

The Advantages of Titanium Dioxide Nanoparticles: A Review of Improved Magnesium Composites for Orthopedic Applications

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ABSTRACT

Magnesium (Mg) alloys have garnered significant attention as temporary biodegradable implants due to their excellent biodegradability and an elastic modulus similar to natural bone. However, their rapid corrosion in physiological environments, which leads to a premature loss of mechanical integrity, hinders their clinical application. To address this, titanium dioxide nanoparticles (TiO₂ NPs) have recently been explored as multifunctional reinforcing agents for Mg-based composites. In addition to activating key strengthening mechanisms, TiO₂ NPs can enhance antimicrobial performance and biocompatibility due to their intrinsic properties. This review examines recent advances in TiO₂ NPs-reinforced Mg composites, focusing on their effects on mechanical strength, corrosion resistance, biocompatibility, bone regeneration, and antibacterial efficacy. Finally, the current limitations and future prospects of these composites for biomedical applications are discussed.

KEYWORDS: Magnesium; Titanium dioxide nanoparticles; Composites; Biomedical application

1. Overview

1.1 Biodegradable Mg

Each year, many people experience bone fractures as a result of illnesses or accidents. Moreover, it appears that osteoporosis is affecting people at younger ages [1,2]. The majority of these fractures require surgical repair with implants since they are too complicated to be treated with exterior medical treatments [2]. Nowadays, the majority of non-biodegradable metals found in fracture fixation implants are stainless steels, cobalt (Co), and titanium (Ti) alloys [3–6]. These metals either remain in the body permanently or need to be removed surgically when the fracture cures [7]. Unfortunately, these materials have two main negative effects: (I) the implant's high elastic modulus difference from natural bone, which causes stress shielding phenomenon and (II) the implant's non-biodegradability in biological

environments; The need for secondary surgery to remove the implant can put mental pressure on the patient in addition to pain and suffering [8–11]. Because of these difficulties, a new chapter in the history of biomedical materials has begun, and scientists are becoming increasingly interested in biodegradable materials [8,12–14]. Until the tissue heals completely, biodegradable compounds, such as biodegradable metals, disintegrate totally. Because the implant gradually corroded in vivo, no implant leftovers could be found [15]. As a result, metallic components play a crucial role in biodegradable materials and can be metabolized in biological contexts such as the human body [16,17]. In addition, it is possible to adjust the rate of degradation of metal elements with modification processes. Alloys based on iron [18,19], Mg [20–22], or zinc [2,23–25] is three types of biodegradable metal materials that attracted the most attention. In this regard, polymers are currently better in the

medical market, while alloys based on Mg, iron, and zinc are better biodegradable materials for load-bearing applications since they are both stronger and stiffer than polymers. When compared to iron (211.4 GPa) or zinc (90 GPa), Mg's elastic modulus (41–45 GPa) is closer to that of natural bone (3–20 GPa). The implant receives a greater share of the load when the elastic moduli are mismatched, which causes the phenomenon of stress-shielding bone to occur [26,27]. Mg also participates well in the surface interaction of bone minerals, which regulates bone remodeling and proliferation [28]. Table 1 shows the physical, mechanical, and biological characteristics of biodegradable metals for comparison.

Mg is the fourth most abundant cation in the human body and the second most prevalent intracellular cation in tissues. The body contains

approximately 30 grams of Mg, with 50% stored in bones and the remainder distributed in soft tissues, muscles, and body fluids. Although blood contains only 1% of the body's total Mg, serum Mg concentration (SMC) is the primary clinical measure for assessing Mg status in patients. Mg is crucial for over 300 enzymatic reactions, including nerve impulse transmission, fatty acid synthesis, and protein production. It also plays a fundamental biological role in energy metabolism—ATP must bind to a Mg ion to become biologically active, and Mg is essential for the transition state during ATP synthesis from ADP and inorganic phosphate. Bone breakdown releases Mg, which serves as a key cofactor for metabolic enzymes upregulated in activated immune cells. Thus, Mg levels significantly influence immune system function.

