Review Article

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A Review of Zinc-based Composites for Biomedical Applications: Processing Routes, Reinforcements, Properties and Applications

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ABSTRACT

Zinc-based composites have emerged as promising materials for biomedical applications, especially in orthopedic implants, due to their unique combination of biodegradability, biocompatibility, and moderate mechanical strength. This review focuses on the properties, applications, and fabrication techniques of Zn-based biomaterials and their composites. Biodegradable metals like Mg, Fe and Zn are gaining attention as alternatives to traditional implants to avoid complications such as stress shielding, inflammation, and secondary surgeries. Zn composites show controlled degradation in the body and promote bone regeneration through the release of Zn ions, which aid osteogenesis. However, challenges such as limited mechanical strength and fast degradation rates have driven research into reinforcing Zn with materials like graphene, hydroxyapatite (HAP), tricalcium phosphate (TCP), and carbon nanotubes. These reinforcements significantly improve strength, corrosion resistance, and biological performance. Graphene and carbon nanotubes mainly contribute to improved mechanical strength and corrosion resistance, though challenges related to uniform dispersion and biocompatibility remain, while bio-ceramic reinforcements such as HAP and TCP enhance bioactivity and bone bonding but may adversely affect ductility at higher reinforcement contents. Various fabrication techniques like stir casting, powder metallurgy, spark plasma sintering, and post-processing methods are discussed to enhance material characteristics. The review emphasizes the importance of optimizing degradation rate and mechanical properties of Zn to match physiological needs. Overall, Zn-based composites hold significant potential for next-generation biodegradable implants that reduce patient risk and healthcare costs, while offering functional performance close to that of natural bone.

Keywords: Zinc composites; Orthopedic implants; Degradation rate; Biomedical applications.

1. INTRODUCTION

Medical science has grown significantly, with biomaterials playing a vital role in gradually improving patient health (Huang *et al.* 2021). One of the most significant advancements in this field is the development of biodegradable implants. These implants are designed to gradually degrade within the human body over time. Their use eliminates the need for secondary surgical procedures for implant removal. These advancements are transforming biomedical field and orthopedic implants. Earlier, the implants such as stainless steel, titanium, and cobalt-chromium alloys have been widely used due to their strength and durability (Mahajan *et al*. 2023). Moreover, these implants do not degrade inside the body, thus leading problems like stress shielding, chronic inflammation, and implant-related infections. To address these limitations, researchers have been exploring biodegradable metals that can be used as implants as an alternative. Among the various options available, Mg, Fe, and Zn have received considerable attention for their various properties that can be suitable as biodegradable implants (Prakasam *et al.* 2017).

2. METALS USED FOR BIOMEDICAL APPLICATIONS

Metals play an important role in biomedical applications, as each metal is selected for its unique properties that meet specific medical requirements. Some of the commonly used metals for biomedical applications are discussed below.

Titanium: Titanium is highly valued in biomedical applications because of its high strength-to-weight ratio, for its excellent biocompatibility, and its resistance to corrosion (Narnaware *et al.* 2017). Titanium is mostly used for orthopedic and dental implants because it has a capability to bond well with bone and integrate with tissues. Titanium reduces the risk of rejection and provides long-term stability and integration within the human body (Narnaware *et al.* 2017).

Magnesium: Magnesium is an evolving metal in biomedical applications for its biocompatibility, biodegradability and elastic modulus which is closely similar to the natural bone of the human body. It shows promise as a temporary bone implant and as a biodegradable stent, as it can gradually dissolve within the body. This biodegradability reduces the need for additional surgeries to remove implants, while magnesium also helps minimize long-term complications (Vaiani *et al.* 2023).

Cobalt-chromium: Cobalt-chromium alloys are widely used in joint replacements, cardiovascular stents and other biomedical applications because of their high wear resistance, high strength, and biocompatibility (Ladani *et al.* 2024). Their properties make them perfectly suitable for bearing the load of implants. Their durability and resistance to body fluids make them essential for success as biomedical materials (Motlagh *et al.* 2024).

Tantalum: It is valued for its excellent biocompatibility and corrosion resistance properties, thus making it valuable and suitable for orthopedic implants and coatings that improves osseointegration of the tissues. This metal has an ability to promote bone growth and can resist degradation in body fluids to sure continuous integration with natural bone (Huang *et al.* 2020). Tantalum has widely proven its capability for its biomedical application.

