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Recent Advances in Metal and Metal Alloy–Based Orthopedic Implants: Processing Strategies, Clinical Challenges, and Future Perspectives

Najmul Hossain[1*], Md. Kowsar Alam[2], Rasheed Ahmad[1], Md. Mizanur Rahman[3], Chowdhury Kaiser Mahmud[4].

[1] *School of Light Industry and Chemical Engineering, Dalian Polytechnic University, Dalian 116034, China*

[2] *Bangladesh University of Textiles, Dhaka-1208, Bangladesh.*

[3] *Bangladesh Medical University, Dhaka-1208, Bangladesh.*

[4] *Bangladesh Atomic Energy Commission, Dhaka-1207, Bangladesh.*

Najmul Hossain: Email: arnazmi03@gmail.com;
Md. Kowsar Alam: Email: kowsaralam017@gmail.com;
Raheed Ahmad: rasheedahmaduetp@gmail.com;
Md. Mizanur Rahman: mizanmmcm50@gmail.com;
Chowdhury Kaiser Mahmud: kaiser.mahmud@baec.gov.bd;

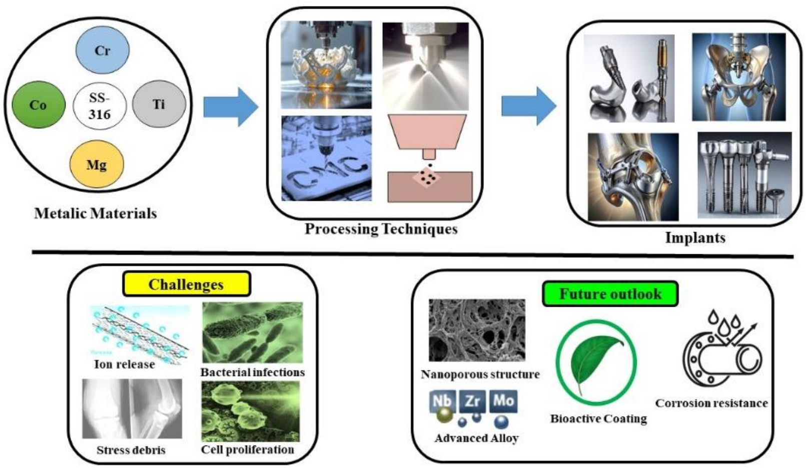
*Corresponding Author
Najmul Hossain
School of Light Industry and Chemical Engineering, Dalian Polytechnic University,
Dalian 116034, China .
Email: arnazmi03@gmail.com;
ORCiD ID: https;//orcid.org/000-003-4657-8724.

Abstract

Orthopedic implants are essential in the restoration of skeletal functions lost through trauma, disease, or congenital abnormalities. Specifically, among biomaterials, metals and metal alloys are the most prominent and popular choice for bearing-loading implants based on their strength, fracture work-of-compliance, wear properties, and long-term utilization in the body. Traditionally, stainless steel, cobalt-chromium alloys, and titanium alloys have been prominent due to their strength and durability under physiological stresses, as well as their anticorrosion properties in biological fluids. Interestingly, recent innovations in metallurgical processing and surface modification have significantly enhanced the performance capabilities and durability of life spans. Processing methods, such as powder metallurgy and rapid prototyping, provide microstructural and geometric designs for implants, while surface modification methods improve efforts directed at enhancement via impedance integration. However, current long-term clinical capabilities are hampered by limitations such as stress-protected implants, ion toxicity, wear-away properties, and reduced impedance bonding. In recent years, emerging innovations such as alloying with biocompatible elements (e.g., Niobium, Zirconium, and Molybdenum) and nanoscale surface modifications have attracted increasing attention, highlighting the need for a comprehensive evaluation of next-generation metallic biomaterials for orthopedic applications. This review gives a comprehensive analysis of recent metallic implants, highlights their mechanical properties, biocompatibility, and surface modification strategies. Furthermore, it also touches existing challenges during processing and clinical application and emphasizes future research directions for next-generation orthopedic implant materials.

Keywords: Biomaterials, Orthopedic implants, Metal Implants, Medical Applications, Metal and Metal Alloys.

Graphical Abstract



1. Introduction

Metallic orthopedic implants are essential in the restoration of the structural and functional integrity of the musculoskeletal system that is affected by trauma, degenerative diseases, and aging. Due to their high mechanical strength, fracture toughness, wear resistance, and fatigue life, metals and their alloys are still the first choice in load-bearing orthopedic applications such as hip and knee prostheses, bone fixation devices, spinal implants, and even dental implants. The metallic biomaterials, stainless steel (316L), cobalt-chromium (Co-Cr) alloys, and titanium (Ti) and its alloys have found extensive utilization in clinical practice due to their long-standing mechanical reliability and their satisfactory biocompatibility (Mani *et al.*, 2024; Sandhu *et al.*, 2025).

More recently, β-type titanium alloys containing biocompatible elements, including niobium (Nb), zirconium (Zr), tantalum (Ta), and molybdenum (Mo), have become more widely studied because they have a lower elastic modulus and higher corrosion resistance, which more closely resemble the mechanical properties of natural bone. Surface engineering, material processing methods, and alloy design have also been enhanced favorably. The porous and lattice structure is capable of implant fabrication within the trabecular bone structure to minimize the mismatch of stiffness and increase the process of osseointegration (Neto *et al.*, 2024). Along with alloy design, surface engineering, and material processing methods have also improved appreciably. Porous and lattice designs allow for implant fabrication in trabecular bone architecture, which reduces stiffness mismatch and enhances osseointegration (Tennyson *et al.*, 2025). Further, there has been a wide application of plasma spraying, ion implantation, and laser texturing to enhance surface roughness, corrosion resistance, and biological activity. Bioactive coatings based on hydroxyapatite, calcium phosphate, and TiO_2 nanotubes further enhance osteoblast adhesion and strengthen bone–implant interfacial bonding (Sunil *et al.*, 2022; Pillai and Mohan, 2025).

Despite these major advances, there are still a number of major concerns that can be identified that prevent the long-term clinical performance of metallic orthopedic implants. One of them is stress shielding, which occurs because of the incompatibility of the elastic modulus between metallic implants and natural bone (1030 GPa), resulting in a non-uniform distribution of loads to bone resorption and subsequent implant loosening (Meng *et al.*, 2023; Marin and Lanzutti, 2025). The release of metal ions and corrosion in physiological conditions is of particular concern since ions such as Ni^{2+}, Cr^{3+}, Co^{2+}, and V^{5+} may cause cytotoxicity and inflammatory reactions, posing a threat to long-term biocompatibility. Besides, wear and tribocorrosion at articulating interfaces release particles of debris that may induce inflammatory osteolysis and implant failure (Gautam *et al.*, 2022; S. *et al.*, 2024). Other issues associated with manufacturing, such as residual stresses, defect formation, and control of porosity, especially in additively manufactured components, also have additional effects on fatigue performance and structural reliability (Davoodi *et al.*, 2022).

To overcome these weaknesses, scientists are now considering low-modulus 0 -type titanium alloys, functionally graded materials, and nanostructured surface coatings. These approaches decrease stress shielding and increase antibacterial characteristics and osseointegration (Balasubramanian *et al.*, 2021; Senopati *et al.*, 2023). Computational modeling and additive manufacturing allow the production and construction of patient-specific implants (Mobarak *et al.*, 2023). Metallic systems that are biodegradable are also under investigation. They offer controllable degradation, release of drugs or ions, and AI-based design to optimize alloy composition, surface functionality, and geometry of implants to achieve the desired properties in particular patients (Xia *et al.*, 2025; Gracheva *et al.*,2025).

In order to curb this gap, the present review provides an integrative perspective of the metallic orthopedic implants in contrasting alloy design, surface and interfacial engineering, advanced manufacturing modalities, and biological performance metrics. Unlike previous reviews, the paper previews the synergistic nexus of mechanical compatibility, osseointegration, immunological response, corrosion and wear dynamics, and degradation pathways, and strictly evaluates the current limitations and ongoing dilemmas. In addition, there are emerging directions in patient-based implant configurational approaches, functionally graded biodegradable materials, intelligent, stimuli-responsive surface geometries that are pointed out in the discussion.

2. Literature search and selection criteria

The literature included in this review was identified through a structured search of major scientific databases, including Web of Science, Scopus, and Google Scholar. Keywords used included 'Metallic biomaterials,' 'Orthopedic implants,' 'Stainless steel-based medical implants,' 'Titanium-based medical implants,' 'Co-Cr alloys for medical applications,' 'Tantalum-based implant materials,' 'Corrosion,' 'Wear,' 'Osseointegration,' and 'Biocompatibility.' The search process focused on peer-reviewed publications based on relevance, scientific merit, and contribution to understanding material properties.

3. Stainless steel-based orthopedic implant

Austenitic 316L stainless steel is still one of the most commonly used metals as a biomaterial in orthopedic implants due to its low cost, ease of manipulation, and excellent mechanical strength, as well as relatively good corrosion resistance. However, it is mainly applied to removable orthopedic implants like bone plates, screws, intramedullary nails, and fixators, in which a substantial load-bearing capacity together with reasonable malleability is mandatory (Ikumapayi *et al.*, 2025). Although these benefits exist, there are various inherent flaws to these materials, such as the erosion of metals in a physiological environment, release of metal ions, wear caused by corrosion, and the bioinert nature of the surface, which negatively affect long-term performance. Therefore, various research studies have been conducted on surface modification, alloying, and composite fabrication towards improving load-bearing, corrosion, antibacterial, and bioactivity (Bandyopadhyay *et al.*, 2023).

3.1. Tantalum-coated 316L stainless steel: tribological and corrosion enhancement

Among various surface modification techniques, tantalum (Ta) coatings effectively enhance the mechanical and biological performance of 316L stainless steel. The enhanced properties of the Ta-coated stainless steel surface are the result of the synergistic combination of the stable tantalum oxide (Ta_2O_5) passive film, the morphology of the surface, and the high adhesive power. Osteoblast adhesion, proliferation, and differentiation are dependent on protein adsorption that is facilitated by the Ta_2O_5 film. The longer the deposition time taken to get the film thickness, the higher the surface coverage and, thus, the mechanical interlocking of the films to the stainless steel substrate, which results in a significant improvement of adhesion strength. The osteoblast adhesion and spreading are further promoted by the hydrophilic nature of the oxide surface, evidenced by cell-culture experiments on the MG-63 osteoblast cell line, and the growth inhibitory and inflammatory effects of the surface are avoided by the Ta-coated surface being inert and the lower ion release rate of the surface (Kumari *et al.*, 2023). Switching to tribological performance, the 316L stainless steel with a deposited Ta film has significant increases in the hardness of the surface and wear resistance. A compact, evenly sputtered Ta film created through DC magnetron sputtering brings with it a plethora of benefits that are associated with the refractory nature of tantalum, which include a very high melting point, strong mechanical strength, and high corrosion resistance. The homogeneity of the movie reduces the skin flaws, thus forming a barrier to the corrosive influence of physiological fluids. Enhanced deposition of the film mass further suppresses the size of the hard Ta-Ta_2O_5 locations at the point of contact, increasing the surface hardness significantly. The decreased elastic modulus of the Ta-coated surface in comparison to bare stainless steel allows elastic deformation under load to prevent the formation of micro-cracks and curb the crack propagation under sustained loads, resulting in wear rates decreasing from 62.50×10^{-5} mm^3/Nm to 3.75×10^{-5} mm^3/Nm (Pathote *et al.*, 2022).

The ability of Ta-coated 316L stainless steel to resist corrosion depends primarily on the inertness and stability of the Ta_2O_5 film and its excellent capacity to attach to the substrate. The Ta layers become thicker, i.e., 1.504 to 6.083 μm, and enhance the quality of the coating by minimising defects and pinhole formation. As a result, the lowest corrosion rate (or approximately 270 mm/year) and the highest impedance curves of the electrochemical impedance spectroscopy are observed in the samples treated for 60 minutes. X-ray photoelectron spectroscopy establishes the presence of Ta elements bonded to substrate elements, Fe, Cr, Ni, and Mo, which reduces the chances of interfacial de -adhesion. The dielectric Ta_2O_5 layer is found to block anodic dissolution and cathodically favored reactions, which significantly reduces electrochemical corrosion (Jaiswal *et al.*, 2023).

3.2. Corrosion behavior and nanoscale compositional engineering of stainless steel

The stability and presence of the chromium oxide (Cr_2O_3) passive layer on the surface of 316L SS are the major factors that promote the corrosion resistance of the material in simulated body fluid (SBF). The polarization studies conducted following immersion in SBF after 60, 90, 180, and 270 minutes depict the sustainability of the passive layer in the presence of low current density to stop anodic dissolution. The high degree of corrosion after 270 minutes indicates the breakdown of the passive layer because of the existence of Cl^- ions in the SBF media. Nyquist plots obtained with electrochemical impedance spectroscopy show a one-time constant passive layer, which is a semicircle that indicates uniform surface coverage and charge transfer resistance values (Pathote *et al.*, 2022).