Table 1. Comparison of physical, mechanical, antibacterial and biological properties of biodegradable metals

Property	Mg [2,29–35]	Zn [2,35–37]	Fe [2,38–40]
Physical Properties	Density: ~1.74 g/cm ³ (closest to bone) E: ~41-45 GPa (close to bone)	Density: ~7.14 g/cm ³ E: ~80-120 GPa	Density: ~7.87 g/cm ³ E: ~200 GPa
Mechanical Properties	UTS: 135-350 MPa UCS: 65-100 MPa ε: 7-40%	UTS: 100-150 MPa UCS: 30-100 MPa ε: 0.3-2%	UTS: ~300 MPa UCS: ~560 MPa ε: ~35-50%
Corrosion Behavior	Rate: Too Fast in physiological Cl ⁻ environment. Mechanism: Anodic dissolution, producing H ₂ gas and OH ⁻ . Key Issue: Hydrogen gas evolution can form pockets, rapid loss of mechanical integrity.	Rate: Nearly Ideal (0.02-0.05 mm/year). Mechanism: Preferentially corrodes via slow, uniform dissolution. Key Issue: Can be too slow in some cases; corrosion products are biocompatible.	Rate: Too Slow (<0.01 mm/year). Mechanism: Corrodes via formation of insoluble oxides (Fe ₂ O ₃ , Fe ₃ O ₄). Key Issue: Persists too long in the body; accumulation of voluminous corrosion products (rust) can cause inflammation.
Antibacterial Properties	Strong. Mechanism: The rapid corrosion increases local pH (alkaline environment) and releases Mg ²⁺ ions, both of which are detrimental to many bacteria.	Moderate to Strong. Mechanism: Release of Zn ²⁺ ions is inherently antibacterial and can disrupt bacterial membrane function.	Weak / Passive. Mechanism: Not inherently antibacterial. The corrosion products (iron oxides) do not inhibit bacterial growth.
Cellular Response	Excellent Osteogenesis: Mg ²⁺ ions are known to stimulate new bone formation and are essential for bone metabolism. Cytocompatibility: Generally good, but a too-fast corrosion rate and H ₂ gas release can harm surrounding cells and tissue.	Good Osteogenesis: Zn ²⁺ ions promote osteogenic differentiation of bone cells and are crucial for bone growth and mineralization. Cytocompatibility: Good within a specific concentration range. High levels of Zn ²⁺ can be cytotoxic.	Good Biocompatibility: Iron is a fundamental element in the body (e.g., hemoglobin). Osteogenesis: Does not actively stimulate bone growth like Mg or Zn. The primary concern is the long-term inflammatory response to persistent corrosion debris.

E: elastic modulus; UTS: ultimate tensile stress; UCS: ultimate tensile stress; ε: elongation

Additionally, Mg supports skeletal and muscular structure, with bones acting as a reservoir. The recommended daily intake of Mg is at least 100 milligrams. Dietary sources such as almonds, cocoa, and brewer's yeast provide over 200 mg of Mg per 100 grams [41]. Mg-based materials have been utilized in medical applications since 1878. As a biodegradable material, Mg degrades entirely within the human body after fulfilling its medical purpose. Patients with bone injuries, dental issues, critical wounds, or coronary artery disease require temporary support during healing, necessitating materials with optimal mechanical integrity, biocompatibility, bioactivity, and controlled biodegradability. The design and selection of Mg-based materials are tailored to specific medical needs [42]. Unfortunately, because of their high reactivity and low corrosion resistance, Mg alloys are not commonly used [28]. As a result, the corrosion resistance of Mg needs greater attention

as it is a crucial matter [43–46]. The basic idea behind incorporating nanoscale reinforcements is to intercomponent synergies that enable the development of novel features that either match or surpass design specifications [47–50]. Numerous factors, in particular the dispersion, size, shape, orientation, and nanoscale dimensions of the reinforcement materials with matrix materials, control the properties of nanocomposites [51–54].

