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Modern Implant Surface Engineering for Optimized Osseointegration and Prevention of Peri-Implant Diseases: a Narrative Review

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Abstract
Introduction
Dental implant therapy has become a predictable and widely accepted treatment modality for the restoration of oral function and aesthetics. Despite high long-term survival rates, biological complications such as peri-implant mucositis and peri-implantitis remain significant challenges that may compromise implant stability and patient quality of life. Implant surface characteristics

play a crucial role in both osseointegration and microbial colonization, creating a complex balance between enhanced bone integration and resistance to biofilm formation. This narrative review aims to provide a comprehensive overview of current strategies in dental implant surface engineering with regard to their dual role in promoting osseointegration and preventing peri-implant diseases.

Materials and Methods

Literature published between 2020 and 2025 was analyzed using PubMed, Scopus, and Web of Science databases.

Results

The review discusses the influence of surface topography, roughness, chemistry, and wettability on biological responses at the implant interface. Furthermore, contemporary modification strategies, including bioactive ceramic coatings, ion and nanoparticle incorporation, nanotopography, anodization, and laser surface treatments, are critically evaluated. Emerging multifunctional approaches combining osteogenic and antimicrobial properties are also highlighted.

Conclusions

Current evidence suggests that no single surface modification fully optimizes both osseointegration and bacterial resistance. However, advanced nanostructured and laser-modified surfaces demonstrate promising potential for improving long-term implant performance. Future progress in implantology will likely depend on integrating biomaterial innovations with individualized clinical approaches and long-term evidence-based evaluation.

Key words: dental implants; osseointegration; peri-implantitis; implant surface, modification; biofilm formation

1. Introduction

Dental implant therapy is now a well-established component of restorative dentistry and represents one of the most predictable approaches for replacing missing teeth, restoring oral function, and improving aesthetics. Contemporary implant therapy is based on the biological principle of osseointegration, which enables a direct structural and functional connection between living bone and the implant surface under functional loading conditions (Buser et al. 2017). Long-term clinical data confirm high implant survival rates, with systematic evidence indicating that implant-level survival may remain high after 10 years in many clinical settings (Howe et al. 2019). However, implant survival alone does not fully reflect treatment success, as contemporary implantology increasingly emphasizes functional stability, peri-implant tissue health, patient-reported outcomes, and oral-health-related quality of life (Reissmann et al. 2017).

The clinical relevance of implant therapy is particularly evident in patients with high functional demands, partial or complete edentulism, reduced masticatory efficiency, or impaired oral comfort. In these patients, stable implant-supported rehabilitation may improve chewing ability, prosthetic stability, oral confidence, and overall quality of life (Reissmann et al. 2017). Nevertheless, predictable osseointegration does not eliminate biological risk. Peri-implant mucositis and peri-implantitis remain among the most important complications affecting long-term outcomes. According to current case definitions, peri-implant mucositis is characterized by inflammation of the peri-implant mucosa without progressive marginal bone loss, whereas peri-implantitis involves inflammation associated with progressive loss of supporting bone around an osseointegrated implant (Berglundh et al. 2018; Renvert et al. 2018). The prevalence of peri-implantitis reported in the literature varies substantially depending on diagnostic criteria, follow-up time, patient characteristics, and implant-level versus patient-level assessment, but recent systematic evidence confirms that it remains a clinically significant problem (Diaz et al. 2022).

The development of peri-implant diseases is multifactorial and results from complex interactions among implant surface properties, microbial biofilms, host immune responses, prosthetic design, oral hygiene, and patient-related systemic and behavioral risk factors (Berglundh et al. 2018; Dhaliwal et al. 2021; Diaz et al. 2022). From a biological perspective, the implant surface is not a passive interface. Immediately after placement or exposure to the oral environment, the surface becomes covered by a conditioning film composed of salivary proteins, blood-derived components, ions, and other organic molecules. This acquired pellicle modifies the physicochemical properties of the implant surface and influences the initial adhesion of oral microorganisms (Martinez-Hernandez et al. 2023). Early biofilm formation on implant components is a dynamic and subject-specific process, and recent clinical evidence shows that early peri-implant biofilms may be highly diverse in both structure and microbial composition (Dieckow et al. 2024). Therefore, the first stages of surface conditioning and microbial adhesion are critical events that may influence later tissue inflammation, biofilm maturation, and the risk of peri-implant disease.