Besides surface modifications, the role of alloying and compositional engineering on the nanoscale is important in managing the release of ions, surface reactivity, or oxide capabilities of stainless steel alloys. In the modified F2581 alloys, the ability of the alloy is influenced by the partial replacement of molybdenum with the inclusion of elements like Al, Ti, W, or cu. Aluminum, titanium, or tungsten enhances the aptitude of the alloy to form oxide surfaces, including Al_2O_3, TiO_2, or WO_3. All these play a role in lowering the release of metal ions, lowering oxidative stress, or lowering immune system activation. The availability of copper, however, enhances the occurrence of the reactive oxide layers of CuO/Cu_2O. Ion release and protein adsorption are also known to be influenced by the morphology of nanoscale surface structures in the form of a clover leaf. The 27.2 nm mean size of Cu nanoparticles makes them immune stimulators due to their high reactivity of surfaces, whereas larger particles of Al, Ti, and W (average size of 73-98.5 nm) release their ions gradually, and this gives them controlled interaction with biological systems, with insignificant toxicity (Fig. 1a) (Abdelwahab *et al.*, 2025).

3.3. Antibacterial and bioactive surface functionalization and ion-releasing multilayer strategies

Implant-related infections and poor biological performance are critical challenges for stainless steel-based implants. To address the problem of implant-related infection and enhance the biological performance, scholars have introduced numerous antibacterial and bioactive surface functionalization techniques to stainless steel implants. Ion-assisted plasma polymerization proves to be very useful in boosting the antimicrobial activity. It produces a high-density and radical-rich surface by ion bombardment and allows covalent immobilization of antimicrobials like CSA-90. The coatings obtained preserve functional groups and retain antibacterial properties against Staphylococcus aureus without being leached (Fig. 1c). The in vivo murine infection studies exhibit alleviation of bone loss and also exhibit inhibition of colonization and biofilm formation (Dao *et al*., 2024).

Another potential polymeric antimicrobial coating is zein and clove extracts, which were electrostatically deposited. The coating is a homogeneous layer, approximately 9 μm thick, and it is formed by using the natural charge properties of ethanol-water mixtures under a 20V/cm electric field. The clove components are held in the matrix by hydrogen bonds and hydrophobic interactions between the amino acids of zein and phenolic compounds of cloves. The topography is moderate on the surface, with a roughness of approximately 0.8 μm and a hydrophobic contact angle of 60º. These characteristics facilitate desirable cell-binding chemistry at the expense of minimizing fouling. The coating gives wide-spectrum antibacterial protection against *E. coli* and the bacteria of *S. aureus*. This is an activity that occurs due to the loss of membrane integrity under the influence of eugenol. Controlled drug release releases approximately 65% of the active drug in a week, and it is fuelled by diffusion and gradual development of the matrix. The hydrophobic barrier and phenolic metal chelation increase resistance to corrosion by an order of three, due to the decrease in water and ion ingress (Ahmad *et al*., 2023).

Further, to increase adhesion, corrosion resistance, and bioactivity on 316L stainless steel, conductive polymer-ceramic hybrid coatings are used that include polypyrrole/hydroxyapatite (PPy/HAp) multilayer systems. PPy binding, π-d binding, and hydrogen bonding enhance the binding by approximately 20%. There are also physical and electrochemical barriers that reduce corrosion current density in the multilayer architecture, which is reduced by approximately 60. Even though electron transfer is hampered by the inert but conductive properties of PPy, the layers of hydroxyapatite anchor the aggressive ions and maintain the pH at dissolving locations. Besides, bilayered and multilayered architectures exhibit significantly enhanced bioactivity, due to a high affinity to hydroxyapatite or bone mineral phases (Mohandesnezhad *et al*., 2022).

Polyelectrolyte multilayer (PEM) composites have been developed with a multifunctional coating that not only has antibacterial properties but also osteoconductive properties. Poly (γ-glutamic acid)/collagen PEMs can be stabilized by using electrostatic interaction, hydrogen bonding, and ionic cross-linkages. These are thin, even films on stainless steel substrates. Vancomycin-impregnated γ-PGA layers slowly release the antibiotic via the PEM matrix and thus offer the antibacterial effect over a long period. Strontium bioactive glass (SrBG) increases osteoconductivity. Sr^{2+} ion dissolution activates the growth and differentiation of osteoblasts by increasing the supersaturation of Ca^{2+} and PO_4^{3-} ions in simulated body fluid. Higher surface roughness and hydrophilicity (contact angle of ~ 58º) enhance the adsorption of proteins and adhesion of mesenchymal stem cells, forming a more osteogenic microenvironment (Dash *et al*., 2022). Another promising approach to the combination of mechanical strength and bioactivity is functionally graded composites that combine 316L stainless steel and β -tricalcium phosphate (β -TCP). The addition of 316L stainless steel provides good strength and toughness because of the face-centered cubic crystal structure. The introduction of β -TCP offers osteoconductivity because of the long-lasting discharge of Ca^{2+} and PO_4^{3-} ions, which stimulate the growth of hydroxyapatite. Powder metallurgy methods, including high-energy ball-milling, produce uniform ceramic dispersibility and high interfacial bonding, and lead to a decrease in porosity. At 1100℃ sintering, intimate diffusion and densification of ceramics are obtained without breaking down β-TCP. The enhancement of surface wettability and biological performance is due to the dual functionality of the stainless-steel oxide surface and bioactive β-TCP surface (Fig. 1b) (Kuffner *et al.*, 2021). Table 1 shows a summary of stainless steel and SS-based implants for orthopedic applications.

Table 1. Summary of representative stainless steel and stainless steel–based orthopedic implant systems, highlighting their processing routes, surface modification strategies, and corresponding mechanical, corrosion, antibacterial, and biological performances.

Coating Technic	Mechanisms	Findings	Reference
Ta-coated 316L SS – Mechanical & Biocompatibility	A stable Ta_2O_5 layer forms spontaneously; a hydrophilic, corrosion-resistant, inert surface enhances protein adsorption and cell adhesion. Increased coating thickness improves surface coverage and mechanical interlocking.	Adhesion strength increases from 7 to 0.0047 μN; improved MG-6 osteoblast adhesion; reduced ion release and inflammation.	(Kumari*et al.*, 2023)
Ta-coated 316L SS – Wear Resistance & Hardness	Ta provides refractory, dense, defect-minimized coating via DC magnetron sputtering. Ta_2O_5 adds ceramic hardness and corrosion protection; thicker coatings increase hard-phase volume and reduce microcracks.	Wear rate decreases from 62.50×10^{-5} to $3.75\times10^{-5}mm^3/Nm$; improved hardness and tribocorrosion resistance.	(Pathote, *et al.*, 2022)
Ta-coated 316L SS – Corrosion Resistance	Ta_2O_5 forms a stable oxide barrier; thicker Ta layers (1.504 → 6.083 μm) improve uniformity and defect reduction. Good substrate adhesion limits delamination.	Lowest corrosion rate 270 mm/year for a 60-minute coating; highest EIS impedance; fewer pits in SEM.	(Jaiswal *et al.*, 2023)
316L SS in SBF – Passive Corrosion Behavior	Corrosion controlled by Cr_2O_3 passive film stability; chloride ions at prolonged immersion (270 min) break down passivation and cause pitting.	Stable low current density initially; passive layer breakdown increases corrosion rate at later stages.	(Pathote *et al.*, 2022)

Modified F2581 Alloys – Nanoscale Behavior & Biocompatibility	Alloying with Al, Ti, W → stable oxides (Al_2O_3, TiO_2, WO_3); low ion release and oxidative stress. Cu forms CuO/Cu_2O but increases ROS. Nanostructures (nanowires, nanotubes, clover-farm) alter ion release and immune response.	Cu nanoparticles (~27.2 nm) show high reactivity; Al/Ti/W (73–98.5 nm) show minimal toxicity and controlled ion release.	(wahab *et al.*, 2025)
316L SS / β-TCP Functionally Graded Materials	A gradual metal–ceramic transition reduces stress mismatch; β-TCP facilitates Ca^{2+}/PO_4^{3-} release for bone formation; homogeneous dispersion is achieved through ball milling; and sintering at 1100 °C ensures densification.	Improved mechanical strength, corrosion resistance, and bioactivity; enhanced hydroxyapatite formation in SBF.	(Kuffner *et al.*, 2021)
Ion-assisted Plasma Polymerization (IPP) – Antimicrobial Stainless Steel	High-density radicals allow covalent bonding of functional groups; uniform plasma over 3D geometries;CSA-90 mobilization prevents biofilm formation.	In vivo: reduced bone loss in infected mouse model; stable antimicrobial effect without drug leaching.	(Dao *et al.*, 2024)
EPD Zein/Clove Coating	~9 µm uniform film via electrophoretic deposition; clove bonded by hydrogen bonding; strong adhesion (5B); balanced hydrophilicity supports cell attachment; eugenol provides antimicrobial activity.	Contact angle ~60°; roughness ~0.8 µm; controlled drug release ~65% in 1 week; corrosion resistance improved 3 orders of magnitude.	(Ahmad *et al.*, 2023)
PPy/HAp Multilayer Coatings	Strong PPy–metal bonding; HAp adds interlocking and ceramic barrier; layered structure improves corrosion resistance and bioactivity.	Adhesion improved ~20%; corrosion current reduced ~60%; enhanced apatite nucleation in SBF.	(Mohandesnezhad *et al.*, 2022)
PEM/VA/SrBG Composite	PEM stabilized by electrostatic/ionic interactions; chitosan improves adhesion; vancomycin provides sustained release; SrBG releases Sr^{2+} for osteogenesis;	Sustained antimicrobial activity;improved osteoconductivity and	(Dash *et al.*, 2022)

	enhanced roughness and hydrophilicity (CA ~58°).	MSC attachment; increased hardness and elastic modulus.

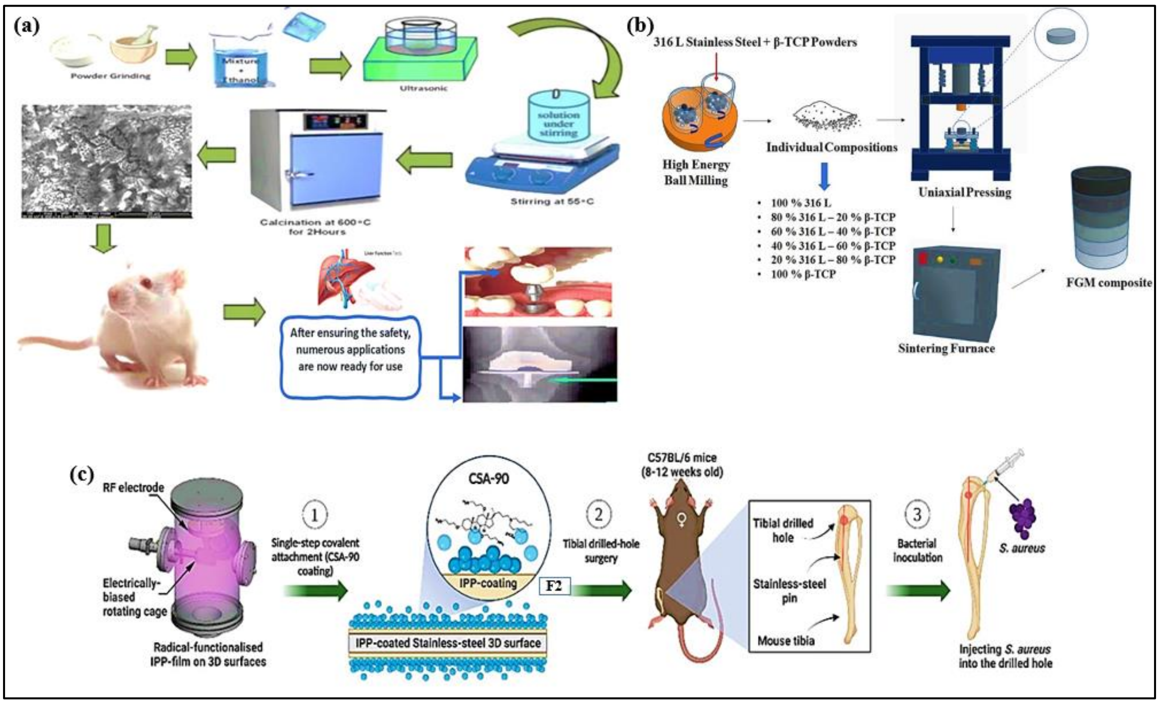


Fig. 1. Overview of biomaterial development and in vivo testing strategies. **(a)** Illustrates the synthesis and characterization of a material, followed by its application in an in vivo animal model (rat) (Abdelwahab *et al.*, 2025). **(b)** Details the fabrication process of functionally graded materials (FGM) composites from 316 L stainless steel and β-tricalcium phosphate (β-TCP) powders via high-energy ball milling, uniaxial pressing, and sintering (Kuffner *et al.*, 2021). **(c)** Describes the surface modification of stainless steel 3D structures using a plasma-polymerized (IPP) coating and a subsequent in vivo infection model using mice to test the material's performance (Dao *et al.*, 2024).

