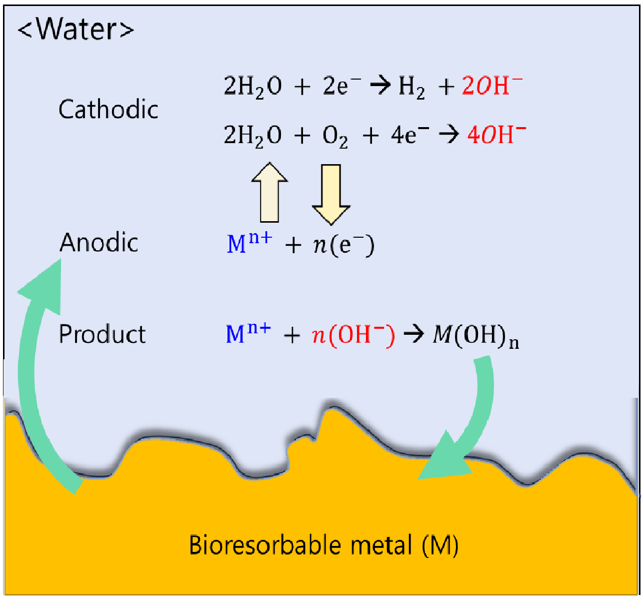

Figure 2. Schematics showing that the bioresorbable metal decomposed in water

Recently, many types of bioresorbable polymers have been developed including poly(lactic-acid) (PLA), polycaprolactone (PCL), and silk fibroin, serve as flexible substrates and encapsulation layers with adjustable degradation rates. These materials provide mechanical stability while ensuring compatibility with biological tissues. For instance, PLGA that include resorbable functional groups such as ester bonds, which hydrolyze to an alcohol (11). In addition to synthetic bioresorbable polymers, natural polymers like silk fibroin can also function as bioresorbable substrates. Depositing polypyrrole polymer directly onto a silk fibroin substrate results in a composite material where the polypyrrole gradually breaks down as the silk undergoes bio-absorption, leading to an overall weight loss of 82% in PBS at 37°Cover 15 days (12). By carefully selecting and engineering bioresorbable materials, researchers can develop transient implantable systems with tailored degradation profiles, paving the way for next-generation medical technologies that eliminate the need for device retrieval while maintaining high performance and biocompatibility.

Integrated bioresorbable devices

The materials discussed in previous section can be integrated into a diverse range of bioresorbable electronic components and sensors. This section explores various categories of these devices, detailing their operating principles and performance. The integration of bioresorbable sensors, memory devices, and wireless communication systems into medical implants, particularly stents, represents a transformative advancement in biomedical engineering. These devices provide real-time monitoring, improve post-surgical care, and mitigate complications such as in-stent restenosis. The ability of bioresorbable materials to dissolve safely within the body over time eliminates the need for additional surgeries, making these systems highly advantageous in temporary biomedical applications. Physical sensors play a critical role in detecting mechanical and thermal changes inside the body, with pressure sensors widely used to monitor blood flow and detect complications related to stents. These sensors rely on point contact or diaphragm-based systems, with strain gauges composed of serpentine metal traces measuring pressure variations. Advanced fabrication techniques such as laser sintering of zinc (Zn) and nanoparticle suspension methods enhance conductivity and sensitivity, while fully bioresorbable pressure sensors made from piezoelectric materials like poly(L-lactic acid) (PLLA) combined with molybdenum (Mo) and magnesium (Mg) electrodes provide flexible and high-performance monitoring solutions. Another approach for pressure monitoring involves LC circuit-based sensors, which use Zn-based inductance (L) and capacitance (C) components embedded in poly(lactic-co-glycolic acid) (PLGA) for high sensitivity. Additionally, miniaturized arterial blood flow pressure sensors enable precise hemodynamic monitoring. Temperature monitoring is essential in biomedical applications, particularly for detecting inflammation or abnormal thermal changes. Resistive temperature sensors exploit the relationship between electrical resistance and temperature, with Mg resistive elements encapsulated within silicon nitride (Si_3N_4) and silicon dioxide (SiO_2) layers to enhance mechanical robustness and stretchability. Additionally, semiconductor-based temperature sensors such as silicon (Si) nanomembrane (NM) diodes and capacitive sensors using LC resonant circuits with polyethylene glycol (PEG) enable high-precision, wireless temperature monitoring. Furthermore, resistive temperature sensors can function as localized heat sources, using Si NM thermal actuators alongside two Si NM sensors positioned along the flow direction to quantify thermal conductivity and blood flow dynamics. To transmit sensor data to external systems, bioresorbable antennas are integrated into implantable medical devices, converting electrical signals into radio waves to facilitate wireless communication and power transfer. Current research explores bioresorbable antenna materials such as Mg, Au, and Mo on PLGA substrates, Cu on polyanhydride, and Mg-based devices on silk substrates. Notably, bioresorbable dipole antennas can wirelessly power red LEDs by harvesting radiofrequency (RF) energy, with their resonant frequency shifting as they dissolve, enabling a physically tunable system for applications in drug delivery, therapeutic stimulation, and real-time physiological monitoring. The combination of bioresorbable sensors and antennas in stents facilitates real-time vascular health monitoring, embedding pressure, temperature, and flow sensors into the stent structure for continuous tracking of physiological parameters. These sensors enable early detection of complications such as restenosis, blood clots, or abnormal hemodynamics, allowing for timely medical intervention. Additionally, controlled dissolution ensures these sensors function throughout the critical monitoring period before safely degrading, with bioresorbable metal oxide coatings optimizing bioresorption rates and device longevity. Future advancements in bioresorbable electronics focus on optimizing material properties, enhancing device longevity, and improving wireless communication efficiency. Research continues to develop bioresorbable materials with tunable degradation rates and enhanced electrical performance, while advancements in RF systems and miniaturized energy harvesting technologies may extend the operational range of bioresorbable antennas. However, challenges remain in ensuring biocompatibility, precise degradation control, and consistent sensor performance throughout the device's lifespan. Refining fabrication techniques, optimizing sensor placement, and improving data transmission reliability are crucial for overcoming these limitations. Ultimately, integrated bioresorbable devices represent a revolutionary step in biomedical technology, offering minimally invasive, self-dissolving solutions for real-time health monitoring. By combining bioresorbable sensors, antennas, and electronic components, these systems enable effective post-surgical care while eliminating the need for device retrieval surgeries. Continued research in material science, sensor technology, and wireless communication will further enhance the capabilities of bioresorbable medical implants, leading to safer and more efficient healthcare solutions in the future.

