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MAGNESIUM ALLOYS FOR BIODEGRADABLE IMPLANTS: INNOVATIONS, CHALLENGES, AND FUTURE DIRECTIONS IN BIOMEDICAL APPLICATIONS

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ABSTRACT

Magnesium (Mg)and its alloys are broadly utilized forbiomedical applications owing to their biocompatibility, mechanical properties, and potential to avoid the need for secondary surgeries. However, the rapid and non-uniform degradation of Mg alloys in physiological environments remains a challenge, hindering their clinical adoption. Present work examinesadvancements in the development, surface modification, and performance optimization of Mg-based alloys for biomedical applications. The work discusses the effect of synthesis methods and surface treatments on the characteristics of corrosion and mechanical behaviour and biocompatibility of Mg alloys. Additionally, the review highlights the ongoing challenges in controlling the degradation rate of Mg alloys and proposes future research directions aimed at achieving a balance between biodegradability and mechanical stability. These comprehensive analyses of the current state of Mg-based biomaterials offer insights into their potential for next-generation implant technologies and bring out the need for continued innovation to reduce the existing limitations.

Keywords: Magnesium Alloy, Biomaterials, Mechanical Properties, Corrosion, Biodegradability

1. INTRODUCTION

Metals and alloys are being utilized for various applications including automobile, construction, aerospace etc (Raabe 2023, Kumar et al. 2019). However, there are very limited metals are alloys are used in medical industries owing to various reasons. The rising cases of musculoskeletal injuries and disorders, due to factors such as sports, trauma, aging, and inflammation, has led to a significant increase in the demand for orthopaedic implant materials. Conventional implants manufactured from metals such as stainless steel and titanium (Ti) are globally utilizing due to their high

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strength and durability. However, these materials many a times lead to complications such as stress shielding, where the implant's high modulus causes reduction in the natural load-bearing capacity of the bone, resulting in bone resorption and weakening. Also, the need for invasive removal surgeries of these non-biodegradable implants used for patient morbidity and healthcare costs (Agarwal and Garcia 2015, Zhou et al. 2021, Agarwal et al. 2016). To reduce these shortcomings, biodegradable polymers have been investigated as alternatives owing to their comparable mechanical properties, biodegradability, and compatibility with imaging techniques (Sezer et al. 2018). However, biodegradable polymers most of the timelack sufficient mechanical properties and results in inflammatory responses in long duration. Thereby, there is anincreasing need for more definitive orthopaedic implants with optimal biological and mechanical characteristics (Samir et al. 2022, Imre and Pukanszky 2013).

Magnesium (Mg) and its alloys are globally known for potential materials for biodegradable implants, due to their mechanical properties whichare closely match those of natural bone and can eliminate the stress shielding and promote natural bone regeneration. Magnesium's biocompatibility, being a naturally occurring element in the human body, further increases its suitability for biomedical uses (Thomas et al. 2024, Jaiswal et al. 2019).

Regardless of theseadvantages, the widespread clinical adoption of Mg-based implants has been hindered by their high corrosion and results in loss of mechanical coherence. Recent growth in material processing and surface treatments have significantly reduces the corrosion rate and biological acceptance of Mg alloys, reigniting interest in their use as bone implants. For instance, Mg-based bio ceramics and bio glasses have found to be suitable replacements for bone grafts, gradually degrading and being replaced by new bone tissue(Tsakiris et al. 2021, Chen et al. 2014, Bairagiand Mandal 2022).

The development of Mg-based biomaterials is further supported by innovations in bioengineering, which have led to the creation of bioactive and bioresorbable Mg-based scaffolds. These scaffolds often incorporated with growth factors which are designed to enhance bone repair and regeneration. However, defiance such as controlling the degradation rate of Mg alloys and keeping mechanical stability during the healing process remain critical areas of research (Kalva et al. 2025, Jiaxin et al. 2023, Shanmugavadivu et al. 2024). Table 1 present the different properties of materials used in biomedical applications. This can be inferred from the table 1 that Mg based materials show good compatible properties required for biomedical applications, however, it shows high rate of corrosion in physiological environments which requires further research(Agarwal and Garcia 2015, Zhou et al. 2021, Agarwal et al. 2016).