4. Titanium and titanium-based alloys for orthopedic implants

Titanium and titanium alloys have been among the most commonly used biomaterials for permanent orthopedic implants because of the unique combination of low density, high specific strength, excellent resistance to corrosion, and good biological compatibility. The naturally occurring stable TiO_2 passive layer in physiological environments provides a good means of preventing corrosion (Bassyouni *et al.*,2025). Nevertheless, conventional titanium alloys such as Ti-6Al-4V remain limited regarding the mismatch of the modulus of elasticity with respect to bones, as well as the use of potentially cytotoxic alloying components. As a consequence, more recent efforts in the design of titanium alloys have been directed towards the stabilization of phases, solid solution alloying, or the removal of toxic components (Gao *et al.*, 2025).

4.1. Alloying strategies for mechanical strengthening and corrosion resistance

The addition of tin (Sn) when used with titanium alloys has been shown to significantly increase the mechanical properties and corrosion resistance. This is enhanced by stabilization of the α-Ti phase, solid-solution strengthening, as well as intermetallic compound formation in the case of Sn content greater than 10 wt. The simultaneous rate of hardness level can be explained to a great degree by the fact that hardness, yield strength, and ultimate tensile strength are correlated; thus, strengthening caused by Sn is one of the leading processes to enhance the level of mechanical performance. Moreover, due to the increase in Sn concentration, the homogeneity of the TiO2-based oxide passive layer is increased, leading to a significant reduction in corrosion rate. This decrease is estimated by a factor of 1/833, and it decreases 0.03mm/year to 3.65×10^{-9} mm/year for the Ti-6Al-4V alloy at 20 wt.% Sn content (Azmat *et al.*, 2021). The use of a high-powered, focused laser beam for surface nitriding is a good processing route. The diffusion of nitrogen into the alloy is done at high concentration levels by the localized laser heating and produces a titania ceramic layer. This nanocomposite coating has a greater elastic modulus than other alloys, giving it the ability to sustain greater elastic deformation before plastic deformation occurs. Even though β-Ti alloys exhibit mechanical flexibility similar to their substrates and exhibit superior mechanical compatibility to α-alloys or α + β-alloys, they exhibit similar surface hardness and elastic-plastic behavior as the TiG_2 systems, TiG_5 systems, and β-Ti systems , 2021).

4.2. Synergistic microstructural and tribocorrosion enhancement via multi-element alloying

The superior tribocorrosion property and antimicrobial activity of nanostructured Ti-based metallic coatings, such as NTNTs–TiN complex, can be due to synergistic effects that are associated with their structural and chemical characteristics. Tin is used as an alpha-phase stabilizer, thus inhibiting galvanic and electrochemical reactions in simulated body fluid. On the other hand, niobium is a strong β-phase stabilizer, which creates a very stable Nb_2O_5 passive oxide, which increases corrosion resistance and biocompatibility. The submicroscopic dispersion forms a pure dual-phase microstructure (α + β) in planar Sn -Nb alloying, which increases hardness, bearing strength, and wear resistance through solid-solution strengthening and lattice-strain-induced distortion mechanisms (Azmat *et al.*, 2023).

A TiN layer is also incorporated that further enhances the grain structure and increases the hardness, which is 33.2 ± 0.6 GPa. The TiO_2 bioreactive layer reacts with Ca^{2+}, Mg^{2+}, and PO_4^{3-} ions in physiological media to form an in situ Ca-Mg-P-rich tribolayer that is a solid lubricant. Thus, direct metal-metal contact and coefficient of friction are reduced to significantly improve tribocorrosion resistance of the alloys, which is about 44 times higher in Ti-6Al-4V and about two times higher in TiN-coated surfaces compared with uncoated Ti-6Al-4V alloys. Also, the strong antimicrobial properties of TiO_2 and TiN surfaces reduce the adhesion and biofilm formation of bacteria, and thus, confer self-protection of microbes against infection (Zhao *et al.*, 2023).

Niobium and molybdenum are subsequently added in a strategic manner into cobalt chromium sintered alloys to increase their structural, corrosion-resistant, and mechanical properties. Both Mo and Nb are carbide-forming elements that are highly grain-boundary segregated; they are solid-solution hardeners and stabilize the γ-Co (FCC) component and suppress the ε-Co (HCP) component. The alloy is dominated by the γ -Co (FCC) component that regulates the ductility of the alloy, and the small proportion of HCP component that is of benefit to its strength. As a result, the Co-Cr-3.5Mo-3.5Nb alloy has better mechanical strength; solid-solution hardening and spreading of the precipitates decrease the depth of indentation, and accordingly, a decrease in the friction coefficient is observed (Phasani *et al.*, 2025).

4.3. β-type titanium alloys for stress-shielding mitigation

The incorporation of Nb and Si nanoparticles enhances the mechanical, corrosion, and biological properties of Co–Cr alloys. Nb and Si nanoparticles were incorporated into CoCr alloys, and this significantly enhanced the mechanical, corrosive, and biological properties of the alloy because of the stabilisation of the β-phase. The stabilisation of the β-phase is proven by X-ray diffraction findings, as this is the source of increased mechanical properties. This is manifested by a massive growth in the hardness value of 4415 MPa and ultimate tensile strength of CoCrSy alloys over that of the base alloy CoCr. Due to this, Co-Cr-5Si exhibited superior wear resistance characteristics owing to the hard phases that were mainly Si-rich at the grain boundaries. Also, the findings demonstrated an increase in corrosion resistance properties owing to the stabilisation of a passive layer of Cr and Nb oxides. The postulated results of the MTT cell viability assays have been cited to be an outcome of the stabilisation of the β-phase and the passive oxide layer (Jabbar *et al.* 2025).

Titanium exists in two allotropic forms: hexagonal closed packing (hcp) α-Ti at room temperature and body-centered cubic (bcc) β-Ti at high temperatures.The use of appropriate stabilizing elements helps maintain the retention of the β-phase at room temperature, leading to lower elastic modulus and mechanical compatibility with bone. Zirconium is an α-stabilizing element and participates in solid-solution hardening, whereas molybdenum is a potent β-stabilizing element; this element helps to induce stable β-phases in titanium-alloys like Ti13Mo and Ti18Zr13Mo (Fig. 2a). These titanium-alloys show comprehensively improved ductility and stable strengths through combined solid-solution and precipitation hardening processes. But excessive Zr can cause negligible degradation of corrosion resistance properties of the resultant titanium alloys like Ti18Zr-series. In biocompatibility and biological aspects, these alloy series register equal cytocompatibility and osteointegration because of the natural biocompatibility of titanium and the non-toxicity of zirconium and molybdenum, respectively (Guo *et al.*, 2023). β-type TNZM titanium alloys of type Ti-Nb-Zr-Mo are excellent examples of the same philosophy of biocompatible alloy design. A greater amount of Nb helps stabilize the bcc β-phase, and Zr helps induce solid-solution hardening through lattice distortion without showing significant influence on the composition of the phases of titanium alloys. TNZM2 shows the highest hardness because of max Nb-Zr interactions; the hardness is lower in TNZM4 because of larger grains and reduced strains (Fig. 2b). These titanium alloys register tensile strengths of 592-702 MPa and Young's moduli ranging between 68 and 73 GPa and are much closer to the values of cortical bone titanium alloys; they do not contain cytotoxic components and possess very high elastic admissible strain values because of excellent biocompatibility and corrosion-resistance properties (Weng *et al.*, 2021).

Similarly, titanium alloys of type Ti-Nb-Ta-Zr (TNTZ) register mechanical properties based on β-crystal structures and composition of titanium alloys. A great amount of Nb and Ta, and Zr are potent β-stabilizing elements and help maintain retention of the stableβ-phases of titanium-alloys at room temperature and register a low Young's modulus of ~55 GPa because of reduced stresses and shielding against stresses; this aspect significantly helps to enhance biocompatibility because of less stress-shedding effects in human bodies during longer periods, and are categorized under low-stiffness titanium alloys. But the grains of the resultant titanium alloys are coarse of ≈250μm and are prepared through vacuum arc melting; this aspect shows reduced tensile strengths of 590 MPa and elongation of 13.47% because of limited slip systems of stableβ-phases of titanium alloys, and are inferior to Ti6Al4V and 316 L SS because of limited slip systems of stable β-phases of titanium alloys (Raza *et al.*, 2022).

4.4. Surface bio-functionalization and osteogenic enhancement

Besides the bulk alloy design, another necessary factor in the enhancement of osteogenic properties is the surface property modification. Cytocompatibility can be maintained by adding low levels (0.3-1%) of boron to Co-Cr alloys and enhancing osteogenic properties. It may be explained by the creation of stable borate complexes with Ca^{2+} and PO_4^{3-}, the perfection of microstructure through the strengthening of grain boundaries, and biologic micronutrient action in the control of the expression of osteogenic genes. Moreover, minuscule quantities may be applied in collagen production, but moderate concentrations (0.6-1%) have a tremendous effect in enhancing alkaline phosphatase (ALP) and Runx2 gene expression, indicating enhanced mineralization (Mendez *et al.*, 2021).

Further improvements in the osseointegration of titanium-coated samples of Co-28Cr-6Mo alloy have to do with plasma immersion ion implantation (PIII). The Ti film provides a bioactive topography of titanium dioxide (TiO_2) surface topography that can be further adsorbed with proteins and osteoblasts, besides the natural matrix biomimicry provided by PIII. Conversely, non-implanted and additively processed Co-Cr-Mo surfaces have good mechanical properties (Fig. 2c) and poor matrix biomimicry and Ti-film bioactivity, resulting in poor bone ingrowth. A perfect result of the osseointegration process could be possible only when synergism is present in surface chemistry or topography features (Iatecola *et al.*, 2021).

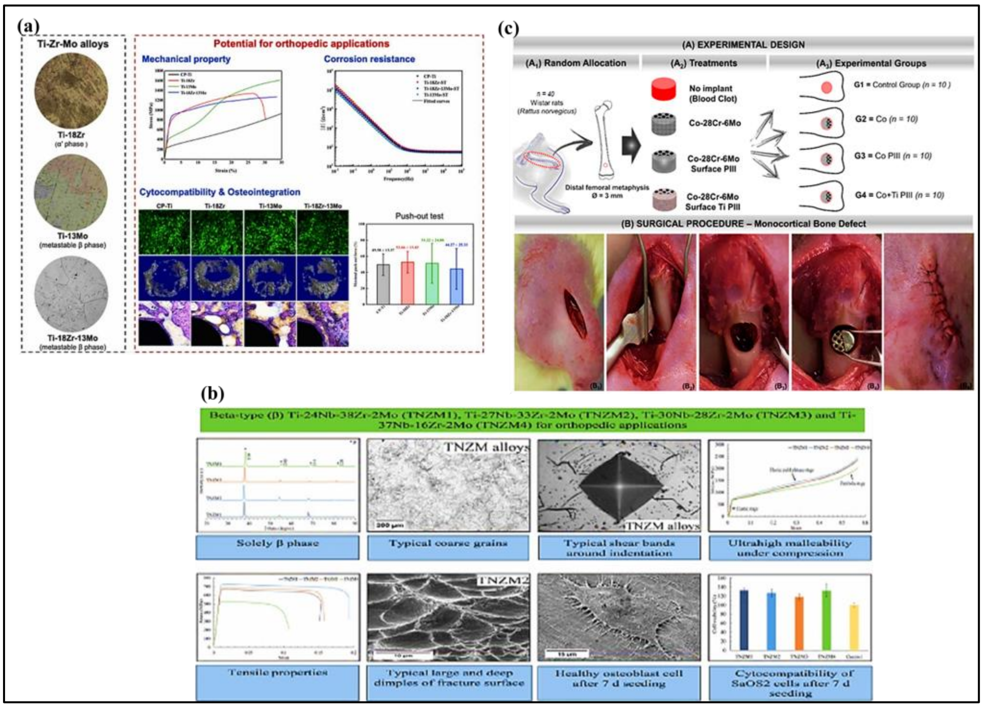


Fig. 2 Comprehensive evaluations of the mechanical, corrosion, biological, and in vivo performance of β-type Ti–Mo and Ti–Nb–Zr–Mo-based alloys for orthopedic applications. **(a)** Microstructural characteristics,

mechanical strength, corrosion resistance, cytocompatibility, osteointegration, and push-out performance of Ti–xMo alloys (Guo *et al.*, 2023). **(b)** Structural features, grain morphology, deformation behavior, tensile properties, fracture characteristics, and in vitro cytocompatibility of Ti–24Nb–3Zr–2Mo (TNZM1), Ti–7Nb–3Zr–2Mo (TNZM2), Ti–30Nb–28Zr–2Mo (TNZM3), and Ti–37Nb–16Zr–2Mo (TNZM4) alloys (Weng *et al.*, 2021). **(c)** Experimental design and surgical evaluation in a monocortical bone-defect model to assess osseointegration and biological response (Iatecola *et al.*, 2021).

