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Soft Science

Ryu. *Soft Sci.* **2026**, *6*, 55 **DOI:**10.20517/ss.2026.61

Functional materials for bioresorbable medical systems: recent advances and emerging biomedical applications

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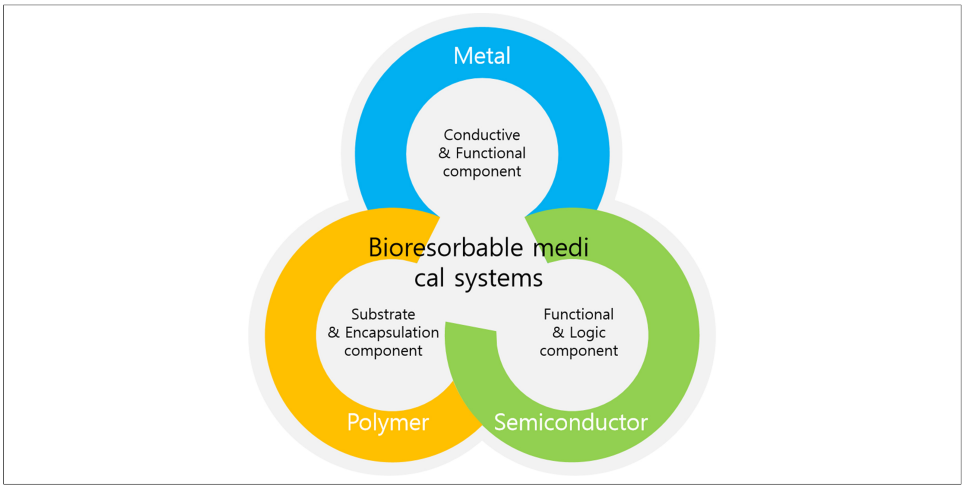
Citation: Ryu, H. Functional materials for bioresorbable medical systems: recent advances and emerging biomedical applications. *Soft Sci.* **2026**, *6*, 55. https://dx.doi.org/10.20517/ss.2026.61

Received: 27 Mar 2026 **First Decision:** 22 Apr 2026 **Revised:** 24 Apr 2026 **Accepted:** 7 May 2026 **Published:** 1 Jul 2026

Academic Editors: Abraham Vazquez-Guardado, Lan Yin **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang



INTRODUCTION

Bioresorbable biomedical systems enable retrieval-free surgery for temporary implantable devices, thereby reducing the burden on patients[1]. Key parameters for device optimization include bioadhesiveness, electrical conductivity, mechanical compliance, thermal conductivity, and bioresorption behavior [Figure 1A]. Functional materials with controlled hydrolysis and degradation characteristics support the development of multifunctional bioresorbable medical devices, ranging from sensors to actuators[2]. Encapsulation strategies that limit water penetration further regulate the functional lifetime of these devices to meet specific medical requirements[3-5]. Although *in vivo* studies demonstrate promising results[6-9], the physiological and biological mismatch between artificial materials and surrounding tissues remains a major challenge[10-13], and further research is required to develop functional materials with improved compatibility. This article highlights recent advances in bioresorbable materials and biomedical systems for next-generation bioresorbable electronics, emphasizing material chemistry, biomedical applications, and future challenges.

