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Coating materials to enhance the corrosion resistance of magnesium-based implants: a review

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Abstract
Biodegradable magnesium implants have attracted significant attention in orthopedics due to their low density, biocompatibility, and natural degradability in the human body. However, their clinical application has been limited by an excessively rapid degradation rate, which may compromise mechanical stability and disrupt tissue healing. To address this challenge, surface coating has been explored as an effective strategy to control the degradation rate, improve corrosion resistance, and preserve the mechanical integrity of magnesium implants. This review analyzed and compared various coating materials and methods applied to magnesium-based implants, including polymers, ceramics, metals, and composites. Each material category was found to offer distinct advantages and limitations in terms of biocompatibility, corrosion protection, and mechanical reinforcement. Furthermore, the study highlighted that the choice of coating method-such as dip coating, physical vapor deposition, micro-arc oxidation, or electrodeposition-significantly affected the performance of the protective layer. A structured literature search and qualitative synthesis of recent studies published between 2020 and 2025 were conducted to assess coating performance, identify trends, and evaluate challenges in clinical translation. The findings indicated that composite and multilayer coatings provided the most promising balance of corrosion resistance, bioactivity, and mechanical strength, despite fabrication complexity. This review concluded that the development of multifunctional coatings and standardized testing protocols remains crucial for advancing the clinical application of magnesium-based biodegradable implants.

Keywords:
Biodegradable Materials;
Corrosion Resistance;
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INTRODUCTION

Magnesium has become a popular choice for developing biodegradable implants due to its lightweight, high strength, and biocompatibility [1]. This element has a density and elastic modulus similar to that of human bone, making it suitable for medical applications such as orthopedic and cardiovascular implants that require temporary structural support [2][3]. In addition, magnesium is an essential element in the human body, and its degradation products can be naturally absorbed or excreted, thereby reducing the risk of complications without the need for implant removal surgery [4]. Because it gradually degrades after tissue recovery, magnesium offers a potentially safe and effective solution for patients [5].

However, one of the major challenges in using magnesium as an implant material is its often-excessive degradation rate. Magnesium tends to corrode when interacting with body fluids, leading to degradation before the bone or tissue has fully healed [6]. If degradation occurs too quickly, the implant may lose strength and stability, compromising its effectiveness as a support during healing. Moreover, rapid degradation generates byproducts such as hydrogen gas, which can form bubbles around the implant site, causing discomfort or even posing medical risks [7][8].

Various approaches have been explored to enhance the corrosion resistance of magnesium, including alloying with aluminum, zinc, and calcium [9][10], surface modification via anodizing or plasma treatment, and chemical conversion coatings [11][12]. While these techniques can improve corrosion resistance to some extent, many face limitations such as reduced biocompatibility, non-uniform degradation, or complicated processing steps. Among these, surface coating has emerged as one of the most effective and versatile strategies, providing a physical barrier against corrosive body fluids while enabling precise control over surface properties and bioactivity [13][14]. By adding a protective layer to the surface of magnesium, direct interaction between the metal and body fluids can be minimized, thereby reducing the corrosion rate typically caused by the chloride-rich physiological environment. These coatings can be made from various materials, such as biocompatible polymers, bioactive ceramics, or other more stable metals [15]. Each coating material has distinct characteristics and protective mechanisms; for instance, polymer coatings can act as physical barriers, while bioactive ceramics can enhance tissue integration and provide additional corrosion protection [16]. By selecting the appropriate coating type, researchers can extend the in vivo durability of magnesium and reduce the risk of premature degradation.

A comparative study of coating materials and methods is essential to ensure the effectiveness of each type of coating for different clinical applications [17]. The conditions and needs of individual patients, such as implant location, level of physical activity, and physiological variability, can significantly influence the performance of the applied coating. For example, a coating that is effective in environments with high corrosion risk, such as joints, may not be suitable for use in arteries, where greater elasticity is required. Comparing various coating types can help identify the most appropriate option for specific applications and provide clearer guidance for clinicians in selecting the optimal coating technique [18]. Furthermore, such studies can identify the limitations of current coatings, thereby encouraging the development of new coating materials to improve the performance of magnesium implants across diverse medical conditions.