4.5. Biological risks associated with metallic nanoparticle release

The biological safety of metallic implant materials is a concern due to the release of metal nanoparticles generated by wear and corrosion processes. Although these materials have many benefits, they can also be potentially toxic from a biological perspective due to the release of metal nanoparticles caused by wear and corrosion. The combined role of Co/Cr/Ti nanoparticles leads to greater cytotoxicity and a higher degree of pro-inflammatory events caused by the synergistic effects of their physicochemical interactions. The partial oxidation of Co and Cr leads to the release of ions such as Co^{2+} ions and Cr^{3+}/Cr^{6+} ions, which are involved in the generation of ROS, alterations in redox homeostasis, mitochondrial damage, and apoptosis. Titanium helps in the agglomeration of metal nanoparticles, co-localization of Mφ, enhancing local ROS production, and metal ions release. These factors activate NF-κB and MAPK signaling pathways, influencing the expression of the pro-inflammatory mediators, such as up-regulated expression of IL-1β, IL-6, IL-8, and TNF-α, which in turn is involved in implant failure due to an increase in the degree of inflammation (Liu *et al.*, 2023). Table 2 summarizes representative titanium and titanium-based alloy systems for orthopedic implants, highlighting their alloying strategies, processing routes, mechanical performance, corrosion resistance, tribological behavior, and biological responses.

Table 2. Application summary of Titanium-based alloys for orthopedic implants.

Alloy	Key Mechanisms	Improvements in mechanical properties	Corrosion and Tribocorrosion Effects	Reference
Ti–Sn Alloys	Sn stabilizes α-Ti, solid-solution strengthening, intermetallics >10 wt.% Sn; SnO_2 passive film formation	↑ hardness, ↑ tensile strength, and impeded dislocation flow	Passive layer becomes denser; corrosion rate decreases from 0.03 mm/yr (Ti6Al4V) to 3.65×10^{-9} mm/yr at 20 wt.% Sn	(Azmat *et al.*, 2021)
Laser-Nitrided Ti Alloys (TiG2, TiG5, β-Ti)	Formation of a TiN-rich ceramic layer; high nitrogen diffusion; residual compressive stress	↑ hardness, ↑ elastic strain energy; β-Ti maintains a low bulk modulus	Stable nitride layer resists wear; microcracks are possible due to thermal gradients	(Shirazi *et al.*, 2021)

Ti5Sn & Ti5Sn5Nb (NTNTs-TiN Coatings)	Sn stabilizes α phase; Nb stabilizes β phase; oxide layers (SnO_2, Nb_2O_5)	↑ hardness, ↑ wear resistance, refined α+β microstructure	Reduced anodic dissolution; improved passivity vs Al/V - containing alloys	(Azmat *et al.*, 2023)
TiO_2 Nanotube + TiN Nanoparticle Coatings	Grain refinement; tribolayer formation (Ca-Mg-P); high surface area	Hardness 33.2 ± 0.6 GPa; ↑ wear resistance	COF = 0.22; 44× better tribocorrosion than bare Ti6Al4V	(Zhao *et al.*, 2023)
Co-Cr-3Mo-3Nb & Co-Cr-3.5Mo-3.5Nb	Mo & Nb form stable oxides (MoO_3, Nb_2O_5); γ-Co stabilization; carbide formation	↑ solid-solution hardness; ↓ indentation depth	Highest polarization resistance; minimal corrosion rate	(Phasani *et al.*, 2025)
CoCr + Nb & Si Nanoparticles	β-phase stabilization; solid-solution (Nb)[+] dispersion strengthening (Si)	Hardness ↑ to 4415 MPa; UTS 95.19 MPa; ↑ compressive strength	Dense Nb-/Cr-rich oxide improves corrosion	(Jabbar *et al.*, 2025)
β-Type TNZM Alloys (Ti-Nb-Zr-Mo)	Nb, Mo = β-stabilizers; Zr = solid-solution strengthening	Hardness highest in TNZM2; tensile strength 592–702 MPa; modulus 68–73 GPa	Excellent corrosion resistance due to non-toxic elements	(Weng *et al.*, 2021)
TNTZ (Ti-Nb-Ta-Zr)	Strong β-stabilizers (Nb, Ta, Zr); metastable BCC	Tensile strength 590 MPa; 13.47% elongation; low modulus 55 GPa	Passive film stable; improved wear after heat treatment	(Raza *et al.*, 2022)
Co-Cr-B Alloys (0.3–1% B)	Borate formation; microstructure refinement	↑ wear resistance; no loss in corrosion resistance	Stable passive film maintained	(Mendez *et al.*, 2021)
Ti-Coated + PIII-treated Co-Cr-Mo	TiO_2 formation + nanotopography; high surface energy	—	Enhanced osseointegration due to bioactive surface	(Iatecola *et al.*, 2021)

5. Cobalt chromium-based orthopedic implants

Spinodal alloys Zr-Nb have been demonstrated to be very beneficial in terms of mechanical, chemical, and biocompatibility properties that will be used in the future generation of bone implants. The nanodomain periodicity of the nanoperiodic structure that develops within the miscibility gap of the alloys as a result of aging treatments conducted at 650℃ forms the nanoperiodic structures of the incompatible Zr (β1 phase) and Nb (β2 phase). For the $Zr_{60}Nb_{40}$ alloy, β-phase precipitation is minimal, and the strength mainly arises from unstable α-phases, influenced by the pinning effect at phase boundaries. Nb and Zr chemically give stable passive oxides (Nb_2O_5, ZrO_2) in physiological conditions (Fig. 3a), like in the Hanks solution, with extremely low discrete corrosion rates of 94-262nm/year. The alloys are highly biocompatible (> 98% MC3T3-E1 cell viability) to facilitate reduced ion leaching and control cell adhesion and growth (Hua *et al.*, 2024).

The Co-Cr alloys containing Mo and W enhance the mechanical hardness and corrosion resistance of the alloys. Mo, being less dense than Co and Cr, takes the interstitial location in the crystal structure, thus resulting in distortion and decreasing dislocation, making it difficult and wear-resistant. Formation of carbides and intermetallic compounds is also experienced by Mo, refining the grain structure and solidifying the HCP structure in addition to W, which, being highly electronegative, facilitates the formation of a protective layer of oxides, including WO_3, around the surfaces, leading to minimized ion dissolution and focal corrosion in Mo submerged in an aqueous solution (Saha *et al.*, 2024).

Surface Mechanical Attrition Treatment (SMAT) causes an enormous change in the microstructure and phase mposition of CoCrMo alloys. This can be attributed to high plastic deformation and hence phase transformations brought about by deformation. The number of dislocations and stacking faults is enormous, and it serves as the place of nucleation of the phase transformation of Co-Cr-Mo. With severe straining, the γ-fcc Co-Cr-Mo metastable phase is changed to the ε-hcp phase. At the atomic level, Co, Cr, and Mo atoms reposition themselves to fit in the new lattice that has been formed. Besides the readjustment, the alloying elements also maintain a stabilizing effect on the structure by reducing the internal stresses and hindrances to diffusion (Nkonta *et al.*, 2021). Co-Cr and L alloys possess almost equal dendritic microstructures that have a low value of porosity, representing a uniform solidified structure containing fewer internal imperfections. The various possible potentials of Co-Cr alloys corrosion lie between −0.280 V vs SCE and −0.250 V vs SCE, and a PREN of over 38. This is directly because of the rapid growth of a stable, strongly binding layer of passive chromium oxide. It is clear that chromium causes the passivation effect, and in turn, cobalt is a powerful mechanical base. Based on the measured data on the EIS, the measured impedance value and the resulting potentials (Fig. 3b) are more likely to indicate that the specimen with label L had a higher value. It is a fact that specimens, which are tagged with the label C, tend to represent a lower order of 134±13 GPa. This may be due to a constant composition component, micro constituents to the size of the arms of the dendrites, and other subtleties of distribution, which allow the specific material to attain a higher degree of elasticity (Fratila *et al.*, 2023). Passivating oxide layer properties of the chromium species are, to a significant degree, what determine the tribological properties of wrought Co-Cr alloys. The chromium oxides play the role of chief agents in the formation of highly passive tribofilms. The dissolution of the alloys could be resisted by the heavy flow in a pH 6.9 (neutral) and a pH 9 (basic) environment of the artificial saliva solution, whereby the electrical resistance to the dissolution of the alloys to heavy metal ions is high. A high concentration of hydrogen ions in the pH 4.8 (acidic) solution of the artificial saliva solution is likely to disrupt the high electrical resistance of the passive layers during the dissolution of the heavy metals. The periods of immersion of 7-28 days lead to minor alterations of surface roughness due to the formation and deposition of oxides, phosphate, and calcium species, as well as to pitting corrosion in the acidic solution. Oxide layers are so hard in the instance of dry sliding that their adhesion is reduced, which leads to abrasive wear due to the relative fragility of the oxide layer compared to the steel material. P and Ca are preferentially deposited on Co-Cr. This means that the chemical affinity of P and Ca with Cr and Co oxide layers and their application in the formation of protective phosphate layers is observed (Saha *et al.*, 2023).

The Co-Cr alloy exhibits high corrosion sensitivity with an unstable and discontinuous passive layer, which has a lower corrosion potential and higher current density. Mo improves the properties of passive layers by forming MoO_4^{2-} ions in the $Cr_2O_3^-$ rich matrix, which provides better pitting and localized corrosion resistance, although this low amount, 5-6 wt%, is insufficient to completely stabilize these layers. For optimal combinations of Mo and Nb, in this case, Co-3.5Mo-3.5Nb, there is an increase in corrosion potential and reduction in current density, resulting in slow and uniform corrosion. On the other hand, the unbalanced ratio of Mo/Nb, for example, in Co–Cr–3Mo–3Nb, compromises the integrity of the passive layer, leading to higher current densities and detrimental corrosion potentials (Dada *et al.*, 2024).

Niobium (Nb) and molybdenum (Mo) exhibit a synergistic effect to improve the microstructure, stability, and strength of Co-Cr biomedical alloys. The first function of Mo in the alloy is the strengthening of the passivation layer Cr_2O_3, whereas the second function of Nb, which is a powerful carbide-former and solid solution strengthener, prevents the conversion to the ε-Co hexagonal close-packed (HCP) martensite. The alloys Co-Cr-3Mo-3Nb that contain the largest amount of Mo and Nb are able to significantly increase the passivation layer. The addition of higher levels of 3.5% Mo and 3.5% Nb to the alloy structure (Co-Cr-3.5Mo-3.5Nb) leads to the homogenization of the alloy particles. The application of the alloy compositions has minimized the average coefficient of friction by creating a smoother abrasive wear layer (Phasani *et al.*, 2025). The characteristics of the cobalt-chromium alloys, especially the body-centered cubic (BCC) alloys, render them very valuable to the biomedical community. These alloys have great crystallography, alloy composition, and transformable phases that have led to excellent mechanical and resistant to corrosion properties. The single-crystal alloys are special in the composition of the direction that is being hot-forged, giving them a low elasticity modulus, hardness, good wear resistance, and superelasticity due to their strong lattice structure. They lack stress-shielding behavior compared to other alloy biomaterial composites, where stiffness exceeds 100 GPa, as compared to the human bone elasticity modulus, which ranges between 10-30 GPa on average. The low stiffness and directionally aligned atomic structure achieve a range of modulus comparable to human bones. The BCC lattice is special, and a reversible transformation can take place between ε-Martensites and the BCC austenite. It renders the super elasticity at low strains up to 17% strains. The lattice structure is also highly resistant to wear due to the good strain, hardening, or strong solid solution hardening (Odaira *et al.*, 2022). The unit cell has offered a strong potential contribution to the super elasticity because of the re-entrant designs associated with the special geometry. The use of the Co-Cr-Mo alloys has enhanced the strength, hardness, and elasticity because of the strong strain hardening and the passivation layer of Cr_2O_3. The passivation layer acts both in low and highly porous scaffolds at 73% to 82% strength. Enhanced porosity is known to negatively affect the strength of these lattice structures, making these scaffolds biomechanically appropriate for load-bearing purposes (Wanniarachchi *et al.*, 2022).