Table 1

Table 1 Comparative Mechanical Properties of Biomaterials (Agarwal and Garcia 2015, Zhou et al. 2021, Agarwal et al. 2016)

Material	Young's Modulus(GPa)	Density (g/cm^3)	Tensile Strength (MPa)	Biodegradability	Corrosion Rate in Physiological Environment
Magnesium	40-45	1.74-2.0	130-160	Yes	High
Cortical Bone	Oct-27	1.8-2.0	130-180	N/A	N/A
Titanium Alloy	110	4.43	800-950	No	Low
Stainless Steel	193	7.9	500-1000	No	Moderate
Biodegradable Polymer	0.1-3.0	0.9-1.4	Oct-50	Yes	Low

This workgives the overview of the different fabrication process, mechanical and corrosion characteristics and effect of secondary processing on Mg ang Mg based alloys. Also, the work discusses the various forms of Mg-based biomaterials, and explores their potential for clinical translation. It also addresses the challenges and future directions in the field, emphasizing the need for continued research to optimize the performance and applicability of Mg-based implants in orthopaedic surgery.

1.1. FABRICATION OF MG BASED BIOMEDICAL MATERIAL

Mg based alloys are increasingly used in biomedical applications because of their biocompatibility, and mechanical properties equivalent to natural bone. Several advanced techniques are employed to fabricate Mg-based materials for implants, each with specific benefits, challenges, and strategies for optimization (Sezer et al. 2018, Akbarzadeh et al. 2024).

Powder Metallurgy (PM) is a key solid-state method, blending alloy powders, compacting them, and sintering below the solidus temperature. Mechanical alloying through ball milling refines microstructures and grain sizes, but challenges like cold welding in ductile Mg can be mitigated using lubricants (Ankit et al. 2020, Asghari et al. 2021). It was observed that space holders such as NaCl create pores, improving corrosion resistance, although uniform pore distribution and complete removal remain challenging. Advanced sintering techniques like Spark Plasma Sintering (SPS) and Metal Injection Molding (MIM) offer better control over microstructure but require careful optimization of sintering conditions. Similar observations were made by other researchers too (Chávez-Vásconez et al. 2024, Niu et al. 2009).

Casting, a liquid-state process, involves heating alloys above its melting point either in an inert or open atmosphere. However, for Mg based alloys the casting being conducted above 7500C in the presence of some inert gas to prevent oxidation, then molding them. This method is economical for large-scale production (Kumar et al. 2024, Tan and Ramakrishna). Further, post-casting processes like hot or cold working are needed to refine the microstructure, with low plasticity posing challenges during cold processing. Techniques such as horizontal twin-roll casting integrate casting and forming, improving formability. Cryogenic machining during casting further reduces grain size and enhances corrosion resistance(Javaid and Czerwinski 2020, Li et al. 2023, Wolff et al. 2010).

Advanced manufacturing techniques like SPS and MIM help produce small, complex Mg components with controlled porosity, though precise control of sintering temperature, time, and vacuum conditions is crucial to prevent poor bonding and reduced hardness (Trzepieciński et al. 2021).

Computational models are essential for optimizing these processes, predicting mechanical properties, and improving implant design. Techniques like boundary element method (BEM) and finite element model (FEM) simulate deformation processes and surface treatments, enhancing corrosion resistance and ductility (Radha and Sreekanth 2017). Figure1 present the Ultimate tensile strength (UTS in MPa) of Mg based alloy synthesised through different fabrication route. This can be understood from Fig. 1 that powder metallurgy emerged out be most efficient fabrication technique to achieve highest ultimate tensile strength for Mg based alloys.

However, the fabrication of Mg-based materials for biomedical use involves a balance of techniques to address challenges such as flammability, oxidation, and low formability. Ongoing research and the use of computational models are key to improving these processes, making Mg alloys more viable for widespread biomedical application (Prasadh et al. 2022).

Figure 1

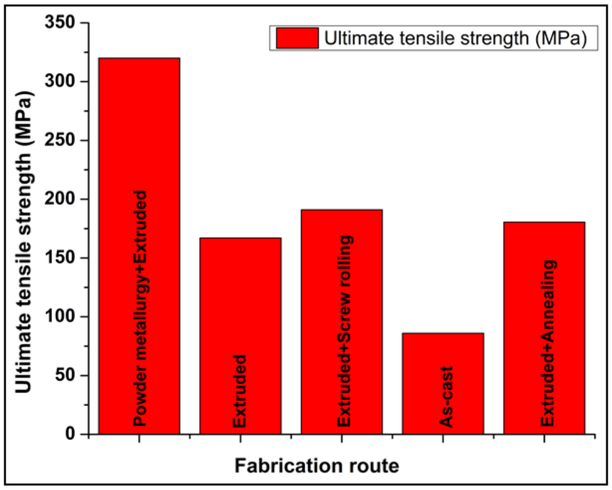

Figure 1 Ultimate Tensile Strength of Mg Based Alloy Synthesised Through Different Processing Route (Prasadh et al. 2022)

