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Surface Modification of Titanium Implants with Chitosan–Hydroxyapatite Composite: A Review on Osseointegration and Bioactivity †

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Abstract

Chitosan–hydroxyapatite (CS–HA) composite coatings offer a multifunctional surface modification to improve titanium implant performance, combining hydroxyapatite's osteoconductivity with chitosan's biocompatibility and antimicrobial properties. This review examines recent in vitro and in vivo studies, noting consistent enhancements in osteoblast adhesion, alkaline phosphatase activity, apatite formation, and bone–implant contact. Incorporation of silver, strontium, or graphene oxide can further boost antibacterial and osteogenic effects. However, variability in coating preparation, substrate treatment, and testing protocols limits reproducibility and clinical extrapolation. Standardised methodologies and extended in vivo validation are essential to advance CS–HA coatings toward reliable dental and orthopaedic applications.

Keywords: titanium implants; surface modification; chitosan–hydroxyapatite composite coatings; osseointegration; bioactivity

1. Introduction

A notable surge has occurred in the advancement of various biomedical materials designed for multiple clinical uses. These materials are specifically referred to as biomaterials due to their ability to maintain prolonged, safe interaction with human tissues and cells [1]. Fundamental criterion for these materials is biocompatibility, ensuring they do not provoke adverse biological responses. Common classes of biomaterials include metals and their alloys, polymers, and ceramics. Among these biomaterials, metals and their alloys are widely favoured in medical applications because of their mechanical robustness and potential for compatibility with biological tissues [2,3]. Titanium and its alloys are the most widely used materials for load-bearing dental and orthopaedic implants due to their favourable mechanical strength, corrosion resistance, and biocompatibility. However, the formation of a direct and stable interface between titanium and surrounding bone tissue can be compromised in challenging clinical scenarios such as poor bone quality, infection risk, or systemic disease [4]. As a result, considerable research has been directed toward modifying titanium surfaces to accelerate bone healing, improve bioactivity, and reduce the likelihood of implant failure [5].

Hydroxyapatite (HA), a calcium phosphate ceramic with a chemical composition similar to the mineral phase of bone, is widely used as a bioactive coating on titanium

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to enhance osteoconductivity and promote early bone bonding [6–8]. Various deposition techniques, including alternating current electrophoretic deposition, plasma spraying, micro-arc oxidation and electrochemical oxidation, have been explored to improve coating density, adhesion, and long-term stability [9–12]. Incorporation of antimicrobial elements, such as silver, has also been investigated to combine osteoconductive and antibacterial properties [13]. Despite these advancements, pure HA coatings may still face limitations such as poor adhesion strength, brittleness, and susceptibility to dissolution in physiological environments, which can compromise long-term implant performance [14]. Chitosan (CS), a natural polysaccharide derived from chitin, is composed of glucosamine and N-acetylglucosamine linked by β bonds and has also been extensively applied as a bioactive coating on titanium implants. Its biodegradability, biocompatibility, and chemical reactivity, attributed to hydroxyl and amino groups, make it highly versatile for biomedical applications. The solubility of CS is pH-dependent and influenced by its degree of deacetylation and molecular weight [15]. CS offers intrinsic antimicrobial properties and supports osteoblast adhesion, proliferation, and differentiation, thereby promoting bone regeneration around implants [15–17]. Furthermore, it can act as a functional matrix for incorporating bioactive molecules, enhancing the performance and versatility of implant surfaces [18]. Functional modifications of CS coatings, including the incorporation of antimicrobial agents such as silver nanoparticles, have been investigated to combine antibacterial efficacy with osteoconductive and osteoimmunomodulatory properties [19–23].

When combined, CS and HA offer mechanical synergy, overcoming the brittleness of HA and the low stiffness of CS while enabling tuneable degradation rates, functionalization with bioactive molecules, and versatile processing into coatings with optimised porosity and surface roughness (Figure 1) [24]. Combining CS with HA into a composite coating also unites the osteoconductive capacity of HA with the mechanical flexibility, film-forming capability, and antibacterial potential of CS [22,25]. Over the past decade, numerous in vitro and in vivo studies have explored CS–HA composite coatings for titanium implants, reporting improvements in osteoblast proliferation, alkaline phosphatase (ALP) activity, apatite layer formation in simulated body fluid, and bone–implant contact compared to uncoated or single-component coatings [14,26,27]. Chitosan–hydroxyapatite (CS–HA) composites can be deposited on titanium using techniques such as electrophoretic deposition, electrochemical methods, or plasma-based processes, producing coatings with a biomimetic organic–inorganic architecture that more closely resembles natural bone [26,28]. Recent research has also expanded the functionality of these composites through the incorporation of dopants such as silver, strontium, or graphene oxide, which are designed to enhance antibacterial performance and osteoinductive signalling further [23,29]. Despite the growing body of primary research, a comprehensive synthesis of the evidence specifically addressing osseointegration and bioactivity of CS–HA coating remains limited. The present review aims to bridge this gap by critically examining experimental and preclinical evidence on CS–HA composite coatings for titanium implants, with a focus on their influence on bioactivity, bone tissue response, and osseointegration outcomes.