The cobalt-chromium (Co-Cr) alloy is applied in the fixation devices of the femoral neck fracture because of its best mechanical and chemical characteristics. Co-Cr has good mechanical strength, stiffness, fatigue, and wear resistance characteristics compared to other alloys such as stainless steel, pure titanium, Ti6Al4V, and magnesium alloys (WE43). Magnesium alloys are easily transportable, degradable, and corrosion-resistant, but magnesium alloys with higher strength, such as WE43, are thrombogenic. The corrosiveness of magnesium may be detrimental to the tissues, but magnesium alloys are considerably lighter than other materials. Neither magnesium nor titanium alloys are as stiff, and titanium is also more biocompatible than magnesium. Stainless steel demonstrates better mechanical performance, but it is not applied in numerous bone fixation interventions because of the reduced stress resistance to fatigue. Therefore, along with optimum chemical passivation, fatigue strength, and stiffness, Co-Cr has incorporated other properties of interest in the cannulated screw fixation of the neck of the femur that are aimed at both mechanical and medicinal aspects in the fixing process of the bones (Cakir *et al.*, 2022). The porosity-related graded structure and surface features make the porous structure of Co-Cr porosity-variable (POR-VAR) significantly better than Co-Cr porosity-fix (POR-FIX) in terms of mechanical and medicinal use. In the case of Co-Cr porosity-variable and variable porous structure, mechanical and medicinal properties are far better because it has the capacity to move and control the overall stress, which, in the case of porosity-variable structure, is far better than porosity-fix compression stress by 2.5 times. The other medical properties of porosity-variable are associated with the surface areas in the event of a porous structure, where bone cells can easily be bound, developed, and absorb important nutrients because of the porosity-related structural characteristics. Evidence of osteogenic signaling was also indicated by a high OPG/RANKL ratio and the decline in pro-inflammatory cytokines IL1b and COX2 during the progression of the condition in support of bone formation(Pagani *et al.*, 2021).

Electrochemical hydrogenation alters the surface chemistries and electronic structures; thus, it enhances the physicochemical properties of H-CoCrMo by improving its biocompatibility. The hydrogen atoms diffused into the alloy lattice at a depth of 106±27 nm due to cathodic hydrogen charging, which may alter the surface electronic structures in terms of the number of unpaired electrons. This reduces the free radicals by 85.2%, resulting in a reduction in oxidative stress as well as inflammation. Hydrogenation enhances the hydrophilic properties of H-CoCrMo as indicated by the reduction in the contact angle value from 83.5±1.9° for CoCrMo to 52.4±2.2° in H-CoCrMo. This improves hydroxyapatite nucleation by 11.4%. Hydrogenation improves the anti-inflammatory, osteogenic, and biocompatibility properties of CoCrMo alloys intended for use in orthopedic implants (Lin *et al.*, 2024).

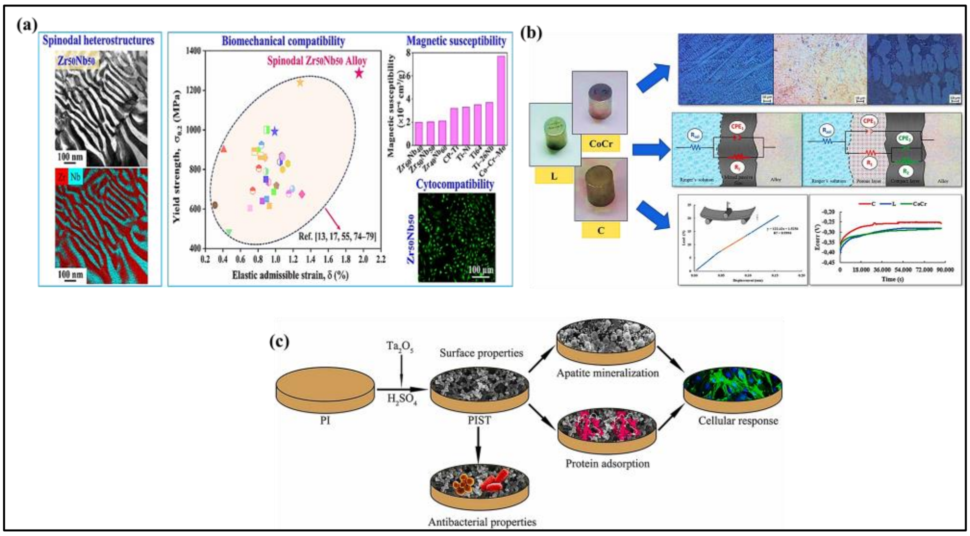


Fig. 3. Multiscale characterization and biological performance of engineered biomaterials. **(a)** Spinodal microstructuring in Zr–Nb–Si-based alloys and its effects on elastic compatibility, magnetic behavior, and cell viability (Hua *et al.*, 2024). **(b)** Surface appearance, microstructure, and functional testing of Co–Cr–C–L alloy variants, including corrosion behavior and mechanical stability (Fratila *et al.*, 2023). **(c)** Fabrication and functional mechanism of sulfonated polyimide with Ta_2O_5 incorporation (PIST), highlighting enhancements in surface reactivity, antibacterial properties, protein adsorption, apatite mineralization, and subsequent cellular interactions (Asadullah *et al.*, 2021).

The Co-Cr alloys were synthesized in this study using conventional powder technology and sintered in an argon atmosphere. Pellets were made using both uniaxial pressing and cold isostatic pressing to achieve high-density pellets. Microstructural analysis was done using SEM, EDX, and AFM analysis. Biocompatibility was analyzed by immersing the materials in SBF, followed by analysis of ions using AAS. The results revealed that the alloy density and microstructure are fundamental factors in alloy performance. The alloy treated at 1200°C for 2 hours increased metal ions in the released ions, but had a decrease in Cr ions, which were found to decrease with time, with an increase in ductility, reduction in hardness, and increased metal ions in the subjected materials compared to the non-treated materials (Vittayakorn *et al.*, 2021). Here, Table 3 shows a summary of Co and Co-based alloys applications as orthopedic implants.

Table 3. Summary table of Copper and copper-based alloys for orthopedic implants.

Alloy	Key Mechanisms	Mechanical Properties	Chemical Behavior	Functional Outcomes	Reference
Cast Co-Cr & Alloy L	Dendritic microstructure; Cr_2O_3 passive layer	Modulus 134 ± 13 GPa for Alloy C	PREN > 38; Alloy L shows slightly better corrosion resistance	Cast Co-Cr & Alloy L	(Fratila *et al.*, 2023)

Spinodal Zr–Nb (e.g., Zr60Nb40)	Spinodal decomposition into β1/β2 nanophases; limited α-phase; phase-boundary strengthening	High yield strength and hardness due to nanoscale phase separation	Very low corrosion rate 94–262 nm/year in Hank's solution	>98% MC3T3-E1 viability; good MRI compatibility	(Hua *et al.*, 2024)
Co–Cr–Mo–W	Mo causes lattice distortion, carbide formation; W promotes WO_3 passive film.	Increased hardness, wear resistance, and grain refinement	Formation of stable Mo- & W-oxides; reduced ion dissolution	High biocompatibility for dental use	(Saha *et al.*, 2024)
SMAT-treated CoCrMo	Severe plastic deformation; $\gamma \rightarrow \varepsilon$ martensite transformation; nanocrystallization	Increased hardness and phase stability	Stable structure due to reduced diffusion & high dislocation density	Enhanced surface mechanical performance	(Nkonta *et al.*, 2021)
Wrought Co–Cr (tribology study)	Cr_2O_3 passive film; tribofilm formation depending on pH	Hard oxide increases abrasive wear in dry sliding	Stable film at pH 6.9–9; breakdown at pH 4.8; Ca/P tribofilm forms in saliva	Reduced friction in saliva; pH-dependent wear	(Saha *et al.*, 2023)
SPS Co–Cr–Mo–Nb	Mo forms MoO_4^{2-}; Nb forms Nb_2O_5; passive film stabilization	Depends on Mo/Nb ratio; optimal in Co–Cr–3.5Mo–3.5Nb	Increased Ecorr, reduced icorr in balanced compositions	Improved corrosion resistance and implant reliability	(Dada *et al.*, 2024)
BCC Co–Cr	<001> texture reduces modulus; reversible martensite transformation	Superelasticity up to 17% recoverable strain; high wear resistance	Cr_2O_3 passivation; stable solid solution	Low stiffness, similar to bone; excellent for implants	(Odaira *et al.*, 2022)
Auxetic CoCrMo Meta-biomaterials	Re-entrant auxetic geometry redistributes load;	High modulus, yield, and ultimate strength	Cr_2O_3 passive chemistry	Enhanced mechanical performance for scaffolds	(Wanniarachchi *et al.*, 2022)

	solid-solution strengthening.	at 73–82% porosity			
Co–Cr for FNF implants	Strong, solid solution; stable passive Cr_2O_3	Superior strength, stiffness, and fatigue life compared to Ti or Mg	Very low ion release	Excellent load transfer; prevents loosening	(Cakir *et al.*, 2022)

6. Tantalum and tantalum-based alloy for orthopedic implants

Biomaterials made of tantalum are also becoming popular in the orthopedic field as they are resistant to corrosion, chemically stable, and highly biocompatible. Their high performance is due to the naturally formed dense Ta_2O_5 layer, which is inert but bioactive and assists in the bone to blend with the implants. Polymeric materials such as PI are bioinert, and they do not have groups that proteins attach to, which limits their biological use. This limitation has been overcome by coating them with Ta_2O_5. To enhance covalent and non-covalent bonds between PI and Ta_2O_5, the addition of a polydopamine (PDA) interlayer assists ceramic nucleation and keeps the coating fixed. Due to high numbers of surface hydroxyl groups, Ta_2O_5-coated surfaces are made more hydrophilic, hence enhancing protein adsorption and cell adhesion. The nanostructured roughness of the Ta_2O_5 layer enhances surface area and topographical cues, which regulate the cytoskeleton organization, focal adhesion establishment, and osteogenic differentiation process in bone marrow stem cells (BMSCs) (Asadullah *et al.*, 2023).

Therefore, tantalum has good surface chemistry and resistance to corrosion and can be a good substrate to deposit hydroxyapatite (HAp). In combination with hydrothermal synthesis, the surface energy and hydroxyl groups of Ta or Ta_2O_5 enhance the process, favoring the heterogeneous nucleation of calcium phosphate. This yields thick crystals of HAp in the form of rods, uniformly distributed (between 0.3 and 0.6 μm). These nano-characteristics increase surface area and promote protein adsorption, cell adhesion, spreading, and osteoblast growth and differentiation. Moreover, the chemical similarity of HAp to native bone, combined with a bioinert but osteoconductive Ta_2O_5 interlayer, makes HAp strongly bonded at the bone-implant interface to enhance the calcium phosphate deposition and increase the interfacial bonding in vitro (Bartkowiak *et al.*, 2022).

Surface roughness is considerably increased with the incorporation of vTO compared to its non-sulfonated and lightly modified counterparts, thus providing mechanical cues that stimulate cytoskeletal organization and promote the proliferation of BMSCs (Fig. 3c). Chemically, vTO interacts with phosphate and calcium ions, accelerating apatite deposition and increasing the overall mineralization.Enhanced antibacterial activity in such systems was believed to arise from a combination of physical hindrance induced by micro-roughness and a localized ionic microenvironment mediated by tantalum oxide species (Asadullah *et al.*, 2021).

The multifunctional role of tantalum and tantalum-based coatings, encompassing corrosion resistance, enhanced bioactivity, osteoconductivity, and antibacterial performance, positions these materials as promising candidates for next-generation orthopedic implants. When combined with polymeric substrates or bioinert materials, Ta-based surface modifications provide an effective strategy to overcome biological limitations without compromising mechanical integrity.

7. Strategies for Enhanced Mechanical Compatibility and Biocompatibility

Metallic and alloy implants work by tailoring microstructure and phase composition. Interacting with the host improves mechanical properties, modifies surface chemistry, and controls corrosion behavior to control biological interactions and ion release (Haghighi *et al.*, 2019; Ammar *et al.*, 2025). Considering mechanical compatibility, metal alloying strategies are essential in enhancing the mechanical properties of implants to ensure that they are close enough to those of natural bone. The mechanical properties that are targeted by metal alloying include the modulus of elasticity, tensile strength, fatigue resistance, and hardness (Jawed *et al.*, 2022; Bandyopadhyay *et al.*, 2023). The modulus of elasticity is essential because it is close to that of bone. The modulus of elasticity is a function of crystal structure and phase composition. The addition of β-stabilizers such as Nb, Ta, Mo, and Zr to Ti alloys increases the content of the β-phase (BCC structure), whose modulus is less than that of the α-phase (HCP structure) (Yang *et al.*, 2011; Banerjee and Williams, 2013; Santos *et al.*, 2024). The addition of alloying elements to metals results in solid-solution hardening, as well as precipitation hardening, which affects mechanical reliability by retarding dislocation movement.

