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Biodegradable Metal Stents for Cardiovascular Diseases: Inflammation Modulation and Functional Optimization

Mingyue Wu

Department of Biological Sciences, University of Bristol, Bristol, United Kingdom
yk24090@bristol.ac.uk

Abstract. Cardiovascular diseases (CVDs) persist as the foremost global cause of morbidity and mortality, pushing the advancement of vascular implants designed to reestablish perfusion ability and promote vessel repair. However, conventional permanent stents often lead to long-term complications such as chronic inflammation, late thrombosis, and impaired vascular remodeling due to their persistent presence. Initial approaches applied pure biodegradable metals for stent fabrication; however, rapid corrosion, inadequate mechanical integrity, and slow degradation frequently constrained their clinical applicability. To address these limitations, biodegradable metal stents (BMSs) have emerged as next-generation alternatives, providing transient mechanical support that resorbs progressively upon fulfilling their therapeutic role, thereby reducing chronic body responses. Alloys based on magnesium, zinc, and iron have garnered significant interest owing to their unique corrosion kinetics, mechanical properties, and biocompatibility. This review outlines recent progress in BMS development, highlighting major strategies for performance enhancement—including compositional design to tailor intrinsic material behavior, microstructural engineering to optimize strength and ductility, surface modification to improve biocompatibility, and multifunctional interfaces to enable controlled degradation and biological modulation. By integrating material science and biomedical perspectives, this review aims to provide insights into current challenges and future directions for the clinical translation of BMSs.

Keywords: Biodegradable, metal stents, inflammation modulation, alloy design

1. Introduction

Cardiovascular diseases (CVDs), encompassing a spectrum of disorders such as myocardial infarction, stroke, and heart failure, continue to represent a dominant global health challenge, accounting for approximately 18.6 million deaths in 2020—nearly one-third of total mortality worldwide. Beyond their profound physiological impact, CVDs impose escalating socioeconomic burdens. Informal caregiving expenses alone were estimated at $61 billion in 2015 and are projected to exceed $128 billion by 2035, underscoring the urgent need for more effective therapeutic solutions [1]. Given the significant burden of CVDs, there is a growing demand in society for innovative technologies that can address the disease more effectively.

Traditional interventions involving metallic stents composed of elements such as calcium, sodium, or titanium have demonstrated inherent limitations. Calcium- and sodium-based devices

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typically suffer from rapid degradation and mechanical failure, while titanium stents exhibit poor biodegradability and prolonged retention within the vasculature, thereby compromising post-implantation vascular healing. While drug-eluting alloy stents subsequently reduced restenosis, they did not resolve the intrinsic drawbacks of permanent implants. These challenges have driven attention to develop next-generation scaffolds that deliver transient support during critical healing windows and biodegrade to leave a functional vessel. Through development, biodegradable stents based on zinc, magnesium, and iron alloys have emerged as mainstream implants for CVD treatment.

In response, biodegradable metal stents (BMSs) have emerged as next-generation vascular scaffolds. Alloys based on magnesium, zinc, and iron offer the ability to provide transient mechanical support during the critical healing phase, followed by gradual degradation in synchrony with vascular remodeling, thereby minimizing chronic complications [2]. Composite strategies further enhance functional performance by integrating desirable attributes of individual metals—for instance, coupling zinc's accelerated corrosion kinetics with iron's mechanical robustness Moreover, BMS functionality can be significantly augmented through rational alloy engineering and advanced surface modification techniques, such as chemical passivation, multifunctional coatings, and nanoarchitectures, to fine-tune degradation behavior, mechanical strength, and biocompatibility [3]. Furthermore, by including immunomodulatory elements or implementing nanostructured surface architectures via advanced material engineering, biodegradable stents can acquire the capability to regulate local inflammatory responses. These functional enhancements allow the stents to maintain adequate mechanical support while simultaneously contributing to the regulation of local immune microenvironments, thereby improving their overall therapeutic performance [4].

