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Recent Advances in Zinc-based Alloys and Composites for Biodegradable Biomedical Implants

N. Srilatha, V. V. D. Sahithi*, Jayashri N Nair, and Narendra Pothula
Department of Mechanical Engineering, VNR VJIET, Hyderabad, TG, India
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*sahithi_vvd@vnrvjiet.in

ABSTRACT

Recently, zinc-based biodegradable biomaterials have been considered promising for next-generation orthopedic and cardiovascular implants because of their favorable degradation properties, high biocompatibility, and essential biological roles in humans. Although significant advances have been made in the development of zinc alloys and composites, systematic insights into the correlations among the composition, microstructure, degradation behavior, mechanical performance, and biological responses of zinc-based materials have yet to be established. This review systematically examines recent developments in the fabrication and properties of zinc-based alloys and zinc matrix composites are systematically reviewed, with particular emphasis on how alloying elements (e.g., Mg, Ca, Li, Ag, Cu, and Sr) and bioactive particles enhance mechanical strength, wear resistance, degradation control, antimicrobial activity, and osteogenic potential. While previous reviews have focused primarily on describing existing biomaterials, this review aims to highlight recent research trends concerning the synergistic effects of alloying and composite strategies combined with modern fabrication technologies (e.g., extrusion, powder metallurgy, additive manufacturing, and surface treatment). In addition, significant challenges, including localized corrosion, inadequate structural stability, ion-induced cytotoxicity, and a lack of translational approaches for medical applications, are highlighted. Potential research directions related to microstructural optimization, the development of smart materials, multifunctional integration, and *in vivo* efficacy evaluation are presented. This review provides a comprehensive guide to the development of clinically applicable zinc-based biodegradable medical devices.

Keywords: Zinc-based composites; Biodegradable implants; Orthopedic applications; Cardiovascular stents; Antibacterial properties; Mechanical performance; Tribology.

1. INTRODUCTION

Recent interest in developing biodegradable implants has focused on zinc-based alloys supplemented with silver, copper, and other alloying elements that impart functional properties, owing to their potential to combine enhanced mechanical properties with intrinsic antibacterial activity (Liu *et al.* 2019). Incorporating Ag and Cu enables more holistic material design; mechanical properties and biological safety can be optimized together in the same processing step, unlike traditional zinc alloying, which has focused on either improving strength or corrosion properties (Li *et al.* 2014). Adding low levels of solute metals to Zn–Ag and Zn–Cu alloy systems may strengthen the solid solution, whereas adding large amounts of alloying elements may precipitate finely dispersed Ag- or Cu-rich intermetallic compounds. These microstructural changes have been reported to play major roles in optimizing hardness, yield strength, and wear resistance (Hussain *et al.* 2023). These factors are especially important for temporary load-bearing implants, where the material should withstand external mechanical stress while degrading in the biological environment.

The size, morphology, and distribution of Ag- and Cu-containing phases are of paramount concern in the overall properties of the alloy from a structure–property perspective (Hernández-Escobar *et al.* 2019). Better-dispersed, finer intermetallic precipitates facilitate effective stress transfer and grain boundary strengthening, whereas coarse or coalesced precipitates may act as sites of stress concentration and consequently result in premature mechanical failures (Bowen *et al.* 2013). In addition to their role in determining the mechanical properties, secondary phases are also critical in determining the corrosion properties. Galvanic potential difference can occur between Ag- or Cu-enriched areas and the zinc matrix, which results in increased microgalvanic corrosion reactions (Yang *et al.* 2017). Consequently, alloy composition, thermomechanical processing, and phase formation require appropriate attention, which results in the achievement of a synergistic integration of mechanical strengthening and corrosion resistance. The Zn–Ag and Zn–Cu alloys exhibit higher hardness and better wear resistance than more conventional binary alloys, such as Zn–Mg and Zn–Ca alloys; however, excessive alloying can reduce ductility unless the alloy composition is optimized (Yang *et al.* 2025).

The electrochemical and immersion corrosion tests in a physiological environment show that the Zn–Ag and Zn–Cu alloys are slightly more vulnerable to corrosion than pure zinc, primarily due to enhanced microgalvanic coupling between the matrix and secondary phases (Kubásek *et al.* 2019). Nevertheless, when the alloy composition is chosen optimally, the corrosion reaction is somewhat uniform and is permissible for biodegradable implant applications (Li *et al.* 2019). The resulting corrosion products are zinc oxides, phosphates, and metal compounds, which are biocompatible and do not cause toxic reactions in the surrounding tissues, and in some cases, they contribute towards the localized antibacterial effect (Mostaed *et al.* 2016). Cytocompatibility tests show that the Zn–Ag and Zn–Cu alloys also have good cell viability and osteoblastic functionality; however, ion release should be limited to non-cytotoxic levels, a fact that confirms the necessity of maintaining optimal compositional control. Other alloying elements, such as manganese, strontium, and iron, have also been studied as a means of further improving the mechanical, corrosion, and biological properties of zinc alloys (Witte *et al.* 2010). These multifunctional zinc alloys, in diverse forms, provide a promising material platform for developing next-generation biodegradable implants, especially in a medical environment where the concomitant properties of mechanical strength, infection resistance, and controlled biodegradation are required. Thus, the application fields of zinc-based biomaterials can be expanded (Chen and Thous, 2015).

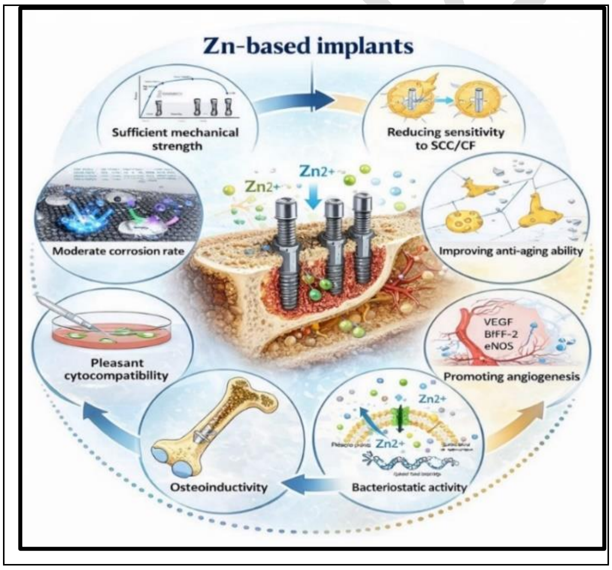

Fig. 1: Biological relevance of zinc (Geetha *et al.* 2009)

Biodegradable metals consisting of magnesium (Mg), iron (Fe), and zinc (Zn) have been identified as promising biomaterials due to their biocompatibility and bio-resorbability. Yet, each material has unique characteristics and limitations. Firstly, magnesium demonstrates high biocompatibility and mechanical characteristics similar to those of bone, yet it suffers from excessively fast degradation, resulting in hydrogen production and early mechanical failure, thus negatively impacting the tissue healing process. Secondly, iron shows better mechanical characteristics yet does not degrade as fast as magnesium under physiological conditions, therefore resulting in prolonged presence of the implant and delayed regeneration process. Zinc serves as an intermediate material between these two materials in terms of its mechanical and biological characteristics. Finally, in addition to all these, zinc is an important component of enzymes and a key trace element participating in bone remodeling, immune regulation, and tissue regeneration processes, while magnesium and iron do not provide the same level of biological benefits. Despite there being some review articles on zinc alloy developments as well as biodegradable metals, it can be argued that an assessment of zinc alloys and zinc matrix composites, which considers all aspects such as mechanical performance, tribology, corrosion behavior, antimicrobial function, biocompatibility, and manufacturing techniques, is currently lacking. Thus, this paper aims to assess recent advancements in zinc biodegradable alloy/composite developments, focusing on the interactions between composition, structure, manufacturing process, degradation properties, and biomedical application properties. The unique aspect of this paper is that it compares different alloying, reinforcement, and fabrication techniques, pointing out existing issues, knowledge gaps, and future research directions needed for next-generation zinc biodegradable implants.