Although the number of studies in this field continues to increase, most existing reviews still focus narrowly on a single type of coating material or method, without providing a comprehensive comparative analysis of various coating strategies for corrosion control and mechanical performance. In addition, discussions on recent advancements, such as nanocomposite and multilayer coatings that integrate both mechanical and biological functions, remain limited. To address this gap, this review aims to provide a structured comparative analysis of coating materials and techniques applied to magnesium-based implants, with an emphasis on mechanical performance, corrosion resistance, and the potential of nanocomposite coatings. Furthermore, this review highlights key emerging trends and identifies future research directions to support the development of durable, biocompatible, and application-specific coating strategies for magnesium-based implants.

METHOD

This article presents a narrative review that summarizes and critically analyzes recent developments in coating technologies to enhance the corrosion resistance of magnesium-based implants, particularly for orthopedic applications. Although not a systematic or scoping review, a structured approach was applied in article selection to ensure the relevance and comprehensiveness of the information.

Literature Search Strategy

A comprehensive literature search was conducted across the following databases: PubMed, ScienceDirect, Scopus, and Google Scholar. The search included articles published between 2020 and 2025, using combinations of the following keywords: "magnesium implant", "corrosion protection", "biodegradable coatings", "orthopedic implant", “polycaprolactone (PCL)”, “hydroxyapatite (HA)”, “coatings”, “surface modification”, and “biodegradable metals”.

Inclusion and Exclusion Criteria

The inclusion criteria were:

- Articles published in peer-reviewed journals or Proceedings.
- Studies focusing on magnesium-based alloys and their surface coatings for biomedical applications.
- Papers that evaluated corrosion behavior, biocompatibility, or mechanical performance of coated magnesium

The exclusion criteria were:

- Non-English publications.
- Studies not related to biomedical or orthopedic applications.
- Papers that did not involve the evaluation of corrosion resistance or surface coatings.

Article Selection and Analysis

Initial screening was based on titles and abstracts. Full-text analysis was then conducted for articles that met the inclusion criteria. Relevant data were extracted and grouped into thematic categories, including:

- Types of coating materials.
- Coating methods.
- Corrosion resistance results.
- Limitations and challenges.

The synthesis was conducted qualitatively by comparing results, identifying trends, and highlighting gaps and opportunities for future research.

RESULTS AND DISCUSSION

Coating Materials

The coatings used on magnesium are generally classified into four categories, as illustrated in Figure 1. These include polymers, ceramics, metals, and composites, each with its own advantages and limitations. Additionally, the choice of coating material often influences the coating method employed.

Polymers

Polymers are widely used as coatings for magnesium implants due to their ease of processing and cost-effectiveness. Both synthetic polymers, such as polylactic acid (PLA), polycaprolactone (PCL), poly(glycolic acid) (PGA), and poly(lactic-co-glycolic acid) (PLGA), and natural polymers such as chitosan, collagen, gelatin, and silk fibroin have been extensively explored as coating materials. Synthetic polymers serve as corrosion barriers and scaffolds that support bone healing [19, 20, 21], with tunable degradation rates that can be adjusted according to the requirements of tissue regeneration [22]. Among these synthetic polymers, PCL has attracted particular attention due to its slow degradation rate and mechanical flexibility. However, interactions between PCL and magnesium may influence the interfacial bonding and mechanical integrity of the coating, necessitating careful material selection and design [23].

Silk fibroin, a natural polymer, has been shown to protect magnesium implants from corrosion and enhance osteogenic activity due to its protein composition, which mimics natural bone components [24]. Its application in hybrid coatings, such as combinations of silk fibroin with calcium phosphate or other natural polymers, such as chitosan, has demonstrated promising improvements in bioactivity, promoting better osseointegration [25][26]. Chitosan, known for its inherent antibacterial properties and excellent biocompatibility, is a strong candidate for preventing microbial infections associated with implants [27][28]. When combined with silk fibroin, it enhances the mechanical properties and degradation control of the composite coating, thereby improving the overall performance of magnesium implants, especially in soft tissue applications [29].