This review systematically examines the evolution of BMSs, beginning with an overview of key material systems and their intrinsic properties, followed by recent advances in fabrication strategies, performance enhancement techniques, and inflammation-modulating functionalities. The review concludes with perspectives on future clinical translation and remaining challenges in the field.

2. Biodegradable metal stents: material selection and properties

While early biodegradable metal stents offered therapeutic value, pure metals often exhibit intrinsic limitations. For example, tungsten suffers from uneven corrosion and potential cytotoxicity, while iron's slow degradation prolongs implant persistence and risks chronic inflammation. Such issues, along with limited tunability in balancing support and resorption, have driven the development of biodegradable alloys. Through compositional and microstructural engineering, these alloys aim to optimize corrosion behavior, mechanical integrity, and biocompatibility, enhancing their clinical potential.

2.1. Zinc-based alloys

Zinc (Zn), widely found in minerals such as sphalerite (ZnS), is a bluish-white transition metal with good electrical and thermal conductivity. It rapidly forms a protective ZnO layer in air, improving corrosion resistance. Notably, zinc demonstrates excellent biocompatibility, modulating immune responses through the NF-κB pathway and regulating T, B cells, and macrophages to balance pro- and anti-inflammatory cytokine production. Bowman et al. implanted high-purity zinc stents in rat abdominal aortas, revealing favorable host responses. Neointimal formation comprised smooth muscle cells (SMCs) and low-density inflammatory cells near the metal and corrosion zones, without necrosis, highlighting zinc's cytocompatibility [2]. Beside biocompatibility, back in 2013,

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Bowen et al. demonstrated that zinc degraded at ~0.5 μm/day—faster than iron (~0.1 μm/day)—yet retained structural integrity over 4–6 weeks, supporting endothelialization and minimizing inflammation [5]. These properties suggest zinc's degradation profile is well-suited for vascular applications. However, concerns remain regarding the cytotoxicity of degradation products (e.g., zinc ions) and zinc's low tensile strength and ductility, limiting its mechanical reliability [6]. To overcome these limitations, researchers explored zinc-based alloys to enhance mechanical properties and refine degradation behavior. Yang et al. evaluated Zn-Li alloys implanted in rat aortas, observing improved corrosion rates (~1.2 μm/day for Zn-0.2Li) and enhanced mechanical properties, with tensile strength increasing from ~110 MPa (pure Zn) to ~250 MPa [7]. These alloys reduced implantation-related inflammation and supported endothelial growth more effectively. Moreover, Li et al. demonstrated that fabricating a ZnO layer on zinc stents markedly enhanced the adhesion of composite coatings (e.g., polydopamine), thereby significantly improving corrosion resistance and mechanical integrity [8]. In general, zinc and its alloys exhibit promising degradation profiles and immunomodulatory potential, yet continued optimization is necessary to address mechanical limitations and cytotoxic degradation byproducts.

2.2. Magnesium-based alloys

Magnesium (Mg) is a lightweight metal with a density of 1.74 g/cm³ and a standard electrode potential of -2.37 V, making it highly reactive in aqueous environments. As the eighth most abundant element in the Earth's crust and the third most prevalent structural metal, magnesium is attractive for biomedical applications. Due to the dense film Mg rapidly forms, magnesium-based stents degrade more rapidly than zinc-based counterparts in physiological conditions. Meanwhile, same as zinc, magnesium exhibits outstanding mechanical properties. Magnesium's low density provides significant weight advantages over conventional metals like stainless steel or titanium, improving patient comfort and reducing local stress. Conversely, rapid degradation and associated hydrogen release can compromise long-term stability and hinder tissue regeneration. To balance degradation and mechanical demands, alloying is a common strategy. Gu et al. investigated the physical and biological properties of various binary magnesium alloys (e.g., Mg-Zr, Mg-Al, Mg-Mn) under room temperature conditions and in simulated body fluid (SBF) [9]. Their findings indicated that alloying with Al, Sn, or Zr simultaneously enhanced tensile strength and reduced corrosion rates of as-cast Mg–X alloys in SBF. In contrast, the presence of Si was found to negatively impact the corrosion resistance of magnesium.