2. BIOLOGICAL RELEVANCE OF ZINC

Zinc is a trace metal whose presence is critical for performing a wide range of physiological and biochemical functions in humans. This metal acts as a catalytic, structural, and regulatory agent for at least 300 enzymes and transcription factors that play a key role in cell growth, immune reactions, DNA replication, and protein synthesis. Thanks to its importance, zinc is becoming increasingly popular as a potential biodegradable material that can be used for implants with both functional and physiological roles in the process of wound healing. As concerns bone metabolism, zinc takes part in bone formation and remodeling through the regulation of the activity of both osteoblasts (bone-producing cells) and osteoclasts (bone-degrading cells). Release of Zn^{2+} ions can promote proliferation of osteoblasts, increase alkaline phosphatase activity, stimulate collagen production, and induce mineralization of the extracellular matrix. Additionally, zinc induces the expression of osteogenic genes Runx2, osteocalcin, and bone morphogenetic proteins, which enhances bone formation and osseointegration. Besides, zinc prevents excessive bone resorption due to osteoclasts (Fig. 1).

Studies in biology have recently demonstrated the importance of zinc in osteoimmunomodulation. Zn^{2+} ions can influence macrophage activity by facilitating their polarization towards an anti-inflammatory M2 type, while decreasing the release of pro-inflammatory cytokines. Modulation of the immune response leads to an optimal environment for regenerative processes and decreases the chances of chronic inflammation developing around the implant. Another function of zinc is to stimulate angiogenesis due to the upregulation of vascular endothelial growth factor (VEGF), thus improving the supply of nutrients to tissues and enhancing repair. In addition to promoting osteogenesis and modulating the immune response, zinc demonstrates bacteriostatic activity. The release of Zn^{2+} ions leads to disruption of the integrity of the bacterial cell membrane, inhibition of their metabolism, prevention of biofilm formation, and inhibition of bacterial colonization by pathogens, including *Staphylococcus aureus* and *Escherichia coli*. Such activity can be especially useful in minimizing bacterial infection of implants, which is considered one of the main causes of implant failure.

The latest studies conducted *in vitro* and *in vivo* from 2023 to 2025 have shown that zinc-containing biomaterials help to stimulate stem cell differentiation and bone regeneration through vasculogenesis and achieve better biocompatibility without causing any significant toxicity due to ion release control. The unique biological functions of zinc allow this metal to differ from many traditional metallic biomaterials and constitute a basis for designing new zinc-containing biodegradable materials for biomedical applications.

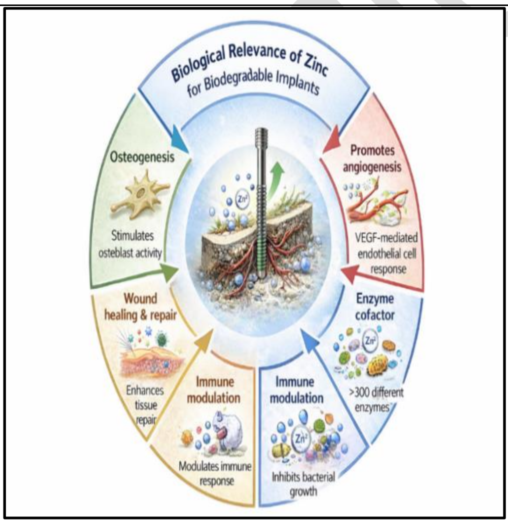

Fig. 2: Zn alloy and its mode of interaction with biodegradable materials in the biological environment (Chin *et al.* 2020)

3. BIOMEDICAL MATERIALS: ZINC-BASED MATERIALS

3.1 Pure Zinc and its Challenges

The low mechanical properties of pure zinc may be attributed to the hexagonal close-packed (HCP) structure of crystalline zinc that offers a small number of effective slip systems at low temperature (Wang *et al.* 2014). The weaknesses of pure zinc in relation to its crystal structure result in poor plastic deformability and poor ductility, and it has a tendency to undergo early mechanical failure when loaded. Moreover, the traditional casting technique of zinc materials results in the formation of coarse-grained microstructures and microstructural inhomogeneities, which also add to the low mechanical properties (Kumar *et al*. 2021). Even though the rate of corrosion of pure zinc is suitably adapted to the bone-healing period and is sufficient to maintain adequate mechanical strength in the initial stages of implantation, the mechanical strength of pure zinc reduces slowly as the degradation process continues (Wu and Chang, 2014). Thus, pure zinc by itself cannot provide sufficient mechanical strength during the healing process, and there emerges the necessity of the creation of effective strengthening technologies to be able to do more with it in biodegradable implant devices.

3.2 Zinc Alloys for Biomedical Use

In order to overcome the natural mechanical shortcomings of pure zinc, without losing the positive biodegradation characteristics and high biocompatibility, significant attempts have been made to develop zinc alloys that can be used in biomedical applications (Gu *et al.* 2009). The aim of developing zinc alloys is to customize the natural characteristics of zinc through careful design of the microstructural, phase, and electrochemical structure. In this way, the mechanical strength, ductility, corrosion resistance, and biological properties can be optimized, which are very difficult to fulfill simultaneously with one material system (Chen *et al.* 2014). The choice of alloying elements is very crucial, since each element influences solid-solution strengthening, precipitation, grain refinement, and crystallographic texture, the principal factors that can determine the structure–property relationships of zinc alloys in the physiological environment.

Mechanically, it is said that there are several mechanisms for strengthening that occur in zinc alloys because of the incorporation of alloying elements, which include solid solution strengthening, secondary precipitation, and grain refinement. The introduction of intermetallic phases such as Mg_2Zn_{11}, $CaZn_{13}$, and $AgZn_3$ has enabled them to resist the movement of dislocations effectively, resulting in an impressive increase in yield strength, tensile strength, and hardness of zinc (Chen *et al.* 2014). The existence of intermetallic compounds such as Mg_2Zn_{11}, $CaZn_{13}$, and $AgZn_3$ is very effective in hindering dislocation movement, which leads to a significant increase in yield strength, tensile strength, and hardness compared with pure zinc. Another effect that grain refinement has is the improvement of the mechanical properties by decreasing stress concentration, which is critical in the maintenance of the load-bearing capacity during the healing process (Bose *et al*. 2012). In certain instances, certain alloying elements, primarily lithium, have been observed to induce crystallographic phase changes, thereby leading to an increase in the quantity of working slip systems in zinc, thereby enhancing ductility without a significant reduction in strength (Dorozhkin *et al.* 2015). An optimal strength–ductility ratio is necessary to avoid brittle failure of biodegradable implants exposed to complicated and cyclic physiological loading conditions (Chen *et al.* 2014).