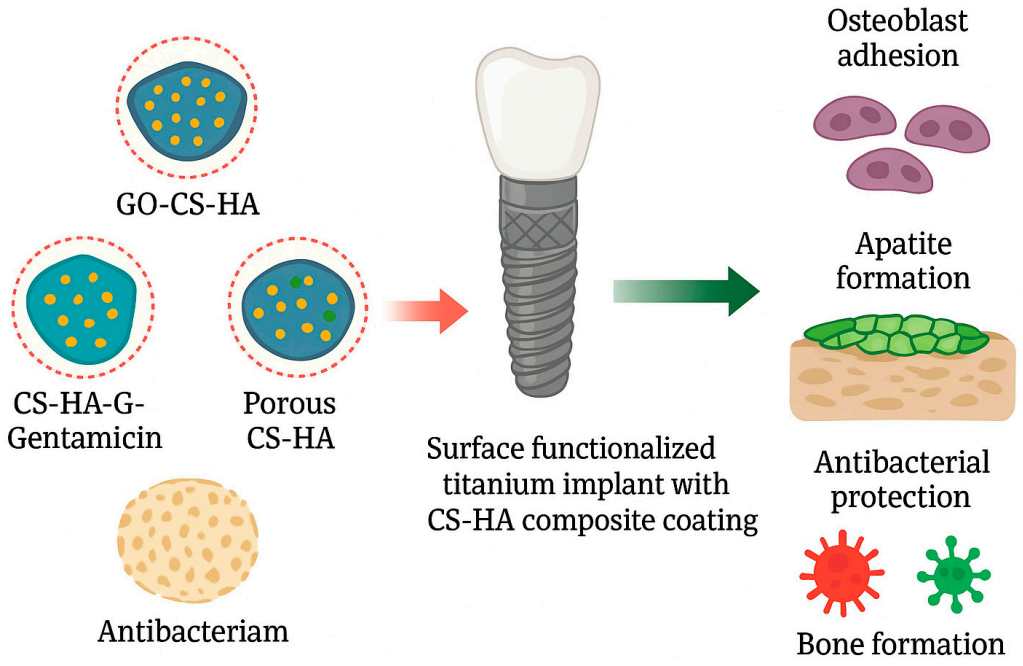


Figure 1. Schematic illustration of effects of titanium implant surface modification with chitosan–hydroxyapatite composite coatings (Created with BioRender.com).

2. Osseointegration and Its Correlation with Surface Modification

Osseointegration is the direct structural and functional connection between living bone and the surface of a load-bearing implant, providing the biological basis for the long-term success of dental and orthopaedic prostheses [30,31]. Bone grows in close contact with the implant surface without forming fibrous tissue, enabling stable load transfer and a natural-like mechanical function. This process occurs over weeks to months through sequential phases of haemostasis, inflammation, proliferation, and remodelling, influenced by patient and material factors (Figure 2) [32,33]. Although the biology is similar in dental and orthopaedic applications, functional demands differ. Dental implants replace tooth roots and endure high-frequency masticatory loads, whereas orthopaedic implants (e.g., hip and knee prostheses) bear heavy loads and allow joint motion. In both cases, rapid, stable osseointegration is essential to avoid micromotion, shorten recovery, and reduce implant failure [4]. Surface modification is a key strategy for enhancing osseointegration. Implant surface properties, topography, roughness, chemistry, wettability, and bioactivity affect protein adsorption, cell attachment, and bone formation [34]. Micro- and nano-texturing can increase bone-to-implant contact (BIC) in dental implants, while porous coatings and bioactive layers promote bone ingrowth in orthopaedics [35]. Methods such as sandblasting, acid etching, plasma spraying, anodization, electrophoretic deposition, and bioactive coatings have been used to create favourable bone–implant interfaces [36,37]. Tailoring surface modifications to meet both mechanical and biological needs can accelerate healing, enhance load-bearing capacity, and prolong implant lifespan. Current research focuses on hybrid coatings, antimicrobial functionalisation, and nanostructured surfaces as next-generation solutions for enhancing osseointegration in both dental and orthopaedic implants [15,38,39].