2.3. Iron-based alloys

Iron is a transition metal with a density of 7.87 g/cm³, melting point of 1538°C, and excellent mechanical properties such as high strength, ductility, and an elastic modulus of ~210 GPa—significantly surpassing magnesium (45 GPa) and zinc (83 GPa).These attributes grant iron-based stents superior load-bearing capacity and long-term structural stability. Unlike magnesium, iron degrades slowly in physiological environments, forming $Fe(OH)_2$, $Fe(OH)_3$, and Fe^{2+}/Fe^{3+} ions, thus avoiding hydrogen gas accumulation and reducing inflammatory risks. Francis et al. reported that iron-based stents have superior strength (~210 GPa), outperforming Mg and Zn. Their dense oxide layer (e.g., Fe_2O_3) slows degradation, offering extended support, but may cause byproduct accumulation and thrombosis [10]. Nevertheless, the inherently slow degradation rate of iron-based stents also leads to uneven degradation and accumulation of degradation products, which may eventually cause severe inflammatory reactions. To address these limitations, researchers have

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pursued alloying strategies. By analyzing the Fe30Mn6Si shape memory alloy using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), Liu et al. studied Fe–30Mn–6Si alloys and found that Mn improved tensile strength and flexibility, while Si increased γ-austenite phase content, enhancing strength and electrochemical reactivity [11]. These changes lowered alloy resistivity and promoted uniform, accelerated corrosion. Recently, Chinese Academy of Sciences conducted a study using a high-nitrogen alloying strategy, which introducing 0.6% nitrogen produced nano-twinned structures (<15 nm) that boosted the degradation rate by over 60% and improved corrosion uniformity [12]. This reduced localized pitting and byproduct buildup, further enhancing safety. Collectively, these modifications demonstrate iron's adaptability and potential for functional enhancement via alloying.

3. Manufacturing strategies and performance enhancement

Surface modification and coating are widely used to enhance the performance of biodegradable alloy stents. By modulating interactions with the biological environment, these techniques optimize degradation rates, improve biocompatibility, and reinforce mechanical strength, thereby extending stent functionality and reducing inflammation . For zinc-, magnesium-, and iron-based stents, tailored coatings can regulate ion release and corrosion, support further functionalization, and maintain controlled biodegradability.

3.1. Surface modification and coating for biocompatibility

3.1.1. Surface modification

Physical surface modification, such as sandblasting and polishing, is an early strategy to alter alloy surface roughness and morphology. In 2015, Quazi et al. applied laser surface engineering (LSE) to aluminum alloys, forming novel microstructures via rapid solidification and alloy element incorporation [13]. This localized approach facilitates the formation of nitrides, oxides, and carbides, improving metallurgical bonding due to the laser's high coherence and energy density . However, this kind of methods face challenges in process control. Laser-based techniques may create heat-affected zones, induce microstructural damage, or lead to stress cracking, while oxidation and gas entrapment can introduce porosity, reducing mechanical integrity [13].

In contrast, chemical surface modification introduces functional groups or biomolecules, enabling precise control over cellular interactions. Akhmedov et al. used gas-phase synthesized carbon-coated Fe@C nanoparticles, functionalized with 4-octadecylbenzenediazonium salt, and blended them with polycaprolactone (PLA) to coat stainless steel [14]. After 7 days of HUVEC culture, coatings with 10–20% modified Fe@C NPs showed enhanced endothelial proliferation (~6000–7000 cells), suggesting improved corrosion resistance and cellular compatibility. However, chemical methods are often complex, involving multiple steps and potential in vivo instability or toxicity. Recent efforts aim to improve interface integration. By analyzing the oxidation behavior of F2063 nitinol wire under acidic conditions, Campeol et al. optimized its plasma treatment process, resulting in enhanced corrosion resistance and superelasticity that improve its potential for stent applications [15].