1.2 TiO₂ NPs

TiO₂ NPs have emerged as a highly versatile material in biomedicine due to their unique properties, including low toxicity, good biocompatibility, high surface area, and photocatalytic activity (Figure 1) [55–59]. Their biomedical applications can be broadly categorized into four main areas: drug delivery systems, antibacterial devices, medical implants, and biosensors [60].

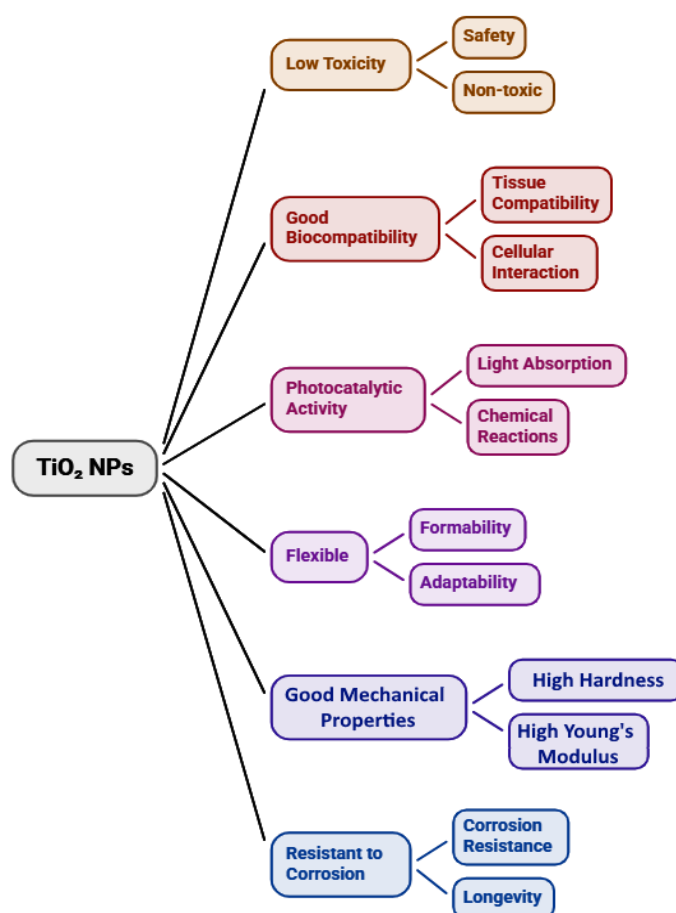


Fig. 1. Some key intrinsic properties of TiO₂ NPs

In drug delivery, particularly for cancer therapy, TiO₂-based nanostructures serve as potent systems for targeted delivery and controlled release of chemotherapeutic agents. Their high surface area allows for significant drug loading, while their surface can be functionalized with targeting ligands (e.g., folic acid) for specific accumulation in cancer cells [61]. The release mechanism can be controlled by external stimuli such as ultraviolet (UV) light [62], ultrasound [47], or radiofrequency [44]. For instance, UV light or ultrasound irradiation generates reactive oxygen species (ROS) that can cleave chemical bonds (e.g., boronic ester bonds) linking the drug to the nanoparticle, triggering a localized release and minimizing systemic side effects [63]. A significant application of TiO₂ is in creating antibacterial surfaces for medical devices and implants. The primary mechanism is photocatalytic activity: upon illumination with UV light, TiO₂ generates ROS (such as •OH and O₂•⁻), which oxidize and destroy the cell walls and membranes of pathogenic microorganisms [60]. This property has been leveraged to coat orthopedic [64,65] and dental implants [66,67], catheters [68,69], and even surgical lancets [70] to prevent device-related infections. To overcome the limitation of requiring UV light, strategies like doping with metals (e.g., Ag) [71] or non-metals (e.g., S) [72] have been developed to enable