At the same time, successful implant therapy depends on rapid and stable osseointegration. Implant surface topography has therefore been extensively modified to improve bone-to-implant contact, enhance protein adsorption, support osteoblast adhesion, and promote mechanical interlocking between bone and the implant surface (Rupp et al. 2018; Matos et al. 2021). Moderately rough surfaces have generally been associated with improved biological responses compared with machined surfaces, particularly in the early stages of healing (Rupp et al. 2018; Matos et al. 2021; Kilgman et al. 2021). However, the same surface features that promote bone integration may also create micro-retentive niches that facilitate bacterial adhesion and biofilm persistence. This creates a central biological and engineering challenge in implant dentistry: the surface should be sufficiently bioactive and osteoconductive to support osseointegration, but not so retentive that it promotes microbial colonization and complicates decontamination (Brum et al. 2021; Kilgman et al. 2021).

This osseointegration-biofilm trade-off is not determined by roughness alone. Contemporary evidence suggests that bacterial adhesion and host-cell behavior are influenced by a combination of surface roughness, micro- and nanotopography, surface free energy, hydrophilicity, oxide layer characteristics, chemical purity, and environmental conditioning (Rupp et al. 2018; Kilgman et al. 2021; Kido et al. 2023). In particular, surface wettability has gained increasing attention because hydrophilic surfaces may enhance early protein adsorption, blood clot stabilization, and osteogenic cell attachment. However, hydrophilicity may also affect pellicle formation and thereby indirectly influence the early microbial colonization process (Martinez-Hernandez et al. 2023; Kido et al. 2023). Surface contamination, including hydrocarbon accumulation on titanium, may further alter wettability and reduce the biological activity of implant surfaces, indicating that manufacturing, sterilization, storage, and handling conditions are also relevant for clinical performance (Kido et al. 2023).

As a result, modern implant surface engineering has moved beyond simple roughening procedures toward multifunctional surface designs. Current strategies include micro- and nano-scale texturing, anodization, controlled modification of the titanium oxide layer, improvement of surface hydrophilicity, incorporation of bioactive ions, antimicrobial metal coatings, nanoparticle-based modifications, bioactive ceramic or biological coatings, and laser-generated surface patterns (Kilgman et al. 2021; Al Shayeb et al. 2024; Gkioka et al. 2024; Kolarovszki et al. 2024; Yu et al. 2024). These approaches aim not only to accelerate osseointegration but also to reduce bacterial adhesion, modulate host inflammatory responses, and improve soft- and hard-tissue integration. Bioactive coatings may enhance early bone formation and bone-to-implant contact, whereas antimicrobial coatings and ion-based modifications may reduce bacterial load and biofilm formation (Al Shayeb et al. 2024; Gkioka et al. 2024). Nanostructured and laser-modified surfaces are especially promising because they can generate controlled topographical patterns that influence cellular and microbial behavior at the micro- and nanoscale (Kolarovszki et al. 2024; Yu et al. 2024).

Emerging evidence also suggests that implant surface modifications may affect biological responses at the molecular level. Beyond direct effects on osteoblast adhesion or bacterial retention, surface characteristics may influence immune-inflammatory signaling, gene expression, and epigenetic mechanisms involved in tissue healing and peri-implant inflammation (Kunrath et al. 2024). This perspective is important because peri-implant stability depends not only on mechanical anchorage but also on the coordinated interaction between biomaterial surfaces, immune regulation, angiogenesis, bone remodeling, and microbial control. Therefore, the ideal implant surface should not be understood as merely rough, smooth, hydrophilic, or antimicrobial, but rather as a biologically active interface capable of guiding multiple tissue responses simultaneously.