3.1.2. Coating

Unlike surface modification, coating strategies add external layers—typically polymers or nanomaterials—onto biodegradable metal stents to serve as barriers, drug reservoirs, and

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biointerfaces [16]. These coatings protect against rapid degradation, enable controlled drug release, and promote endothelialization, thus improving vascular healing. Their design flexibility allows the integration of multiple functions such as antithrombotic, antiproliferative, and anti-inflammatory effects.

Passive protective coatings are the most basic type, designed to delay corrosion and improve early biostability. Lin et al. fapplied a phosphate conversion coating to a Mg-Nd-Zn-Zr alloy (JDBM), resulting in reduced hydrogen gas evolution and corrosion [17]. Cytotoxicity assays confirmed good biocompatibility, with coated alloys promoting endothelial proliferation. However, such coatings are limited by their inability to adapt to dynamic physiological conditions. Environmental changes in pH or ion concentration may degrade their barrier effect and even induce inflammation.

To overcome these limitations, bioactive and drug-eluting coatings have been developed. These coatings can release therapeutic agents in a controlled manner and provide biochemical cues. In 2019, McKittrick et al. designed a drug-eluting coating with surface groups mimicking RGD motifs, enhancing endothelial cell proliferation and inhibiting smooth muscle growth [18]. Techniques like AFM and electrospinning enabled precise control over coating thickness and drug loading. Lakalayeh et al. further improved drug-release kinetics by applying electrospray-deposited nanoparticles on WE43 Mg alloys [19]. Recently, smart and responsive coatings have attracted attention for their stimulus-triggered functionality. These coatings offer improved selectivity and safety by releasing drugs only under specific conditions. For instance, Xiong et al. developed a self-healing coating composed of silk fibroin and K_3PO_4 (Silk-KP) [20]. It exhibited uniform corrosion resistance and superior healing ability when scratched, outperforming bare and silk-only surfaces.

Overall, coating technologies play a pivotal role in enhancing both the functionality and biocompatibility of biodegradable stents. While physical and chemical surface treatments offer targeted modifications, their scalability and precision remain limited. Coatings, particularly smart variants, provide broader functional potential through corrosion resistance, drug release, and bioadaptation. Nonetheless, challenges such as long-term stability, controlled degradation, and manufacturing scalability remain critical for clinical translation.

3.2. Alloy design for mechanical properties

Implant degradation is closely linked to alloy microstructure, making microscale structural design a key factor in optimizing mechanical strength and elasticity. Strategies such as grain refinement, texture control, and second-phase dispersion have shown considerable potential.Grain refinement, in particular, has been widely recognized as an effective strategy for improving both strength and ductility. Vardhan et al. employed friction stir processing (FSP) to fabricate refined-grain WE43 magnesium alloys, achieving a significant reduction in grain size alongside a notable decrease in the volume fraction of intermetallic compounds [21]. The refined microstructure improved material–media affinity, thereby augmenting mechanical performance. Moreover, microstructural optimization through second-phase control is equally pivotal in determining the corrosion resistance, mechanical retention, and biocompatibility of stent materials over the degradation period. Mostaed et al. optimized Zn-Mg and Zn-Al alloys via alloy design and extrusion, achieving uniform second-phase dispersion [22]. This suppressed localized galvanic corrosion and enabled more uniform degradation. Among compositions tested, Zn-0.5Mg exhibited optimal strength, elongation, and corrosion rate, supporting its potential for biodegradable stent use.In summary, microstructural optimization—including grain refinement, texture engineering, and second-phase dispersion—plays a pivotal role in improving mechanical performance and degradation kinetics of biodegradable

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stents. Grain refinement improves ductility and fatigue resistance while promoting biocompatibility. Crystallographic texture engineering, especially in HCP alloys, enables tailored anisotropic responses, improving deployment and in vivo mechanical stability. Uniform second-phase distribution mitigates galvanic corrosion, ensuring consistent degradation and structural integrity during vascular healing. Compared to conventional compositional approaches, microstructural design offers greater precision and adaptability, establishing a promising direction for next-generation, high-performance vascular implants.