1.2. MECHANICAL AND CORROSION PROPERTIES OF MAGNESIUM BASED BIOMATERIALS

Mg-based alloys have essential mechanical properties required in various biomedical applications which makes them most suitable material, especially as an implant (Prasadh et al. 2022). However, these alloys face challenges such as stress shielding in bone implants and limited ductility for cardiovascular stents. Alloying Mg with elements like Calcium (Ca), Aluminium (Al), Zic (Zn), Zirconium (Zr), and rare earth elements (REEs) enhances mechanical performance through mechanisms like solid solution strengthening (SST), precipitation hardening, and reduction in grain size. For instance, adding Y and Nd increases strength but reduces ductility, making these alloys more suitable for orthopaedic rather than cardiovascular applications. Additionally, secondary phase formation, influenced by alloying elements and manufacturing methods, plays a significant role in mechanical integrity. Processing routes like hot extrusion (Hot Extr), equal channel angular pressing (ECAP), and cyclic extrusion compression (CEC) further reduces the grain size and refining of structure, results in increase in tensile characteristics, making Mg alloys more suitable for special purpose biomedical applications. Heat treatments like solution and aging treatments maymodify mechanical properties for desired applications, with aging treatments generally boosting strength for bone implants(Prasadh et al. 2022, Prasad et al. 2022, Verma et al. 2024).

The corrosion characteristics of Mg based alloys, especially for biomedical uses, are complex phenomena and depend on various factors. In aqueous atmosphere, Mg undergoes electrochemical corrosion, involving anodic and cathodic reactions that lead to the formation of Magnesium hydroxide ($Mg(OH)_2$). However, the protective layer ofMagnesium hydroxide is many a times compromised by chloride ions in physiological conditions, results to pitting corrosion and decreasing the overall corrosion resistance(Jiang et al. 2020).

Corrosion rates are also affected by alloying elements, impurities, secondary phases, and the microstructure of the Mg alloy. Impurities like Fe, Ni, and Cu can increase corrosion rates due to their higher electrode potentials, while the presence of secondary phases can either enhance or deteriorate corrosion resistance depending on their distribution, grain size, and electrochemical potential. Microstructural defects, including dislocations and twins, as well as mechanical stresses, further exacerbate corrosion(Xie et al. 2021).

Different alloying elements influence corrosion resistance variably. For instance, calcium (Ca) enhances corrosion resistance and refines grain structure, with Mg-Ca alloys showing optimal performance at around 0.6 wt% Ca. REEs such as gadolinium (Gd) and lanthanum (La) also improve corrosion resistance by forming passive films or stable phases along grain boundaries, though their biocompatibility must be considered due to potential toxicity (Verma et al. 2024, Xu et al. 2022).

To enhance both mechanical and corrosion performance of magnesium alloys, strategic alloying and processing are essential. Magnesium in its cast form typically exhibits low strength and high degradation rates. Improvement can be achieved by carefully selecting alloying elements that not only enhance mechanical properties but also consider degradation rates and biocompatibility (Xu et al. 2022).

Mg based alloys are susceptible to corrosion in biomedical applications due to their electrochemical interactions in physiological environments. The corrosion process involves anodic dissolution of Mg to form cations, coupled with cathodic reactions that produce hydrogen gas and hydroxides. In bodily fluids, Mg corrodes rapidly due to its high electrochemical potential, leading to the formation of a hydroxide layer on the surface. This layer initially acts as a protective barrier but is prone to breakdown, especially in the existence of chloride ions, resulting in pitting corrosion (Jiang et al. 2020, SekarandPanigrahi 2024).

The corrosion behaviour of Mg alloys in real situations are complex and influenced by environmental factors and alloy composition, making careful material selection and processing critical for their successful application in biomedical devices(Zerankeshi et al. 2022). There are various alloying elements have been incorporated to increase the mechanical and corrosion characteristics of Mg based alloys.Alloying elements result in strengthening of magnesium alloys due toSST, precipitation hardening, and grain refinement. Elements with high solubility limits are effective in solid solutions within magnesium's hexagonal close-packed (HCP) structure (Kumar et al. 2023). Additionally, refining grain size improves both mechanical strength and corrosion resistance, following the Hall-Petch relation. Effective processing techniques including casting, powder metallurgy, and severe plastic deformation, play a key role in attaining grain refinement astrengthening of the matrix.