The control of the corrosion and the degradation rates of zinc in a physiological environment also includes alloying. Although the corrosion rates of zinc alloys are comparable to, or even slightly higher than, those of pure zinc, the composition and homogeneity of the microstructure of the alloys have an enormous impact on the rates of corrosion and degradation kinetics (Zheng *et al.* 2014). Homogeneous solid solutions and secondary phases are associated with more uniform corrosion, which is much more desirable than controlling mechanical degradation and ion liberation (Chen *et al.* 2014). Conversely, inhomogeneous intermetallic compounds can potentially form microgalvanic couples, which result in enhanced localized corrosion and loss of mechanical properties (Wu and Chang, 2014). Compositional design and processing, therefore, are of utmost importance to be able to obtain a well-balanced combination of both mechanical properties and corrosion resistance. It is necessary to add that zinc alloys preserve the advantage of hydrogen-free degradation, thereby resolving the issue of gas evolution commonly found in biodegradable materials based on magnesium (Geetha *et al.* 2009). Biologically, the selection of alloying elements is usually done on the basis of their physiological importance and biocompatibility (Wang *et al.* 2014). The alloying elements magnesium, calcium, strontium, silver, and copper can be added to control the release of multiple ions during degradation and thereby influence cellular responses, bone metabolism, and antimicrobial effects.

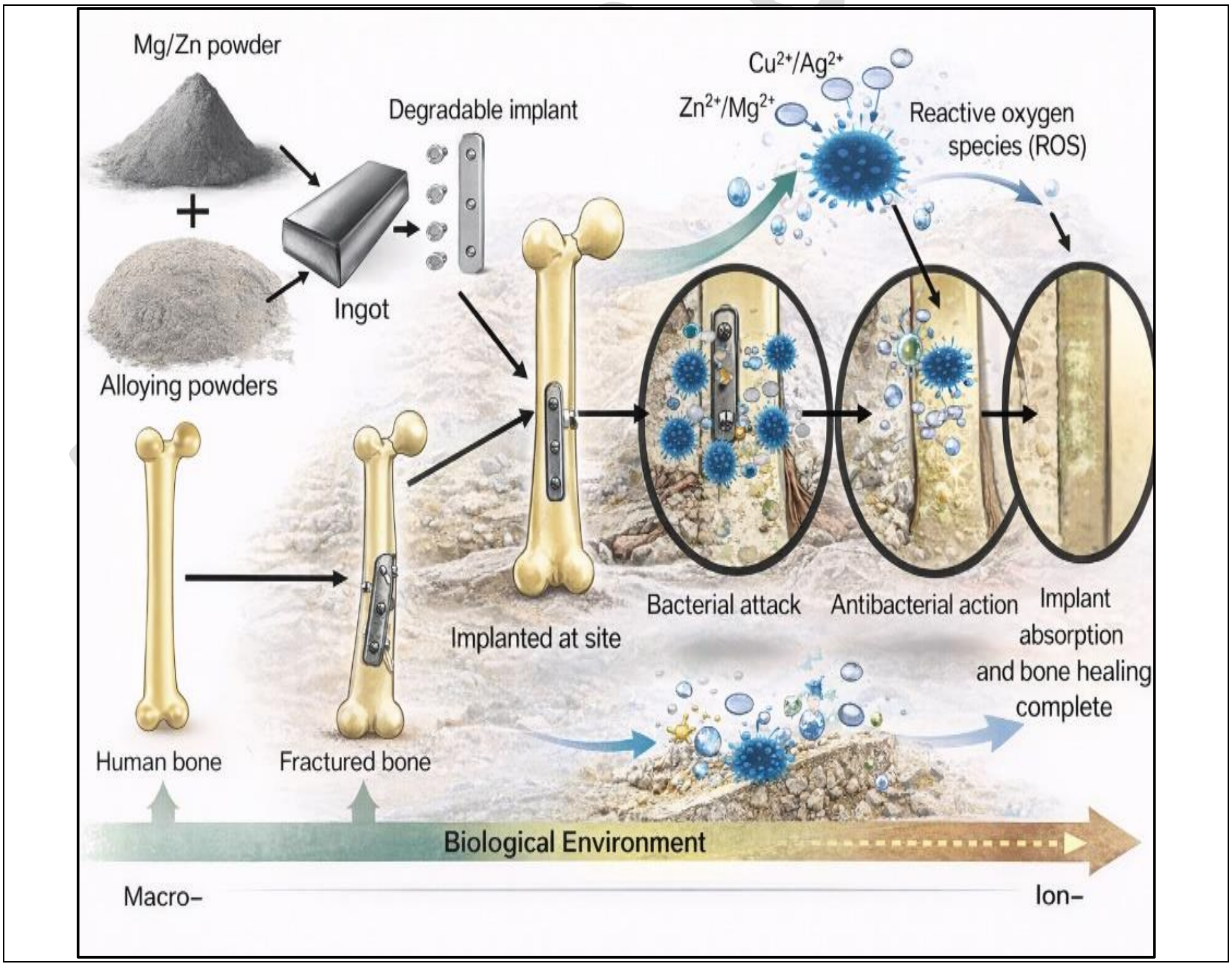

Fig. 3: Zn–Mg alloy for biomedical applications (Li *et al.* 2019)

Magnesium and calcium ions are reported to stimulate osteogenic differentiation and bone mineralization, whereas silver and copper ions were reported to have antibacterial activity due to their interaction with bacterial membranes and the prevention of biofilm formation (Wang *et al.* 2014). The synergistic release of Zn^{2+} ions and alloying-element ions can enable the active involvement of zinc alloys in the biological healing process, instead of serving as a passive mechanical constituent. Nevertheless, excessive release of ions may cause cytotoxicity, which explains the importance of proper control of alloy composition, microstructure, and degradation rates when developing biodegradable zinc-based implants (Zhao *et al.* 2017)

Nevertheless, optimizing the processing routes, including extrusion, rolling, additive manufacturing, and other thermomechanical processing routes, has also been identified by recent studies as increasingly important in the further optimization of microstructure and properties of zinc-based alloys. Such processing paths allow the optimization of grain refinement, grain texture, and interfacial stability across multiple phases, which are extremely critical to the optimization of mechanical reliability and degradation behavior of zinc-based alloys under physiological conditions.

By means of optimization of processing methods, optimization of the strength–ductility–corrosion balance of zinc-based alloys can be optimized with reference to certain clinical needs. The zinc-based alloys are now known to be versatile biodegradable biomaterials and could find applications in a wide range of medical devices, including orthopedic fixation devices, cardiovascular stents, biodegradable screws, and temporary load-bearing implants. More generally, the development of zinc alloy compositions and more efficient manufacturing methods is a step in the right direction towards the creation of biodegradable metallic implants that can offer a combination of sufficient mechanical strength, controlled corrosion rates, and desirable biological behavior (Fig. 2).

3.2.1 Zn–Mg Alloys

Zn–Mg alloys are also among the most currently studied systems of zinc-based materials for use as biodegradable biomedical materials, primarily due to the fact that a low level of magnesium addition has been observed to significantly increase the strength of the material. Generally, the incorporation of a small quantity of magnesium, which is normally not much more than 1 wt.%, has been observed to improve the tensile strength, yield strength, and, significantly, the hardness of the material, chiefly due to grain refinement and precipitation strengthening. It has also been established that the inclusion of magnesium in the alloy improves the formation of Mg_2Zn_{11} intermetallic compounds, which serve as dislocation barriers, therefore increasing the mechanical strength of the material (Bowen *et al*. 2016). Optimized Zn–Mg alloys have been reported to have a tensile strength of over 200 MPa, which is substantially greater than that of pure zinc. Microstructurally, the mechanical properties of Zn–Mg alloys have been found to be greatly influenced by the size, shape, and distribution of magnesium-containing intermetallic compounds. The presence of finely dispersed Mg_2Zn_{11} precipitates has been found to enhance strength with acceptable levels of ductility. The biomedical applications of Zn–Mg are depicted in Fig. 3.