From a biological point of view, the effect of alloying is significant on surface chemistry, corrosion properties, and ion release, which are key factors in biocompatibility. The effect of alloying is related to the interaction of the material with the biological environment at the surface level and electrochemically (Ding *et al.*, 2014; Gouda *et al.*, 2026a, 2026b). The elements Nb, Ta, and Zr form stable, dense oxide films, as shown by the examples of Nb_2O_5 and Ta_2O_5. The replacement of Al and V eliminates the harmful effect of ion leaching, while the biocompatible elements release fewer cytotoxic or even bioinert ions (Rosalbino *et al.*, 2011; Xu *et al.*, 2018; Antolinez *et al.*, 2026). Metal and metallic alloy-based implants improve passivation behavior, reducing degradation and preventing inflammatory responses caused by metal ion release. Alloying regulates electrochemical potential and micro-galvanic effects, allowing precise tuning of degradation rate to match tissue healing. Modified surface chemistry influences protein adsorption, which governs cell adhesion, proliferation, and ultimately osteointegration.

8. Comprehensive comparison of different metallic biomaterials for implants

The properties of biomaterials that are used in orthopedic and biomedical applications are different based on their original materials and specific alloy formation. Metallic biomaterials like 316L steel show excellent mechanical properties with a Young's modulus of approximately 190–200 GPa, and their tensile strength is from about 500 to 700 MPa. 316L stainless steel is also shows adequate flexibility with 40% elongation(Ang *et al.*, 2017; Kraišnik *et al.*, 2018; Bandyopadhyay *et al.*, 2023c). These properties of 316L steel, along with its low cost and resistance to corrosion, make 316L stainless steel a good choice for devices that fix fractures for stents and for implants that can be removed. Cobalt–chromium alloys are even stronger than 316L steel. Cobalt–chromium alloys have a stiffness of about 200–230 GPa, and their tensile strength is often more than 900 MPa (Ang *et al.*, 2017; Kraišnik *et al.*, 2018; Bandyopadhyay *et al.*, 2023). Cobalt–chromium alloys also show excellent wear resistance properties. This makes Cobalt–chromium alloys very suitable for applications where they have to bear a lot of weight, such as joint replacements and dental prostheses (Fu *et al.*, 2022).

Pure Titanium that is used for commercial purposes has a lower modulus of about 110 GPa and moderate strength of about 240 MPa (Ang *et al.*, 2017). However, titanium is very compatible with the body and has better osseointegration. Titanium shows a modulus of ~107–125 GPa and tensile strength up to 1200 MPa, along with a high strength-to-weight ratio, making it useful for implants like bone plates and joint prostheses (Ang *et al.*, 2017; Niinomi, 2019; Bandyopadhyay *et al.*, 2023). In recent research, β-type titanium alloys have gained attention due to their lower elastic modulus (~40–60 GPa), which is close to that of natural bone, which helps minimize stress shielding. For instance, Ti–Nb–Ta-based alloys such as Ti–10Nb–5Ta and Ti–13Nb–5Ta exhibit modulus values of ~40–50 GPa and tensile strength ~600 MPa, making them promising candidates for dental and orthopedic applications. Alongside, complex concentrated alloys (e.g., Ti–Zr–Hf–Nb–Ta–Mo–Sn) show comparable low modulus (40–50 GPa) and high strength (600–915 MPa), considered as an advanced material for next-generation implants (Niinomi, 2019; Wu *et al.*, 2025; Yin *et al.*, 2025).

Magnesium and Zinc alloys are also studied as potential implant materials. Magnesium alloys have a tensile strength of 180-350 MPa, with a high strength-to-weight ratio. The degradation time varies from 3 to 12 months. This makes them suitable for implants that can dissolve in the body, like stents for blood vessels. For example, the WE43 alloy has a modulus of 40–50 GPa and a strength of 220–330 MPa. However, magnesium alloys show a rapid damage tendency, which is a major concern (Kraišnik *et al.*, 2018; Xia *et al.*, 2025).

On the other hand, Zinc alloys decay at a more controlled rate, usually over 12-24 months. Their tensile strength range varies from 200 to 300 MPa with an elastic modulus of 110 GPa. This indicates Zinc alloys' potential for blood vessel and bone implant applications(Xia *et al.*, 2025). Overall, Material selection for implants requires a balance between mechanical properties, performance, and host body interaction. This balance is crucial for the long-term success of the implant. Here, Table 4 represents a summary of the properties comparison of the most common metallic implants.

Table 4. Summary table of comparison of different metallic biomaterial implants.

Materials	Specification	Young's Modulus (GPa)	Tensile Strength (MPa)	Degradation timeline	Performance highlights	Reference
Titanium	Commercially Pure Ti	~110	~240	Non-degradable	Excellent biocompatibility and osseointegration; dental implants	(Kraišnik *et al.*, 2018)
	Ti-10Nb-5Ta	40–50	~600	Non-degradable	Dental implants	(Wu *et al.*, 2025;

						Yin *et al.*, 2025)
	β-type Ti alloys	40–60	Varies	Non-degradable	Low modulus to reduce stress shielding; next-gen implants	(Niinomi, 2019)
	Ti-6Al-4V	110–125	~900	Non-degradable	High strength-to-weight ratio, fatigue resistance; bone plates, joint replacements	(Kraišnik *et al.*, 2018; Bandyopadhyay *et al.*, 2023)
Cobalt-Chromium	Co–Cr Alloys / CoCrMo	200–230	~900	Non-degradable	Very high wear resistance, joint replacements, femoral heads, dental prostheses	(Ang *et al.*, 2017; Kraišnik *et al.*, 2018; Bandyopadhyay *et al.*, 2023)
Stainless Steel	316L Stainless Steel	~200	500–700	Non-degradable	Cost-effective, good corrosion resistance; fracture fixation, stents, and removable implants	(Ang *et al.*, 2017; Kraišnik *et al.*, 2018; Bandyopadhyay *et al.*, 2023)
Magnesium Alloy	General Mg Alloys	N/A	250–350	3–12 months	Biodegradable, low radiopacity, fast degradation	(Xia *et al.*, 2025)
	WE43	40–50	220–330	3–12 months	Bioresorbable stents	(Ang *et al.*, 2017)

Zinc Alloys	Zn Alloys	90–110	200–300	12–24 months	Cardiovascular stents, bone implants	(Xia *et al.*, 2025)
Complex Alloys (CCA)	Ti-Zr-Hf-Nb-Ta-Mo-Sn	40–50	600–915	Non-degradable	Advanced orthopedic implants	(Yin *et al.*, 2025)

9. Clinically established and experimental developments and metallic implants

In the field of metallic biomaterials, it is necessary to differentiate established clinical applications and emerging experimental developments (Prasad *et al.*, 2017). The conventional metallic biomaterials, such as stainless steel, Co–Cr alloys, and titanium alloys, have been successfully used for clinical purposes due to well-documented mechanical properties, corrosion resistance behavior, and long-term biocompatibility (Hanawa, 2022; Shalawi *et al.*, 2023). Recent developments, including surface engineering, nanoparticle-reinforced metallic alloys, bioactive nanostructures, and functionally graded materials, are still at the experimental stage. The majority of these emerging developments have been supported by in vitro studies and limited in vivo studies (Davoodi *et al.*, 2022; Mobarak *et al.*, 2023; Hao *et al.*, 2026). Although these emerging developments have shown significant potential for improvement of osseointegration, wear, and corrosion, clinical application is limited by issues of safety, regulatory approval, and long-term performance (Saad *et al.*, 2024; Ghodrati *et al.*, 2025).

10. Challenges and future direction

Although there is innovation in the design, surface engineering, and manufacturing technologies, metallic orthopedic implants continue to possess significant mechanical, biological, manufacturing, and clinical shortcomings, which reduce their long-term reliability and performance. The most basic issue is the discrepancy in the elastic modulus of implant materials and native bone. Conventional orthopedic metals, i.e., stainless steel (~200 GPa), cobalt-chromium alloys (~210-230 GPa), and titanium alloys (~100-120 GPa), are much stiffer than cortical bone (~10-30 GPa). The result of this imbalance of stiffness is stress shielding: physiological loading of the bone adjacent to the implant is reduced, and remodeling slows down; bone resorption and osteopenia occur, and ultimately the implant becomes loose (in particular, in load-bearing joints, such as the hip and the knee).

The metallic implants, too, are exposed to a chemically hostile environment abundant in chloride ions, dissolved oxygen, and proteins. These environments facilitate electrochemical corrosion, which becomes aggravated with time. Surface corrosion exposes potentially cytotoxic metal ions (e.g., Ni^{2+}, Cr^{3+}, Co^{2+}, and V^{5+}) that can cause inflammation, hypersensitivity, and cytotoxic or genotoxic reactions endangering long-term biocompatibility. Examples of protective coatings include TiN, hydroxyapatite, anodization, and surface passivation, which can wear out over a prolonged period. During articulation of the joints, tribocorrosion produces metal debris and oxide particles. Rather, surface roughening increases the rate of corrosion, which forms a self-enhancing process of deterioration that reduces the life of an implant. Presently used mitigation measures are concerned with optimization of alloy chemistry, nano-engineered surfaces, and self-lubricating or wear-resistant surfaces; long-term stability under physiological loading is unknown.

All conventional metallic biomaterials, like stainless steel and Co-Cr alloys, are biocompatible and do not have the inherent ability to bond with bone. Adverse tissue responses can be elicited by poor osseointegration caused by a lack of interfacial stability or delayed healing. Bioactive calcium phosphate coatings, TiO_2 nanotubes, and immobilization of biomolecules onto surfaces enhance initial cell adhesion and osteogenesis, although it is difficult to retain the integrity of the coating, reproducibility, and adhesion to mechanical cyclic loading. The initiation and propagation of cracks is also a great risk in long-term fatigue of metallic implants. Micromotion on the modular junction, e.g., head-neck interface of hip implants, hastens the growth of cracks, release of metal ions, and mechanical failure. Zinc, magnesium, and iron-based alloys are examples of biodegradable metals which may provide a good solution to temporary fixation devices, as opposed to secondary surgery. Nevertheless, the ability to regulate the kinetics of degradation, the maintenance of mechanical integrity during the healing process, and the ability to control the byproducts of corrosion are significant barriers to clinical translation. The effects of metallic implants include foreign body reactions, which include macrophage activation, fibrous encapsulation, and chronic inflammatory reactions. Bacterial adhesion and biofilm formation on implant surfaces lsoundermine clinical outcomes and are the primary causes of implant failure. Despite these promising results of antibacterial surface modification, the question of whether or not it is possible to provide permanent infection resistance without adverse biocompatibility outcomes has yet to be answered. Additive manufacturing and surface nano-engineering are advanced manufacturing methods that bring about challenges in the control of porosity, residual stress, defect formation, and reproducibility. These technologies are not easy to scale to clinical application without being economically viable and without their quality remaining consistent. The conversion of new metallic materials and surface modifications into the clinic would need a significant amount of biocompatibility testing, in vivo verification over an extended period of time, and regulatory acceptance. Frequently, harmonised testing procedures and assessment standards are not available, and the clinical uptake is slowed. Other problems also include diversity in the quality of bones, immune responses, and physiological states of patients. Such complex problems will require an interdisciplinary approach that combines materials science, surface engineering, biomechanics, additive manufacturing, and biomedical engineering. The work in the future needs to be dedicated to low-modulus alloys, multifunctional durable coatings, intelligent implant designs, and patient-specific approaches to enhance the success and reliability over the long-term.

The future of metallic orthopedic implants depends on the multidisciplinary approach that encompasses metal alloy development, new surface coatings, novel productive methods, computer modeling, and biomedicine. The modern implant will strive to be similar to bone in mechanical properties, provide dynamic biological functioning, resist corrosion and wear, and adapt to the conditions of the specific patient. There is emerging interest in the use of low-modulus titanium and β-type titanium alloys containing β-stabilizers like Nb, Ta, Mo, and Zr that are compatible with the body. These materials stabilize the body-centered cubic structure of the β-phase, reducing the modulus while retaining good strength and corrosion resistance properties. Constant streamlining of composition and structure will be needed.

The future strategies of surface modification will focus on multifunctional coatings that can promote the process of osseointegration and minimize bacterial colonization, in addition to offering corrosion and wear resistance. TiO_2 nanotube arrays, laser-textured micro/nanostructures, and hydroxyapatite-coated surfaces are nanostructured surfaces that enhance osteoblast adhesion and protein adsorption. With the inclusion of osteoinductive factors such as growth factors and bioactive ceramics, additional optimization of inflammatory and bone-forming reactions is possible. Such coatings should be capable of cyclic loading. Intelligent implant designs will have responsive surfaces exposed to the environment (sensing pH, temperature, mechanical forces, etc.) and will release antibacterial or anti-inflammatory substances when required. Electric-conducting and piezoelectric coatings can be used to create signals during loading to induce osteogenesis.

Additive manufacturing promises complex geometries, porosity, and lattice structures that are hierarchically structured like bone through selective laser melting and electron beam melting. Structures of functional grading with varying porosities and elasticity share stresses more evenly. 3D printing is capable of mimicking the complex geometrical structures, porosity, and lattice structures within the implant. Blending implant design with topology optimization and finite element analysis can optimize implant design. Among the various 3D printing ethnics, FDM, SLM, and DLP have more potential from the point of material processing and precision.