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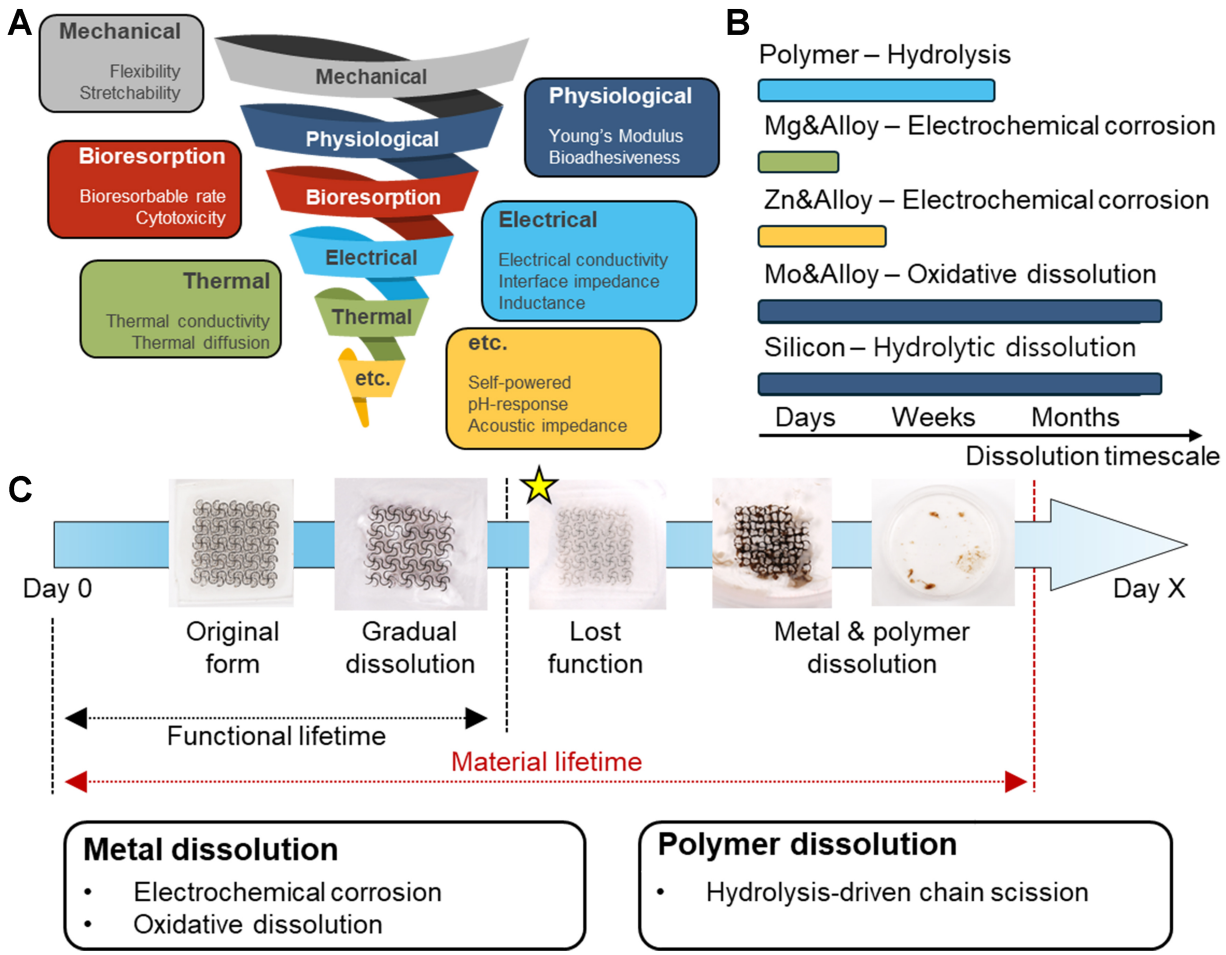

Figure 1. (A) Key requirements for bioresorbable medical systems; (B) Overview of bioresorbable materials[17-31,34,47]; (C) Dissolution processes of bioresorbable medical systems. Adapted from Ref.[48]. © 2023 The Authors. CC-BY 4.0. Advanced Science published by Wiley-VCH GmbH.

RECENT ADVANCES IN FUNCTIONAL MATERIALS FOR BIORESORBABLE SYSTEMS

Metals, silicon, and polymers each play distinct roles in bioresorbable systems owing to their unique properties [Figure 1B and C]. Polymers commonly serve as substrates and encapsulation layers due to their favorable mechanical properties and compatibility with convenient fabrication processes[14-16]. Water penetration into polymer matrices induces hydrolysis-driven chain scission, which gradually degrades the material and enables bioresorption over timescales ranging from days to months[17-31]. Metals form conductive layers that support applications ranging from simple electrodes to complex circuit architectures[1]. Biocompatible metals such as gold (Au) and titanium (Ti) exhibit electrical resistivities of 2.05×10^{-8} and 39×10^{-8} Ω·m, respectively, at 273 K, whereas bioresorbable metals such as magnesium (Mg), zinc (Zn), and molybdenum (Mo) show resistivities of 4.05×10^{-8}, 5.46×10^{-8}, 4.85×10^{-8} Ω·m, respectively[32]. Electrochemical corrosion ionizes Mg and Zn-based metals, generating rapid chemical reactions that limit their functional lifetime in the body to days or weeks[1]. In contrast, Mo-based metals undergo slow oxidative dissolution and maintain stable surface impedance over timescales of weeks to months[1]. Metal powder–polymer composite structures provide conductive ink platforms that enable via formation and electrical interconnections between components[33]. Silicon (Si) and doped Si serve as key semiconductor materials in bioresorbable electronics. Hydrolytic dissolution of silicon occurs through the formation of orthosilicic acid [$Si(OH)_4$], typically at rates ranging from a few to tens of nanometers per day[34]. Si nanomembrane (NM) devices overcome several limitations of bulk silicon, including limited flexibility, slow degradation, and mechanical fragility, thereby enabling their integration into implantable medical systems.

In 2012, the demonstration of physically transient Si electronics initiated the field of bioresorbable electronics[34]. Mg electrodes, MgO dielectric layers, and Si NMs form metal–oxide–semiconductor field-effect transistors that achieve on/off ratios exceeding 10^5 at a drain voltage of 0.1 V and a gate voltage of 5 V. Silicon-on-insulator (SOI) wafers allow repeatable fabrication through photolithography and support stable electronic operation. However, water penetration through the silk substrate and MgO encapsulation layer corrodes Mg electrodes, which rapidly degrades device performance within several days.