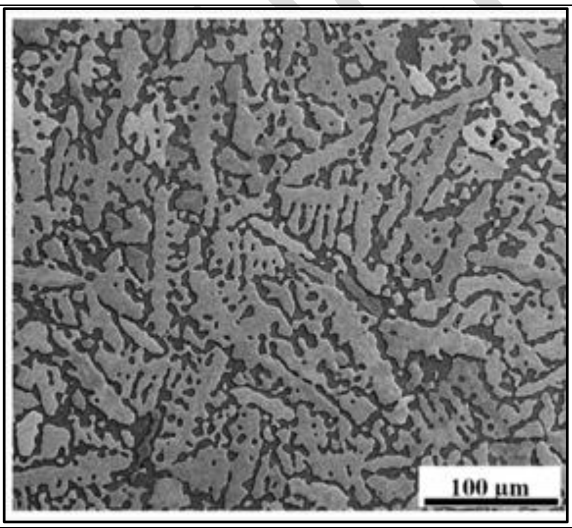

Fig. 4: SEM micrograph of the heat-treated Zn–3Mg alloy. The more contrasting phase is the Mg-rich phase, whereas the lighter contrasting phase is the Zn-rich phase (Mostaed *et al.* 2016)

Quite the contrary, in the case of excess magnesium, coarse and brittle intermetallic networks are formed, and these form undesirable sites for crack formation. Concerning corrosion resistance, Zn–Mg alloys are known to have a faster degradation rate than pure zinc because of microgalvanic couples between the Zn matrix and magnesium-rich areas. Yet, it is anticipated that the corrosion rates would still be within tolerable limits for biodegradable implants, as long as the alloy composition and the microstructural homogeneity are optimized, allowing the mechanical strength to decrease gradually as degradation progresses. Table 1 presents a comparison of the mechanical properties of pure Zn and Zn–Mg alloys with different Mg contents. A SEM micrograph of the heat-treated Zn–3Mg alloy is shown in Fig. 4.

Table 1. Comparison of Mechanical Properties of Pure Zn and Zn–Mg Alloys with Different Mg Contents

Material	Ultimate Tensile Strength (MPa)	Elongation (%)	Corrosion Rate (mm/year)	Degradation Behavior
Pure Zn	100–150	0.3–2	0.02–0.10	Slow and uniform degradation
Zn–0.8Mg	~300	~13	0.10–0.15	Moderate degradation with good mechanical retention
Zn–1Mg	300–350	10–20	~0.14	Uniform degradation; improved corrosion resistance
Zn–1.6Mg (ECAP processed)	~474	5–10	0.10–0.20	Higher strength but increased susceptibility to localized corrosion
Zn–3Mg	350–400	<5	~0.10	Faster localized degradation due to the larger intermetallic fraction

3.2.2 Zn–Ca Alloys

Calcium is a biologically important element that has been shown to play a role in the formation and mineralization of bones, and therefore Zn–Ca alloys are highly desirable for use as orthopedic and bone fixation materials. One of the primary tissue elements in bone is calcium, which forms an active part of osteoblast differentiation and extracellular matrix mineralization; therefore, this gives a clear biological explanation of why calcium is used in zinc-based biodegradable alloys. Regarding the design of materials, it is possible to use calcium as the additive to zinc to enable the addition of biofunctionality without the undesirable loss of the desirable biodegradation characteristic of zinc (Mostaed *et al.* 2016).

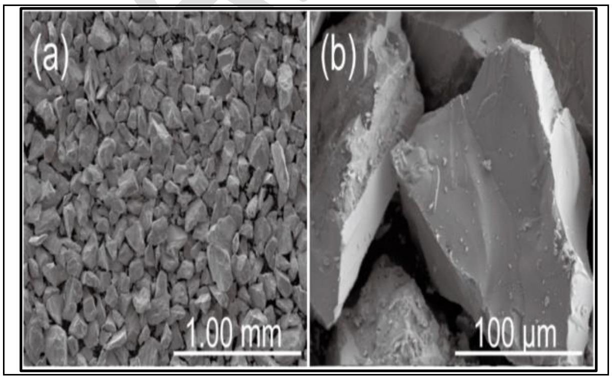

Fig. 5: (a) SEM image of the Zn–Ca alloy powder and (b) magnified SEM image of the powder (Kubasek *et al.* 2016)

Therefore, Zn–Ca alloys are now under investigation as biodegradable implant materials that can offer temporary mechanical support, while also delivering biologically significant ions to the healing process (Fig. 5).

Calcium promotes the formation of $CaZn_{13}$ intermetallic compounds, which play a significant role in determining the mechanical properties of Zn–Ca alloys. The strengthening of Zn–Ca alloys through dispersion hardening is primarily attributed to these intermetallic compounds. The principle of dispersion hardening is that smaller particles provide greater resistance to dislocation movement, thereby increasing the strength of the material. Compared with Zn–Mg alloys, Zn–Ca alloys exhibit moderate strengthening and tensile strength while retaining high ductility, which is advantageous for implants subjected to complex physiological loading. The moderate strengthening effect of calcium, compared with that of magnesium, reduces the brittleness of Zn–Ca alloys, allowing them to deform readily without catastrophic failure. Microstructural refinement is an important approach for optimizing the mechanical properties of Zn–Ca alloys. This can be achieved by ensuring that the Ca-rich regions are uniformly distributed. A uniform distribution of precipitates enhances the strength of the material by reducing stress concentrations, which can otherwise act as sites for crack initiation. Further refinement of the microstructure of Zn–Ca alloys can be achieved through extrusion, rolling, and thermomechanical processing, thereby enhancing their mechanical properties.

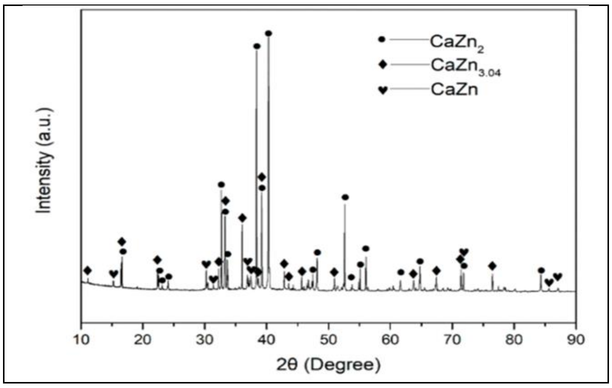

Fig. 6: XRD pattern of Zn–Ca alloy powder

In terms of corrosion and degradation, Zn–Ca alloys are found to exhibit consistent corrosion behavior in an artificial physiological condition, which is extremely significant concerning reliable biodegradation and safe resorption of the implants. The role of the $CaZn_{13}$ phases in the corrosion mechanism is to affect the corrosion rates by changing the electrochemical potential in the alloy microstructure. With properly controlled calcium, Zn–Ca alloys are likely to experience an almost uniform corrosion reaction, similar to their ability to provide a controlled material loss and a resulting loss of mechanical characteristics more consistent with the healing times of natural tissues. The corrosion products that are formed during the degradation, such as the zinc and calcium compounds, are normally accepted to be biocompatible and can be readily absorbed into normal metabolic activities. Nonetheless, excessive calcium content may enhance microgalvanic corrosion owing to the difference in electrochemical potential between the zinc matrix and the $CaZn_{11}$ intermetallic phases, resulting in localized corrosion and degradation, and premature loss of mechanical properties (Fig. 6).