Despite substantial progress, there is still no clear consensus on which surface characteristics provide the optimal balance between osseointegration and resistance to peri-implant disease. Many promising surface modifications have been evaluated mainly in vitro, in animal models, or in short-term clinical observations, which limits direct translation into long-term clinical recommendations (Brum et al. 2021; Al Shayeb et al. 2024; Gkioka et al. 2024; Kolarovszki et al. 2024; Yu et al. 2024). Moreover, differences in experimental models, bacterial strains, implant materials, surface characterization methods, clinical endpoints, and follow-up duration make comparison between studies difficult. This is particularly relevant for multifunctional surfaces, where osteogenic, antimicrobial, anti-inflammatory, and mechanical effects may interact in complex and sometimes unpredictable ways.

Therefore, a comprehensive and clinically oriented synthesis of current evidence is needed to better understand how implant surface design can support both biological stability and sustained functional performance. Such a synthesis is especially important because the long-term success of implant therapy depends not only on the implant surface itself, but also on patient-related risk factors, oral hygiene, prosthetic design, maintenance protocols, and the ability to prevent or manage peri-implant biofilm formation (Fig. 1).

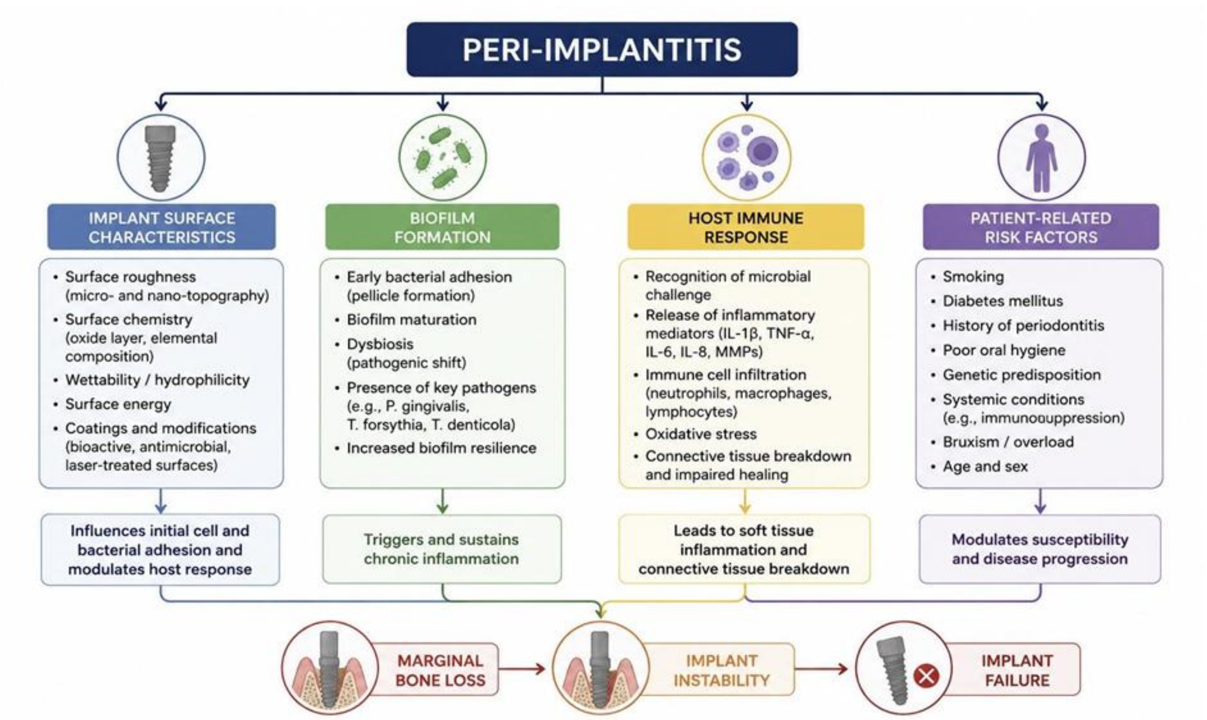

Figure 1. Multifactorial etiology of peri-implantitis showing the interaction between implant surface characteristics, biofilm formation, host immune response, and patient-related risk factors leading to marginal bone loss and potential implant failure.