Laser ablation techniques extend SOI-based silicon electronics toward bioresorbable microelectromechanical systems (MEMS)[35]. Transfer printing to flexible substrates and integrated circuits further enables electrocapacitive sensors, electrostatic actuators, and electrothermal actuators. Process simplification reduces chemical waste and improves the fabrication yield of ecoresorbable and bioresorbable MEMS (eb-MEMS) with micrometer-scale resolution. Biocompatibility tests indicate no significant cytotoxicity associated with Si-based electronics[35]. Encapsulation strategies based on mixtures of candelilla wax and beeswax, polylactic acid (PLA), or semi-water-permeable hydrogel adhesive matrices regulate device lifetimes and isolate the electronics from the surrounding biological environment. The convergence of advanced semiconductor technology and bioresorbable packaging strategies enables highly precise implantable bioresorbable sensor systems for continuous health monitoring[36]. The resonance frequency of resistor–inductor–capacitor (RLC) circuits provides a convenient platform for passive wireless diagnosis[37].

Bioadhesive materials play a critical role in stabilizing implantable devices in biomedical applications because conventional surgical suturing can mechanically damage device structures and provoke local biological responses at the implantation site[38]. A mixture of polyethylene glycol–lactide acid diacrylate, a photoinitiator, sodium alginate, chitosan, 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide, and sulfo-N-hydroxysuccinimide forms a photocurable bioadhesive hydrogel that functions as a bioelectronic–tissue interface material (BTIM). Carboxylic acid and amine groups present in biological tissues and device encapsulation layers form covalent bonds with functional groups in the BTIM. *In vivo* studies demonstrate that the BTIM maintains device fixation for up to two months and exhibits negligible cytotoxicity[38]. Histological analyses further show that the BTIM prevents suture-induced fibrotic tissue formation, which helps minimize foreign-body responses by reducing the mechanical mismatch between biological tissues and bioelectronic devices.

Bioresorbable heterogeneous material systems exhibit intrinsic differences from native tissues in their physical and acoustic properties, which enables circuit-free deep-tissue diagnostics[39]. The acoustic impedance mismatch between precisely aligned metal structures embedded in a pH-sensitive polymer matrix and surrounding soft tissue enables *in vivo* pH monitoring through ultrasound imaging. pH-responsive swelling or shrinkage of the polymer matrix modulates the spatial arrangement of Zn patterns, thereby enabling indirect visualization of gastrointestinal pH levels beyond the capabilities of conventional ultrasound imaging. The metastructured hydrogel sensor, incorporating an air-hydrogel heterostructure, broadens its potential applications to include intracranial pressure, temperature, pH, and flow rate sensing.

SUMMARY AND OUTLOOK

Advanced device-level functionalities, particularly for therapeutic modulation and wireless integration, represent promising directions for future applications[40-46]. Interactions between wearable and implantable systems further enable autonomous diagnosis and therapeutic intervention, including emergency cardiac pacing[40]. Electromagnetic induction provides an effective strategy for wireless power transfer; however, susceptibility to structural deformation, water penetration, and environmental variation necessitates robust

encapsulation to preserve resonant behavior *in vivo* over extended durations[41]. Transitioning from electromagnetic induction to light-driven electrostimulation enables substantial miniaturization of bioresorbable devices by eliminating RLC circuitry[42]. Integration with optical filters further enables selective electrostimulation at multiple locations. Microchannel systems also enable temporary nerve-cooling implants that reversibly block peripheral nerve activity[43]. Alternating current generation through triboelectric effects under ultrasound stimulation further enables a metal-electrode–free nerve block system that minimizes mechanical mismatch with biological tissue[44]. Such simplified functional material systems provide structurally streamlined solutions for complex therapeutic interventions. Bioresorbable passive RFID systems also offer expanded opportunities for applications such as patient adherence monitoring[45].

Future research in bioresorbable medical systems requires the maturation of innovative technologies and the development of advanced functional materials that meet the physical and operational demands of next-generation devices. Key challenges include heterostructure interfacial instability, localized corrosion caused by water penetration, galvanic corrosion in heterogeneous metal systems, and polymer swelling induced by moisture uptake, which can alter mechanical and electrical performance. In addition, fibrotic capsule formation around implanted devices remains a significant concern. Soft hydrogel-like encapsulation materials offer a promising strategy to inhibit water ingress at edge heterointerfaces, which represent primary pathways for localized corrosion and sudden functional failure of bioresorbable devices by employing covalent or interpenetrating polymer networks that enhance interfacial adhesion and suppress delamination. However, challenges such as swelling-induced deformation and limited long-term stability remain. Improved adhesion to biological tissues combined with low mechanical stiffness can further reduce foreign-body responses. Embedding conductive bioresorbable microwires within compliant polymer matrices can improve mechanical flexibility and enable tunable degradation, thereby addressing the limitations of solid metal electrodes. However, ensuring electrical continuity during degradation remains a key challenge. Minimally invasive strategies based on *in vivo* shape transformation may further expand therapeutic possibilities by overcoming the constraints associated with preformed structural implantation. Continued advances in functional materials designed to meet these requirements will drive the development of the next generation of clinically translatable bioresorbable medical systems.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

Not applicable.

Financial support and sponsorship

This work was supported by the Korean Fund for Regenerative Medicine (KFRM) grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Health & Welfare, KFRM 25A0105L1).

Conflicts of interest

The author declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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