Copper: Copper contains antimicrobial properties and is used in wound dressings and medical surfaces which are prone to infection. Copper has the ability to kill bacteria and viruses and helps to prevent infections, making it suitable and preferably useful in hygiene-priority applications, in which maintaining a stable environment is critical (Chua *et al.* 2021).

Nickel-Titanium (Nitinol): This material stands out because of its shape memory property which ensures it returns to its original shape after deformation of the material. This makes nitinol preferable for use in orthodontic wires, vascular stents, and guide wires. Moreover, its super elasticity, flexibility and adaptability to dynamic environments within the body are important for biomedical applications (Billah *et al.* 2024).

3. PROPERTIES REQUIRED BY MATERIAL FOR BIOMEDICAL APPLICATIONS

Materials used in biomedical applications should have various critical properties to ensure that they perform precisely and safely within the body. Some of the properties of Zn-based composites are discussed.

Biocompatibility: The material should not cause worse reactions when implanted, when in contact with body tissues. Metals or materials should integrate and be compatible with the body's biological environment without causing inflammation or rejection in body (Pandey *et al.* 2025).

Mechanical Properties: The material must exhibit essential properties such as strength, elasticity, and toughness to withstand and sustain the mechanical stresses encountered in the body. These properties include resistance to wear and fatigue, especially for load-bearing applications (Sun *et al.* 2023).

Bioactivity: Materials must induce certain biological responses, for example, bonding with bone tissue or stimulating growth of the tissue. This is especially pertinent for tissue engineering scaffolds and implants (Todros *et al.* 2021).

Biodegradability: Biodegradability is essential for temporary implants or devices. The materials should have the capability to degrade safely and in a controlled manner within the body with passing of time, without releasing toxic ions. This property is essential for materials used in drug delivery systems and biodegradable stents (Vinchurkar *et al.* 2025).

Corrosion Resistance: The material should be capable of resisting degradation caused by body fluids and other environmental factors within the body. This property ensures the longevity and reliability of the implant or device (Sanjay *et al.* 2024).

Surface Properties: The material's surface should be engineered to optimize its interaction with biological tissues. This property may involve modifying or enhancing the surface to improve cell adhesion, reduce bacterial infection, and promote tissue integration (Lama *et al.* 2021).

Thermal Stability: Materials used for biomedical applications should retain their essential properties at body temperature and withstand any thermal treatments encountered during manufacturing or sterilization (Dambatta *et al.*2015).

Zinc-Based Composite for Biomedical Applications: Recent advances in zinc-based composites have emphasized their potential for biomedical applications, mainly in orthopedic and other implantable devices. These materials are favored for their unique combination of biodegradability, antibacterial activity, biocompatibility, and mechanical strength, making them a promising alternative to traditional implants (Hussain *et al.* 2022).

Biodegradability and Biocompatibility: A Zn-based composite which will degrade at a controlled and moderate rate is suitable for bone healing within the human body. It facilitates tissue engineering and enhances healing of the tissues (Shuai *et al.* 2018). This controlled degradation ensures that the Zn-based implant

provides support during the critical phase of healing and gradually dissolves, eliminating the need for secondary surgeries to remove the implant. Biocompatibility studies have confirmed that Zn composites are non-toxic and do not induce adverse tissue reactions, an essential requirement for all biomedical materials (Liu *et al.* 2022; Lu *et al.* 2023).

Enhanced Mechanical Properties: The main primary issue with the Zn-based composites is the lack of few essential mechanical properties. Recent studies have shown that alloying Zn with elements such as magnesium, zirconium, manganese, calcium, and lithium can significantly enhance its mechanical properties resulting in significant improvements in tensile strength, yield strength and durability (Tang *et al.* 2025). For instance, in certain Zn-based alloys, tensile strength rises from about 100–150 MPa (for pure Zn) to about 250–350 MPa (Chu *et al.* 2025). Alloying and other enhancements improve the properties of Zn composites for load-bearing applications, ensuring that they can meet the mechanical demands required for orthopedic and biomedical implants (Wong *et al.* 2016).

Corrosion Behavior: The corrosion behaviour of zinc-based composites is a crucial factor influencing their overall performance. Research has focused on optimizing the composition to control the corrosion rate and limit the release of harmful ions (Utu *et al*. 2020). For instance, incorporating small amounts of hydroxyapatite (HAP) or graphene into zinc- and magnesium-based composites enhances corrosion resistance while preserving the biocompatibility of the material (Lu *et al.* 2025; Zhao *et al.* 2020).