The aim of this narrative review is to provide a comprehensive and critical synthesis of current strategies in dental implant surface engineering with respect to their dual role in enhancing osseointegration and preventing peri-implant diseases.

2. Materials and methods

This study was designed as a narrative review of the literature on contemporary implant surface engineering strategies aimed at enhancing osseointegration and preventing peri-implant diseases. Particular emphasis was placed on implant surface topography, chemistry, wettability, bioactive coatings, nanostructured modifications, laser surface treatments, and multifunctional approaches combining osteogenic and antimicrobial properties.

The literature search was conducted using the PubMed/MEDLINE, Scopus, and Web of Science databases and included publications published between 2016 and 2025. The search strategy was based on combinations of the following keywords: "dental implant surface", "implant surface modification", "osseointegration", "peri-implantitis", "peri-implant mucositis", "biofilm formation", "surface roughness", "nanotopography", "hydrophilicity", "bioactive coatings", "hydroxyapatite", "calcium phosphate", "anodization", "laser surface modification", "antibacterial coatings", "silver nanoparticles", "titanium dioxide", and "implant surface engineering".

Additionally, the reference lists of selected publications were screened to identify further relevant studies. Because of the narrative nature of this review, no formal protocol registration or quality assessment procedure typical of systematic reviews was applied.

The review included original research articles, in vitro and in vivo experimental studies, clinical studies, cohort studies, systematic reviews, and meta-analyses published in English and focused on implant surface characteristics and their influence on biological responses at the implant-tissue interface. Studies evaluating the effects of surface modifications on osseointegration, bacterial adhesion, biofilm formation, peri-implant tissue health, and long-term implant performance were considered eligible for inclusion.

Publications unrelated to implant surface engineering, studies focused exclusively on surgical techniques or prosthetic procedures without assessment of implant surface characteristics, conference abstracts, editorials, commentaries, and publications lacking sufficient methodological information were excluded.

After duplicate removal, studies were screened based on titles and abstracts, followed by full-text evaluation of potentially relevant articles. Publications meeting the predefined criteria were included in the review. A narrative synthesis of the literature was subsequently performed, with particular attention given to the biological mechanisms underlying osseointegration, the relationship between surface properties and bacterial colonization, the effectiveness of contemporary surface modification strategies, and their potential role in reducing the risk of peri-implant diseases.

3. Overview of Surface Characteristics

Surface topography remains one of the most critical determinants of implant integration and peri-implant health. Machined and minimally rough surfaces have historically been associated with lower bacterial accumulation but also less favorable osseointegration compared with contemporary modified surfaces. Advances in surface engineering introduced micro- and nano-texturing techniques such as grit blasting, acid etching, anodization, and laser modification, which can enhance osteoblast attachment and bone-to-implant contact through increased surface area, protein adsorption, and improved cellular anchorage (Rupp et al. 2018; Matos et al. 2021; Kilgman et al. 2021; Han et al. 2022). Moderate microroughness, commonly described around Ra values of approximately 1.0-2.0 micrometers, is generally considered favorable for protein adsorption, osteoblastic attachment, and bone-to-implant contact, thereby supporting both primary and secondary stability (Rupp et al. 2018; Matos et al. 2021; Kilgman et al. 2021).

However, these same roughened topographies can serve as reservoirs for bacterial adhesion and biofilm accumulation, increasing the risk of peri-implant inflammation (Brum et al. 2021; Dhaliwal et al. 2021; Kilgman et al. 2021). Recent studies emphasize that bacterial colonization depends not only on average roughness but also on hierarchical structure, micro- and nano-feature distribution, surface chemistry, fluid dynamics, and conditioning layers (Brum et al. 2021; Martinez-Hernandez et al. 2023; Dieckow et al. 2024). Surfaces with controlled nanotopography may promote osteogenic cell adhesion while physically limiting bacterial attachment through unfavorable spatial geometry for microbial binding (Kilgman et al. 2021; Han et al. 2022; Yu et al. 2024).