Hamid Reza et al. demonstrated that the PCL/CS/ZnO composite coating on magnesium forms a uniform layer that significantly enhances corrosion resistance and antibacterial activity. Zinc oxide (ZnO) helps inhibit the diffusion of corrosive ions and is effective against E. coli and S. aureus. Coatings with low ZnO content maintain good biocompatibility, whereas higher concentrations may exhibit cytotoxicity [30]. Other examples include collagen-based coatings, which can improve bioactivity and enhance mechanical interlocking between the implant and surrounding tissue [31]. Meanwhile, gelatin, with its rapid biodegradability and ability to enhance surface hydrophilicity, significantly promotes cell adhesion and tissue integration [32]. Collectively, these studies indicate that both synthetic and natural polymer coatings provide valuable corrosion protection and biological functionality. However, challenges related to coating adhesion, interfacial stability, and long-term durability remain critical areas for further development.

Ceramics

The most commonly used ceramic coatings for magnesium are hydroxyapatite (HA) and calcium phosphate (CaP). HA is particularly -

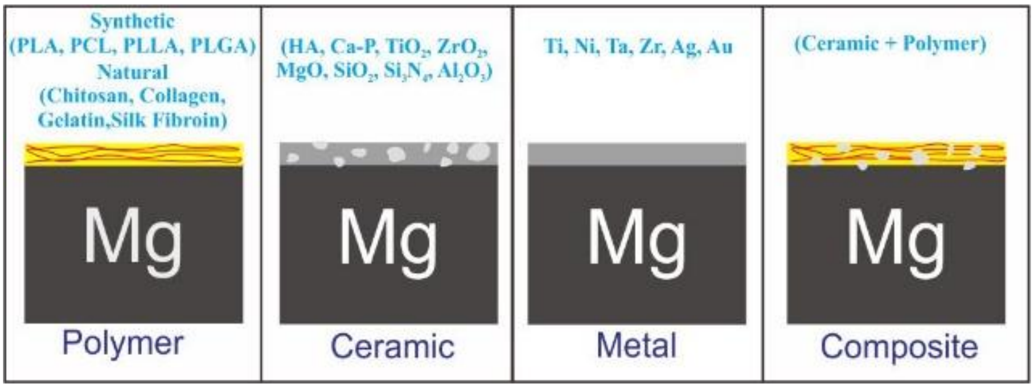

Figure 1. Coating Materials for Magnesium Implants

relevant due to its chemical similarity to human bone, which enhances its biocompatibility and bioactivity [33][34]. HA coatings improve the corrosion resistance of magnesium implants by facilitating the formation of bone-like apatite on the surface, a critical factor for successful osseointegration [35]. In addition, HA has been shown to stimulate positive cellular responses, promote osteoblast activity, and enhance bone-implant bonding [36]. However, despite their excellent bioactivity, HA coatings tend to be brittle and exhibit limited mechanical strength, which may reduce their durability under load-bearing conditions. Therefore, HA coating is often combined with tougher materials or applied as part of composite and multilayer coating systems to enhance mechanical performance [37].

Taro Tezuka et al. evaluated the effectiveness of HA coatings on femoral implants used in total hip arthroplasty through a randomized controlled trial. Their results demonstrated that HA-coated implants significantly reduced bone mineral density loss and enhanced bone metabolism in the surrounding implant area. These findings underscore the critical role of HA coatings in promoting osseointegration and maintaining periprosthetic bone quality after surgery [38]. Furthermore, Chung-Wei Yang and Guan-Kai Wang developed a hydrothermally synthesized strontium-substituted hydroxyapatite (Sr-HAC) coating on AZ91D magnesium alloy. This Sr-HAC coating demonstrated superior corrosion resistance, reduced Mg^{2+} ion release, and improved osteoblastic cell viability compared to conventional HA and alkali-treated $Mg(OH)_2$ coatings. Their results highlight the potential of Sr-HAC as an advanced bioactive ceramic coating for biodegradable magnesium implants [39]. Murni Nazira Sarian et al. reviewed the use of bioactive ceramic coatings to address the rapid corrosion of absorbable magnesium alloys for bone implant applications. They identified hydroxyapatite as one of six promising bioactive agents, noting its strong ability to promote osteoconduction and accelerate bone healing [40].