The effect of alloying elements on the mechanical and corrosion properties of Mg alloys can be categorized into four main groups: pure Mg, Al-containing alloys (e.g., AZ91, AZ31), REEs (e.g., AE21, WE43), and Al-free alloys (e.g., MgCa0.8, MgZn6). Alloying elements enhance Mg alloys used in orthopaedic by optimizing grain size, enhancing corrosion resistance, strengthening the material through inter-metallic compounds, and simplifying manufacturing processes.Al, added in 1–5% concentrations, refines grain size and forms Mg17Al12 phases, which can either act as corrosion barriers or accelerate corrosion if excessively present. Calcium (Ca) refines grain size up to 0.5% but increases Mg2Ca phase formation with higher concentrations, reducing ductility and corrosion resistance. Manganese (Mn) decreases grain size and boosts tensile strength in Mg-Al-Mn alloys, though excessive Mn can impair corrosion resistance due to galvanic effects. Zinc (Zn) improves strength and refines grains but can enhance corrosion at concentrations above 5% due to high Mg-Zn phase formation. Lithium (Li) enhances ductility and formability but excessive amounts can worsen corrosion resistance. REEs, such as yttrium (Y) and gadolinium (Gd), enhance strength and corrosion resistance through solid solution and precipitation hardening, forming stable intermetallic phases that delay corrosion. Common impurities like copper (Cu), nickel (Ni), iron (Fe), and beryllium (Be) should be controlled to avoid exacerbating corrosion and adversely affecting alloy performance. Thus, careful selection and concentration of alloying elements are crucial for optimizing the mechanical and corrosion properties of Mg alloys in biomedical applications(Prasadh et al. 2022, Kumar et al. 2023, Chen et al. 2023, Xing et al. 2022).Figure 2present the tensile strength (MPa), Yield strength (MPa), and % elongation properties of powder processed Mg based alloys(Sezer et al. 2018).

Figure 2

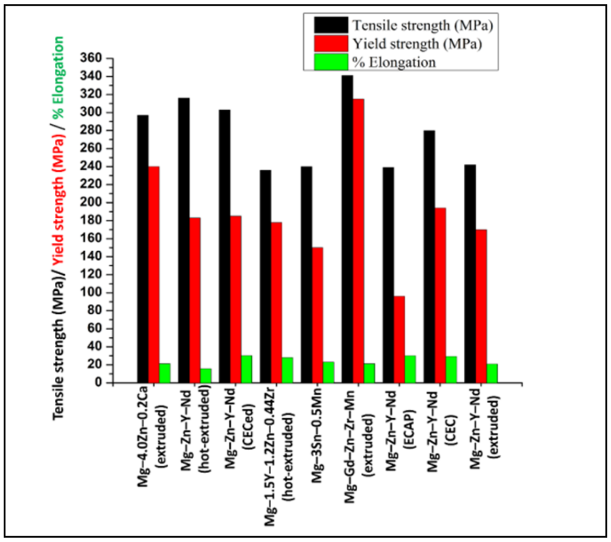

Figure 2 Mechanical (Tensile Strength, Yield Strength, and % Elongation) Properties of Powder Processed Mg Based Alloys (Sezer Et Al. 2018).

Figure 3 gives the ultimate tensile strength (MPa) of Mg-based alloys fabricated by casting, followed by various post treatments process such as solid solutioning treatment (SST), hot rolling (HR), extruded (Extr), squeezing (sqz), and heat treatments (HT) (Zhou et al. 2021). Figures 4 and 5 presents the tensile strength (MPa) and corrosion properties in millimetre/year (mm/y) in vitro condition under simulated body fluid (SBF) of Mg and Mg alloys (Prasadh et al. 2022).