antibacterial activity under visible light or even dark conditions [73]. As an implant material, TiO₂ nanostructures—primarily in the form of nanotubes (NTs)—are used to enhance the performance of titanium bone and dental implants. The nanotopography of TiO₂ NTs significantly improves osseointegration by promoting adsorption of proteins like collagen, enhancing osteoblast adhesion, proliferation, and differentiation [74,75]. Furthermore, these nanostructures can be loaded with bioactive agents (e.g., antibiotics, osteogenic drugs like strontium or magnesium) to create local drug-releasing implants that combat infection and stimulate bone growth directly at the implantation site [76–78]. Finally, TiO₂ NPs are a fundamental component in photoelectrochemical (PEC) biosensors for the sensitive detection of biological analytes. In these biosensors, a TiO₂-based working electrode is functionalized with a bio-recognition element (e.g., an antibody or DNA strand). Upon illumination, TiO₂ absorbs light and generates electron-hole pairs. The binding of a target analyte (e.g., a cancer biomarker like PSA) to the recognition element alters the photocurrent generated by this system, providing a quantifiable signal [79]. The sensitivity is often enhanced by coupling TiO₂ with narrow-bandgap semiconductors like CdS quantum dots to improve visible light absorption and electron transfer

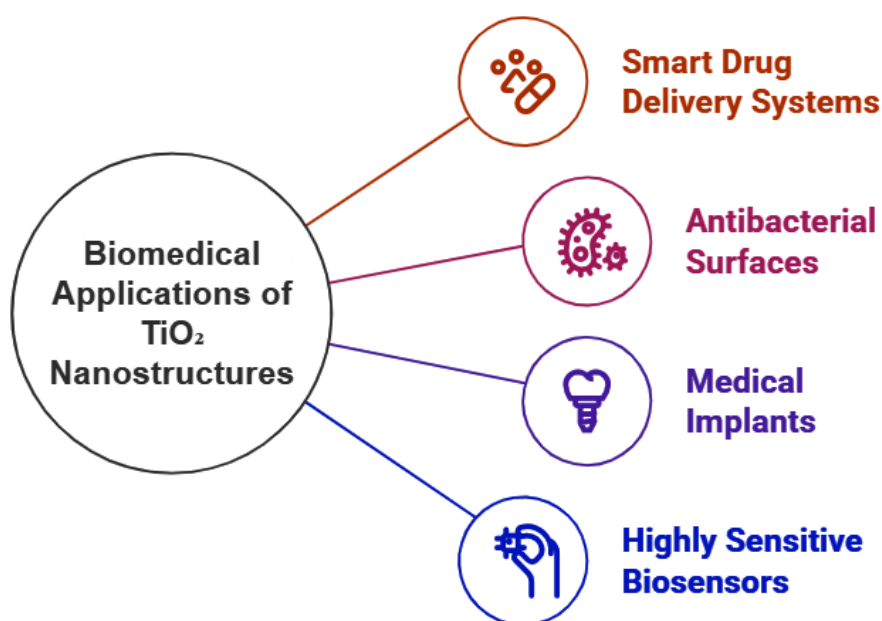


Fig. 2. Schematic of the multifaceted application of TiO₂ NPs in biomedicine.

efficiency [60,79,80]. Figure 2. schematically summarizes the multifaceted application of TiO₂ NPs in biomedicine.

1.3 Mg/ TiO₂ NPs Composites

The two most popular implant biomaterials are extra-low interstitial (ELI) Ti-6Al-4V alloy (ASTM F136) and commercially pure (CP) titanium (ASTM F67). The physical and chemical properties of the oxide layer on the surface of both materials are of growing interest. In addition to offering corrosion resistance, the oxide might improve Ti's biological properties at the molecular and tissue levels [81]. Nevertheless, the biosafety of Mg alloys employed in biological applications may be impacted by these additions. Because TiO₂-based biomaterials are biologically compatible with the body, they are frequently employed as bone substitutes. In orthopedic applications, nanoscale TiO₂ enhances implant integration with host tissue. Additionally, it has been shown that nano-TiO₂ is biocompatible because Ti-OH groups facilitate the development of hydroxyapatite (Hap) [82–84]. It is non-toxic, flexible, strong in tensile strength, resistant to corrosion, has a large specific surface area, is reasonably priced, and forms a stable colloidal solution. By adding TiO₂ NPs to the composite, the *in vitro* bioactivity of bone-like apatite formation ability in simulated bodily fluid (SBF) can be improved [85]. According to these benefits, scientists employed titanium oxide in a variety of therapies and classified it as a biomaterial [86]. Additionally, it has been demonstrated that adding titanium oxide nanofiber to an aluminium metal matrix could enhance the mechanical characteristics of the metal matrix [87]. Furthermore, titanium oxide has been utilized as a filler by numerous researchers to improve the tribological characteristics of materials utilized in biomedical applications [88]. Metal oxides include titanium dioxide (TiO₂) and titanium oxide (IV). Three primary types of TiO₂ crystallize naturally: rutile, anatase, and brookite. This oxide's structure is based on a titanium atom that is encircled by six deformed octahedral oxygen atoms. Titanium oxide is stable and harmless to both people and the environment. Additionally, it is stable against corrosion. It also possesses antimicrobial effects. According to some researchers, calcium phosphates or apatite that resembles bone precipitate on its surface when exposed to titanium oxide. Because of these characteristics, TiO₂ NPs is a good option