4. Inflammation modulation and biological performance of biodegradable metal stents

The biodegradability of metal stents offers clinical advantages by eliminating secondary surgeries and reducing long-term complications. However, it also introduces biological challenges, particularly immune responses to degradation by-products. Uncontrolled inflammation—acute or chronic—can impair vascular healing, delay re-endothelialization, and lead to restenosis or thrombosis, compromising stent efficacy [23]. These effects stem from the local immune microenvironment, especially macrophage activation and elevated pro-inflammatory cytokines. Thus, beyond structural integrity and degradation control, alloy stents must exhibit strong immunomodulatory capabilities to reduce inflammation. Effective immune regulation is essential for tissue integration, vascular patency, and favorable long-term outcomes.

4.1. Immunomodulatory effects of biodegradable metal stents

Biodegradable metal stents can induce inflammation through ion-mediated immune responses. As the stents degrade, released metal ions—such as Fe^{2+} and Fe^{3+}—activate innate immunity. While trace amounts are generally tolerated, acidic environments can accelerate Fe^{2+}-driven Fenton reactions, generating reactive oxygen species (ROS). These damage lysosomal and mitochondrial membranes, releasing cathepsins and mtROS, which activate the NLRP3 inflammasome and trigger IL-1β maturation, eliciting strong inflammation [24].

Beyond direct toxicity, metal ions influence macrophage polarization. Magnesium-based stents, for instance, release bioactive Mg^{2+} that modulates redox signaling. Kwesiga et al. demonstrated that Mg^{2+} attenuates oxidative stress by suppressing pro-oxidant enzymes and enhancing antioxidant defenses, stabilizing ROS/RNS and reducing IL-6 and TNF-α levels [25]. This promotes M2 macrophage polarization, reduces chronic inflammation, and enhances tissue integration. Overall, understanding metal-ion-induced immunomodulation is vital for balancing degradation behavior with favorable host responses, especially under pathological conditions like ischemia.

4.2. Alloying and composition optimization

Altering the base composition of metal stents enables intrinsic immunomodulation by introducing bioactive alloying elements. For instance, Cu-doped 316L stainless steel (316L-Cu SS) retains mechanical stability while significantly suppressing inflammatory cytokines (TNF-α, IL-1β, IL-6) and leukocyte infiltration, largely due to Cu's interference with inflammatory signaling and macrophage polarization [26]. Similarly, Peng et al. developed a Mg-Zn-Ag alloy in which Ag^{+} release enhanced microstructure and reduced oxidative stress, improving corrosion resistance and biocompatibility [27]. However, alloying introduces potential risks. Bioactive elements like Ag and Cu, while functional, possess inherent cytotoxicity and may induce off-target effects. Rapid or uneven ion release during degradation can lead to localized concentration spikes, triggering adverse

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immune reactions. Furthermore, co-doping may cause grain coarsening or heterogeneous precipitates, undermining mechanical performance and long-term safety [28].

4.2.1. Microstructural regulation for macrophage polarization

Compared to alloying-based approaches, microstructural regulation offers a more biocompatible and precise method for modulating inflammation. By engineering surface topography, roughness, and porosity, macrophage polarization can be directed toward a pro-healing M2 phenotype without altering bulk composition or inducing cytotoxicity. For instance, a biodegradable Mg-Nd-Zn-Zr alloy (JDBM) has been employed to modulate the inflammatory response associated with percutaneous coronary intervention (PCI), which typically triggers a pronounced inflammatory cascade characterized by excessive proliferation and migration of vascular smooth muscle cells (VSMCs) [29]. In this study, macrophages were first stimulated with lipopolysaccharide (LPS) to induce an M1 pro-inflammatory phenotype, and then exposed to the ionic microenvironment created by the degradation of JDBM alloy. Released Mg^{2+} ions actively repolarized M1 macrophages toward M2, evidenced by upregulation of M2 markers (CD206, Arg-1) and downregulation of pro-inflammatory cytokines (IL-6, TNF-α).