The application of calcium phosphate coatings via micro-arc oxidation (MAO) has also shown significant benefits. On AZ31 magnesium alloy, Ca-P coatings effectively reduced corrosion current density and supported tissue regeneration [41]. Similarly, a CaP chitosan composite coating on AZ91D alloy improved compressive strength and sustained osteogenic activity for up to 90 days, demonstrating strong potential for use in biodegradable implants [42]. The degradation products of magnesium implants, namely Mg^{2+} ions, hydrogen gas (H_2), and hydroxide ions (OH^-), act synergistically to promote bone regeneration. Mg^{2+} ions enhance cell adhesion and extracellular matrix formation, while H_2 and the resulting alkaline environment stimulate periosteal cell proliferation [43]. A hydrothermally coated Mg-Zn-Ca alloy, produced via micro-arc oxidation followed by heat treatment, exhibited significantly enhanced corrosion resistance and biocompatibility in both in vitro and in vivo studies. Bone marrow-derived mesenchymal stem cells (BMSCs) showed higher proliferation and adhesion on the coated surfaces, and Mg^{2+} levels in the bloodstream of animal models remained within normal ranges without inducing pathological changes in major organs [44].

Metals

Metals possess excellent mechanical properties. Titanium coatings have been applied by physical vapor deposition (PVD), resulting in significant improvements in corrosion resistance [45]. Other metals, such as copper, have been used to enhance vascular function, extend implant lifespan, and provide antimicrobial properties, although primarily as alloying elements in magnesium-based materials [46].

Calcium is also widely used as a coating for magnesium; however, it is not applied in its pure metallic form but rather as an inorganic compound, typically as calcium phosphate ceramics [47].

Composites

Composites are materials formed by combining two or more constituents to create a new material with enhanced properties. In the context of magnesium-based implants, composite coatings, particularly those combining polymers and ceramics, have shown great promise for improving corrosion resistance, biocompatibility, and mechanical performance [48]. One example is a hydroxyapatite (HA)-reinforced pure magnesium composite fabricated via stir casting, followed by surface treatment with HNO_3 and coating with electrospun polycaprolactone (PCL) fibers (~670 nm in diameter). This composite exhibited a 70% reduction in corrosion rate to 4.5 mm/year after 72 hours of immersion in simulated body fluid (SBF), attributed to the protective fiber layer, calcium phosphate (Ca-P) deposition, and the acid-treated surface. These results highlight the strong potential of Mg/HA-PCL composites for biodegradable implant applications [49]. Similarly, Mg/HA composites produced through stir casting and extrusion, and subsequently coated with PCL and PCL/2.5% HA nanofibers via electrospinning, showed notable performance improvements. After 14 days of immersion, the PCL/2.5% HA coating reduced the corrosion rate to 0.95 mm/year. It preserved mechanical integrity, showing only a 28.9% reduction in yield strength compared to 53.7% in uncoated samples. The protective porous coating and prior HNO_3 surface treatment were credited for this enhanced corrosion resistance and structural retention, indicating the suitability of PCL/HA-coated Mg/HA implants for applications requiring controlled degradation [50]. Further advances include the coating of AZ91 magnesium alloy with a bioceramic nanocomposite composed of diopside, bredigite, and fluoridated hydroxyapatite. This was achieved through a two-step process combining micro-arc oxidation (MAO) and electrophoretic deposition (EPD). The dual-layer coating significantly reduced corrosion and hydrogen gas evolution in vivo, promoted bone formation, and decreased inflammatory response, demonstrating enhanced bioactivity and corrosion resistance of the biodegradable Mg implant [51].

An organic/HA composite coating prepared by spray-depositing polyethyleneimine (PEI) onto silica, followed by hydrothermal HA treatment, also demonstrated promising results. After 13 days of immersion, the coating exhibited low corrosion current density, minimal hydrogen gas release, and stable pH, indicating superior corrosion protection. The simplicity and effectiveness of the spray deposition method further support its potential for orthopedic applications [52]. Another innovative approach involved a sandwiched composite coating applied to a magnesium-based implant. The inner layer consisted of triclosan (TCS)-loaded PLA for antimicrobial activity, while the outer layer comprised brushite for corrosion protection. This design significantly improved corrosion resistance, enabled sustained TCS release over 2 weeks, and achieved>99.8% antibacterial efficacy against common pathogens. Additionally, it enhanced cell adhesion, proliferation, and bone formation in vivo, confirming its excellent biocompatibility and osteogenic potential for orthopedic use [53].

