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REVIEW OF MAGNESIUM ALLOYS FOR BONE IMPLANTS – BIODEGRADABILITY, BIOCOMPATIBILITY AND MECHANICAL PROPERTIES

BY

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Abstract. Magnesium (Mg) alloys have gained significant attention as biodegradable materials for orthopedic applications due to their excellent biocompatibility, mechanical properties like natural bone, and ability to promote bone regeneration. However, their rapid corrosion rate in physiological environments remains a major challenge, which can lead to premature implant failure and unwanted side effects, such as hydrogen gas accumulation.

To address these limitations, researchers have explored various strategies, including alloying with elements like zirconium (Zr), strontium (Sr), and scandium (Sc) to enhance mechanical strength, corrosion resistance, and biological performance. Additionally, surface modifications–such as polymer and inorganic coatings–have been employed to slow down degradation and improve the stability of Mg-based implants.

Both in vitro and in vivo studies confirm that Mg alloys exhibit promising osteogenic and angiogenic properties, supporting their potential use in clinical applications. However, differences between laboratory and biological environments require further investigation to optimize degradation rates and ensure safe and effective long-term use. Continued research in alloy development and surface engineering is essential to maximize the benefits of Mg-based biomaterials for bone repair and regeneration.

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1. Introduction

Traditional orthopaedic fixation devices and prostheses are typically constructed from rigid materials such as stainless steel, titanium or its alloys, and cobalt-chromium alloys (He *et al*., 2024). Magnesium derives its name from its historical place of origin, Magnesia in Greece. In Chinese characters, the left component signifies metal, while the right component denotes beauty. In 1808, British chemist Sir Humphrey Davy identified this element as magnesium (Mg), (He *et al*., 2024). Naturally occurring materials often exhibit remarkable mechanical properties and can serve as valuable templates for the design of microarchitectured materials. Bone, as a biological material, possesses high stiffness and strength relative to its density. In humans, most bones can withstand more than 50 years of regular loading without experiencing failure. In cases of bone fractures, implants must offer support until the original bone fully recovers to its pre-fracture condition. While certain types of fractures can be managed externally with plaster, more critical fractures necessitate internal support using implants (Chandra and Pandey, 2020).

Bone defects, whether caused by traumatic avulsions, infection-related bony sequestration, congenital abnormalities, or neoplastic resections, present a significant challenge in reconstructive surgery. The need for effective bone regeneration to address structural deficiencies has driven extensive research and the development of various bone repair materials. Bone healing is a complex physiological process influenced by biomechanical, biochemical, cellular, hormonal, and pathological factors. Successful bone repair depends on continuous deposition, resorption, remodelling, and adequate blood supply. Guided by fundamental principles of bone tissue healing, diverse bone repair materials have been designed to enhance regeneration (Liu C. *et al*., 2018).

This review focus on the uses of Mg alloys, their classification and different series, the effect of adding different elements to the alloy composition, and the recommended methods and techniques to improve the properties of Mg-based alloys.

2. Metallic biomaterials with biomedical applications currently used

The most used biomaterials for orthopaedic implants have been, and still are, those made from metallic materials, such as titanium and its alloys, stainless steels, and cobalt-chromium alloys, which continue to be used today.

Biomaterials, including metals, bioceramics, and polymers, play a crucial role in the development of bone grafts for regeneration and are considered promising therapeutic solutions. Researchers are continuously working on improving these materials to enhance key properties such as osteoinduction, osteoconductivity, osseointegration, and resistance to infections. These improvements help facilitate bone defect repair, reduce patient discomfort, and restore normal function. However, biomaterials have historically been regarded as foreign substances that can provoke immune responses, potentially causing excessive inflammation, tissue damage, and the formation of collagen fibre capsules around implants, leading to fibrous tissue encapsulation. To address this issue, traditional biomaterials have been designed to be biologically inert, aiming to reduce interactions with cells and minimize immune reactions (Liu L. *et al*., 2025).

Biomaterials used in orthopaedic implants for osteosynthesis can be classified into two categories: non-resorbable and resorbable. Biodegradable metals are those that gradually corrode in the host organism, allowing it to tolerate the corrosion products and completely dissolve them after the healing process is complete. Thus, biodegradable metals primarily contain essential metallic elements that can be safely absorbed by the body. These metals must provide the necessary mechanical support to facilitate the healing process.