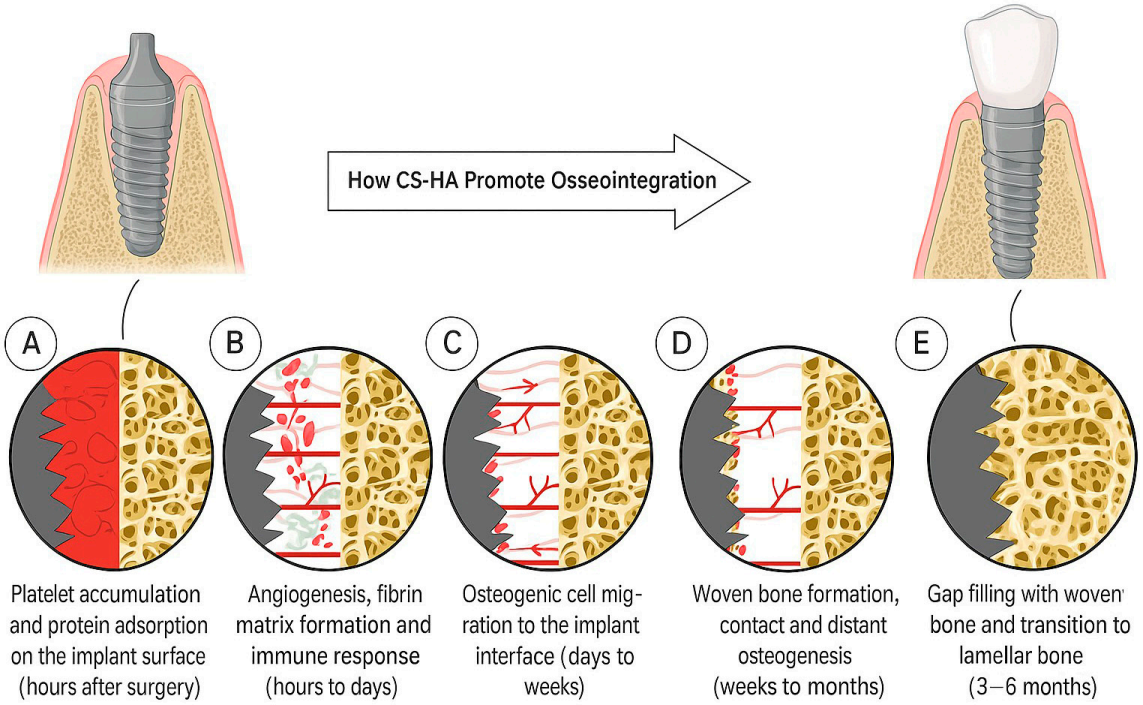


Figure 2. Schematic illustration of the sequential stages of osseointegration and how chitosan–hydroxyapatite (CS–HA) composite coatings promote bone–implant integration. (**A**) Platelet accumulation and blood clot formation immediately after implantation, with protein adsorption onto the implant surface initiating the healing cascade. (**B**) Early inflammatory response and provisional matrix formation, where fibrin networks stabilize the clot and begin recruiting inflammatory and progenitor cells. (**C**) Migration and attachment of osteogenic cells to the implant surface; CS–HA coatings enhance cell adhesion, proliferation, and antibacterial protection. (**D**) New bone formation (woven bone) around the implant, with active osteoblast activity and extracellular matrix deposition supported by the osteoconductive HA phase. **(E)** Gap filling with newly formed bone and maturation into lamellar bone, resulting in strong bone–implant contact and long-term osseointegration. (Created with BioRender.com).

3. Materials and Methods

A literature search was conducted to identify studies on osseointegration and bioactivity of chitosan–hydroxyapatite (CS–HA) composite coatings on titanium implants, covering January 2015–June 2025. The databases searched included PubMed, Scopus, Web of Science, and ScienceDirect, using the terms: ("chitosan" AND "hydroxyapatite" AND "titanium" AND ("coating" OR "surface modification" OR "surface treatment") AND ("osseointegration" OR "bioactivity")). Reference lists of relevant articles were also screened. The search was restricted to English-language studies on titanium substrates.