It is noteworthy that while many efforts to improve the corrosion resistance of magnesium-based implants inadvertently reduce their inherent antibacterial properties, typically derived from the alkaline environment during degradation, composite coatings with antibacterial functionality offer a viable solution. These coatings are particularly valuable for patients with infected wounds or underlying conditions such as diabetes [54]. In this regard, composite coatings combining inorganic and polymeric layers are considered among the most promising, as they offer a balance of corrosion protection, controlled biodegradability, strong adhesion, and antibacterial capability [55].

Coating Methods

The coating methods used for magnesium implants are influenced by several factors, including the coating materials, which play a crucial role in determining the protective layer's effectiveness, biocompatibility, bioactivity, and chemical properties. Common substrates include high-purity magnesium and magnesium alloys such as AZ31, AZ91, and AZ60, as well as other alloy variations incorporating elements such as Ca, Zn, Sr, ZK, Si, Ag, Ni, and Ti. The effectiveness of each coating technology is closely dependent on the coating material used, as different materials require distinct deposition parameters to achieve optimal adhesion, surface uniformity, and corrosion resistance. For instance, polymer coatings are typically applied through dip coating or spray coating to ensure uniform surface coverage, while ceramic coatings often rely on high-energy-

Table 1. Comparison of Coating Materials

Coating Material	**Advantages**	**Disadvantages**	**Recommended Applications**	**Coating Method**	**Ref**
Polymer	• High biocompatibility • Easily moldable and flexible • Can be modified for drug delivery	• Generally, poor corrosion resistance • Some polymers degrade slowly, potentially causing local inflammation	• Coating for biodegradable implants • Drug-eluting stents	• Dip coating • Spin coating • Spray coating • Electrodeposition • Micro-drop deposition • Anodization	[56, 57, 58] [56] [14] [59][60] [61][62] [63]
Ceramic	• Excellent corrosion resistance • High osteoconductive activity • Bone-like mineral composition	• Brittle • Low flexibility • Prone to cracking if not applied properly	• Orthopedic applications (bone-contact implants) • Bioactive coatings	• Plasma spraying • Sol-gel • Electrophoretic deposition (EPD) • Dip coating • Electrostatic spray coating • Micro-arc oxidation •	[64] [65] [66] [67] [68] [69]
Metal	• Improves mechanical strength • Corrosion protection • Some offer antimicrobial effects	• Potential metal ion toxicity • Risk of galvanic corrosion if incompatible with the substrate	• Corrosion-resistant coatings • Conductive layers in medical devices	• Electroplating • Magnetron sputtering • Physical vapor deposition (PVD) • Cold spray • Ion implantation	[70] [71] [45] [72] [73]
Composite	• Combines the best properties of its components • Can be both bioactive and corrosion-resistant • Customizable for specific applications	• Complex fabrication process • Uneven particle distribution may be problematic	• Multifunctional orthopedic implants • Coatings requiring both biocompatibility and mechanical strength	• Dip coating • Spin coating • Electrodeposition • Spray coating • Magnetron sputtering	[74, 75, 76] [56] [77] [52] [71]

processes such as micro-arc oxidation (MAO) or sol-gel deposition to achieve strong interfacial bonding with the magnesium substrate. Metallic coatings, on the other hand, are generally applied using electrochemical or physical vapor deposition (PVD) methods to enhance both corrosion resistance and mechanical strength.

A comparative summary of various coating materials and deposition techniques is provided in Table 1, outlining their respective advantages, limitations, and effects on corrosion protection and mechanical integrity. This expanded discussion provides a more comprehensive understanding of how the choice of coating material directly influences the selection of deposition method and the final performance of magnesium-based implants.

Effects of Coating

In addition to biocompatibility, bioactivity, and other chemical properties, corrosion resistance and mechanical properties are among the most frequently analyzed factors in numerous studies on coating applications.

Corrosion Resistance

Corrosion resistance is a critical parameter and a primary objective in the surface coating of magnesium, especially for biodegradable implant applications. The purpose of evaluating corrosion resistance is to determine the coating's effectiveness in reducing the degradation rate of magnesium under physiological conditions. A widely used method for this evaluation is in vitro testing, conducted under controlled laboratory conditions using simulated physiological solutions, such as Simulated Body Fluid (SBF) [78, 79, 80], Phosphate Buffered Saline (PBS) [81], or Hank's Balanced Salt Solution (HBSS) [82][83], which closely mimic the ionic composition of human body fluids.