The use of resorbable materials in the manufacturing of orthopaedic implants represents an innovative approach, offering significant benefits for both the patient and the physician. These bioresorbable implants are designed to support tissue regeneration and healing, gradually degrading completely once they have fulfilled their function.

3. Current trends regarding metallic biomaterials with biomedical applications

The search for biocompatible and bioresorbable metallic materials for medical applications dates to the late 19th century when Huse used magnesium wires as sutures. Nearly a century later, iron (Fe) was recognized as a potential material for temporary implants (Guillermo Estrada *et al*., 2025).

The review of specialized literature has shown that both the addition of alloying elements and the manufacturing process play a significant role in influencing the microstructural modifications of titanium alloys. In particular, optimizing the microstructure of β-type titanium alloys can result in a lower elastic modulus, enhanced strength, improved microhardness, and overall superior physical properties. Moreover, the tribological performance of these alloys is critical for biomedical applications, as they must demonstrate low wear rates and high wear resistance to minimize wear debris formation and metal ion release. Previous studies have confirmed the exceptional wear resistance of the analysed alloys, highlighting a strong relationship between this property and their microstructural characteristics (Dahmani *et al*., 2025).

Recently, β-type titanium alloys have gained significant attention for medical applications due to their lower Young's modulus, superior corrosion resistance, and improved mechanical properties. Several titanium-based high-entropy alloys (HEAs) with a single β phase have been developed using alloying elements such as titanium (Ti), tantalum (Ta), hafnium (Hf), niobium (Nb), zirconium (Zr), and molybdenum (Mo), thanks to their non-toxic and non-allergic properties, which enhance their overall performance. The parent β phase, which has a body-centered cubic (BCC) structure, can transform into the α"-martensitic phase with an orthorhombic structure in certain titanium-based alloys (Hua *et al.*, 2025).

4. Magnesium and its alloys

Alloying for mechanical and anticorrosive properties optimization of other magnesium-based alloys. The addition of alloying elements allows for effective adjustment of the characteristics and increase of the electrochemical potential of magnesium substrates, which significantly contributes to the mechanism of thermodynamic stability and corrosion resistance (Shi *et al.*, 2017). Thereby, alloying can alleviate the problem of low biocompatibility caused by rapid degradation by corrosion, reducing to a certain extent the risk of undesirable complications. However, the addition of alloying elements can lead to an increase in the number of cathodic phases, thus increasing the risk of galvanic corrosion (Pan *et al.*, 2024).

Magnesium (Mg) and its alloys present numerous unresolved challenges that hinder their application as biodegradable orthopaedic implants. The primary concern is their rapid degradation in the complex physiological environment. Mg-based implants typically deteriorate within four to six weeks–considerably shorter than the customary eight to twelve weeks required for natural bone regeneration. Additionally, the constantly changing physiological conditions within the human body contribute to variations in degradation rates. Notably, the degradation behaviour of Mg alloys differs significantly between in vitro and in vivo environments, though some studies have attempted to replicate semi-dynamic and quasi-static conditions during in vitro testing. For Mg alloys to be used in a safe clinical setting, the rate of deterioration must be regulated until the bone heals (Singh *et al.*, 2024).

Pure magnesium (Mg) implants exhibit poor corrosion resistance and suboptimal mechanical properties, with their rapid degradation and systemic distribution potentially leading to clinical complications. The primary goal of alloying Mg is to enhance its mechanical strength, corrosion resistance, and cost-effectiveness. Common alloying elements include aluminium (Al), calcium (Ca), copper (Cu), iron (Fe), lithium (Li), manganese (Mn), nickel (Ni), strontium (Sr), yttrium (Y), zinc (Zn), zirconium (Zr), and rare earth elements (Pogorielov *et al.*, 2017).

5. Biocompatibility of magnesium alloys

Numerous studies have investigated biocompatible coatings on magnesium and its alloys to enhance their potential as biodegradable materials.

Magnesium is a vital element for the human body and is naturally found in bone tissue, highlighting its strong biocompatibility. However, an excessive release of Mg ions from implants can affect nearby cells and tissues, and if too much enters the bloodstream, it may lead to systemic toxicity. To fully evaluate the biocompatibility of Mg-based implants, it is crucial to assess their cytocompatibility, histocompatibility, and hemocompatibility. While cytotoxicity tests provide insight into the biocompatibility of metal cations, real biological conditions differ from the standardized ISO in vitro tests. Since Mg^{2+} ions released from implants are rapidly diluted in body fluids and enter the circulatory system, in vitro experiments should be designed to accurately replicate this dilution process (Pranaya Joshi *et al*., 2025).