Inclusion criteria: Peer-reviewed in vitro, in vivo, or combined studies on titanium or titanium alloys modified with CS–HA composites, with or without dopants (zinc, silver, strontium, graphene oxide), reporting at least one of the following: osseointegration (bone–implant contact, trabecular thickness), bioactivity, ALP activity, apatite formation, protein adsorption, cell proliferation), or antibacterial performance. *Exclusion criteria*: reviews, conference abstracts, editorials, patents, and studies using CS-only or HA-only coatings without combination; non-peer-reviewed sources. *Study selection*: database records were imported into EndNote, and duplicates were removed and screened in two stages: (1) title/abstract and (2) full-text review against criteria. The selection process followed the PRISMA 2020 guidelines for systematic reviews [40]. The process is shown in Figure 3. Data extraction and analysis: data on author/year, study design, coating type, modification technique, and key biological outcomes were tabulated. Comparative qualitative synthesis

was used to identify trends, innovations, and differences across studies. No formal risk-of-bias assessment was conducted due to the rapid review design.

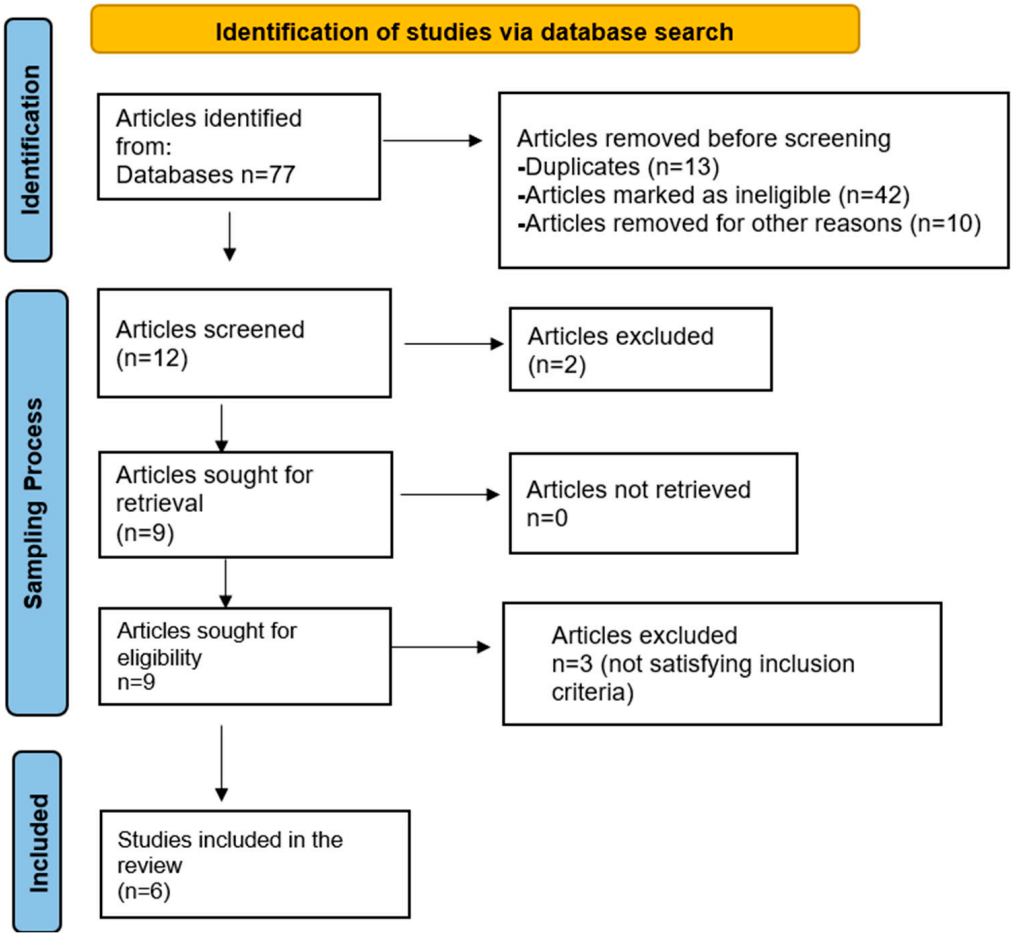


Figure 3. PRISMA flow diagram illustrating the study selection process.