Figure 3

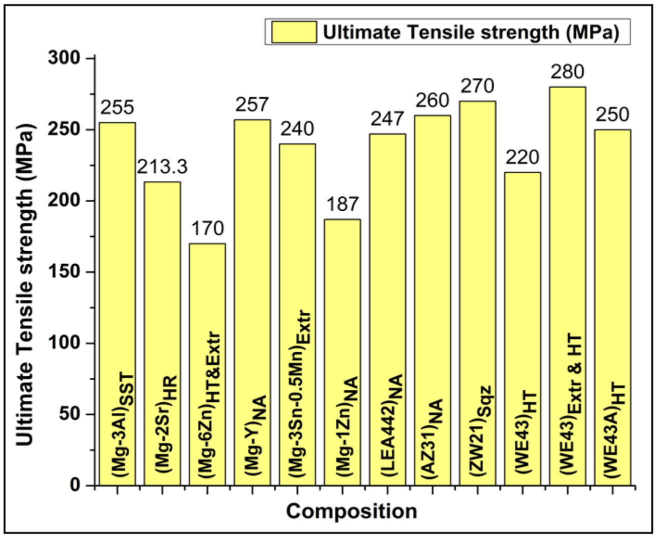

Figure 3 Ultimate Tensile Strength (Mpa) of Mg-Based Alloys Fabricated by Casting, Followed by Various Posttreatments (Zhou et al. 2021)

Note: Solid Solutioning Treatment (SST), Hot Rolling (HR), Extruded (Extr), Squeezing (Sqz), And Heat Treatments (HT), NA- Not Applicable I.E. No Post Treatment.

Figure 4

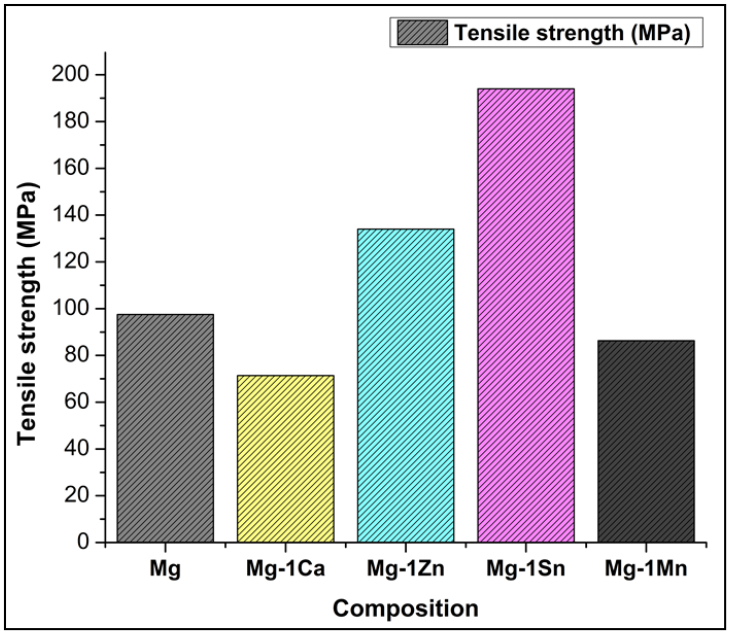

Figure 4 Tensile Strength of Pure Mg Vs Mg Based Alloys (Prasadh Et Al. 2022)

Figure 5

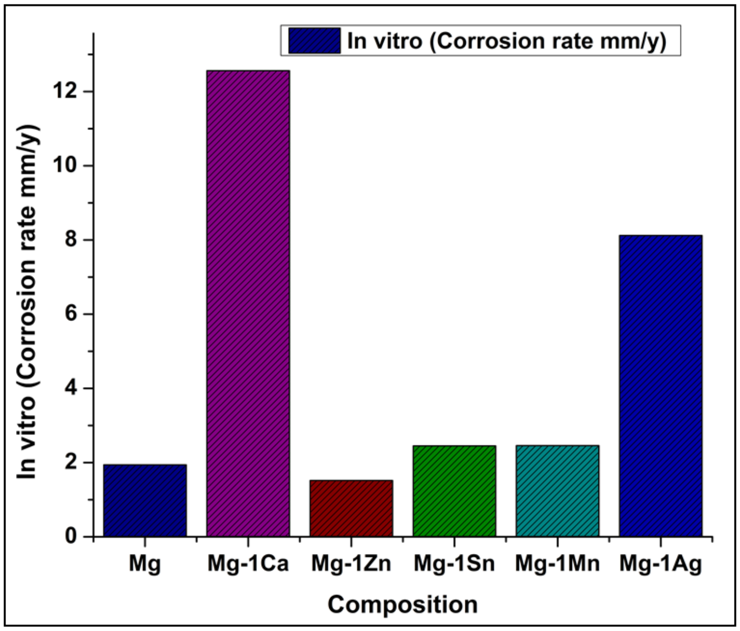

Figure 5 Corrosion Behaviour in SBF Corrosion Medium (In Vitro) Of Pure Mg Vs Mg Based Alloys (Zhou Et Al. 2021).