Bone Metabolism: Zinc is an essential trace element in bone metabolism and very important for the growth of new cells. Zinc in implants greatly promotes healing of bone and bone regeneration, which is an advantage over traditional materials (Wen *et al.* 2023). Zinc promotes the osteoblast activity through stimulation of cell proliferation, osteogenic differentiation by activating alkaline phosphatase and extracellular matrix mineralization. It also lowers oxidative stress and osteoclast-mediated resorption, to promote net bone formation. Research shows that Zn-based composites support and promote the activity of osteoblasts (bone-forming cells), therefore aiming at the natural healing process.

Applications: Zn-based composites are being used for developing various biomedical devices and implants, with a major focus on orthopedic implants such as bone screws and plates. Their biodegradable nature is of great advantage, as it clearly eliminates the need for revision surgeries, and reduces overall healthcare burden and improves patient outcomes (Wafi and Khan, 2025; Kong *et al.* 2023). Fig. 1(a) shows applications and effects of Zn composites and 1(b) is a pictorial representation of major applications of Zn-based metallic biomaterials.

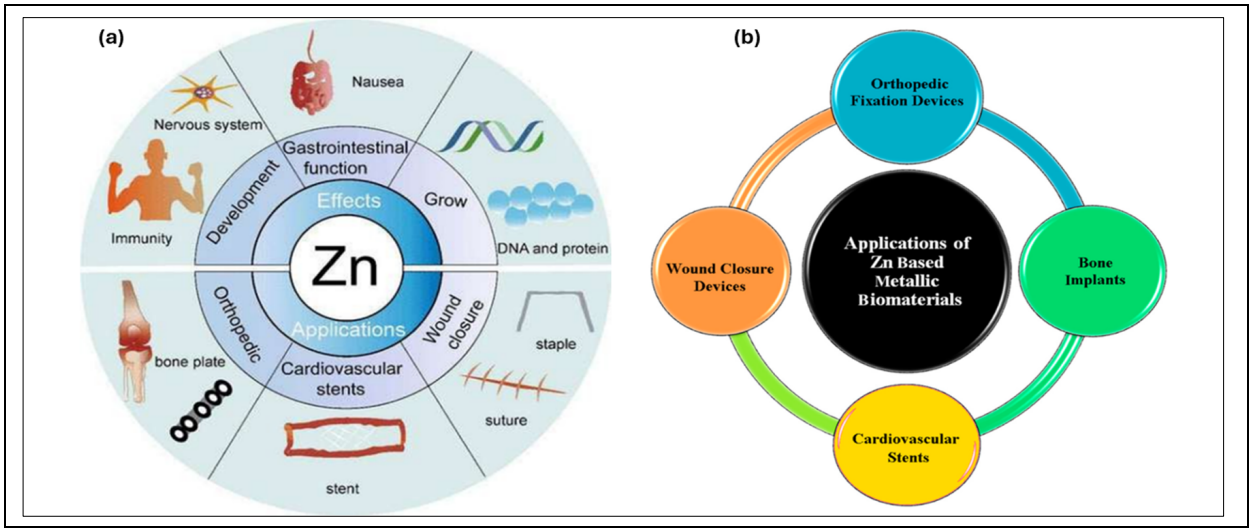


Fig. 1: (a) Biological roles and biomedical applications of zinc (Rao *et al.* 2024) and (b) major clinical applications of zinc-based metallic biomaterials (Kong *et al.* 2023)

4. REINFORCEMENT MATERIALS FOR Zn-BASED COMPOSITES

Zn-based graphene is widely used reinforcement for zinc-based composites. It is a two-dimensional nanomaterial composed of carbon atoms. Graphene is recognized for its high electric conductivity, large surface area, and exceptional mechanical strength (Malisz *et al.* 2023). In biomedical applications, graphene-reinforced composites are used in sensors, implants, gene delivery and drug delivery systems, tissue engineering, and particularly in anticancer therapies.

Graphene's biocompatibility makes it more suitable for interaction with human tissues. However, its low biodegradability requires further investigation into its long-term safety and biological fate. Moreover, the long-term effects and safety for other forms of graphene are being researched (Fadeel *et al.* 2018).