Laser-treated surfaces represent a promising approach to achieving this balance, as controlled laser ablation can generate reproducible micro- and nano-patterns that enhance cellular response while potentially reducing bacterial retention (Fenelon et al. 2022; Kolarovszki et al. 2024). Laser modification can also alter the oxide layer composition and increase surface energy, thereby improving cell adhesion and decontamination potential (Fenelon et al. 2022; Kolarovszki et al. 2024). However, excessive laser energy or inappropriate parameters may damage the titanium microstructure, emphasizing the need for precise parameter optimization (Fenelon et al. 2022). In the context of peri-implant disease management, laser cleaning has additionally been shown to preserve implant surface integrity and support subsequent mesenchymal stem cell adhesion following decontamination of infected surfaces (Furtsev et al. 2023).

3.2 Surface Chemistry and Wettability

The chemical composition and wettability of titanium surfaces strongly influence the early biological events leading to osseointegration. Hydrophilic surfaces can enhance protein adsorption, blood coagulation, and osteogenic cell adhesion, thereby promoting faster integration (Rupp et al. 2018; Kido et al. 2023). Conversely, carbon contamination and surface oxidation heterogeneity may interfere with these interactions and delay early biological responses (Kido et al. 2023). The formation of a stable and chemically favorable titanium oxide layer is therefore crucial for long-term biocompatibility and corrosion resistance (Rupp et al. 2018; Kilgman et al. 2021).

Surface wettability also modulates bacterial adhesion, but the relationship is complex. While hydrophilic surfaces may enhance tissue compatibility, they can also affect pellicle formation and thereby influence early microbial adhesion (Martinez-Hernandez et al. 2023; Kido et al. 2023). Recent findings show that chemical modifications incorporating metallic ions such as silver, copper, or zinc may confer antimicrobial properties by reducing bacterial colonization and biofilm formation in peri-implant tissues (Gkioka et al. 2024; Yu et al. 2024). Nanostructured surfaces incorporating bioactive ions can additionally modulate osteoblast behavior and support osteogenic differentiation at the bone-implant interface, suggesting that antimicrobial and osteogenic functions need not be mutually exclusive (Han et al. 2022; Soe et al. 2024; Yu et al. 2024).

Photoactivated titanium dioxide surfaces have also demonstrated improved wettability and photocatalytic antimicrobial effects, providing a potential passive self-cleaning mechanism under light exposure (Kilgman et al. 2021; Yu et al. 2024). Laser modification can further influence surface chemistry and wettability by altering the oxide layer and increasing surface energy, thereby improving both cell adhesion and decontamination potential (Fenelon et al. 2022; Kolarovszki et al. 2024). Collectively, these findings indicate that optimal surface chemistry should combine hydrophilicity, chemical purity, controlled oxide characteristics, and antibacterial potential, creating an environment that supports tissue integration while minimizing microbial colonization (Rupp et al. 2018; Kilgman et al. 2021; Gkioka et al. 2024).

4. Modification Strategies

The principal contemporary strategies for implant surface modification and their biological effects are summarized in Table 1.

Surface Modification Strategy	Main Mechanism	Effect on Osseointegration	Effect on Bacterial Adhesion/Biofilm	Main Limitations
Bioactive ceramic coatings (hydroxyapatite, calcium phosphates)	Biomimetic osteoconductive surface promoting bone apposition	High	Limited direct antimicrobial effect	Long-term superiority over conventional titanium remains uncertain
Ion and nanoparticle incorporation (Ag, Cu, Zn)	Controlled release of bioactive and antimicrobial	Moderate to high	Significant reduction in bacterial colonization	Potential cytotoxicity and dose-dependent effects

	ions			
Nanotopography (nanopores, nanospikes, nanotexturing)	Modulation of cell and bacterial interactions through nanoscale architecture	High	Reduced bacterial adhesion and potential bactericidal activity	Limited long-term clinical evidence
Sandblasting and acid etching (SLA)	Increased surface roughness and bone-to-implant contact	High	May increase bacterial retention due to surface irregularities	Biological trade-off between osseointegration and biofilm accumulation
Anodization	Formation of titanium oxide nanotubes and increased surface area	High	Potential anti-inflammatory and antibacterial effects	Manufacturing complexity and variability
Laser surface modification	Controlled micro- and nano-patterning without chemical contamination	High	Reduced bacterial retention and improved decontamination potential	Requires precise parameter optimization
Multifunctional combined surfaces	Integration of topographical, chemical, and antimicrobial modifications	Very high potential	Simultaneous antimicrobial and osteogenic activity	Lack of standardized protocols and long-term clinical data