for bone grafting and replacement [89].

Mg has attracted the attention of researchers as a biodegradable metal for use as orthopedic implants, including fracture fixation implants. However, the biggest challenge in using Mg is its mechanical weakness and corrosion in biological environments. One of the popular techniques to increase the effectiveness of Mg matrix is to create composites using bio-based nanoparticles [90–93]. Typically, the fillers used in the composite are selected based on the properties required for that specific application. TiO₂ ceramic nanofillers are among the candidates for filler materials to influence the mechanical and biological properties of Mg matrix [94,95].

The recent discovery of unique properties in TiO₂ NPs has generated growing interest in their application as reinforcing agents within Mg matrices. This review aims to understand their impact on key performance metrics, including mechanical properties, corrosion behavior, and tissue-material interactions. However, despite extensive studies, a comprehensive review that critically examines the underlying mechanisms and specific aspects of TiO₂ NPs' role in Mg composites for biomedical use remains absent. Aiming to fill this gap, this review first provides an introduction to biodegradable Mg before conducting a thorough evaluation of TiO₂ NPs' effectiveness as reinforcements. Furthermore, it identifies future research challenges and prospects to guide subsequent investigations.

2. The effect of TiO₂ NPs on mechanical properties

The incorporation of finely dispersed TiO₂ particles—whether at the micro or nano scale—within a Mg matrix can significantly enhance the material's mechanical properties through multiple strengthening mechanisms. The uniformly distributed TiO₂ particles act as physical barriers, impeding the motion of dislocations within the Mg matrix. This restriction on dislocation glide increases the material's resistance to plastic deformation, leading to improved strength and hardness. Also, TiO₂ particles can serve as effective nucleation sites for Mg grains during solidification or recrystallization processes [96,97]. This promotes the formation of a finer grain structure, which is known to enhance both strength (via the Hall-Petch effect) and ductility. A refined grain structure also contributes to better wear resistance by reducing

grain boundary sliding and improving surface integrity. On the other hand, a strong interfacial bond between the Mg matrix and TiO₂ particles ensures efficient load transfer from the softer matrix to the harder ceramic reinforcement. This minimizes localized stress concentrations and prevents premature failure, further enhancing the composite's overall hardness and strength. The combined effects of dislocation strengthening, grain refinement and effective stress distribution contribute to superior wear resistance [98,99]. The hard TiO₂ particles help mitigate abrasive wear, while the refined microstructure reduces the likelihood of crack initiation and propagation under frictional forces. In summary, the addition of TiO₂ particles to a Mg matrix leads to a multifaceted improvement in mechanical properties, including increased strength, hardness, ductility, and wear resistance, making such composites highly suitable for demanding structural and tribological applications [100–103]. Alnaser et al. [89] examined the mechanical and tribological characteristics of Mg following the incorporation of varying loading fractions of TiO₂ nanofibers. The electro spinning method was used to create the TiO₂ nanofibers. To make sure that the TiO₂ nanofibers were distributed uniformly inside the Mg matrix, the ball-milling process was employed. Next, using a high-frequency induction heat sintering process, samples of the combined powder with varying loading fractions of TiO₂ nanofibers—0, 1, 3, 5, and 10%—were created. The mechanical properties and wear resistance improved up to 5% weight fraction. The study of Pillai et al. [104] The use of argon as a shielding gas to prevent oxidation in vacuum casting was made for pure Mg as the base metal as well as TiO₂ particles with different amounts (2.5, 5, 7.5 and 10% by weight) as reinforcement. A range of load values (10N, 15N, 20N, and 25N), sliding velocities (1 m/s, 1.5 m/s, and 2.0 m/s), and the weight percentage of the reinforcement were used to compute wear losses. The findings demonstrated that wear loss rose as the load increased and fell as the sliding velocity increased. An increase in the percentage of reinforcements in the matrix improves wear resistance. In another study, Reddy et al [105] Using the stir casting procedure, studied TiO₂ NPs with different weight proportions were created. The Nano reinforcement particulates result in a reduced dendritic pattern and homogenous distribution of Nano reinforcement particles throughout the Mg phase. Mg Nano composites with a higher