Hydroxyapatite is another important reinforcement widely used with Zn-based composites which improves the properties of the composite. It is a calcium phosphate bioceramic that closely matches the mineral element of bones (Mo *et al.* 2023). It is widely used in bone tissue engineering, dental implants, and drug delivery systems because of its biocompatibility, osteoconductivity, and ability to promote bone growth (Kowalski *et al.* 2016). Hydroxyapatite is bioactive and its incorporation into composites provides a balance between mechanical strength and flexibility (Gul *et al.* 2024). Tricalcium phosphate is a calcium phosphate bioceramic which has wide biomedical applications because of various factors such as osteoconductivity and excellent biocompatibility. It helps in bone regeneration and tissue engineering as it can be used as bone graft substitute and scaffold material (Carrodeguas *et al.* 2011). Tricalcium phosphate can be used as a coating for prosthetic implants, where it supports bone repair and promotes bone growth.

Carbon nanotubes are made of carbon atoms which are like cylindrical structures. Carbon nanotubes are known for their exceptional properties such as various positive and useful mechanical, electrical properties, this makes the carbon nanotubes versatile in biomedical

Applications: Carbon nanotubes are often used as carriers for the targeted drug delivery systems and will improve the efficiency of the treatments (Murjani *et al.* 2022). Carbon nanotubes are used to aid and improve the tissue engineering of the body. These days carbon nanotubes are used for precise oncology and targets the cancer cells destruction through drug delivery systems (Saliev *et al.* 2019).

5. FABRICATION TECHNIQUES FOR Zn-BASED ALLOYS AND COMPOSITES

Many fabrication techniques are used to fabricate Zn-based alloys and composites. Some of them are casting, powder metallurgy, additive manufacturing, spark plasma sintering, transient directional solidification and other advanced processing techniques (Bakhsheshi *et al.* 2017; Yan *et al.* 2018). Among these techniques casting is the most used method for mass production of Zn-based alloys.

The mechanical, degradation, and corrosion behaviours are strongly dependent on the microstructural parameters and the distribution of the secondary phase in the matrix (Bagha *et al.* 2018). Uniform distribution of the second phase throughout the composite may result in improved properties for Zn-based alloys that are biodegradable. The microstructures and the properties can be customized by applying different metal-forming processing techniques like rolling, selective laser sintering, spark plasma sintering, drawing, hot extrusion, and severe plastic deformation techniques like Equal Channel Angular Pressing (ECAP), high-pressure torsion, twist extrusion, friction-stir processing, etc. It is difficult to study the effect of post-processing techniques on the characteristics of Zn alloys because of small size of processed Zn-based materials. Čapek *et al.* (2020) conducted a study on the influence of extrusion parameters such as extrusion ratio and temperature on the microstructure and mechanical characteristics of $Zn_{-0.8}Mg_{-0.2}Ca$ alloys. Fig. 2 shows applications of HAP biomaterials. The microstructures and SEM analysis are shown in Fig. 3. The microstructures of the materials that underwent post-processing show that the sizes of both the Zn matrix and intermetallic particles were notably affected due to extrusion.

Adding reinforcements to form Zn matrix composites is another way to control the characteristics of Zn metals. Composites having pure Zn as matrix and HAP were prepared by spark plasma sintering (Yang *et al.* 2018). A huge range of degradation rates can be achieved by varying the concentration of HAP.

Powder metallurgy is a solid-state fabrication technique used for the production of near net shape metallic alloys and composites using metal powders. The sample can be obtained by cold or hot isostatic pressing. The hot isostatic pressing technique showed enhanced densification, reduced porosity and eliminated sintering steps. This method had been used for the processing of high temperature melting metals such as titanium, nickel, cobalt and their alloys used in biomedical applications (Čapek *et al.* 2013). Literature survey revealed that the metal composites fabricated using metal casting technique for biomedical applications had below acceptable clinical standard mechanical properties. They required extra post-processing like extrusion, rolling, drawing and thermal treatments such as annealing and quenching (Li *et al.* 2014) further increasing the cost implications. Studies have shown that processing techniques influence the properties and applicability of the materials (Katarivas *et al.* 2017; Andani *et al.* 2014).

Many works had been reported on powder metallurgy processing of magnesium and its alloys (Wang *et al.* 2017; Yusof and Zuhailawati, 2017) to examine one or two parameters involved in powder metallurgy. Results of these studies showed that the properties of the materials fabricated by powder metallurgy depended on parameters like weight fraction of alloying composition, compaction pressure, heating rate, milling time, sintering temperature and time.