Table 1. Comparison of contemporary implant surface modification strategies for enhancing osseointegration and reducing bacterial colonization.

4.1 Bioactive Ceramic Coatings — Hydroxyapatite and Other Calcium Phosphates

Coating implant surfaces with bioactive ceramic materials such as hydroxyapatite or calcium phosphate is a well-studied strategy to improve bone bonding and early osseointegration. These materials are considered biomimetic because they resemble the mineral phase of bone and support osteoconduction (Han et al. 2022; Al Shayeb et al. 2024).

Bioactive surface modifications, including calcium phosphate-based coatings, have been shown in systematic reviews and meta-analyses to enhance bone-to-implant contact and early implant integration compared with untreated titanium surfaces (Al Shayeb et al. 2024). However, some long-term clinical evidence suggests that differences between coated and non-coated implants may decrease over extended follow-up periods. Therefore, the long-term superiority of such coatings still requires confirmation through further high-quality clinical studies (Han et al. 2022; Al Shayeb et al. 2024).

4.2 Ion and Nanoparticle-Based Surface Modifications

Incorporating bioactive ions or nanoparticles onto titanium surfaces is an emerging approach that can enhance the biological performance of implants by facilitating osteogenic signaling and promoting new bone formation (Soe et al. 2024; Yu et al. 2024). Nanoparticle surface modifications have been used to improve controlled release of therapeutic agents and stimulate processes such as angiogenesis, matrix formation, and early mineralization, which are critical for effective osseointegration (Soe et al. 2024).

Certain nanostructured surfaces also serve as reservoirs for bioactive ions that can modulate cell behavior, potentially improving osteoblast differentiation and reducing inflammatory responses at the bone-implant interface (Han et al. 2022; Soe et al. 2024; Yu et al. 2024). Nevertheless, ion release must be carefully controlled because antibacterial efficacy and cytotoxicity are often dose-dependent, particularly for silver and copper-based modifications (Gkioka et al. 2024; Yu et al. 2024).

4.3 Nanotopography and Hierarchical Surface Structures

Altering the nanotopography of implant surfaces, for example by creating nanopores, nanospikes, or nano-textured layers, has been associated with enhanced osteoblast activity and improved integration with host bone tissue (Kilgman et al. 2021; Han et al. 2022; Yu et al. 2024). Nanostructured surfaces can improve wettability and surface energy, which have been linked to increased protein adsorption and osteogenic cell adhesion, key elements of early bone healing around implants (Rupp et al. 2018; Han et al. 2022; Kido et al. 2023).

Recent research demonstrates that titanium surfaces modified with nanospike structures may not only improve osseointegration in vivo but also exhibit pronounced bactericidal capacity, significantly reducing bacterial colonization while maintaining mechanical integrity (Gil and Sanz 2025). This concept is particularly relevant because it suggests that nanostructured surface design may help partially decouple osseointegration from bacterial retention, although long-term clinical evidence remains limited (Brum et al. 2021; Yu et al. 2024; Gil and Sanz 2025).

4.4 Surface Topography - Sandblasting, Acid Etching, and Anodization

Mechanical and chemical treatments such as sandblasting combined with acid etching remain foundational methods for increasing surface roughness and promoting bone-implant interlocking. These techniques generate micro- and nano-scale features that enhance cellular contacts and accelerate osseointegration (Rupp et al. 2018; Matos et al. 2021; Kilgman et al. 2021; Han et al. 2022).