Recent bio-implants applications

Integrating bioresorbable components and sensors with sensor and wireless components enables the development of bioresorbable systems that deliver diagnostic or therapeutic functions for clinical applications. Figure 3 illustrates the range of clinical applications for bioresorbable electronics.The U.S. Food and Drug Administration (FDA) currently recommends in vivo degradation assessments for bioresorbable or biodegradable medical implants, in accordance with International Standards Organization (ISO) guidelines. Key requirements include cytotoxicity (cell damage), irritation (inflammatory responses), systemic toxicity (organ effects due to chemical constituents) (13). Based on these standards, some of the materials reviewed in previous sections such as Mg, Mg alloys, Zn, PLAhave received FDA approval. To show the potential of these materials for biomedical applications, there have been many progresses with diverse kinds of implantable applications. Real-monitoring after surgery ofblood vessel is critical to patient recovery. Bioresorbable devices for monitoring blood flow (14) can be useful in this context, with the potential to eliminate complications and costs and invasiveness associated with surgical extraction. In addition, bioresorbable cardiac pacing system is necessary to prevent the risk induced to patients such as anopen-heart surgery, heart attack, side effects of medications, or infection, which might happen during post-surgical process. Previous result shows implantation of such a pacemaker aspart of a chronic *in vivo* study in a rat model (15). Researchers have demonstrated successful pacing, as evidenced by ECG signals recorded before and during electrical stimulation. To monitor brain activity, a bioresorbable device can be implanted on the surface of the brain (16). Multiplexed devices enable high-resolution, high-channel-count neural interfaces or transient spatiotemporal mapping of electrical activity from the cerebral cortex.

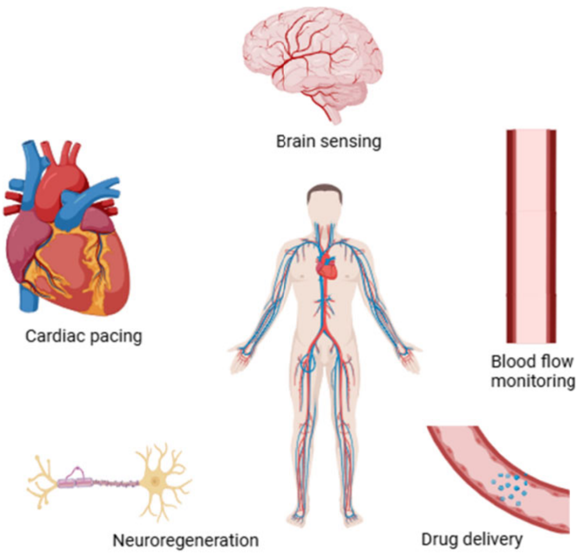

Figure 3. Bioresorbable system for diverse implantable sensor applications

Conclusion

In conclusion, the integration of bioresorbable materials into implantable medical devices marks a groundbreaking advancement in biomedical engineering. These materials, which naturally degrade over time through metabolic processes, offer substantial benefits over traditional permanent implants, such as reducing the risk of complications, eliminating the need for secondary surgeries, and enhancing patient outcomes. The ongoing development of bioresorbable materials—including polymers, ceramics, and metallic alloys—has paved the way for highly functional, patient-centric devices across a range of medical fields, from orthopedics and cardiovascular care to tissue engineering and drug delivery.As bioelectronics continue to evolve, incorporating bioresorbable components and sensors into fully degradable systems opens new possibilities for both diagnostic and therapeutic applications. The key to creating successful devices lies in balancing controlled degradation kinetics with high mechanical performance, ensuring that the device remains functional throughout the healing process while transitioning smoothly to complete bio-absorption. Although challenges remain in fine-tuning degradation rates and maintaining mechanical strength, ongoing research and innovations in material science are steadily addressing these issues, bringing us closer to realizing the full potential of bioresorbable systems. Looking ahead, the future of bioresorbable implants depends on continued collaboration among engineers, clinicians, and researchers, alongside advancements in fabrication technologies like 3D printing and nanotechnology. With these efforts, bioresorbable materials have the potential to revolutionize the medical device industry, providing customized, minimally invasive solutions tailored to the unique needs of each patient. As we progress, the development and clinical validation of bioresorbable devices will be essential to unlocking their transformative impact on modern medicine, improving patient care while minimizing the need for invasive procedures and long-term medical interventions.

Acknowledgement

I would like to thank Sunny Kim and Essential academy for guidance, encouragement during process of this review paper

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