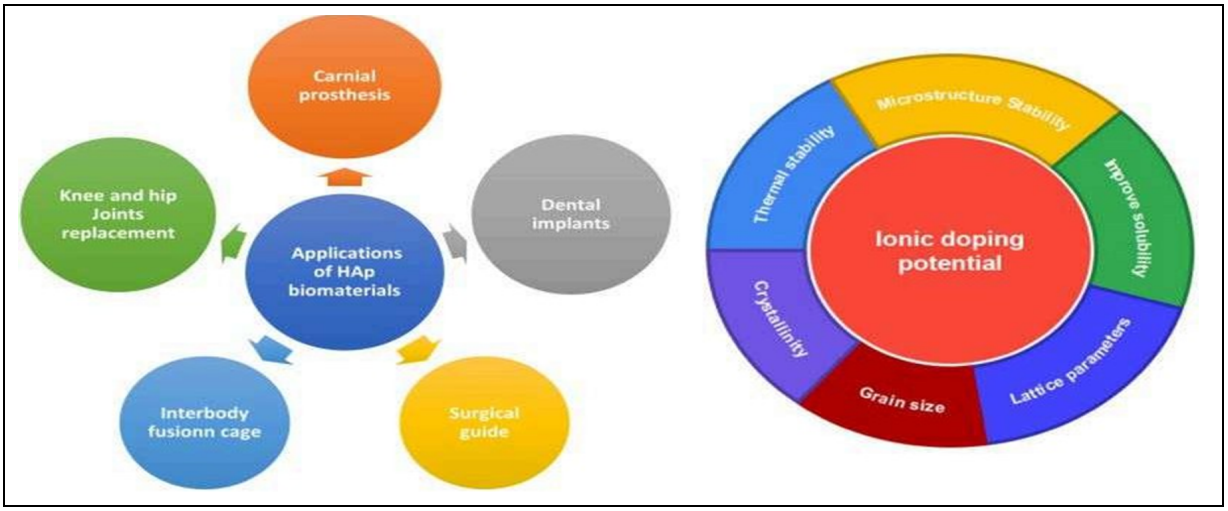


Fig 2: Applications of hydroxyapatite biomaterials and factors influencing the ionic doping potential of biomaterials (Mehta *et al.* 2023)