Anodization, an electrochemical surface modification, produces controllable titanium oxide nanotube structures that increase surface area and may improve osteoblast differentiation and soft-tissue responses, offering both osseointegrative and potential anti-inflammatory benefits (Han et al. 2022; Yu et al. 2024). Collectively, these physical surface modifications aim to balance enhanced mechanical interlocking with biological activity, but must be carefully optimized to avoid excessive roughness or irregularity that could facilitate bacterial adhesion (Brum et al. 2021; Kilgman et al. 2021; Han et al. 2022).

4.5 Laser Surface Modifications

Laser irradiation is a precision technique capable of generating defined micro- and nano-structures on titanium surfaces, which can enhance cellular responses and physical properties relevant to osseointegration (Fenelon et al. 2022; Kolarovszki et al. 2024). Reviews of laser surface modification research indicate that various laser systems can alter surface morphology without introducing chemical contaminants, potentially improving surface energy and cell adhesion characteristics (Fenelon et al. 2022; Kolarovszki et al. 2024).

In addition to their use in surface patterning, lasers are increasingly investigated in the context of peri-implant disease management, where controlled laser treatment may remove biofilm from contaminated implants while preserving surface features beneficial for subsequent re-osseointegration (Baima et al. 2022; Fenelon et al. 2022; Furtsev et al. 2023). However, laser effects differ according to wavelength, energy density, pulse duration, irradiation time, and surface type; inappropriate settings may produce undesirable melting, cracking, or alteration of surface microstructure (Fenelon et al. 2022).

4.6 Multifunctional and Combined Surface Modification Strategies

Emerging approaches in implant engineering aim to combine multiple surface treatments, such as nanostructuring, bioactive coatings, ion incorporation, anodization, and laser texturing. The goal is to achieve multifunctional surfaces that concurrently promote bone growth, reduce bacterial retention, and support soft-tissue integration (Han et al. 2022; Kunrath et al. 2024; Yu et al. 2024).

Such multifunctional surfaces interact with osteogenic, immune, and microbial processes simultaneously, potentially influencing inflammatory signaling and epigenetic mechanisms that regulate early bone healing and soft-tissue behavior at the implant interface (Kunrath et al. 2024). Although these approaches are highly promising, standardized methodologies and long-term clinical evidence are still needed to confirm their effectiveness and optimize their implementation for routine clinical use (Al Shayeb et al. 2024; Gkioka et al. 2024; Kolarovszki et al. 2024; Kunrath et al. 2024; Yu et al. 2024).

5. Discussion

5.1 Surface Roughness and the Osseointegration-Biofilm Trade-Off

The literature consistently shows that implant surface roughness is a key determinant of implant performance. Increased microroughness enhances osteoblast adhesion and accelerates osseointegration, as described by Matos and further supported by Kligman et al. and Han et al. (Matos et al. 2021; Kilgman et al. 2021; Han et al. 2022). These modifications improve early stability and bone-to-implant contact. However, the same surface characteristics that favor bone integration may also create niches for bacterial colonization. Rougher or irregular surfaces may facilitate biofilm persistence and thereby increase the risk of peri-implant inflammation (Brum et al. 2021; Dhaliwal et al. 2021; Kilgman et al. 2021). This highlights a fundamental biological trade-off: optimizing surfaces for osseointegration may simultaneously increase susceptibility to microbial retention if surface architecture is not precisely controlled.

5.2 Antimicrobial and Chemical Surface Modifications

To counteract biofilm formation, antimicrobial coatings and chemical surface modifications have been widely investigated. The systematic review by Gkioka and Rausch-Fan indicates that metal-based coatings and physical or chemical surface modifications can reduce bacterial load in vivo (Gkioka et al. 2024). Nevertheless, concerns remain regarding long-term biocompatibility, dose-dependent cytotoxic effects, and the durability of antimicrobial activity under clinical loading and oral environmental conditions (Gkioka et al. 2024; Yu et al. 2024)).