Two primary in vitro methods are commonly employed: immersion testing and electrochemical testing. In immersion testing, magnesium samples are submerged in the test solution at 37 °C for a predetermined duration. Key parameters measured include the gravimetric corrosion rate (based on weight loss), changes in solution pH (indicating corrosion activity), the volume of hydrogen gas (H_2)

evolved from magnesium degradation, and the concentration of dissolved magnesium ions (Mg^{2+}) in the solution [84][85]. Electrochemical testing, on the other hand, provides a faster, more quantitative assessment of corrosion behavior, as illustrated in Figure 2. This method provides rapid estimation of degradation rates, typically expressed in mils per year (mpy) [86]. Potentiodynamic polarization is used to determine the corrosion potential and current density, which are directly related to the corrosion rate. Additionally, Electrochemical Impedance Spectroscopy (EIS) is used to analyze the passive layer resistance and the interfacial capacitance between the coating and the electrolyte. These measurements provide insight into the coating's ability to hinder corrosion effectively.

Mechanical Properties

Magnesium implants play a crucial role in maintaining structural integrity and ensuring short- to mid-term functionality while residing in the body [87]. Surface coatings are intended not only to act as corrosion barriers but also to preserve or enhance the mechanical properties of the magnesium substrate, which is inherently soft and susceptible to rapid degradation. Figure 3 shows the comparison of ultimate tensile strength (UTS) and modulus of elasticity (ME) among 3D-printed PLA, uncoated AM60 magnesium alloy, and 3D-printed PLA-coated AM60. The UTS of 3D-printed PLA is 59.37 ± 2.47 MPa, while the AM60 magnesium alloy exhibits a value of 220.77 ± 8.12 MPa. Meanwhile, the 3D-printed PLA-coated AM60 (MgAM60+PLA) exhibits a higher tensile strength than the uncoated AM60, reaching 237.98 ± 4.63 MPa.

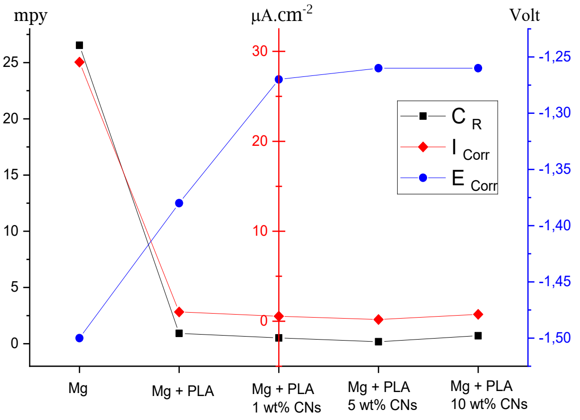

Figure 2. Effect of Coating on Electrochemical Degradation [21]

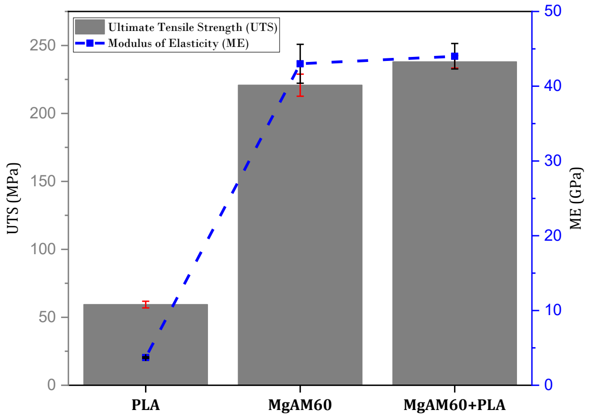

Figure 3. Effect of PLA Coating on MgAM60 Tensile Strength [88]

These results indicate that coating with 3D-printed PLA not only protects the AM60 magnesium surface from degradation but also has the potential to enhance its mechanical performance. In terms of modulus of elasticity, 3D-printed PLA exhibits a value of approximately 3.7 ± 0.1 GPa, whereas AM60 and MgAM60+PLA show values of 43.00 ± 2.60 GPa and 44.01 ± 1.70 GPa, respectively.