Magnesium-based alloys and composites have attracted significant interest as temporary biodegradable implants or scaffolds due to their biocompatibility and the release of Mg^{2+} ions, which do not induce cellular toxicity in the human body. Instead, these magnesium ions, generated as degradation byproducts, are naturally absorbed and utilized by the body for essential functions, such as promoting osteogenesis (bone formation), (Nair *et al*., 2025).

6. Mechanical properties of biodegradable materials

A key advantage of magnesium in orthopaedic applications is its elastic modulus, which closely resembles that of human bone. This property allows magnesium-based implants to reduce stress shielding–a phenomenon where the implant absorbs too much of the load, leading to bone resorption and eventual implant loosening. By minimizing stress shielding, magnesium implants support bone regeneration and enhance implant stability. Additionally, magnesium exhibits excellent biocompatibility, meaning it is well-tolerated by the body without triggering adverse reactions. The release of magnesium ions from the implant can further stimulate osteogenic and angiogenic activities, promoting bone formation and accelerating the healing process. Another significant benefit of magnesium is its biodegradability, allowing the implant to gradually degrade within the body, eliminating the need for a secondary surgical removal. This biodegradability also facilitates bone regeneration by acting as a temporary scaffold for tissue growth and remodelling (Kalva *et al*., 2025).

To minimize inflammation and allergic reactions caused by biomaterial implants in the human body, ensuring the corrosion resistance of these materials has become essential. Metallic implants often interact with biological fluids such as blood and body tissues, leading to corrosion, which can negatively impact their performance. Among the available materials, titanium (Ti) and its alloys stand out due to their high strength-to-weight ratio, excellent corrosion resistance, and superior biocompatibility. As a result, they have become the preferred choice for medical applications, particularly in orthopaedic and dental implants, compared to other biomaterials like Co-Cr alloys and stainless steels. Moreover, the corrosion resistance of titanium alloys improves with the addition of specific alloying elements, further enhancing their durability and performance in biomedical applications.

Among the various surface modification techniques, applying polymer coatings to the surface does not affect the properties of the substrate. Additionally, these coatings offer controllable biodegradation and biocompatibility and can also carry bioactive substances. As a result, they have become one of the most effective methods for simultaneously enhancing both the corrosion resistance and biocompatibility of magnesium-based alloys.

It is well established that the properties of a coating are primarily determined by its composition and microstructure, which, in turn, affect the corrosion resistance and biological activity of magnesium alloys. As a result, various surface coatings, including inorganic coatings, polymer coatings, and composite coatings, have been applied to magnesium and its alloys to improve their corrosion resistance and slow down degradation. In recent years, enhancing the overall performance of biomaterials through coatings has been a key focus of research (Chen *et al*., 2025).

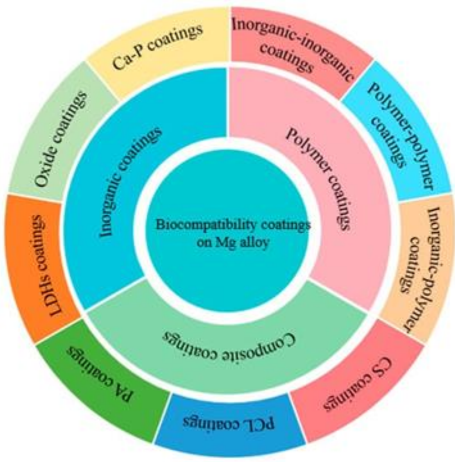

Fig. 1 − Schematic diagram of different composed coatings on Mg surface (Chen *et al*., 2025).

One of the key factors that influences the long-term performance and durability of these materials is their tribological characteristics, such as friction, lubrication, and wear resistance. Many studies have been conducted to understand the mechanical properties of the new biomaterials that have emerged recently. However, there is still a strong need for more research into their tribological properties to determine their suitability for medical applications. The existing literature on the tribological evaluation of biomaterials under different operating conditions (such as load, counter-body properties, duration, and especially lubricating media) is limited (Avcu, 2025).

Magnesium ions (Mg^{2+}) released during the biodegradation of the implant influence proteins essential for osteogenesis by activating various signalling pathways and helping to regulate the pH of the surrounding environment. One of the recently identified pathways in which Mg^{2+} ions play a crucial role is Wnt signalling. These ions contribute to the activation of this pathway, promoting the differentiation of stromal cells in the bone marrow into osteoblasts and thereby enhancing osteogenic activity (Nair *et al*., 2025).