2. APPLICATIONS OF MG BASED BIOMATERIALS

Magnesium (Mg) was first used as a biomaterial in the mid-19th century, following its commercial production. In the early 20th-century, it is explored for orthopaedic implants, but rapid corrosion and insufficient stabilization results in limited uses. However, continuous research was performed with Mg for bone graft fixation and fracture healing. Although Mg implants were initially sidelined owing to high rate of corrosion, however, search for suitable martials for biomedical applications compelled scientist and research community to look for Mg based alloys which resulted in significant advancements in the area. Modern studies have shown the effectiveness of biodegradable Mg alloys for biomedical applications, showing promising clinical outcomes in cases like hallux valgus deformities and osteonecrosis of the femoral head, marking resurgence in the development of Mg-based biomaterials. The timeline of development of Mg based alloys for various biomedical applications are presented in Table 2.

Table2

Table 2 Timeline of Utilization of Mg Based Alloy for Biomedical Applications (Zhou et al. 2021, Liao et al. 2024)

Sr. No.	Year (Period)	Mg for biomedical applications
1	Mid-19th Century	As biomaterials
2	1906	Joint arthroplasties by Mg plates and sheets
3	1913	A trial to repair fracture: fixed the supracondylar by fracture Mg nails
4	1934	Applied into diaphyseal human fracture
5	1938	Employed as fixation devices for autogenous bone graft
6	1948	Treated pseudarthrosis by Mg-Cd alloy plat and screw
7	Late 20th Century	Improved the corrosion resistance of Mg based orthopaedic implants
8	2013	Treated hallux valgus deformities by MgYREZr
9	2015	Fixed vascularized bone graft for treating ONFH by Mg screws
10	2019	A case to repair the trauma induced femoral head necrosis by biodegradable pure Mg screws
11	2022	Another approach to treating bone diseases and a novel method for addressing complex bone conditions

3. CHALLENGES AND FUTURE PROSPECTS:

Despite significant progress in the development of Mg-based orthopaedic biomaterials, including some materials advancing to clinical trials, challenges remain before these materials can be widely adopted in clinical settings.Mg-based implants need to provide adequate structural support, but currently, their mechanical strength is still lower than that of native bone. This limits their use primarily to non-load-bearing or semi-load-bearing applications. Incorporating other materials, such as alloying elements or retardants, has shown promise in enhancing these properties. Further optimization of material compositions and experimental conditions could significantly improve their mechanical strength, with composite materials offering a broader range of applications, particularly in ceramics and glasses, which are naturally brittle.The degradation rate of Mg-based biomaterials, must align with the bone healing process to ensure successful outcomes. Ideally, these implants should offer temporary mechanical support and then degrade at a rate that matches tissue reconstruction. However, most of the Mg-based biomaterials corrode very fast, compromising their mechanical properties and results to decrease in their durability. Increasing the corrosion properties while keeping strength and biocompatibility is an ongoing interest of research (Liao et al. 2024).

Controlling Mg^{2+} ion release is key, as both deficiency and excess can negatively impact bone health. Proper Mg^{2+} concentrations advance bone mineralization, but too much can restrict the process and results to systemic issues like hypomagnesaemia. Future implant designs must centre on controlling Mg^{2+} release to balance these impacts to make sure optimal biological performance.

Mg-based alloys have inherent osteopromotivecharacteristics, however,incorporating additional functionalities, such as antibacterial elements or drug delivery systems, could further increase their effectiveness. For example, Mg alloys containing antibacterial metals like silver or copper have found to be suitable for bactericidal activity. Further, Mg-based materials can be manipulated for controlled drug release, with surface coatings or mesoporous structures representing new areas for research(Davoodi et al. 2022).

The modification of implants and scaffolds isin rising demand, and additive manufacturing (AM) can provide a better solution. Additive manufacturing has shown great advantage due to their capability fabricate almost all kind of metal, alloys and complex shapes while having high precision. AM canmanufactureporous structure with potentially excellent mechanical, and corrosion properties. However, the melting and boiling points of Mg present challenges in laser-based AM processes, leading to defects. Further investigation into optimizing these manufacturing techniques is essential to advance the application of AM in Mg-based implants.Table 3 gives the holistic view of challenges and future Scope for Biodegradable Magnesium Alloys in Implants.