Several important mechanical parameters to evaluate include tensile strength, surface hardness, resistance to cracking and delamination, and adhesion between the coating and the magnesium substrate. Coatings that are too brittle or have low adhesive strength are at risk of cracking or delaminating during implantation or under physiological forces within the body. The combination of good mechanical strength and corrosion protection is essential to ensure the performance and safety of magnesium implants in clinical applications. In this context, various coating materials, including polymers, ceramics, and metallic coatings, have been explored to achieve an optimal balance between corrosion control and mechanical performance. The choice of coating material plays a crucial role in determining the mechanical integrity and corrosion resistance of magnesium-based implants throughout the healing process. Polymeric coatings generally provide flexibility and biocompatibility, while ceramic coatings enhance bioactivity and surface hardness, and metallic coatings improve adhesion and load-bearing capacity.

Nevertheless, only a few recent studies have specifically investigated how these different coating materials influence the mechanical properties of such implants. Effectively mitigating corrosion through coating not only enhances resistance to degradation but also helps preserve the mechanical strength of the metallic implant.

Figure 4 shows the relationship between the bone strength percentage and the implant during the healing process. The bone becomes stronger during healing, while the magnesium implant's strength decreases due to degradation. The implant must continue to support the load until the bone is fully healed, and once healed, the implant is expected to have completely degraded, thus preventing complications.

Table 2 provides a comparative overview of the different coating types used for magnesium-based implants, highlighting their respective advantages and limitations. Polymeric coatings stand out for their excellent biocompatibility and ease of fabrication, though their corrosion resistance is only moderate and highly dependent on polymer composition and thickness. Ceramic coatings offer good corrosion-protection and high bioactivity, but tend to be brittle and sensitive to processing conditions. Metallic coatings offer superior durability and corrosion resistance; however, their biocompatibility varies with the metal used, and fabrication can be complex. Composite coatings combine multiple material systems, achieving excellent corrosion resistance, mechanical strength, and biocompatibility, though this often comes at the cost of increased fabrication complexity and potential interfacial challenges.

However, it is important to note that the data summarized in Table 2 are derived from studies with different experimental setups, coating techniques, and testing conditions, which may influence the reported performance scores. Furthermore, direct quantitative comparisons are limited due to the lack of standardized testing protocols in the literature. Future research should therefore focus on systematic studies and cross-comparative analyses to validate the performance of coating systems under consistent experimental conditions. From this comparative evaluation, composite coatings are the most promising approach for achieving both corrosion resistance and mechanical reliability in clinical applications, provided that fabrication complexity and interfacial stability can be effectively managed.

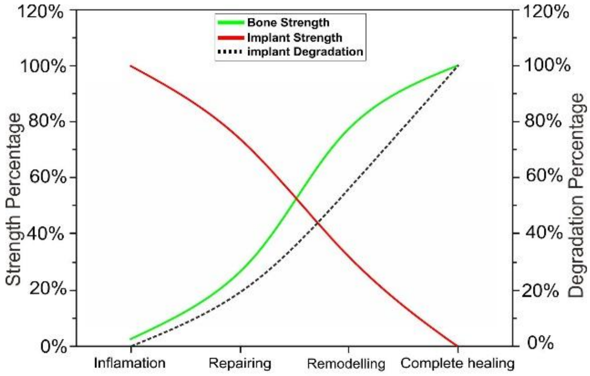

Figure 4. Improvement of bone strength and implant degradation [89]

Challenges and Future Research Directions

The development of optimal coatings for magnesium implants faces both technical and economic challenges. An ideal coating must effectively slow down the degradation of magnesium without compromising its bioactivity or mechanical performance. Polymer-based coatings tend to degrade rapidly, while ceramic coatings, although more durable, can become brittle and crack. Meanwhile, advanced coating techniques such as Physical Vapor Deposition (PVD) and sol-gel processing offer superior performance but are often costly and complex, limiting their scalability for mass production. Moreover, coatings must be able to modulate the degradation rate of magnesium to align with the healing timeline of surrounding tissues. Striking a balance between durability, cost-efficiency, and biological compatibility remains a major research focus.