Biologically, the regulated discharge of Ca^{2+} ions in the dissolution of Zn–Ca alloys has been identified to have a number of advantages in the use of this material in bone. The reason is that the calcium ions have been reported to increase the growth of osteoblasts, cell adhesion, and deposition of the mineralized bone framework, which has the benefit of enhancing the rate of bone regeneration at the implantation site. The coordinated action of the Zn^{2+} and Ca^{2+} ions may also activate osteogenic activities, wherein the zinc ions regulate enzyme activity and cellular signaling, and the calcium ions directly enhance mineral deposition. Also, as revealed in *in vitro* and *in vivo* studies, Zn–Ca alloys are better than pure zinc in bone-implant integration and inflammatory reactions. Nevertheless, it should also be considered that high ion release, which can be linked to high calcium content or high degradation rates, can lead to disruptions in ionic homeostasis and cytocompatibility. Table 2 shows a comparison between Zn–Mg and Zn–Ca alloys.

Table 2. Comparative summary of Zn–Mg and Zn–Ca alloys for biodegradable biomedical applications

Property	Zn–Mg Alloys	Zn–Ca Alloys
Ultimate tensile strength (MPa)	250–474	180–320
Yield strength (MPa)	150–380	120–250
Elongation (%)	5–20	10–30
Hardness improvement	High	Moderate
Corrosion rate (mm/year)	0.10–0.20	0.05–0.15
Degradation behavior	Faster due to Mg-rich intermetallic phases and microgalvanic effects	More uniform and controlled degradation
Osteogenic potential	Enhanced through Mg^{2+} ion release and bone mineralization	Enhanced through Ca^{2+} ion release and direct participation in bone formation
Antibacterial activity	Moderate	Moderate
Risk of localized corrosion	Relatively higher at elevated Mg contents	Lower under optimized Ca concentrations
Mechanical reliability	High strength but potential brittleness at high Mg levels	Better balance between strength and ductility

3.2.3 Zn–Mg–Ca Alloys

The Zn–Mg–Ca ternary alloys have received attention as a promising class of zinc-based biodegradable materials, which are projected to combine the strength-enhancing effect of magnesium with the biological significance of calcium and its potential to enhance ductility. Binary Zn–Mg alloys are well known for their outstanding strengthening effect, which is due to strong precipitation strengthening and grain refinement. These benefits are, however, mostly realized at the cost of lower ductility and increased localized corrosion, which may be caused by strong microgalvanic coupling. Conversely, the Zn–Ca alloys are reported to have better ductility and favorable osteogenic ion-release characteristics, although their strengthening effect is moderate. The ternary alloys of Zn–Mg–Ca that contain magnesium and calcium in the zinc framework can offer a beneficial combination of properties that provides alloy strengthening while retaining reasonable ductility and enhanced biological functionality. Thus, the development of such a ternary alloy system represents a reasonable material-design approach that aims at overcoming the inherent trade-offs associated with binary zinc alloy systems. At the microstructure level, Zn–Mg–Ca alloys are typically recognized to consist of a fine-grained zinc matrix with a dispersion of Mg-rich and Ca-rich intermetallic phases, namely Mg_2Zn_{11} and $CaZn_{13}$, depending on the composition of the alloy (Atrens *et al.* 2011). The two intermetallic phases contribute synergistically to strengthening, wherein dispersion hardening and grain-boundary strengthening are beneficial for improving the yield and tensile strengths of Zn–Mg–Ca alloys. In addition, the presence of calcium-rich phases may mitigate the loss of ductility typically observed in Zn–Mg alloys, thereby offering a better mechanical response in biodegradable implants. Several recent *in vitro* studies have additionally confirmed the biocompatibility of Zn–Mg–Ca-based biodegradable orthopedic implants (Mark *et al.* 2006). *In vivo* experiments carried out with animal bone defect models such as rats and rabbits have revealed that Zn–Mg–Ca implants can provide sufficient mechanical stability during the initial stages of bone healing while undergoing controlled biodegradation. Histological assessments demonstrated tissue biocompatibility of Zn–Mg–Ca implants without significant inflammatory responses. Zn^{2+}, Mg^{2+}, and Ca^{2+} ions released from the implants have been found to enhance osteoblast proliferation and accelerate bone regeneration (Li *et al.* 2015). Micro-computed tomography analysis of bone volume fraction and the bone–implant interface has demonstrated better performance than that achieved by pure zinc implants. Increased expression of osteogenic factors including Runx2, osteocalcin, and alkaline phosphatase has also been observed around the implant sites in several studies. The synergistic role of magnesium and calcium ions was responsible for better mineralization of newly formed bone tissue. It was further demonstrated that there was no excessive degradation-product toxicity or organ damage during the extended implantation time periods. The degradation rate of the alloy implants was also sufficiently well-regulated to provide the necessary mechanical support until the bone-healing process was completed. These results indicate that Zn–Mg–Ca alloys have a desirable set of properties regarding biodegradability, osteogenesis stimulation, and in vivo biocompatibility; thus, Zn–Mg–Ca alloys can be considered potential materials for biodegradable bone fixators and implants (Vallet-Regí *et al.* 2004).