A total of 77 articles were identified from database searches. Before screening, 65 articles were removed, including duplicates ($n = 13$), articles marked as ineligible ($n = 42$), and articles removed for other reasons ($n = 10$). The remaining 12 articles were screened, of which 2 were excluded. Nine articles were sought for retrieval, and all 9 were assessed for eligibility. Of these, 3 articles were excluded for not satisfying the inclusion criteria, resulting in 6 studies included in the review.

4. Results

An initial search was conducted using PubMed, Scopus, Web of Science, and ScienceDirect, covering the period from January 2015 to June 2025. The search yielded a total of 77 articles. Of these, 42 articles were removed before eligibility screening, 13 were duplicates, and 10 were removed for other reasons. A total of 12 articles were screened by title and abstract, leading to the exclusion of two studies. The full texts of the remaining nine articles were then reviewed against the inclusion criteria, and three of these were excluded based on eligibility, leaving six studies to be included in this review. The final included articles fully met all inclusion criteria, and they were selected for qualitative synthesis due to their relevance. Detailed characteristics of the included studies are presented in Table 1.

Table 1. Studies of chitosan–hydroxyapatite-composite coatings on titanium implants.

Author, Year	Study Type	Surface Modification	Key Findings
Shi et al., 2016. [14]	In vitro	Experimental Group: CS-HA 1.0 Graphene oxide-loaded CS–HA (GO-CS-HA) GO-CS-HA nanocomposite via electrophoretic deposition (EPD) on CP-Ti Control group: HA-coated CP-Ti	After 5 days of incubation, the GO-CS-HA composite coating induced significant cytotoxicity towards MG63 cells. GO-CS-HA showed significant apatite formation when put in simulated body fluid (SBF). GO-CS-HA enhanced corrosion resistance, antimicrobial activity against Staphylococcus aureus, and osteoblast-like MG63 cell adhesion or proliferation versus other coatings.
Suo et al., 2019. [26]	In vitro & In vivo	Experimental Group: GO-HA, CS-HA and GO-CS-HA, by EPD on CP-Ti Control group: HA-coated CP-Ti	**In vitro:** GO-CS-HA stimulated osteoblast proliferation or differentiation. The relative proliferation rates of the cells on the CS-HA and GO-CS-HA were significantly higher than those on the HA and GO-HA-Ti samples from 5 to 9 days ($p < 0.05$) **In vivo**: Rat tibiae model GO-CS-HA improved bone–implant contact. Histological analysis showed quantitative bone area (BA) and bone-to-implant (BI) ratios. Both CS-HA and GO-CS-HA showed significantly higher BA and BI ratios than HA and GO-HA ($p < 0.05$). GO-CS-HA push-out force and the ultimate shear strength were significantly higher than other groups after 12 weeks of implantation
Stevanović et al. 2020. [41]	In vitro	Experimental Group: CS-HA, CS-HA with gentamicin via EPD on CP-Ti Control group: Uncoated CP-Ti	The ALP assay results indicated that the CS-HA-Gentamicin coating exhibited the highest ALP levels in the cell extract, which is the most widely recognised biochemical marker for osteoblast activity. CS-HA and CS-HA–Gentamicin increased ALP activity and were noncytotoxic to fibroblasts.
Zhang et al., 2020. [27]	In vitro & In vivo	Experimental Group: Porous Ti6Al4V implants coated with CS-HA composite (via SLS and EPD) Control group: Dense Ti6Al4V implants without any coating.	**In vitro:** CS-HA porous implants showed higher ALP activity ($p < 0.05$) and >85% cell viability, promoting early MC3T3-E1 differentiation and pore proliferation. **In vivo:** Rabbit femoral model implantation At week 4, porous CS-HA exhibited bone ingrowth, while dense Ti6Al4V showed only surface bone formation. At week 12, porous CS-HA showed thicker trabecular bone and increased bone ingrowth, whereas dense Ti6Al4V had limited bonding.
Zarif et al., 2024. [29]	In vitro	Experimental Group: HA CS-HA Strontium-doped HA (Sr-HA) Strontium-doped CS-HA (Sr-CS-HA) (generated by radio-frequency magnetron sputtering and assisted pulsed laser evaporation) Control group: Uncoated CP-Ti	Formation of Ca–P apatite layer was fastest and densest on Sr–CS-HA than others. Incorporated Sr into CS–HA layers; enhanced Fibroblasts (L929 cells) proliferation. Sr–CS-HA showed the strongest antibacterial effect against *S. aureus*, attributed to Sr ions and chitosan's cationic charge disrupting bacterial membranes.