Among various surface modification methods, polymer coatings stand out as an effective solution for improving both overall and localized degradation resistance, thereby slowing down the degradation rate of magnesium alloys. Their flexibility, biodegradability, and abundance of functional groups make polymer coatings highly promising for the clinical application of magnesium-based biomaterials (Ayaz *et al*., 2025).

Researchers have explored various strategies to modify scaffold surfaces, focusing on both physical properties–such as surface topography, stiffness, pore size, and porosity–and chemical characteristics, including hydrophilicity, surface charge, and functional groups. Additionally, scaffolds embedded with bioactive molecules have been developed to further enhance their functionality. These modifications aim to reduce harmful immune responses while promoting osteogenic regeneration. Compared to traditional bone tissue engineering materials, biomaterials with tailored surface properties can create a more favourable immune microenvironment, minimizing post-implantation complications. Gaining a deeper understanding of how biomaterials trigger remodelling processes through immune modulation can significantly improve the integration and success of bone tissue implants (Liu L. *et al*., 2025).

7. Conclusions

In conclusion, magnesium alloys hold significant promise as biodegradable materials for orthopedic applications due to their favourable mechanical properties, biocompatibility, and ability to support bone regeneration. However, their rapid degradation in physiological environments presents a major challenge, requiring advancements in alloying strategies, surface coatings, and corrosion resistance techniques.

The development of biodegradable metallic biomaterials, particularly magnesium alloys, has introduced new possibilities for orthopedic and medical applications. Their ability to integrate with biological tissues while gradually degrading reduces the need for secondary surgeries, improving patient outcomes. Nevertheless, addressing issues related to their corrosion behaviour and mechanical stability remains crucial. Ongoing studies on alloy composition, surface modification, and in vivo performance will shape the future of magnesium-based medical implants. In addition to bettering the corrosion resistance of magnesium alloys, coatings can also improve biocompatibility, controllable biodegradability, self-healing, drug delivery and osteoinduction.

While magnesium alloys demonstrate excellent biocompatibility and mechanical properties like bone, their application in medical implants is hindered by rapid degradation and inconsistent in vivo performance. Advances in alloying elements, protective coatings, and scaffold structures have helped mitigate these challenges, but further innovations are required. The future of magnesium-based biomaterials lies in achieving a balance between biodegradability and long-term functionality, ensuring both safety and effectiveness in clinical use.

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REFERENCES

Avcu E., *Tribological Behaviour of Biomaterials*, Journal Mech. Behav. Biomed. Mater., 155, 2, 215-222 (2025).

Ayaz Z., Gong Y., Jiang Y., Zhou L., Zhou Y., Liang W., Zhao A., Jing F., Akhavan B., Leng Y.X., *Bioinspired surface modification of AZ31 Mg alloy with cellulose-derivative HPMC: Enhancing corrosion protection with biocompatibility*, Surface and Coatings Technology, 2025, 496.

Chandra G., Pandey A., *Biodegradable bone implants in orthopedic applications: a review*, Biocybernetics and biomedical engineering, 2020, 40, 596-610.

Chen H., Wang Y., He L., Zhang X., Mei Y., Wu T., Wang J., Zheng Y., Tang H., *Surface Engineering of Biodegradable Magnesium Alloy as Orthopedic Implant Materials: Recent Developments and Future Prospects*, Coatings, 15, 191 (2025).

Dahmani M., Hezil N., Fellah M., Benoudia M.-C., Kotan H., Perez Larios A., El-Hiti G.A., *An Overview of the Microstructural, Physical, Mechanical, and Tribological Performance of Beta-Type Titanium Alloys for Total Hip Replacement*, The Minerals, Metals & Materials Series, 2025, 321-333.

Gillermo Estrada R., Fagali N.S., Multigner M., Lieblich M., *Past, Present, and Future of Fe-Mg Bioresorbable Alloys for Medical Applications*, Degradation behavior of biodegradable metals for medical applications, 2024.