dislocation density and a different coefficient of thermal expansion show higher toughness. The tendency towards a progressive increase in ultimate tensile strength appears to be attributed to the ductility due to the increased bonding strength between the nanoparticles. The nanocomposites have a better compressive strength due to the finer grain structure, fewer residual pores, and uniform dispersion of reinforcing particles throughout the matrix alloy. Elumalai et al. [106] The effective synthesis of the pure Mg and bulk composite (Mg-TiO₂) with 1.5, 2.5, and 5 weight percent TiO₂ NPs involved powder compaction, two stages of microwave sintering, and hot extrusion. As the TiO₂ content rises, the experimental mass density and porosity increase gradually. A rise in TiO₂ concentration refines the Mg granules to a size of around 27 μm. An examination of the interior microstructure in three dimensions using micro computed tomography (μCT) revealed that the TiO₂ NPs were evenly distributed throughout the Mg content, showing no signs of substantial agglomeration. Because Mg₅TiO₂ has tougher TiO₂ reinforcement, it was shown to have the highest micro hardness and Nano indentation. Meenashisundaram et al. [107] Disintegrated melt deposition, followed by hot extrusion, can be used to create nearly dense < 2.5 vol.% Mg-TiO₂ nanocomposites. The composite with TiO₂ NPs has finer grains, higher microhardness and negligible effect on CTE compared to pure Mg. The tensile characteristics of the nanocomposites at room temperature show that ≥ 2 vol. % TiO₂ NPs are needed to increase the strength of pure Mg. Mg 1.98vol.% TiO₂ (11.5%) demonstrated the highest ductility, exceeding that of pure Mg by almost 50%. It was discovered that adding up to 2 vol.% of TiO₂ to pure Mg changed its strong basal texture. For Mg 1.98vol.% TiO₂ nanocomposites, a maximum tensile fracture strain of about 12% was noted. It was discovered that the manufactured nanocomposites had less anisotropy and asymmetry than pure Mg. It appears that a number of variables, such as the concentration, size, and form of TiO₂ NPs, affect the unique characteristics and benefits of TiO₂-reinforced Mg composites. Achieving the desired qualities requires careful optimisation of these factors. The microstructure and properties of manufactured composites can be affected by different manufacturing techniques, manufacturing variables, and also finishing operations after manufacturing.

3. The effect of TiO₂ NPs on biological properties

The biocompatibility of the composite material, as well as its overall suitability for biomedical applications, can be significantly improved through careful control of TiO₂'s physical form and processing methodology [92]. One of the key advantages of TiO₂ in medical applications is its ability to undergo osseointegration—a biological process in which the material directly bonds with surrounding bone tissue without triggering an adverse immune response. This property makes TiO₂ an excellent candidate for bone repair materials, orthopedic implants, and dental implants, where strong integration with natural bone is essential for long-term stability and functionality. Furthermore, TiO₂ NPs exhibit notable antibacterial properties, which can play a crucial role in reducing the risk of post-surgical infections around implants and other medical devices [92,108]. By inhibiting bacterial growth, TiO₂ NPs help minimize complications such as inflammation or implant rejection, thereby improving patient outcomes. Previous studies have highlighted these antimicrobial effects, suggesting that TiO₂-enhanced materials could be particularly valuable in clinical settings where infection control is a major concern [96,103,109–112]. Amirzade-Iranaq et al. [92] found that composites with lower TiO₂-MWCNT content (TM1 and TM2) exhibited superior osteoblast cell viability and proliferation