Table 1. *Cont.*

Author, Year	Study Type	Surface Modification	Key Findings
Li et al., 2025. [42]	In vitro	Experimental groups: CS-HA via in situ MAO CS-HA via two-step MAO + anodic oxidation (ANO) Control group: HA via MAO	HA showed the best cell (MC3T3-E1) proliferation. CS-HA via in situ MAO showed intermediate cell proliferation. CS-HA via two-step MAO + ANO showed the lowest cell proliferation. All CS-containing coatings improved antibacterial performance against *E. coli* vs. HA only. MAO + ANO (two-step) CS-HA exhibited better antibacterial activity than in situ MAO CS-HA.

5. Discussion

The collective body of reviewed studies demonstrates that CS–HA composite coatings represent a highly promising surface modification strategy for Ti implants, offering synergistic improvements in osseointegration and bioactivity through the combination of the bioactive ceramic HA and the multifunctional biopolymer CS. Over the past decade, both systematic and narrative reviews have addressed chitosan-based coatings, with a smaller but growing subset focusing on CS–HA composites. Several recent investigations highlight the versatility of CS–HA systems in enhancing implant functionality through tailored composition and deposition techniques.

Shi et al. [14] successfully employed EPD to fabricate graphene oxide–chitosan–hydroxyapatite (GO–CS–HA) nanocomposite coatings on titanium (Ti) substrates, aiming to enhance their performance for orthopaedic implant applications. The methodology involved creating stable colloidal suspensions of GO, CS, and HA, which were then deposited onto Ti under a 20 V electric field. Characterisation revealed that the addition of GO significantly improved the suspension stability (as evidenced by increased zeta potential) and coating uniformity, while also enhancing surface hydrophilicity. Functionally, the GO–CS–HA coatings exhibited a marked improvement in corrosion resistance, with the corrosion current density decreasing by orders of magnitude compared to HA coatings. Biologically, although some initial cytotoxicity was observed, the coatings supported osteoblast-like MG63 cell proliferation and differentiation over time, as indicated by increased ALP activity and successful apatite formation in simulated body fluid. Furthermore, the composite coatings showed a notable reduction in Staphylococcus aureus adhesion, suggesting inherent antibacterial properties derived from both GO and CS [14]. These findings underscore the potential of GO–CS–HA coatings to address key limitations of conventional Ti implants by offering a multifunctional surface that promotes bio-integration while resisting corrosion and infection.

Similarly, Suo et al. [26] fabricated and evaluated four types of multilayer coatings, HA, GO-HA, CS-HA, and GO-CS-HA, on titanium substrates using a layer-by-layer (LBL) self-assembly method, aiming to enhance the antibacterial performance and biocompatibility of implant surfaces. The LBL approach enabled precise control over the deposition of each component, forming uniform, nanoscale multilayers [26]. Characterisation revealed that GO improved coating compactness and mechanical integrity, while CS contributed to surface smoothness and better dispersion of graphene oxide, which was used as the antimicrobial agent. Among the four sample types, GO-CS-HA exhibited the most favourable performance, combining high antibacterial efficacy against Staphylococcus aureus and Escherichia coli with low cytotoxicity toward fibroblast cells. This coating achieved a near-complete bacterial kill rate while maintaining acceptable cell viability, attributed to the synergistic effects of GO's membrane-disruptive properties, CS's inherent antimicrobial

and biocompatible nature, and the sustained release of GO. In contrast, HA and single-additive coatings (GO-HA and CS-HA) showed either reduced antibacterial activity or slightly higher cytotoxicity [26]. The findings highlight that the integration of GO and CS into HA-based multilayers provides a promising strategy for engineering multifunctional implant surfaces with enhanced antibacterial properties and biocompatibility, supporting their potential application in infection-resistant biomedical implants.

Other studies further reinforced the multifunctionality of CS–HA composites. Stevanović et al. [41] fabricated CS-HA and hydroxyapatite/chitosan/gentamicin (CS-HA-Gent) composite coatings on titanium (Ti) substrates via single-step EPD to enhance bioactivity, osseointegration, and antibacterial potential for orthopaedic applications. The co-deposition method enabled direct incorporation of gentamicin into the coating matrix, producing uniform layers with similar morphology to drug-free coatings [41]. In vitro assays demonstrated non-cytotoxicity (viability > 85%) toward human fibroblast cell line derived from the lung tissue (MRC-5) and mouse fibroblast cell line (L929), with the CS-HA-Gent coating yielding slightly higher alkaline phosphatase activity (4.039 U mL^{-1}) than CS-HA (3.206 U mL^{-1}), reflecting enhanced osteogenic potential [41]. These findings suggest that EPD-produced CS-HA-Gent coatings combine strong bioactivity, favourable biocompatibility, and effective antibacterial performance, making them promising candidates for multifunctional Ti implant surfaces.