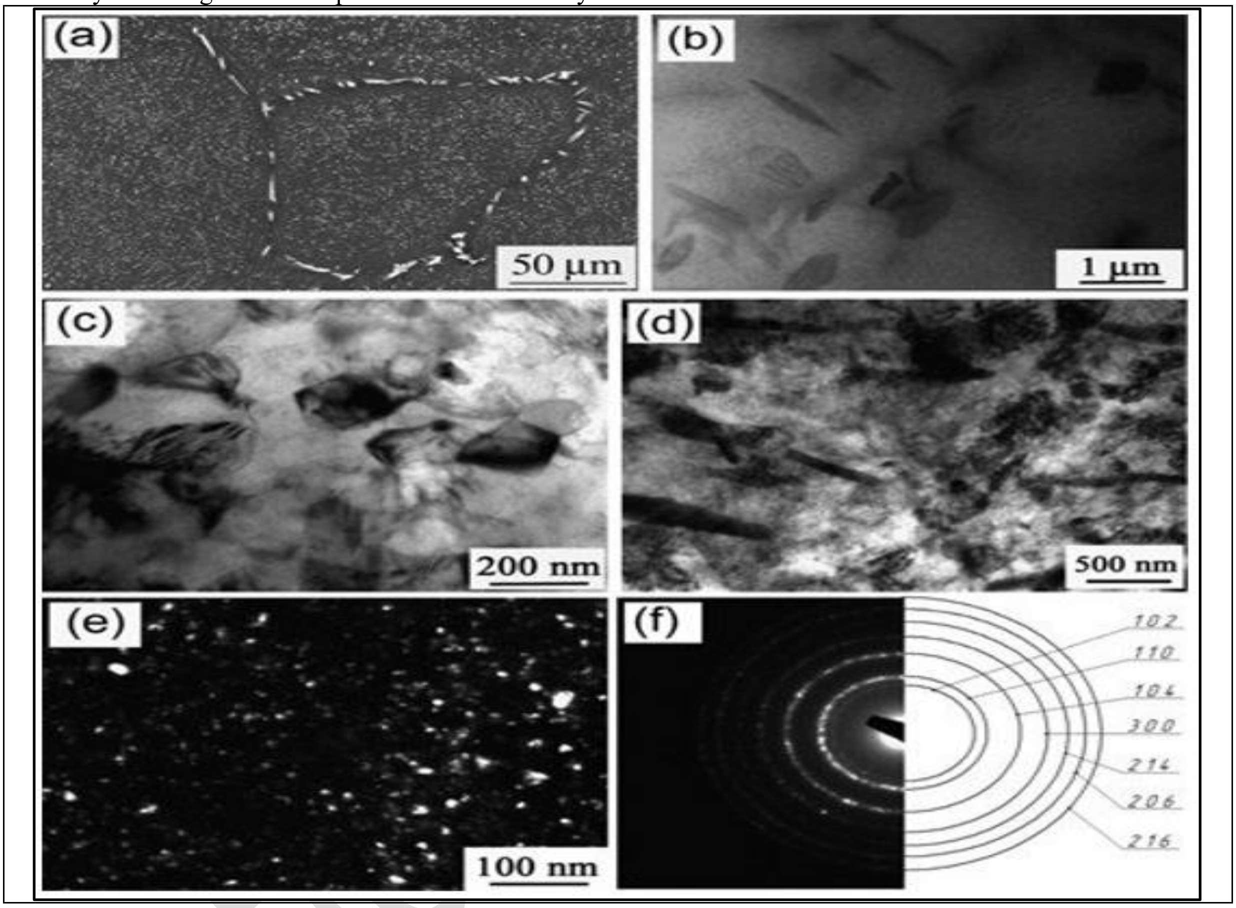

Fig. 7: Microstructure of the Mg–Zn–Ca alloy: (a, b) initial state: (a) SEM image and (b) TEM image; (c–f) after HPT: (c) bright-field TEM image; (d) bright-field TEM image of $Ca_2Mg_6Zn_3$ particles; (e) dark-field TEM image of Mg_2Ca particles; and (f) electron diffraction pattern from Mg_2Ca particles (Li *et al.* 2015)

It is necessary to mention that the presence of calcium influences the morphology and distribution of Mg-containing intermetallic compounds in the Zn matrix (Fig. 7). The presence of Ca promotes precipitate formation and results in a more uniform microstructure. This assists in the reduction of stress concentration points and prevents brittle-fracture features, which are usually seen in Zn–Mg alloys with high magnesium content. As a result, the alloy exhibits more predictable mechanical behavior under applied loads. Concerning corrosion and degradation resistance, it has been noted that Zn–Mg–Ca alloys exhibit more stable and less variable corrosion behavior than Zn–Mg alloys, while the degradation rate is maintained at a clinically permissible level in biodegradable implants.

The magnesium and calcium additions in the alloy significantly affect the electrochemical reactions within the microstructure, thereby reducing microgalvanic corrosion, which is mostly witnessed in Zn–Mg alloys. Even though Zn–Mg–Ca alloys prove to degrade slightly faster than Zn–Ca alloys, which have been observed to degrade slowly with highly consistent degradation rates, the degradation of Zn–Mg–Ca alloys can be predicted and controlled, provided that alloy composition and microstructure are optimized appropriately. Moreover, the corrosion products, which are zinc-, magnesium-, and calcium-containing compounds, can also be considered biocompatible and have the potential to actively promote bone-tissue regeneration. Biologically, Zn–Mg–Ca alloys possess several advantages because of the synergy between the concomitant discharge of several biologically active ions.

As an example, zinc ions (Zn^{2+}) may stimulate enzymatic activity, cell growth, and antibacterial activity, and magnesium ions (Mg^{2+}) may stimulate cell adhesion and bone mineralization. Calcium ions (Ca^{2+}) can, in turn, directly induce osteogenic differentiation and mineralization. The synergistic actions of the simultaneous co-release of these biologically active ions have been found to enhance osteoblast activity and bone–implant interface formation compared with those of binary Zn–Mg alloys, as well as to confer improved mechanical durability compared with that of Zn–Ca alloys.

Moreover, several *in vitro* studies have revealed that Zn–Mg–Ca alloys are particularly cytocompatible and osteogenic, provided that their ion-release rates are appropriately controlled to prevent local ionic concentration gradients. In conclusion, Zn–Mg–Ca alloys are potential ternary alloys that can effectively bridge the gap between Zn–Mg and Zn–Ca alloys by offering a balanced combination of mechanical behavior, corrosion resistance, and biological performance for biodegradable orthopedic and bone-fixation applications.

3.2.4 Zn–Li Alloys

Lithium is a promising alloying element of zinc as it is able to alter the crystal structure of zinc fundamentally. The crystal structure of Zn–Li alloys is modified with the addition of an appropriate amount of lithium; at sufficient lithium contents, the hexagonal close-packed (HCP) structure of zinc can transform into a body-centered cubic (BCC) structure. This transformation in the crystal structure causes a marked increase in the number of active slip systems in the crystal, thereby facilitating deformation under stress. Accordingly, Zn–Li alloys exhibit significant increases in ductility, plasticity, and tensile strength. Elongation values greater than 50 have been recorded in optimized alloys, and this is a sign of the good mechanical properties of the alloys. Owing to the unique characteristics of high strength and high flexibility, Zn–Li alloys are very promising in load-bearing biodegradable implants, where load stability and resistance to deformation are required during the healing process. Nevertheless, lithium has a high chemical reactivity, which also poses some challenges (Shuai *et al.* 2019).

In general, Zn–Li alloys will always have comparatively high corrosion rates in physiological environments, resulting in rapid degradation and mechanical strength loss before the completion of tissue regeneration. To eliminate this issue, compositional control, surface modification, and protective coating are generally employed to decrease the degradation rates and retain the mechanical benefits introduced by lithium addition.

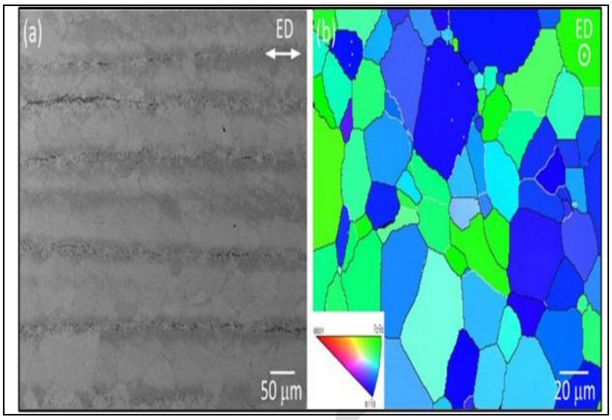

Fig. 8: Microstructure of the as-extruded Zn–0.1Li alloy: (a) SEM secondary electron image showing the grain structure and stringers of an intermetallic phase along the extrusion direction (ED); and (b) EBSD orientation map and inverse pole figure perpendicular to ED (Shuai *et al.* 2019). *Note:* The white lines in (b) indicate low-angle grain boundaries.

Recent research has indicated the need for assessing the biocompatibility and degradation behavior of Zn–Li alloys before any clinical application. Even though the addition of lithium enhances the mechanical properties and ductility of zinc via crystalline structure modifications and grain refinement, the role of lithium on the degradation behavior of Zn–Li alloys warrants attention (Fig. 8). Both *in vitro* and *in vivo* tests conducted on Zn–Li alloys have confirmed that they tend to show faster corrosion than pure zinc owing to the presence of lithium-based phases. This causes an increased rate of ion release from the alloy when implanted into the body. Nevertheless, the rate of degradation remains fairly constant provided the percentage of lithium in the alloy is below 0.8%. Implantation tests using animal models have shown positive reactions with no significant inflammatory cell migration or formation of a fibrous capsule surrounding the implanted alloy. Histological observations have suggested bone formation around the alloy. In addition, Zn^{2+} ions play an important role in osteogenesis, whereas Li^{+} ions, in minute amounts, are known to activate the Wnt/β-catenin signaling pathway that is very important in bone formation and resorption. No toxic effects were found in major organs during the course of long-term studies, thus suggesting satisfactory systemic biocompatibility for these materials provided that degradation is properly controlled. However, excessive amounts of lithium could accelerate corrosion processes and lead to increased concentrations of ions in the vicinity of an implant above biologically safe levels (Hernández-Escobar *et al*. 2019).