Biodegradable metals are still appealing for temporary fixation gadgets. Future studies will aim at the strict regulation of degradation rates with alloy composition (Mg, Ca, Zn-Li, Fe-Mn) and surface treatment (passivation layers, conversion coatings) of metals. Aligning tissue healing with degradation is important. Owing to the prevalence of implant-related infections, state-of-the-art antibacterial surface nanotechnologies will be of significant importance. Persistent antibacterial activity may be maintained using silver, copper, zinc oxide nanoparticles, photocatalyst coating, and nitric oxide-releasing systems.

Bioinspired surfaces inspired by natural antiadhesive surfaces, such as the lotus leaf or shark skin, could be used to minimize the adhesion of bacteria and biofilm formation, and still promote the integration of the tissue with the bioinspired surface. Computational modeling, artificial intelligence, and machine learning are making predictions on corrosion behavior, tribological performance, and mechanical properties under different loads faster. The personalized design of an implant with the help of AI-assisted analysis of imaging and biomechanics data is a breakthrough in personalized orthopedic care. Further effort should be made to create standardized testing protocols in corrosion, fatigue, cytotoxicity, and bio-interaction to support the rapid clinical translation.

Conclusion

Based on the current progress, metallic medical implant β-type titanium alloys like TNTZ and TNZM are rated as the best overall materials for implants, whereas titanium-based systems with TiO_2 nanotubes or TiN coatings exhibit the best surface performance; tantalum-coated 316L stainless steel is rated as the best cost-effective material, and CoCrMo alloys are rated as the best choice for wear-dominated applications. The orthopedic implant technology still relies on metals and metal alloys as its basic building block due to their high mechanical strength, fracture toughness, and long-term durability in physiological load conditions. Different systems made of stainless steel, cobalt chrome alloy, and titanium have played a significant role in enhancing the clinical efficacy of joint replacement and fracture fixation devices. However, such materials are still characterized by issues such as stress shielding due to a mismatch of elastic modulus, release of ions caused by corrosion, wear, and tribocorrosion, insufficient osseointegration, and vulnerability to implant-related infections. Developments in alloy, mode of processing, and surface engineering within the last 20 years have greatly improved the mode of operation of metallic implants. With the introduction of low-modulus β-type titanium alloys, additive-manufactured structures, and nanostructured or bioactive surface coats, mechanical compatibility has been promoted, along with bone-implant integration and design freedom, including patient-specific solutions. At the same time, new biodegradable metal frameworks based on magnesium, zinc, and iron alloys are promising directions of temporary fixation solutions that attain a target resorption after bone repair. In this respect, rational design of next-generation metallic implants that fulfill mechanical, biological, and tribological properties simultaneously is expected to be available in the near future, due to the accelerated convergence of computational modeling, machine learning, and advanced manufacturing technologies. A further expansion of the functional horizon of metallic biomaterials is smart surfaces that have physiological responsiveness and active tissue repair abilities. Such innovations will eventually be converted into clinical use; however, with tight interdisciplinary cooperation of materials scientists, engineers, clinicians, and regulatory agencies to come up with safer, more long-lived, and more biologically integrated orthopedic implants.

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Conceptualization, writing—original draft preparation, writing—review and editing, methodology, software, data curation, Najmul Hossain;
Validation, visualization, formal analysis, and investigation, Md. Mizanur Rahman and Chowdhury Kaiser Mahmud;
Writing—review and editing, resources, data curation, MD. Kowsar Alam and Rasheed Ahmad;
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Conflict of Interest

The authors declare that they have no conflict of interest.

Reference

Abdelwahab, S. A., Warda, M., Zewaid, M., Saleh, H., Ahmed-Farid, O. A., Hendawy, H. A., Kamoun, E. A., Negm, A., Son, J. Y., & Ali, A. I. (2025). Nickel-free porous stainless-steel nanocomposites for versatile biomedical applications: Fabrication, characterization, and evaluation of electrochemical and immunogenicity detection. *Materials Advances, 6*(1), 448–462.

Ahmad, K., Manzur, J., Tahir, M., Hussain, R., Khan, M., Wadood, A., Avcu, E., & Rehman, M. A. U. (2023). Electrophoretic deposition, microstructure, and selected properties of zein/clove coatings on 316L stainless steel. *Progress in Organic Coatings, 176*, 107407.
Al-Shalawi, F. D., Mohamed Ariff, A. H., Jung, D.-W., Mohd Ariffin, M. K. A., Seng Kim, C. L., Brabazon, D., & Al-Osaimi, M. O. (2023). Biomaterials as implants in the orthopedic field for regenerative medicine: Metal versus synthetic polymers. *Polymers, 15*(12), 2601.
Ammar, H. R., Sivasankaran, S., & Karunanithi, R. (2025). Microstructure, mechanical properties, and corrosion behavior of Zn-x wt.% Ti (x = 0, 0.3, and 1) alloys for biomedical applications. *Journal of Materials Research and Technology, 36*, 4968–4984.
Ang, H. Y., Huang, Y. Y., Lim, S. T., Wong, P., Joner, M., & Foin, N. (2017). Mechanical behavior of polymer-based versus metallic-based bioresorbable stents. *Journal of Thoracic Disease, 9*(Suppl. 9), S923–S934.
Antolinez, L. K. R., Look, W. K., Feyzi, M., Xiao, W., & Hashemi, R. (2026). Enhanced wear resistance and tribocorrosion performance of new Ti–Zr–Nb–Ta and Ti–Zr–Nb–Mo alloys for biomedical implants. *Journal of Bio- and Tribo-Corrosion, 12*(1), 51.
Asadullah, S., Ahmed, M., Sarfraz, S., Zahra, M., Asari, A., Wahab, N. H. A., Sobia, F., & Iqbal, D. N. (2023). Polyimide biocomposites coated with tantalum pentoxide for stimulation of cell compatibility and enhancement of biointegration for orthopedic implants. *Heliyon, 9*(12), e23284.
Asadullah, S., Mei, S., Yang, K., Hu, X., Wang, F., Yu, B., Wu, Z., & Wei, J. (2021). Tantalum oxide submicroparticles in microporous coatings on polyimide possessing antibacterial properties and inducing cellular responses for orthopedic applications. *Journal of the Mechanical Behavior of Biomedical Materials, 124*, 104800.
Azmat, A., Asrar, S., Channa, I. A., Ashfaq, J., Chandio, I. A., Chandio, A. D., Shar, M. A., AlSalhi, M. S., & Devanesan, S. (2023). Comparative study of biocompatible titanium alloys containing non-toxic elements for orthopedic implants. *Crystals, 13*(3), 467.
Azmat, A., Tufail, M., & Chandio, A. D. (2021). Synthesis and characterization of Ti–Sn alloy for orthopedic applications. *Materials, 14*(24), 7660.
Balasubramanian, R., Nagumothu, R., Parfenov, E., & Valiev, R. (2021). Development of nanostructured titanium implants for biomedical applications: A short review. *Materials Today: Proceedings, 46*, 1195–1200.
Bandyopadhyay, A., Mitra, I., Goodman, S. B., Kumar, M., & Bose, S. (2023). Improving biocompatibility for next generation of metallic implants. *Progress in Materials Science, 133*, 101053.
Banerjee, D., & Williams, J. C. (2013). Perspectives on titanium science and technology. *Acta Materialia, 61*(3), 844–879.
Bartkowiak, A., Zabila, Y., Menaszek, E., Zarzycki, A., Perzanowski, M., & Marszałek, M. (2022). Effect of tantalum interlayer on hydroxyapatite biointerface for orthopedic applications. *Surface and Coatings Technology, 447*, 128882.
Cakir, F., Özkal, F. M., & Sensöz, E. (2022). Performance assessment of biocompatible metals used in the treatment of femoral neck fractures. *ACS Applied Bio Materials, 5*(6), 3013–3022.
Calazans Neto, J. V., Celles, C. A. S., de Andrade, C. S. A. F., Afonso, C. R. M., Nagay, B. E., & Barão, V. A. R. (2024). Recent advances and prospects in β-type titanium alloys for dental implant applications. *ACS Biomaterials Science & Engineering, 10*(10), 6029–6060.
Dada, M. O., Abe, J. O., Popoola, A. P. I., & Phasani, T. M. (2024). Effects of Nb and Mo alloying elements

on the corrosion characteristics of sintered cobalt–chromium alloys in Hank's solution for biomedical applications. *Journal of Bio- and Tribo-Corrosion, 10*(4), 88.
Dao, A., Gaitanos, C., Kamble, S., Sharifahmadian, O., Tan, R., Wise, S. G., Cheung, T. L. Y., Bilek, M. M. M., Savage, P. B., Schindeler, A., & Akhavan, B. (2024). Antibacterial plasma polymer coatings on 3D materials for orthopedic applications. *Advanced Materials Interfaces, 11*(2), 2300063.
Dash, P., Thirumurugan, S., Hu, C.-C., Wu, C.-J., Shih, S.-J., & Chung, R.-J. (2022). Preparation and characterization of polyelectrolyte multilayer coatings on 316L stainless steel for antibacterial and bone regeneration applications. *Surface and Coatings Technology, 435*, 128254.
Davoodi, E., Montazerian, H., Mirhakimi, A. S., Zhianmanesh, M., Ibhadode, O., Shahabad, S. Esmaeilizadeh, R., Sarikhani, E., Toorandaz, S., Sarabi, S. A., Nasiri, R., Zhu, Y., Kadkhodapour, J., Li, B.Khademhosseini, A., & Toyserkani, E. (2022). Additively manufactured metallic biomaterials. *Bioactive Materials, 15*, 214–249.
Ding, Y., Wen, C., Hodgson, P., & Li, Y. (2014). Effects of alloying elements on the corrosion behavior and biocompatibility of biodegradable magnesium alloys: A review. *Journal of Materials Chemistry B, 2*(14), 1912–1933.
Ehtemam-Haghighi, S., Attar, H., Dargusch, M. S., & Kent, D. (2019). Microstructure, phase composition, and mechanical properties of new, low-cost Ti–Mn–Nb alloys for biomedical applications. *Journal of Alloys and Compounds, 787*, 570–577.
El-Bassyouni, G. T., Mouneir, S. M., & El-Shamy, A. M. (2025). Advances in surface modifications of titanium and its alloys: Implications for biomedical and pharmaceutical applications. *Multiscale and Multidisciplinary Modeling, Experiments and Design*. Advance online publication.
Fratila, A., Jimenez-Marcos, C., Mirza-Rosca, J. C., & Săceleanu, A. (2023). Mechanical properties and biocompatibility of various cobalt–chromium dental alloys. *Materials Chemistry and Physics, 304*, 127867.
Fu, W., Liu, S., Jiao, J., Xie, Z., Huang, X., Lu, Y., Liu, H., Hu, S., Zuo, E., Kou, N., & Ma, G. (2022). Wear resistance and biocompatibility of Co–Cr dental alloys fabricated with CAST and SLM techniques. *Materials, 15*(9), 3263.
Garcia-Mendez, M. C., Urrutia-Baca, V. H., Cuao-Moreu, C. A., Lorenzo-Bonet, E., Alvarez-Vera, M., Ortiz-Martinez, D. M., & de la Garza-Ramos, M. A. (2021). In vitro biocompatibility evaluation of a new Co–Cr–B alloy with potential biomedical application. *Metals, 11*(8), 1267.
Gautam, S., Bhatnagar, D., Bansal, D., Batra, H., & Goyal, N. (2022). Recent advancements in nanomaterials for biomedical implants. *Biomedical Engineering Advances, 3*, 100029.
Ghodrati, H., Goodarzi, A., Golrokhian, M., Fattahi, F., Anzabi, R. M., Mohammadikhah, M., Sadeghi, S., & Mirhadi, S. (2025). A narrative review of recent developments in osseointegration and anti-corrosion of titanium dental implants with nano surface. *Bone Reports, 25*, 101846. Gouda, M., Salaman, S., ElDeeb, A. B., Kobayashi, S., Borek, W., & Ebied, S. (2026). Effect of alloying elements on the characteristics of metallic biodegradable materials: A review. *Chinese Journal of Mechanical Engineering, 39*, 100024.
Gracheva, A., Polozov, I., & Popovich, A. (2025). Additive manufacturing of biodegradable metallic implants by selective laser melting: Current research status and application perspectives. *Metals, 15*(7), 754.
Guo, Z., Huang, Y., Sun, C., He, Z., Li, Y., Qiu, H., Yuan, D., Zhang, J., Chu, C., & Shen, B. (2023). Preparation and characterization of metastable β-type titanium alloys with favorable properties for orthopedic applications. *Journal of Alloys and Compounds, 949*, 169839.