compared to the unreinforced alloy (TM0) and the composite with the highest filler content (TM3), as evidenced by the cell viability and ALP activity results presented in Figure 3. Specifically, the TM2 composite (10 wt% TiO₂-1 wt% MWCNTs) showed the highest cell viability (96%) after 3 days, attributed to its favorable surface structure and lower corrosion rate, which resulted in a more biocompatible environment. Furthermore, ALP activity, an indicator of osteogenic differentiation, was also highest for TM2, suggesting that the TiO₂ component promotes the formation of a bioactive apatite layer that enhances protein binding and stimulates bone cell activity.

4. The effect of TiO₂ NPs on corrosion behaviors

The following section discusses the process of Mg alloy degradation in SBF solution. The following cathodic processes are the redox reactions that cause Mg alloys to corrode overall (Eq.1-4):

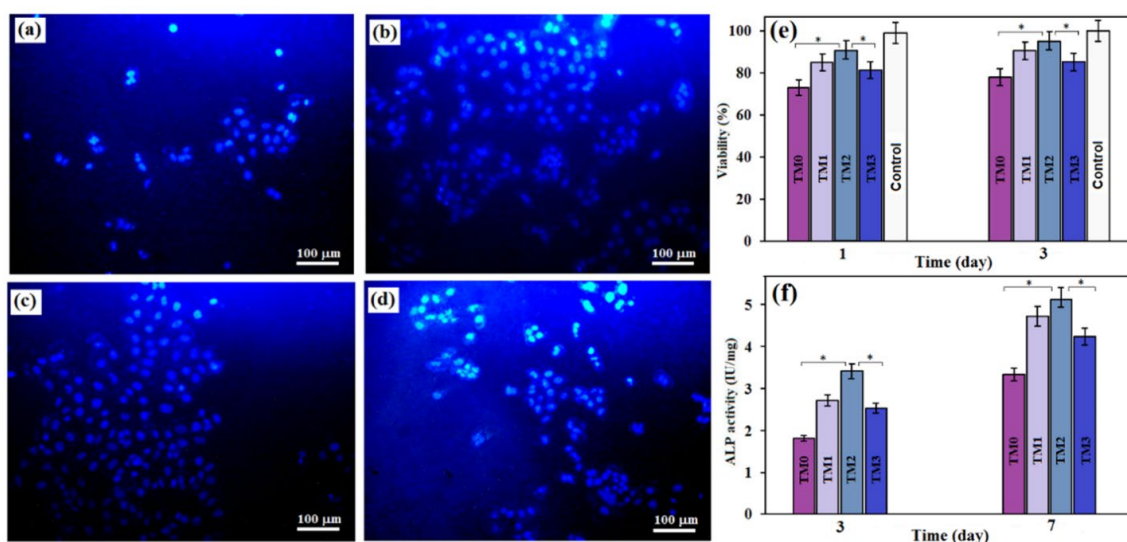
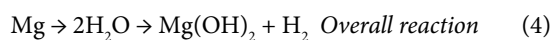
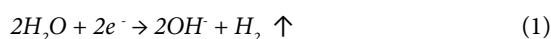


Fig. 3. Fluorescent microscopic images of (a) (Mg-6Zn) TM0, (b) (5TiO₂-0.5MWCNTs) TM1, (c) (10TiO₂-1MWCNTs) TM2 and (d) (15TiO₂-1.5MWCNTs) TM3 (e) Cell viability and (f) ALP activity of TM0, TM1, TM2 and TM3 samples. Reprinted from Ref. [92].