3.2.5 Zn–Ag, Zn–Cu, and Other Functional Alloys

Zinc alloys containing silver, copper, and other functional alloying elements have drawn significant attention in the study of biodegradable implants due to the ability of the alloys to provide both improved mechanical properties and antibacterial properties. Compared with conventional zinc alloying strategies, the addition of Ag and Cu is more focused on enhancing both mechanical and biological functionality, including antibacterial activity (Muqtadar *et al.* 2021). The strengthening effect of the solid solution is enhanced at lower alloying levels, and finely dispersed intermetallic particles containing Ag or Cu precipitate at higher alloying levels. These microstructural characteristics are very beneficial to temporary load-bearing implants since they are subjected to mechanical stresses in their *in vivo* service life.

When it comes to structure–property correlations, the properties of Zn–Ag and Zn–Cu alloys are very sensitive to the size and morphology of Ag-rich and Cu-rich phases as well as their distribution. Fine dispersions of intermetallic phases are preferable because they enhance load transfer and grain-boundary strengthening, and coarse or aggregated phases can act as sources of stress concentration and eventual failure. The secondary phases also greatly influence the corrosion characteristics, with the difference in electrochemical potential between the zinc matrix and Ag-rich or Cu-rich phases potentially leading to microgalvanic corrosion.

Thus, the alloy composition, thermomechanical processing, and phase formation must be properly controlled to achieve an optimal balance between improved properties and corrosion resistance. Zn–Ag and Zn–Cu alloys are harder and more wear-resistant than Zn–Mg and Zn–Ca alloys, but they may exhibit reduced ductility unless the alloy composition is optimized (Vojtěch *et al*. 2011).

Among the benefits of Zn–Ag and Zn–Cu alloys, their strong and persistent antibacterial properties are among the most significant, as infection prevention is an essential requirement for implants, and implant-related infection is one of the most frequent causes of implant failure in orthopedic and dental practice. The antibacterial activity of such alloys may be caused by the controlled release of Zn^{2+}, Ag^{+}, and Cu^{2+} ions during alloy degradation. These ions are able to damage bacterial cell membranes, promote the generation of reactive oxygen species, disrupt protein synthesis, and suppress the development of biofilms on the surfaces of implants. The broad-spectrum antibacterial action of the Ag^{+} ions, in particular, can be effectively used at very low concentrations, whereas Cu^{2+} ions can help counter bacterial resistance while being continuously released during alloy degradation. Unlike surface coatings, which may degrade or delaminate over time, alloys can provide long-lasting antibacterial activity.

Corrosion experiments conducted under physiological conditions indicate that both Zn–Ag and Zn–Cu alloys experience slightly higher corrosion rates than pure zinc, principally owing to increased microgalvanic coupling. Nevertheless, with optimal composition design, the corrosion rate can be maintained at a relatively stable and tolerable level for biodegradable implants. The corrosion products, which are predominantly zinc oxides, phosphates, and metal compounds, are biocompatible and can even help create a localized antibacterial microenvironment (Zhang *et al.* 2016).

It is noteworthy that have demonstrated that Zn–Ag and Zn–Cu alloys can support good cell viability and osteoblastic activity, provided that the level of ion release does not exceed cytotoxic levels, which explains the significance of optimal compositional control. Some other alloying elements like manganese, strontium, and iron have also been investigated to further improve the mechanical, corrosion, and biological properties of the zinc-based alloys. Overall, Zn–Ag and Zn–Cu alloys represent a shift in the design of biodegradable metals from optimizing individual properties toward developing multifunctional materials, thereby providing a new opportunity for the broader clinical application of zinc-based biomaterials. The tensile strength of Zn–Ag and Zn–Cu alloys is considerably higher, reaching about 250–450 MPa, along with hardness values above 100 HV, while retaining elongation values of 10–30%. The corrosion rate of these materials (0.05–0.20 mm/year) has been reported to be within the range considered acceptable for biodegradable alloys. Moreover, Zn–Ag and Zn–Cu alloys have inherent antibacterial properties, which are usually absent in Zn–Mg and Zn–Ca alloy systems.

4. ZINC MATRIX COMPOSITES FOR BIOMEDICAL APPLICATIONS

The recent development of zinc matrix composites as a new generation of biodegradable biomaterials is primarily due to the fact that zinc matrix composites can address the shortcomings of pure zinc, including the low mechanical strength and low load-bearing capacity. Through the incorporation of appropriate reinforcing agents, zinc matrix composites can be developed with improved mechanical, degradation, and biological properties. Their properties render them very appealing for temporary orthopedic and dental use, where strength, biodegradability, and biocompatibility are required simultaneously.

Among the various reinforcement schemes, the incorporation of bioactive ceramic particles, such as hydroxyapatite (HA), fluorapatite (FAP), β-tricalcium phosphate (β-TCP), and bioactive glass, has been widely investigated due to their chemical and structural compatibility with the mineral phase of the bone (Fig. 9). The incorporation of these ceramic phases into a zinc matrix can lead to significant enhancements in hardness, compressive strength, and wear resistance, primarily due to dispersion strengthening and grain refinement. Introduction of fine ceramic phases can hinder grain-boundary movement, which leads to a more refined microstructure and improved load transfer at the matrix–reinforcement interface (Chen *et al.* 2014). The bioactivity of ceramic-reinforced zinc composites has also been demonstrated, besides the mechanical properties. They have been known to enhance the formation of the apatite layer, the adhesion of osteoblast cells, as well as the rate of bone regeneration; HA, FAP, and β-TCP are among the ceramic reinforcements investigated for these purposes. The zinc composites reinforced by fluorapatite have attracted much attention because of the high chemical stability and reduced degree of degradation of FAP as compared to HA, thus enabling sufficient bioactivity with controlled degradation.

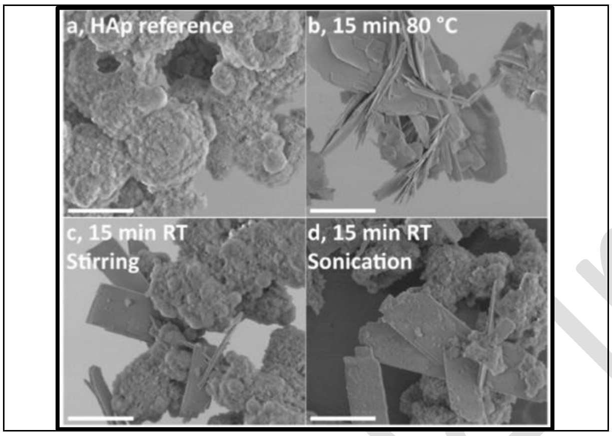

Fig. 9: SEM images of (a) HAP before ion exchange and (b–d) Zn-HAP and hopeite crystals obtained after exposure of HAP to a 1 M $Zn(NO_3)_2$ solution at pH 2.7: (b) 15 min at 80 °C, (c) 15 min of stirring at RT, and (d) 15 min of sonication at RT. Scale bar: 10 µm (Kannan and Raman, 2008)

From a corrosion perspective, the homogeneous distribution of ceramic reinforcement can serve as a physical barrier against corrosion, thereby facilitating controlled corrosion of the composite. In contrast, inhomogeneous dispersion, particle agglomeration, and weak interfacial bonding may promote localized corrosion.