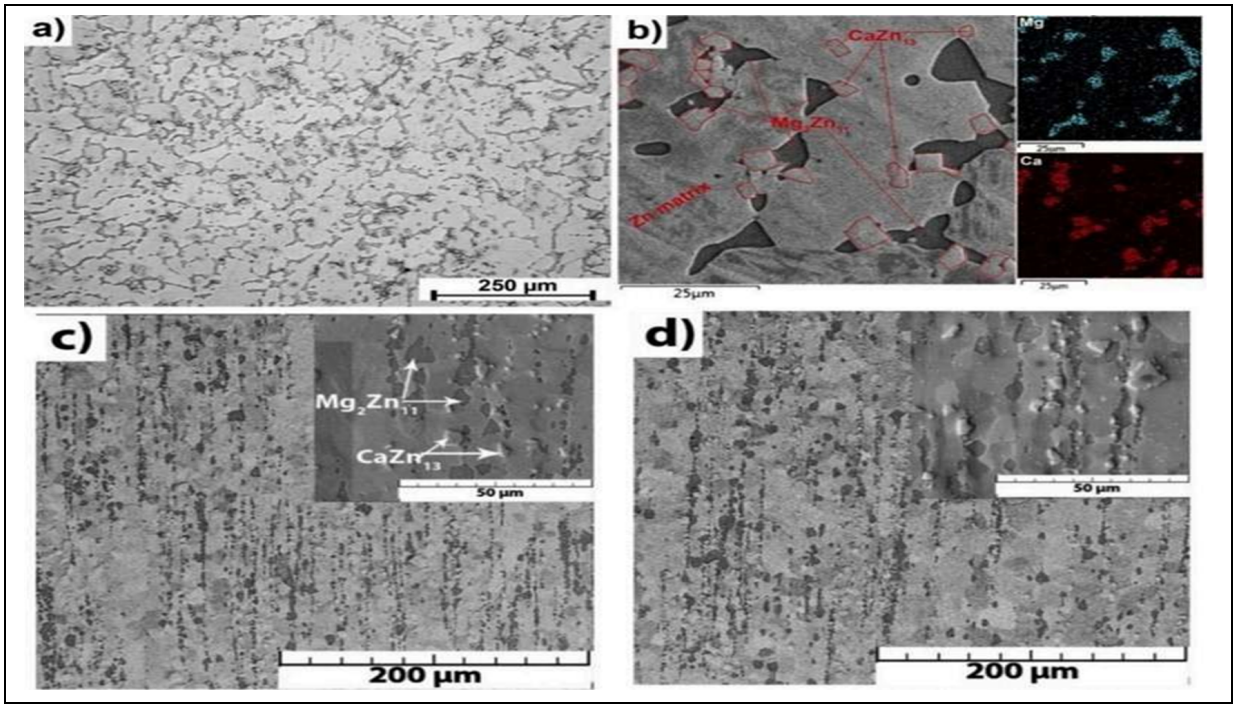


Fig. 3: Microstructures of Zn−0.8Mg−0.2Ca alloys (a) microstructure of as-cast (cast and annealed) alloy; (b) a detailed SEM view with corresponding X-ray elemental maps of Mg and Ca; (c) SEM image of extruded material at 300 °C and an extrusion ratio of 11:1; (d) SEM image of extruded material at 300 °C and an extrusion ratio of 25:1 (Pachla *et al.* 2021)

By analysing the above information, it can be concluded that the powder metallurgy process is more suitable for fabricating biodegradable composites for biomedical applications when compared to other techniques.

Zinc-based materials have become popular in the biomedical industry due to their favourable properties including biodegradability, biocompatibility, and mechanical properties. While pure Zn fails to meet the biodegradation rate requirements of a material which is 0.5 mm/year for biomedical applications, its alloys show improved strength compared to traditional implants (Vida *et al.* 2019). These materials degrade at a normal rate, producing Zn ions that promote bone growth and mineralization. But before Zn-based materials can be used for implants, several implications must be addressed, including their degradation rate, mechanical stability under different conditions, and biocompatibility concerns regarding excessive release of Zn ions.

To improve the performance of Zn-based materials, research should be done to optimize their properties, like degradation rate to match bone healing

and their behaviour under static and dynamic loads. The modulus of elasticity of Zn alloys (94–110 GPa) is higher than that of natural bone, which may lead to stress shielding. Additionally, the creep of Zn alloys at body temperature must be investigated to prevent implant failure. As already mentioned, Zn ions are released while the material is decomposing. This is helpful till a certain extent, but if the concentration of the released ions is high it can be toxic to cells. Enhancing antibacterial properties and shifting *in vivo* studies from small to large animal models could further validate their suitability for orthopaedic applications.

The processing techniques play a critical role in customizing Zn-based implants for clinical use. Various approaches, such as casting, additive manufacturing, and powder metallurgy, have been explored. However, Zn-based composite development remains underexplored, and using biocompatible ceramics as reinforcements could greatly enhance bioactivity and mechanical properties. Additive manufacturing, though still in its early stages for Zn alloys, offers great potential due to its flexibility in material design, but limitations such as low melting temperature, high vapor pressure, and processing challenges could pave the way for clinically acceptable Zn-based orthopedic implants.

6. CONCLUSION

Zinc-based composites have undergone significant development and are increasingly selected for applications requiring precise performance and reliable properties. These composites exhibit improved hardness, improved wear, corrosion resistance, and self-lubricating behaviour, making them suitable for demanding conditions. The microstructure of zinc-based composites plays a critical role in determining their performance and characteristics. In addition, manufacturing techniques strongly influence their properties. Processes like severe plastic deformation and ECAP are widely employed to refine the grain structure, resulting in a desirable balance of strength and ductility. For example, Mg-Zn-Ca alloys prepared through ECAP technique have shown promising mechanical properties and good biocompatibility, making them attractive candidates for biomedical applications.

Electrodeposition technique is mostly utilized for creating corrosion-resistant coatings, while powder metallurgy technique is used to produce dense and uniformly distributed composites. Additive manufacturing, or 3D printing is an emerging technology which enables the formation of complex geometries, significantly useful for biomedical implants. These advancements have increased their applications beyond corrosion resistance to include high-performance coatings and biodegradable materials for medical use. The combined use of these techniques and new approaches ensure that zinc-based composites lead in the field of material science.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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