He X., Li Y., Zou D., Zu H., Li W., Zheng Y., *An overview of magnesium-based implants in orthopaedics and a prospect of its application in spine fusion, Bioactive Materials*, 2024, 39, 456-478.
Hua Z., Guo L., Zhang Y., Dai Y., Zhang D., Mei F., Lin J., *Development of a* $Ti_{49}Zr_{20}Hf_{15}Al_{10}Nb_6$ *high entropy shape memory alloy for biomedical applications*, Intermetallics, 2025, 180.
Kalva S.N., Ali F., Koç M., *Recent advances in the post-processing of magnesium based scaffolds for orthopedic applications*, Next Materials, 6, 1-15 (2025).
Liu C., Ren Z., Xu Y., Pang S., Zhao X., Zhao Y., *Biodegradable Magnesium Alloys Developed as Bone Repair Materials: A Review*, Wiley, 2018, 1-15.
Liu L., Chen H., Zhao X., Han Q., Xu Y., Liu Y., Zhang A., Li Y., Zhang W., Chen B., Wang J., *Advances in the application and research of biomaterials in promoting bone repair and regeneration through immune modulation*, Materials Today Bio, 2025, 30, 101-104.
Nair A., Gupta S., Jangitwar A., Kandasubramanian B., *Innovations in 3D printing of magnesium alloys and composites for biodegradable biomedical devices*, Bioprinting, 46, 1-13 (2025).
Pan C., Liu X., Hong Q., Chen J., Cheng Y., Zhang Q., Meng L., Dai J., Yang Z., Wang L., *Recent advances in surface endothelialization of the magnesium alloy stent materials*, Journal of Magnesium and Alloys, 2023, 11, 48-77.
Pogorielov M., Husak E., Solodivnik A., Zhdanov S., *Magnesium based biodegradable alloys: Degradation, application, and alloying elements*, Interventional Medicine & Applied Science, 2017, 9 (1), 27-38.
Pranaya Joshi C., Rao R.N., Babu Golla C., ¨Ozcan M., Syam Prasad P., *Comprehensive review of Mg-based alloys: Mechanical, chemical and biological properties for prosthetic and orthopedic applications*, Journal of Materials Research and Technology, 2025, 35, 2487-2502.
Shi Y.-J., Pei J., Zhang J., Niu J.-L., Zhang H., Guo S.-R., Li Z.-H., Yuan G.-Y., *Enhanced corrosion resistance and cytocompatibility of biodegradable Mg alloys by introduction of* $Mg(OH)_2$ *particles into poly (L-lactic acid) coating*, National Natural Science Foundation of China, 2017, 7.
Singh J., Hashmi A.W., Ahmad S., Tian Y., *Critical review on biodegradable and biocompatibility magnesium alloys: Progress and prospects in bio-implant applications*, Inorganic Chemistry Communications, 2024, 169, 113111.

REVIZUIREA ALIAJELOR DE MAGNEZIU PENTRU IMPLANTURI OSOASE – BIODEGRADABILITATE, BIOCOMPATIBILITATE ȘI PROPRIETĂȚI MECANICE

(Rezumat)

Aliajele de magneziu (Mg) au atras o atenție semnificativă ca materiale biodegradabile pentru aplicații ortopedice, datorită biocompatibilității excelente, proprietăților mecanice similare osului natural și capacității de a stimula regenerarea osoasă. Cu toate acestea, rata lor rapidă de coroziune în mediile fiziologice rămâne o

provocare majoră, care poate duce la eșecul prematur al implantului și la efecte secundare nedorite, cum ar fi acumularea de gaz hidrogen.

Pentru a depăși aceste limitări, cercetătorii au explorat diverse strategii, inclusiv alierea cu elemente precum zirconiu (Zr), stronțiu (Sr) și scandiu (Sc), pentru a îmbunătăți rezistența mecanică, rezistența la coroziune și performanțele biologice. În plus, modificările de suprafață – precum acoperirile polimerice și anorganice – au fost utilizate pentru a încetini degradarea și a îmbunătăți stabilitatea implanturilor pe bază de Mg.

Atât studiile in vitro, cât și cele in vivo confirmă faptul că aliajele de Mg prezintă proprietăți osteogenice și angiogenice promițătoare, susținând potențialul lor de utilizare în aplicații clinice. Totuși, diferențele dintre mediile de laborator și cele biologice necesită investigații suplimentare pentru optimizarea ratelor de degradare și pentru asigurarea unei utilizări sigure și eficiente pe termen lung. Cercetările continue în dezvoltarea aliajelor și în ingineria suprafețelor sunt esențiale pentru maximizarea beneficiilor biomaterialelor pe bază de Mg în repararea și regenerarea osoasă.