In recent times, carbon-based reinforcements, such as graphene, reduced graphene oxide (rGO), and carbon nanotubes (CNTs), have been investigated as potential reinforcements of zinc matrices because of their excellent mechanical characteristics. These carbon nanostructures have been demonstrated to give significantly large contributions to tensile strength, elastic modulus, and corrosion resistance at low loadings, through dislocation strengthening and grain refinement. Carbon nanostructures are favored by the large aspect ratio and high specific surface area, which allow efficient interfacial interactions with the zinc matrix and may enhance overall structural homogeneity (Drelich *et al.* 2017).

Furthermore, reinforcement with carbon might enhance corrosion resistance by creating diffusion barriers that limit the diffusion of aggressive ions under physiological conditions. Zinc–carbon composites have been reported to exhibit antibacterial properties, potentially due to the combined effects of Zn^{2+} ion release and the membrane-disruptive capability of carbon nanostructures. However, excessive reinforcement content or poor dispersion can lead to agglomeration and galvanic corrosion, thus necessitating uniform dispersion of the reinforcement through optimized processing techniques. Polymer-reinforced and hybrid zinc matrix composites represent emerging areas of research that require optimization of mechanical properties, corrosion rates, and biological responses. Secondary phases and surface coatings: biodegradable polymers such as poly(lactic acid), polycaprolactone, and chitosan are commonly used to improve the ductility, toughness, and corrosion resistance of zinc matrix composites (Srilatha *et al.* 2025).

The polymeric phase can be applied as a protective coating to regulate the release of zinc ions and degradation at an early stage, therefore maintaining mechanical properties during the early healing phase. The synergistic advantages of hybrid composite materials with ceramic and polymeric reinforcements are evident in the complementary functions of the two phases: ceramic materials provide strength and osteogenic characteristics, whereas polymeric materials provide flexibility, interfacial compatibility, and more uniform degradation characteristics. Interfacial bonding and phase distribution in these materials are critical to their structure–property relationships, and they directly affect the corrosion properties and stress transfer efficiency. Polymer-based and hybrid zinc composites have been shown to exhibit better cell adhesion, less inflammation, and better tissue integration, and as such, they are being investigated as graded implants, bone-fixation devices, as well as tissue-engineering scaffolds that require controlled mechanical and degradation properties. A comparison of reinforcement types used in zinc matrix composites for biomedical applications is presented in Table 3.

Table 3. Comparison of reinforcement types used in zinc matrix composites for biomedical applications

Reinforcement Type	Representative Reinforcement	Mechanical Properties	Degradation Behavior	Biological Performance
Bioactive Ceramics	Hydroxyapatite (HA)	Increased hardness, compressive strength, and wear resistance; moderate improvement in tensile strength	Slightly reduced degradation rate due to the barrier effect; generally uniform corrosion	Excellent osteoconductivity, enhanced cell adhesion, apatite formation, and bone regeneration
Bioactive Ceramics	Fluorapatite (FAP)	Higher hardness and interfacial stability than HA; improved wear resistance	More controlled degradation owing to the lower solubility of FAP	Enhanced osteogenesis, superior chemical stability, antibacterial potential, and improved osseointegration
Bioactive Ceramics	β-Tricalcium Phosphate (β-TCP)	Moderate strengthening effect; improved load-transfer capability	Faster degradation than HA/FAP due to higher solubility	Promotes bone remodeling and mineralization through Ca^{2+} and phosphate ion release
Bioactive Glass	45S5 Bioactive Glass	Improved compressive strength and surface bioactivity	Accelerated apatite-layer formation; moderate degradation control	Excellent bioactivity, promotion of angiogenesis, and bone-bonding ability
Carbon-Based Reinforcements	Graphene (GNP)	Significant increase in tensile strength, elastic modulus, and hardness through grain refinement	Improves corrosion resistance by acting as a diffusion barrier	Supports cell proliferation; antibacterial activity reported at optimized concentrations
Carbon-Based Reinforcements	Reduced Graphene Oxide (rGO)	Enhanced strength, wear resistance, and fatigue performance	Improved corrosion resistance when uniformly dispersed	Promotes osteoblast adhesion and antibacterial behavior
Carbon-Based Reinforcements	Carbon Nanotubes (CNTs)	Excellent strengthening efficiency due to the high aspect ratio and load transfer	May improve corrosion resistance; excessive content can induce galvanic corrosion	Good cytocompatibility; supports cell attachment and proliferation
Polymeric Reinforcements	Poly(lactic acid) (PLA)	Improved toughness and ductility; limited strengthening effect	Reduces the initial corrosion rate by acting as a protective layer	Good biocompatibility and controlled ion release
Polymeric Reinforcements	Polycaprolactone (PCL)	Enhanced flexibility and fracture resistance	Slower degradation and improved corrosion control	Favors tissue integration and cell viability
Polymeric Reinforcements	Chitosan	Improved surface properties and toughness	Provides temporary corrosion protection	Antibacterial activity and enhanced cell adhesion
Hybrid Composites	FAP + Polymer / HA + Polymer	Balanced strength, toughness, and wear resistance	Controlled and uniform degradation behavior	Synergistic osteogenic, antibacterial, and tissue-regenerative properties

5. CONCLUSION

The development of biodegradable biomaterials from zinc has proven to be a viable choice for next-generation implants due to their special attributes, including moderate biodegradability, adequate mechanical strength, good biocompatibility, and various biological functions. The properties of zinc-based biomaterials have been enhanced by alloying them with other metals, such as Mg, Ca, Li, Ag, and Cu, along with the use of ceramics, carbon nanomaterials, and biodegradable polymers as reinforcements to improve their strength, corrosion resistance, tribology, antimicrobial effect, and osteogenic potential. Some of the recent advances in processing techniques include powder metallurgy, thermomechanical processing, additive manufacturing, and surface engineering. However, there are several key challenges that still need to be overcome before the wide-scale adoption of such implants in clinical practice. Achieving an optimal balance between mechanical properties and the degradation profile is one of the most important scientific challenges, especially for orthopedic devices subjected to mechanical loads. Another important challenge is the control of localized corrosion, the accumulation of degradation products, and the kinetics of ion release. At the same time, *in vivo* research is still limited, and additional research on the long-term behavior of such devices needs to be carried out. Future work needs to be focused on developing versatile zinc alloys that provide mechanical strength, controlled biodegradation, antibacterial function, immunomodulation, angiogenesis, and tissue regeneration. Emerging approaches include computational materials science, alloy design using artificial intelligence, manufacturing with digital twins, and machine learning–assisted predictive modeling. Additive manufacturing is another promising technology that allows us to develop personalized implants with unique structures and controlled biodegradability. From the viewpoint of translational medicine, there is a need to develop standardized testing procedures, perform animal studies using large-animal models, and conduct multicenter trials to establish the long-term safety and efficacy of zinc-containing implants. It should be noted that the problem of regulatory approval is particularly important, since biodegradable implants have to show reliability and biocompatibility in addition to specific characteristics such as predictable degradation and biosafety after their use. There are not yet any universal guidelines concerning the assessment of degradability, permissible ion-release rates, toxicology, and other important issues. In any case, collaboration between materials scientists, biomedical engineers, clinicians, regulators, and industry representatives will be vital to overcome possible obstacles. With further advances in materials science and biology, zinc-based alloys and composites are expected to become important components of temporary implants in the near future.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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