Zhang et al. [27] designed and evaluated porous Ti6Al4V titanium implants coated with a CS-HA composite using selective laser sintering (SLS) and electrochemical deposition, aiming to enhance osseointegration and mechanical compatibility with bone tissue. The implants featured either a fully porous structure or a dense core with a porous outer layer, allowing control over porosity levels and mechanical properties. SEM characterisation confirmed uniform pore distribution and a dense, lamellar CS-HA coating structure with minimal cracks, with 30–60% porosity. Mechanical testing of CS-HA achieved elastic moduli of 34.3 GPa and 4.63 GPa, which are close to those of cortical and cancellous bone [27]. In vitro studies using osteoblast-like MC3T3-E1 cells demonstrated that porous implants promoted cell adhesion, proliferation, and differentiation, as evidenced by high cell viability and increased ALP activity. In vivo experiments in rabbits revealed enhanced osseointegration, with new bone growth observed in the implant pores at both 4- and 12-week post-implantation. The results confirmed that the CS-HA-coated porous titanium implants significantly improved biocompatibility, mechanical performance, and osseointegration, offering a promising strategy for next-generation dental and orthopaedic implants [27].

Incorporation of additional bioactive elements has also shown promise. Zarif et al. [29] fabricated and assessed four types of composite coatings: HA, hydroxyapatite with strontium (Sr-HA), (CS-HA), and hydroxyapatite with strontium and chitosan (Sr-CS-HA) on CP-Ti substrates via a two-step process, radio-frequency magnetron sputtering and assisted pulsed laser evaporation, to improve the antibacterial properties and osteogenic potential of implant surfaces [29]. Material characterisation revealed that Sr doping enhanced the crystallinity and roughness of HA coatings, while CS addition improved surface homogeneity and supported strontium (Sr) incorporation. Antibacterial tests demonstrated that Sr-CS-HA coatings exhibited the highest antimicrobial activity against Staphylococcus aureus and Escherichia coli, primarily due to the synergistic effects of Sr^{2+} ion release, along with CS's intrinsic antimicrobial properties. In vitro biocompatibility studies using MC3T3-E1 pre-osteoblasts showed that all coatings supported cell attachment and proliferation, with the Sr-CS-HA sample inducing the highest ALP activity and mineralisation, indicative of enhanced osteogenic differentiation [29]. Among the four coatings, Sr-CS-HA demonstrated the most favourable balance of bioactivity and antibacterial performance,

outperforming the single-additive layers (Sr-HA and CS-HA), which showed either moderate antibacterial efficacy or lower osteogenic stimulation. The base HA layer, while bioactive, lacked sufficient antibacterial properties on its own. These findings suggest that integrating Sr and CS into HA-based coatings via radio-frequency magnetron sputtering and assisted pulsed laser evaporation offers a promising strategy for developing multifunctional titanium implant surfaces capable of promoting bone healing while preventing infection [29].

Li et al. [42] prepared CS-HA composite coatings on CP-Ti substrates using two different electrochemical routes, in situ micro-arc oxidation (MAO) and a two-step MAO + anodic oxidation (ANO) to improve the bioactivity, osteogenic potential, and antibacterial properties of Ti. The in situ MAO method incorporated CS directly into the electrolyte, yielding a more homogeneous and rougher coating surface, while the MAO + ANO method deposited a thicker CS layer after initial HA formation. Both coating types promoted bone-like apatite formation in simulated body fluid, demonstrating good bioactivity [42]. In vitro osteoblastic cell line (MC3T3-E1) revealed that all coatings were biocompatible, with the MAO-HA control showing the highest cell proliferation, followed closely by in situ MAO CS-HA, and then MAO + ANO CS-HA, which exhibited slightly reduced proliferation but enhanced antibacterial performance [42]. These findings indicate that CS incorporation can endow HA coatings with antibacterial properties while maintaining bioactivity, and that the in situ MAO approach offers a balanced strategy for achieving both osteogenic and antibacterial functionality on Ti implant surfaces.