Table 3

Table 3 Challenges and Future Scope for Biodegradable Magnesium Alloys in Implants

Category	SpecificIssues /Challenges	Current Innovations / Solutions	Future Scope and Research Need	References
Corrosion and Degradation Control	Rapid and unpredictable degradation in physiological fluids canlead toprematuremechanical failure and gas formation (hydrogen) around the implant site.	Surface coatings, alloying with elements like Zn, Ca, rare-earth adjustments, and "smart coatings" that self-heal to slow degradation.	Tailored degradation that matches tissue healing timelines; advanced in-vitro/in-vivo predictive models (e.g., phase-field modelling).	Thomas et al. 2024
Mechanical Integrity and Strength	Mg alloys often have lower mechanical strength, especially under weight-bearing conditions; strength deteriorates as corrosion progresses.	Alloy design (including Mg-Ti systems), grain refinement via processing, additive manufacturing to control microstructure.	Explore multi-phase composites and hybrid materials for higher sustained mechanical integrity.	Sharma et al. 2024
Biocompatibility and Biosafety	Ion release (e.g., Mg^2+, Al from some alloys) and pH shifts can affect cellular environments; limited long-term safety data.	Bio-inert surface modifications and alloying strategies eliminating toxic elements (e.g., rare-earth-free systems).	Extended longitudinal animal and human safety studies; cellular microenvironment modelling.	Zhou et al. 2024
Standardization and TestingReproducibility	Lack of universal testing standards for in-vitro vs in-vivo degradation rates, mechanical tests, and biological endpoints.	Early work on international standard frameworks and regulatory guidelines (ASTM/ISO draft standards).	Harmonize global testing and reporting protocols to enable cross-study comparisons and regulatory approval.	Aikin et al. 2025
Manufacturing and Scalability	Variability in Mg alloy production leads to defects and inconsistent properties; limitations in powder processing due to reactivity.	Advanced deformation and additive manufacturing (LPBF, ECAP, FSP) enabling refined, reproducible microstructures.	Scale safe processing technologies; powder safety improvements to facilitate mass production.	Aikin et al. 2025
Environmental Sensitivity of Degradation	Degradation influenced by local pH and ionic content, making predictions difficult.	Phase-field andcomputational modelling of corrosion behaviour in simulated biofluids.	Real-time in-vivo monitoring algorithms and coupled mechanical/corrosion models.	Sasa et al. 2025

It can be inferred that controlling degradation behaviour remains a most important priority. Further scientist and researcher must carefully synchronize material degradation profiles with the biological timeline. This requires the establishment of clear standardization protocols and regulatory frameworks to facilitate and fasten the clinical translation. Also, mechanical properties, corrosion resistance, and biocompatibility should be optimized in an integrated manner rather than addressed separately. Furthermore, the development of smart biomedical functionalities, such as drug delivery systems and real-time monitoring capabilities, represents a high-impact frontier in the advancement of biodegradable magnesium implants.

4. CONCLUSIONS

From the above study following conclusion can be drawn:

1) Magnesium and its alloys hold significant potential for biomedical applications owing to their biodegradability, biocompatibility, and mechanical properties equivalent to natural bone, however, their successful application needs a careful balance of fabrication techniques to overcome inherent challenges such as flammability, oxidation, and low formability.
2) Powder Metallurgy (PM) emerges as the most efficient technique for achieving high ultimate tensile strength in Mg-based alloys, with advanced methods like Spark Plasma Sintering (SPS) and Metal Injection Molding (MIM) offering improved control over microstructure, though precise optimization of sintering conditions is essential to prevent issues like poor bonding and reduced hardness.

3) Alloying magnesium with elements like Ca, Zn, and REEs significantly enhances mechanical strength through solid solution strengthening, precipitation hardening, and grain refinement.
4) The corrosion resistance of Mg alloys is highly dependent on the type and concentration of alloying elements, with impurities like Fe and Cu markedly increasing corrosion rates in physiological environments.
5) Effective control of Mg^{2+} ion release is crucial in Mg-based implants to ensure optimal bone health, with additional functionalities like antibacterial elements and drug delivery systems further enhancing their clinical potential

CONFLICT OF INTERESTS

None.

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None.

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