Subsequently, conditioned media from treated macrophages inhibited VSMC phenotypic switching and proliferation, evidenced by reduced α-SMA, OPN, and PCNA expression. Mechanistically, Mg^{2+} scavenged intracellular ROS and suppressed the TLR-4–MYD88–NF-κB/MAPK signaling pathwa, attenuating inflammatory signaling [30]. However, the complex nature of macrophage polarization and limited understanding of structure-function relationships hinder precise control. The absence of predictive models also restricts clinical translation and optimization.

4.2.2. Smart-responsive alloy

Among emerging anti-inflammatory strategies, smart-responsive alloys have shown significant promise by dynamically reacting to inflammatory microenvironments, enabling more precise ion release than conventional passive systems [31]. In 2024, a novel surface nanoengineering approach was applied to zinc-based stents to address their rapid corrosion and pro-inflammatory effects [32]. Using heteroepitaxial ZnO nanorods patterned via ion adsorption, a hierarchical structure was formed that enhanced mechanical strength and biocompatibility. These stents modulate macrophage responses by upregulating anti-inflammatory genes and extracellular matrix proteins like COL-I and fibronectin, promoting tissue regeneration [33]. Moreover, a multifunctional coating integrating lysozyme and zinc ions enabled stents to generate nitric oxide in response to specific molecular cues, effectively suppressing inflammation [4]. While the design complexity poses challenges for clinical translation, the molecular specificity and multifunctionality of smart-responsive alloys provide a highly targeted, biosafe solution for inflammation control in biodegradable stents.

4.3. Improvements to drug-delivery

Beyond sustained in vivo activity, recent strategies to modulate inflammation in biodegradable stents have centered on embedding controlled drug-delivery systems within the stent scaffold. Moravej et al. fabricated a multifunctional coating on AZ81 magnesium alloy that synergistically combined micro-arc oxidation (MAO), poly-L-lactic acid (PLLA), and a PLGA layer embedded with paclitaxel [34]. The MAO layer improved initial corrosion resistance, while PLLA served as an interfacial barrier stabilizing the structure; the outer drug-loaded PLGA enabled sustained

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pharmacological action. In vivo implantation in rabbit iliac arteries revealed that this multilayer strategy not only prolonged drug release over four weeks but also led to a near-halving of macrophage infiltration and a approximate 50% reduction in neointimal hyperplasia compared to uncoated stents, significantly improving vascular healing outcomes. These results underscore the promise of using natural polymer-based systems to modulate inflammation and promote healing without compromising the biocompatibility of the stent. In 2021, Lenzuni et al. developed a bilayer zein/alginate coating for stents that enabled controlled rutin release—an initial burst in 24 h followed by sustained delivery over 21 days [35]. This system reduced ROS and pro-inflammatory cytokines (IL-6, TNF-α) in LPS-stimulated macrophages and remained biocompatible, highlighting its potential for inflammation modulation using natural polymers.

Building on these findings, further efforts have optimized drug-delivery designs to better align degradation with anti-inflammatory effects. One strategy involves electrospun nanofiber membranes containing methylprednisolone applied to zinc-based stents [36]. Coaxial electrospinning forms a core–shell structure that enables sustained drug release while maintaining mechanical integrity. In vivo studies showed reduced macrophage infiltration, enhanced re-endothelialization, and a more controlled degradation profile. These results highlight the potential of electrospun drug-delivery systems to suppress inflammation and stabilize degradation, thereby improving the overall performance and longevity of biodegradable stents.These result were conclusion (Table 1).

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Table 1. Inflammation-modulating strategies in biodegradable metal stents