Future investigations should prioritize the development of innovative materials such as nanomaterials and next-generation biocompatible polymers to enhance corrosion resistance, bioactivity, and structural stability. One promising approach is the use of multilayer and nanocomposite coatings, as illustrated in Figure 5. These systems integrate multiple nano-materials and coating techniques to capitalize on their respective advantages.

Table 2. Comparison of Coating Types for Magnesium-Based Implants

Coating Type	Corrosion Resistance (1–5)	Mechanical Integrity (1–5)	Biocomp-atibility (1–5)	Fabrication Complexity (1–5)*
Polymeric	3	4	5	2
Ceramic	4	3	5	3
Metallic	4	5	3	4
Composite	5	5	5	4

Note: 1= Poor/ Low, 5 Excellent *Fabrication Complexity 1 = simple, 5 = complex

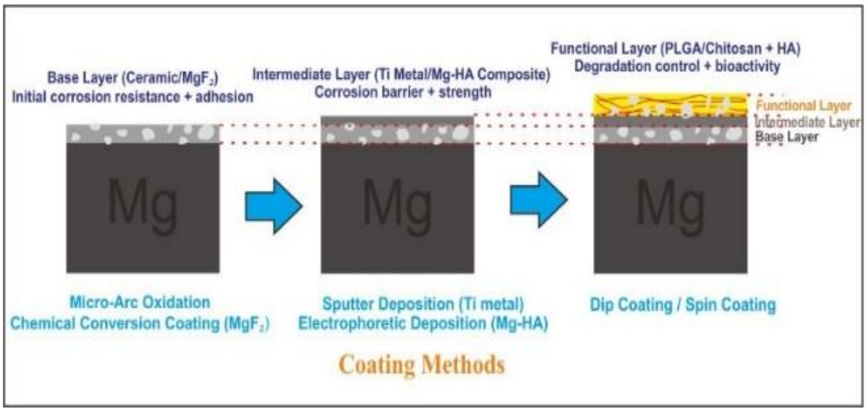

Figure 5. Advanced Coating for Magnesium Implant

Nanocomposite coatings, such as polymer–ceramic or metal–ceramic hybrids, show significant potential by offering improved mechanical strength and more controlled degradation behavior. Comprehensive studies are needed to explore the synergistic interactions between layers and to optimize processing methods that are not only efficient and high-performing but also economically viable. Such advancements are essential to support the development of safer, more reliable, and clinically effective biodegradable magnesium implants.

CONCLUSION

This review comprehensively analyzes various coating materials and technologies developed to enhance the corrosion resistance and mechanical integrity of magnesium-based biodegradable implants. The discussion also highlights a research gap in the comparative evaluation of coating materials and the limited attention to recent advancements, such as nanocomposite and multifunctional coatings. Surface coating has been proven effective in reducing the degradation rate of magnesium while maintaining its biocompatibility. Each coating material, polymer, ceramic, metallic, and composite has its own advantages and limitations. Polymeric coatings offer excellent biocompatibility and flexibility but only moderate corrosion resistance; ceramic coatings, such as hydroxyapatite and calcium- phosphate, provide superior corrosion protection and bioactivity, but are inherently brittle. Metallic coatings exhibit high mechanical strength but may induce galvanic corrosion.

In contrast, composite and nanocomposite coatings combine the advantages of multiple materials, thereby improving corrosion resistance, mechanical strength, and biological response. In addition, coating technologies such as dip coating, Physical Vapor Deposition (PVD), Micro-Arc Oxidation (MAO), and electrodeposition have been shown to influence coating performance significantly. The compatibility between the coating material and the application method determines the quality of adhesion, degradation control, and overall stability of the protective layer.

Comparative analysis indicates that composite and nanocomposite coatings represent the most promising approach for future magnesium implant development, as they can balance corrosion control, mechanical performance, and biofunctionality. Therefore, future research should focus on multifunctional coatings, standardized evaluation methods, and long-term in vivo studies that more accurately simulate human physiological conditions. In clinical practice, selecting appropriate coating materials and techniques should take into account implant location, patient-specific conditions, and infection risk to ensure optimal performance and safety. Overall, this review emphasizes that continuous advancement in coating materials and surface engineering will be the key to unlocking the full clinical potential of magnesium-based biodegradable implants.

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