5.3 Nanotechnology and Advanced Surface Engineering

Recent advances in nanotechnology have introduced new possibilities for implant surface design. Soe et al. reported that nanoparticle-modified surfaces may enhance angiogenesis and bone regeneration around dental implants (Soe et al. 2024). Similarly, Gil and Sanz described bactericidal nanotopographies that may help reduce bacterial colonization without compromising osseointegration (Gil and Sanz 2025). Despite promising preclinical outcomes, the translation of these technologies into routine clinical practice requires further long-term in vivo and clinical studies with standardized surface characterization and clinically relevant endpoints (Yu et al. 2024; Gil and Sanz 2025).

5.4 Surface Contamination and Wettability

Surface contamination, particularly by hydrocarbon pellicles, is an often-overlooked factor influencing implant performance. Kido et al. showed that contaminants can significantly alter surface wettability, which in turn affects protein adsorption and cellular responses (Kido et al.

2023). Reduced wettability may impair early healing processes and compromise osseointegration. These findings emphasize that not only surface design but also manufacturing, packaging, storage, sterilization, and chairside handling conditions are critical for clinical success (Kido et al. 2023).

5.5 Decontamination Strategies in Peri-Implantitis Treatment

Effective decontamination of implant surfaces remains a major challenge in the treatment of peri-implantitis. Reviews by Dhaliwal et al. and Baima et al. indicate that no single decontamination method has demonstrated clear and consistent superiority across clinical settings (Dhaliwal et al. 2021; Baima et al. 2022). Among available techniques, laser-based approaches appear particularly promising when appropriate parameters are selected. Furtsev et al. reported improved stem cell adhesion following laser cleaning of contaminated implant surfaces, while Kolarovszki et al. highlighted the precision and controllability of laser surface modifications (Furtsev et al. 2023; Kolarovszki et al. 2024). However, as noted by Fenelon et al., improper laser settings may lead to undesirable alterations in surface structure (Fenelon et al. 2022).

5.6 Clinical Outcomes and Risk Factors

Long-term clinical outcomes depend on multiple factors, including implant surface characteristics, prosthetic components, patient age, maintenance protocols, and systemic or local risk factors. A nationwide cohort study by Lee et al. reported that implant surface type may influence the risk of late implant loss and peri-implantitis, whereas abutment type showed no significant association in their analysis (Lee et al. 2024). These findings underscore the importance of individualized treatment planning that accounts for both implant-related and patient-specific factors rather than relying on surface modification alone.

5.7 Emerging Role of Epigenetics

An emerging area of research involves the epigenetic effects of implant surface modifications. Kunrath et al. suggested that surface characteristics may influence gene expression related to inflammation, immune response, and tissue regeneration (Kunrath et al. 2024). Although this field is still in its early stages, it offers a novel perspective on how biomaterials can actively modulate biological processes at the molecular level and may help explain why similar surface modifications produce different biological outcomes in different clinical or experimental contexts.

6. Conclusions

Overall, the available evidence indicates that there is no single implant surface capable of simultaneously maximizing osseointegration and completely preventing bacterial colonization.

The most promising strategies are based on combining topographical and chemical modifications with bioactive and antimicrobial properties. Advanced approaches, such as nanotechnology, ion incorporation, bioactive coatings, and laser-based methods, show considerable potential. However, they still require confirmation in long-term clinical studies. Ultimately, long-term treatment success depends not only on implant surface properties but also on patient-related factors, appropriate hygiene protocols, maintenance care, and prosthetic design. Therefore, future approaches should integrate innovations in materials science with personalized clinical strategies to achieve optimal, predictable, and durable therapeutic outcomes.

Disclosure

Author Contributions:

Conceptualization: GC

Methodology: KB

Formal analysis: WC

Investigation: AJ

Data curation: KG

Writing – original draft preparation: GC, AJ, KB

Writing – review and editing: WP, AJ, WZ

Supervision: WZ

Project administration: GC

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Declaration of the use of generative AI and AI-assisted technologies in the writing process.

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) exclusively for language editing, grammar correction, and translation support. Following the use of this tool, the authors carefully reviewed and edited the manuscript and take full responsibility for the final content of the publication.

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