Target Function	Material Design	Design Description	Significance	Reference
Inflamm ation modulati on	Mg-based alloy with immunomodulat ory release	Biodegradable Mg scaffold that modulates nitroso-redox balance and enhances antioxidant responses to promote M2 macrophage polarization.	Reduced IL-6 and TNF-α expression; improved tissue integration; better biocompatibility	[25]
	Cu-doped 316L stainless steel (316L-Cu SS)	Copper ions incorporated to retain mechanical integrity while enhancing anti-inflammatory response.	Reduced TNF-α, IL-1β, IL-6 expression;decreased leukocyte infiltration; regulation of macrophage polarization	[26]
	Mg-Zn-Ag alloy	Silver addition for corrosion resistance and anti-inflammatory action.	Improved corrosion resistance; suppressed oxidative stress; downregulated pro-inflammatory cytokines; validated via	[27]
	JDBM (Mg-Nd-Zn-Zr alloy)	Microstructural control for M1→M2 macrophage polarization without changing composition; inhibits downstream VSMC activity.	IL-1α assays Enhanced M2 markers (CD206, Arg-1), suppressed IL-6, TNF-α; inhibited VSMC migration, phenotypic switch, and proliferation via ROS scavenging and NF-κB/MAPK pathway suppression	[29,30]
	ZnO NanorodPatterned Zn Scaffold	Nanoengineered Zn stent using ZnO crystallization to form responsive nanorod arrays for structural and biological enhancement.	Enhanced mechanical strength; induced anti-inflammatory gene expression; upregulated COL-I and fibronectin; accelerated tissue regeneration	[32,33]
	Phase-Changing Lysozyme–Zn Multifunctional Coating	Smart coating using lysozyme–Zn coordination to generate nitric oxide in response to specific molecular cues.	Local NO release; effective suppression of inflammation; potential for vascular remodeling	[4]
	MAO/PLLA/PL GA–Paclitaxel Coating	Triple-layer drug-release coating on AZ81 Mg alloy with PLGA-paclitaxel outer layer for anti-inflammation and PLLA barrier for stability.	4-week sustained release; ~50% macrophage reduction; reduced neointimal hyperplasia; improved vascular healing	[34]
Drug delivery	Zein–Sodium Alginate–Rutin Bilayer Coating	Natural polymer-based bilayer coating with rutin-loaded porous structure for long-term release.	ROS and cytokine (IL-6, TNF-α) reduction in LPS-treated macrophages; sustained biocompatibility over 21 days	[35]
	Electrospun Methylprednisol one Core–Shell Fiber Coating	Coaxially electrospun nanofiber system on Zn stent with corticosteroid core and protective shell.	55% reduction in CD68+ macrophages; 40% enhanced re-endothelialization; improved degradation and mechanical performance	[36]

5. Conclusion

This review synthesizes recent advances in biodegradable metal stents as next-generation vascular implants, emphasizing innovations in material design, fabrication techniques, and inflammation-targeted functionalization versus traditional pure-metal devices. The development of zinc-, magnesium-, and iron-based systems has improved corrosion control and biocompatibility. Zinc alloys demonstrate moderate corrosion rates while exhibiting intrinsic anti-inflammatory

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properties. Magnesium alloys have evolved to exhibit enhanced mechanical stability, whereas iron-based stents, though advantageous in strength, still face limitations due to their slow degradation and potential accumulation of corrosion products. Advances in manufacturing methodologies, including precision microfabrication and additive manufacturing, have further bolstered clinical viability. Surface modification techniques and biocompatible coatings have significantly improved early endothelial responses and mitigated local inflammation. Simultaneously, strategic alloy design has allowed for the adjustment of strength and degradation kinetics, though challenges remain in ensuring reproducibility, long-term durability, and adaptability under physiological stress. Biologically, functional optimization has pivoted toward immunomodulatory strategies. Emerging approaches, including composition refinement, tailored microstructures, smart-responsive materials, and drug-loaded coatings, have collectively contributed to regulating macrophage behavior, reducing pro-inflammatory signaling, and promoting vascular healing in both acute and chronic contexts. However, many of these methods are currently restricted to preclinical validation, and their efficacy in complex patient-specific immune environments awaits further investigation and clinical corroboration. Overall, the development of BMSs marks a significant leap toward safer and more adaptive cardiovascular therapies. Yet, achieving clinical translation requires continued refinement in material selection, device engineering, and immune-responsive customization, in order to ensure precise, predictable, and personalized therapeutic outcomes. Future biodegradable stents will likely transcend mere structural support, evolving into multifunctional platforms for dynamic bioregulation, precision therapeutics, and regenerative modulation across diverse vascular pathologies.

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