Gao, Y., Jiang, W., Zeng, D., Liang, X., Ma, C., & Xiao, W. (2025). *Additive manufacturing of titanium alloys for biomedical applications: A systematic review*. *Review of Materials Research, 1*(1), 100011.
Hanawa, T. (2022). Biocompatibility of titanium from the viewpoint of its surface. *Science and Technology of Advanced Materials, 23*(1), 457–472.
Hao, M., Chen, Y., Meng, Y., Yan, E., Qiu, J., & Xia, Y. (2026). Functionally graded surfaces and materials: From fabrication to biomedical applications. *Chemical Reviews, 126*(3), 2143–2196.
Hua, Z., Zhang, D., Guo, L., Lin, J., Li, Y., & Wen, C. (2024). Spinodal Zr–Nb alloys with ultrahigh elastic admissible strain and low magnetic susceptibility for orthopedic applications. *Acta Biomaterialia, 184*,444–460.
Iatecola, A., Longhitano, G. A., Antunes, L. H. M., Jardini, A. L., Miguel, E. de C., Béreš, M., Lambert, C. S., Andrade, T. N., Buchaim, R. L., & Buchaim, D. V. (2021). Osseointegration improvement of Co–Cr–Mo alloy produced by additive manufacturing. *Pharmaceutics, 13*(5), 724.
Jaiswal, D., Pathote, D., Singh, V., Gautam, R. K., & Behera, C. K. (2023). Wear behavior and microhardness studies of tantalum (Ta)-coated 316L stainless steel by DC magnetron sputtering for orthopedic applications. *Journal of Materials Science, 58*, 2829–2848.
Jabbar, S. A., Abdulkader, N. J., & Ahmed, P. S. (2025). Effect of niobium and silicon on the CoCr alloy characteristics used for biomedical applications. *AIP Conference Proceedings, 3169*(1), 040048.
Jawed, S. F., Rabadia, C. D., Khan, M. A., & Khan, S. J. (2022). Effect of alloying elements on the compressive mechanical properties of biomedical titanium alloys: A systematic review. *ACS Omega, 7*(34), 29526–29542.
Kraišnik, M., Đurić, A., & Milutinović, M. (2018). Characterization of mechanical properties of metal biomaterials. In F. Zivic, S. Affatato, M. Trajanovic, M. Schnabelrauch, N. Grujovic, & K. L. Choy (Eds.), *Biomaterials in clinical practice: Advances in clinical research and medical devices* (pp. 601–631).
Kuffner, B. H. B., Capellato, P., Ribeiro, L. M. S., Sachs, D., & Silva, G. (2021). Production and characterization of a 316L stainless steel/β-TCP biocomposite using the functionally graded materials (FGMs) technique for dental and orthopedic applications. *Metals, 11*(12), 1923.
Kumari, P., Pathote, D., Singh, V., Jaiswal, D., Gautam, R. K., & Behera, C. K. (2023). Biocompatibility evaluation, wettability, and scratch behavior of Ta-coated 316L stainless steel by DC magnetron sputtering for orthopedic applications. *Surface and Coatings Technology, 459*, 129392.
Lin, Y.-C., Hu, C.-C., Liu, W.-C., Dhawan, U., Chen, Y.-C., Lee, Y.-L., Yen, H.-W., Kuo, Y.-J., & Chung, R.-J. (2024). Hydrogen-treated CoCrMo alloy: A novel approach to enhance biocompatibility and mitigate inflammation in orthopedic implants. *Journal of Materials Chemistry B, 12*(32), 7814–7825.
Liu, Z., Liu, H., Vowden, R., Hughes, L., Qi, D., Francis, W., Perino, G., Pink, R., Xiao, J., & Li, B. (2023). Combination of cobalt, chromium and titanium nanoparticles increases cytotoxicity in vitro and pro-inflammatory cytokines in vivo. *Journal of Orthopaedic Translation, 38*, 203–212.
Meng, M., Wang, J., Huang, H., Liu, X., Zhang, J., & Li, Z. (2023). 3D printing metal implants in orthopedic surgery: Methods, applications and future prospects. *Journal of Orthopaedic Translation, 42*, 94–112.
Mobarak, M. H., Islam, M. A., Hossain, N., Al Mahmud, M. Z., Rayhan, M. T., Nishi, N. J., & Chowdhury, M. A. (2023). Recent advances of additive manufacturing in implant fabrication: A review. *Applied Surface Science Advances, 18*, 100462.

Marin, E., & Lanzutti, A. (2025). History of metallic orthopedic materials. *Metals, 15*(4), 378. Mani, G., Porter, D., Collins, S., Schatz, T., Ornberg, A., & Shulfer, R. (2024). A review of manufacturing processes of cobalt chromium alloy implants and their impact on corrosion resistance and biocompatibility. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*.

Mohandesnezhad, S., Etminanfar, M., Mahdavi, S., & Safavi, M. S. (2022). Enhanced bioactivity of 316L stainless steel with deposition of polypyrrole/hydroxyapatite layered hybrid coating: Orthopedic applications. *Surfaces and Interfaces, 28*, 101604.

Niinomi, M. (2019). Design and development of metallic biomaterials with biological and mechanical biocompatibility. *Journal of Biomedical Materials Research Part A, 107*(5), 944–954.

Nkonta, D. T., Drevet, R., Fauré, J., & Benhayoune, H. (2021). Effect of surface mechanical attrition treatment on the microstructure of cobalt–chromium–molybdenum biomedical alloy. *Microscopy Research and Technique, 84*(2), 238–245.

Odaira, T., Xu, S., Hirata, K., Xu, X., Omori, T., Ueki, K., Ueda, K., Narushima, T., Nagasako, M., Harjo, S., Kawasaki, T., Bodnárová, L., Sedlák, P., Seiner, H., & Kainuma, R. (2022). Flexible and tough superelastic Co–Cr alloys for biomedical applications. *Advanced Materials, 34*(27), 2202305.

Ikumapayi, O. M., Bankole, O. O., Bayode, A., Onu, P., & Ting, T. T. (2025). Finite element analysis and simulation of 316L stainless steel and titanium alloy for orthopedic hip and knee prosthetics. *Prosthesis, 7*(3), 64.

Pathote, D., Jaiswal, D., Singh, V., & Behera, C. K. (2022). Optimization of electrochemical corrosion behavior of 316L stainless steel as an effective biomaterial for orthopedic applications. *Materials Today: Proceedings, 57*, 265–269.

Pathote, D., Jaiswal, D., Singh, V., & Behera, C. K. (2023). Electrochemical corrosion behavior of tantalum-coated 316L stainless steel by DC magnetron sputtering for orthopedic applications. *Applied Surface Science Advances, 13*, 100365.

Pagani, S., Liverani, E., Giavaresi, G., De Luca, A., Belvedere, C., Fortunato, A., Leardini, A., Fini, M., Tomesani, L., & Caravaggi, P. (2021). Mechanical and in vitro biological properties of uniform and graded Cobalt-chrome lattice structures in orthopedic implants. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, *109*(12), 2091–2103.

Phasani, M., Abe, J., Popoola, P., Aramide, O., & Dada, M. (2025). Synthesis and characterization of cobalt-chromium-based alloys via spark plasma sintering for biomedical applications. *Next Materials, 6*, 100291.

Pillai, R. R., & Mohan, L. (2025). Plasma surface modification of biomedical implants and devices: Emphasis on orthopedic, dental, and cardiovascular applications. *Prosthesis, 7*(6), 143.

Prasad, K., Bazaka, O., Chua, M., Rochford, M., Fedrick, L., Spoor, J., Symes, R., Tieppo, M., Collins, C., Cao, A., Markwell, D., Ostrikov, K., & Bazaka, K. (2017). Metallic biomaterials: Current challenges and opportunities. *Materials, 10*(8), 884.

Raza, D., Kumar, G., Uzair, M., Singh, M. K., Sultan, D., & Kumar, R. (2022). Development and heat treatment of β-phase titanium alloy for orthopedic application. *Materials Today: Proceedings, 50*, 649–654.

Rosalbino, F., Macciò, D., Giannoni, P., Quarto, R., & Saccone, A. (2011). Study of the in vitro corrosion behavior and biocompatibility of Zr-2.5Nb and Zr-1.5Nb-1Ta (at%) crystalline alloys. *Journal of Materials Science: Materials in Medicine, 22*(5), 1293–1302.

Senopati, G., Rashid, R. A. R., Kartika, I., & Palanisamy, S. (2023). Recent development of low-cost β-Ti alloys for biomedical applications: A review. *Metals, 13*(2), 194. Saad, K. S. K., Saba, T., & Bin Rashid, A. (2024). Application of PVD coatings in medical implantology for enhanced performance, biocompatibility, and quality of life. *Heliyon, 10*(16), e35541.

Saha, S., Grandhi, M., Kiran, K. U. V., Liu, Z., & Roy, S. (2024). Investigating the effect of select alloying elements in additively manufactured Co-Cr alloy for dental prosthetics. *Journal of Materials Processing Technology, 329*, 118434.

Saha, S., Kiran, K. U. V., Zhang, X., Hou, X., & Roy, S. (2023). Investigating the tribological and corrosion behavior of Co-Cr alloy as an implant material for orthodontic applications. *Wear, 523*, 204755.

Sandhu, M., Kumar, N., Sawhney, R. S., Jyoti, J., Singh, K., & Kaur, P. (2025). Ultimate biomaterial: Titanium, a gold standard choice for current orthopaedic implants. In K. K. Dwivedi, P. Uniyal, & A. Verma (Eds.), *Mechanics and materials science of biological materials: Experimental and modeling approaches* (pp. 107–131).

Santos, R. F. M. dos, Kuroda, P. A. B., & Afonso, C. R. M. (2024). New low elastic modulus equimassic β-Ti-Nb-Zr-(Ta-Mo) multiprincipal alloys. *Journal of Alloys and Compounds Communications, 4*, 100040.

Shirazi, H. A., Chan, C.-W., & Lee, S. (2021). Elastic-plastic properties of titanium and its alloys modified by fibre laser surface nitriding for orthopaedic implant applications. *Journal of the Mechanical Behavior of Biomedical Materials, 124*, 104802.

Sunil, B. R., Kranthi Kiran, A. S., & Ramakrishna, S. (2022). Surface functionalized titanium with enhanced bioactivity and antimicrobial properties through surface engineering strategies for bone implant applications. *Current Opinion in Biomedical Engineering, 23*, 100398.

Tennyson, J. M., Sohn, M. O., Movva, A. K., Mitra, K., O'Neill, C. N., Anastasio, A. T., & Adams, S. B. (2025). Porous Structures, Surface Modifications, and Smart Technologies for Total Ankle Arthroplasty: A Narrative Review. *Bioengineering*, *12*(9), 955.

Vittayakorn, W., Poolphol, P., Aimprakod, K., & Maluangnont, T. (2021). Processing development a properties of cobalt-chromium alloys fabricated by traditional method. *Materials Today: Proceedings, 43*, 2629–2634.

Wanniarachchi, C. T., Arjunan, A., Baroutaji, A., & Singh, M. (2022). Mechanical performance of additively manufactured cobalt-chromium-molybdenum auxetic meta-biomaterial bone scaffolds. *Journal of the Mechanical Behavior of Biomedical Materials, 134*, 105409.

Weng, W., Biesiekierski, A., Lin, J., Ozan, S., Li, Y., & Wen, C. (2021). Development of beta-type Ti-Nb-Zr-Mo alloys for orthopedic applications. *Applied Materials Today, 22*, 100968.

Wu, H., Jiang, T., Kong, L., Chen, X., & Liu, P. (2025). The mechanical properties, corrosion resistance, and biocompatibility of a novel Ti-xNb-5Ta ternary alloy for biomedical applications. *Materials, 18*(3), 602.

Xia, B., Liu, Y., Xing, Y., Shi, Z., & Pan, X. (2025b). Biodegradable Medical Implants: Reshaping Future Medical Practice. *Advanced Science*, *12*(35), e08014.

Xu, J., Bao, X. ke, Fu, T., Lyu, Y., Munroe, P., & Xie, Z.-H. (2018). In vitro biocompatibility of a nanocrystalline β-Ta2O5 coating for orthopaedic implants. *Ceramics International*, *44*(5), 4660–4675.

Yahya, A. A., Hosny, G., El-Banna, S. G., & Alsakhawy, S. A. (2026). Toxicological Assessment of Cobalt-Chromium Dental Alloys: Ion Release, Cytotoxicity, and Possible Systemic Effects. *Biological Trace Element Research*, *204*(6), 3878–3895.

Yang, R., Hao, Y. L., & Li, S. (2011). *Development and Application of Low-Modulus Biomedical Titanium Alloy Ti2448*.
Yin, Q., Wu, Y., Wu, H., Zhang, X., Jiang, S., Wang, H., Liu, X., & Lu, Z. (2025). A multi-objective synergistic design for low modulus and high yield strength in complex concentrated alloys. *Npj Computational Materials*, *11*(1), 206.
Zhao, C., Gao, W., Wang, J., Ju, J., & Li, J. (2023). A novel biomedical TiN-embedded TiO_2 nanotubes composite coating with remarkable mechanical properties, corrosion resistance, tribocorrosion resistance, and antibacterial activity. *Ceramics International, 49*(10), 15629–15640.