The primary by products of the corrosion reaction is insoluble Mg hydroxide and hydrogen gas, as shown by Eq. (4). Additionally, the hydroxides of the alloying elements and hydrated oxides may be encouraged to develop by the local circumstances. Galvanic corrosion is the main challenge for Mg in orthopaedic applications. In the galvanic series, Mg is the most active metal, serving as the anode when in contact with other metals that act as cathodes due to their higher potential. As a result, Mg alloy implants corrode preferentially [34,113,114]

Additionally, impurities or intermetallic phases within the Mg matrix can lead to uneven galvanic attack. Pitting is a type of localized corrosion that occurs due to the breakdown of the passivation layer in aggressive environments. Compared to other forms of corrosion, pitting is particularly severe because surface pits are often obscured by corrosion products, making them difficult to detect. These pits are highly corrosive, small in size, and can perforate the metal matrix. In Mg alloys, initial pit nucleation on the surface is often followed by accelerated corrosion due to microstructural impurities, which create galvanic differences [34,115,116]. Furthermore, the chloride-rich environment of bodily fluids, combined with Mg ions released from anodic dissolution, accelerates pit growth. Once pitting begins, Mg components can corrode rapidly, compromising the load-bearing capacity of orthopaedic implants. Additionally, pitting increases localized stress, which may lead to crack formation. The development of stress corrosion cracking (SCC) and fatigue cracks within pits can ultimately cause implant failure, even under normal loading conditions [117]. The incorporation of nano-sized reinforcements into the matrix phase can enhance corrosion resistance, provided they are uniformly distributed and present at optimal concentrations. A homogeneous dispersion of nanoparticles promotes the formation of a stable passive film, mitigates localized corrosion, and reduces galvanic effects. However, agglomeration or excessive amounts of nano-reinforcements may have the opposite effect, acting as preferential corrosion initiation sites due to increased interfacial defects or micro-galvanic coupling. Thus, achieving a well-dispersed and controlled concentration of nanoparticles is critical to ensuring improved corrosion performance in nanocomposite materials [118–120]. Radhakrishnan et al. [121] The process of powder metallurgy was used to create the TiO₂

NPs reinforced pure Mg matrix composite, which was then heated to an extrusion ratio of 1.56:1 and sintering. For five distinct reinforcement weight fractions, such as 4, 8, 12, 16, and 20 wt%, in that order. Demonstrated that the powder metallurgy approach, which avoids Mg oxidation and produces reduced porosity, is an effective way to create Mg-based composites. As the weight percentage of reinforcement grows, density is shown to increase, and porosity is at its lowest because of the mixture's finely bonded Mg and TiO₂ particles, demonstrating the least amount of Mg oxidation.

5. Summary and future roadmaps

Overall developments of new biodegradable Mg alloys for medical use are based on the control of the corrosion rate and, thereby, the mechanical integrity of the material in a physiological environment. If the alloy elements are selected correctly, alloy making can refine and optimize the microstructure. Composite making is also one of the effective methods for improving mechanical properties, in addition, composite making can create features by mixing components together, and none of the components alone have it. Composites incorporating innovative materials can activate strengthening mechanisms and, when optimally designed with uniform distribution, may also reduce corrosion rates while enhancing bone-implant integration. However, achieving uniform TiO₂ dispersion and strong interfacial bonding presents challenges, often requiring specialized techniques. In certain environments, TiO₂ may increase the composite's susceptibility to corrosion. Nevertheless, as previously noted, this issue can be mitigated through careful selection of processing and manufacturing parameters. However, further research is needed to better understand how Mg interacts with TiO₂ in biological systems. Currently, there are limited studies in the literature reporting performance results in in-vivo animal models. Overall, biodegradable Mg composites reinforced with TiO₂ present a promising solution to overcome existing material limitations and develop safer, more effective implants for various medical applications. However, research in this field is still evolving, and further optimization is required to address key challenges such as achieving uniform reinforcement distribution, exploring customized distribution via advanced methods like additive manufacturing, and ensuring long-term biocompatibility.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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