Taken together, these findings emphasise that while HA coatings are primarily osteoconductive and favour bone mineralisation, CS offer broader bioactivity, including antimicrobial, anti-inflammatory, and osteoinductive effects. Composite coatings combining CS and HA can leverage these complementary advantages, enhancing implant integration through both biological and mechanical pathways. Advances in deposition technologies, such as electrophoretic deposition and micro-arc oxidation, enable the fabrication of robust coatings with controlled morphology and composition, further optimising implant performance. These findings are consistent with recent investigations on the machinability and surface properties of Ti–6Al–4V alloys produced via additive manufacturing, which demonstrated how microstructure and cooling conditions influence coating adhesion and surface finish [43,44].

6. Limitations and Future Scope of Ti Surface Modification

Despite substantial progress in titanium surface modification strategies, including the application of CS–HA composite coatings, several limitations remain before their widespread clinical translation can be achieved. Many current studies are confined to in vitro settings or short-term in vivo animal models [26,27,31], which may not fully replicate the complex biological and mechanical environment encountered in human implantation [45]. Furthermore, variability in coating deposition techniques, such as electrophoretic deposition [28], galvanic deposition [23], and magnetron sputtering, can produce differences in coating adhesion, thickness, porosity, and degradation rates, making direct comparison across studies challenging.

Another key challenge lies in the lack of standardisation across experimental protocols, including animal models, differences in animal species are used (e.g., rabbit, rat, canine), each with distinct bone metabolism and healing rates, though bovine bone remains most comparable to human bone [46,47]. Implant surface characterisation and evaluation timelines, which limit reproducibility and inter-study comparison, are another challenge. Inconsistent implant dimensions, surface roughness, and testing durations (2–12 weeks) also affect osseointegration and comparability [48]. Additionally, complex coatings that

integrate antimicrobial agents (silver, zinc, or strontium) into CS-HA matrices require precise control over ion release kinetics, as uncontrolled release may induce cytotoxic effects or premature depletion of active agents [49]. Comparable challenges occur in processing titanium alloys such as Ti-6Al-4V and Ti-6Al-4V ELI, where variations in additive manufacturing parameters and cooling conditions alter surface integrity and mechanical response. Rajan et al. [44] reported that the machinability of DMLS-produced Ti-6Al-4V depends strongly on process control and post-machining, with cooling and tool geometry influencing surface roughness and tool wear. Likewise, Mishra et al. [43] found that cutting speed and feed rate dominate wear and surface finish behaviour in Ti-6Al-4V ELI under flood cooling, emphasising the impact of process variability. Without unified standards in manufacturing, testing, and evaluation, both coating performance and substrate integrity remain difficult to reproduce. Establishing harmonised guidelines, akin to ISO 23317:2025 [50]. Apatite-forming ability, would enhance the reliability and comparability of CS–HA coating studies.

Scalability is another key concern. Advanced surface modification processes often rely on laboratory-specific conditions or specialised equipment, posing difficulties in large-scale, cost-effective manufacturing that aligns with clinical regulatory standards. Furthermore, long-term biocompatibility and immunological responses to modified surfaces remain inadequately studied, especially in diseased or immunocompromised models [51].

To translate CS–HA composite coatings into routine clinical use, future research must focus on long-term, standardised, and clinically relevant studies, with careful optimisation of coating composition, deposition technique, and functional additives. By integrating material innovation with robust biological validation, CS–HA coatings have the potential to significantly improve the longevity and success of titanium-based implants in both dental and orthopaedic applications.

7. Conclusions

CS–HA composite coatings represent a promising approach to enhancing the bioactivity and osseointegration of titanium implants by combining the osteoconductive properties of hydroxyapatite with the biocompatibility, antibacterial activity, and mechanical adaptability of chitosan, as evidenced by in vitro and in vivo studies performed over the past decade. Recent developments, including the incorporation of functional dopants such as silver, strontium, and graphene oxide, have expanded the potential of these coatings to deliver multifunctional benefits, notably improved antibacterial protection alongside osteogenic stimulation. In addition to improving bioactivity, CS–HA coatings can serve as platforms for controlled drug release, such as antibiotics or osteogenic factors, thereby integrating therapeutic functionality into implant design. However, future research should prioritise long-term in vivo studies, standardised coating protocols, and mechanical fatigue testing to ensure clinical durability. Incorporating insights from machining and additive manufacturing studies, such as those on Ti–6Al–4V alloys fabricated via direct metal laser sintering and machinability under flood-cooling environments, can guide the optimisation of surface topography and coating adhesion. This integration between surface engineering and manufacturing processes will be essential for translating CS–HA composite coatings into robust clinical applications.

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