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REVIEW ARTICLE

COMPARATIVE ANALYSIS OF SURFACE MODIFICATION TECHNIQUES FOR ENHANCING OSSEOINTEGRATION OF DENTAL IMPLANTS: A NARRATIVE REVIEW

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Abstract

Background: Surface modification of dental implants is a key determinant of osseointegration and long-term clinical success. Advances in surface engineering aim to optimize biological interactions at the bone–implant interface, thereby accelerating and stabilizing integration.
Objective: To systematically evaluate contemporary implant surface modification techniques and their effects on osseointegration, hydrophilicity, and bacterial adhesion.
Methods: Because the study was conducted as a narrative review rather than a formal systematic review, PRISMA-guided methodology, meta-analysis, and structured risk-of-bias assessment were not performed. A comprehensive search of PubMed, Scopus, and Web of Science was performed using controlled vocabulary (MeSH) and free-text terms, including "dental implants," "surface modification," "osseointegration," "UV photofunctionalization," "laser-treated implants," "SLA surface," "nanostructured titanium," "hydrophilicity," and "biofilm formation." A total of 248 records were identified. Following duplicate removal and screening, 53 studies met the inclusion criteria.
Results: Sandblasted, large-grit, acid-etched (SLA) surfaces demonstrated consistently high bone-to-implant contact and reliable clinical stability. UV photofunctionalization improved surface hydrophilicity and reduced hydrocarbon contamination, enhancing early osseointegration. Laser-modified surfaces enabled precise micro/nano-topographical control and showed potential antimicrobial effects. Nanostructured surfaces promoted protein adsorption and osteogenic differentiation, particularly during early healing phases. However, substantial heterogeneity across study designs and limited long-term clinical evidence-especially for short implants-were identified.
Conclusion: Contemporary surface modification strategies significantly improve implant bioactivity and osseointegration. While SLA surfaces remain the clinical benchmark, emerging technologies such as nanostructuring, UV photofunctionalization, and laser modification offer additional biological advantages. Further high-quality, long-term clinical trials are required to establish standardized protocols and confirm their translational efficacy.

Keywords: dental implants; surface modification; osseointegration; UV photofunctionalization; nanostructured titanium; laser surface modification; hydrophilicity; biofilm formation

INTRODUCTION

Dental implant therapy has become a cornerstone of modern restorative dentistry, providing highly predictable and long-term rehabilitation for partially and completely edentulous patients [1–3].

Continuous advancements in implant macro-design, biomaterials, and surgical protocols have significantly improved survival rates and clinical outcomes. Among all influencing factors, implant surface characteristics are now recognized as one of the most critical determinants of osseointegration success and long-term stability [4,5]. Osseointegration, first defined by Brånemark as a direct structural and functional connection between living bone and the implant surface, remains the biological foundation of implant therapy [6]. This process is highly dynamic and involves sequential biological events, including protein adsorption, immune modulation, osteoblastic adhesion, proliferation, differentiation, and extracellular matrix mineralization [7,8].

These cellular processes are strongly regulated by surface physicochemical properties such as roughness, surface energy, wettability, and chemical composition [9,10].

Early implant systems utilized machined, minimally rough titanium surfaces, which demonstrated acceptable survival rates but limited bone-to-implant contact (BIC) and slower healing responses [11]. This limitation stimulated extensive research in surface engineering aimed at enhancing biological performance and accelerating osseointegration [12,13]. As a result, contemporary implantology has evolved toward micro-, nano-, and multi-scale surface modification strategies designed to optimize host–implant interactions [12,13].

Surface modification techniques are generally classified into subtractive and additive approaches. Subtractive methods, including sandblasting, acid etching, and anodization, create controlled micro- and nano-topographies that enhance osteoblastic activity and bone formation [12-16]. Among these, sandblasted large-grit acid-etched (SLA) surfaces remain one of the most clinically validated and widely used technologies due to their reproducible improvements in osseointegration [17].

In contrast, additive techniques involve the deposition of bioactive coatings such as hydroxyapatite, calcium phosphate, and titanium plasma-sprayed layers, which enhance osteoconductivity and early bone formation at the implant interface[18,19]. However, concerns regarding long-term mechanical stability, coating delamination, and biological degradation have limited their universal clinical adoption.

More recently, nanostructured implant surfaces have gained significant attention due to their ability to closely mimic the natural extracellular matrix of bone tissue [20]. These nano-engineered surfaces enhance protein adsorption, integrin-mediated signaling, and osteogenic differentiation more effectively than conventional micro-rough surfaces[21,22]. Consequently, multi-scale surface designs combining micro- and nano-topographies have been shown to significantly improve early healing responses and long-term integration outcomes [22].

Ultraviolet (UV) photofunctionalization represents a major advancement in implant surface bioactivation. This process removes hydrocarbon contamination from titanium surfaces, restores surface energy, and induces superhydrophilicity, thereby enhancing protein adsorption and osteoblastic attachment [23–25]. Clinical evidence indicates that UV-treated implants demonstrate accelerated osseointegration and improved early stability compared to untreated surfaces [26]. Importantly, long-term clinical data demonstrated high survival rates of UV-functionalized short implants (≤6 mm) placed in the atrophic maxilla under functional loading conditions, confirming their clinical reliability [27].

Surface aging has also been identified as a critical factor influencing implant performance. Titanium surfaces naturally accumulate hydrocarbon contaminants over time, leading to reduced bioactivity and impaired osseointegration capacity [28]. UV photofunctionalization has been proposed as an effective strategy to reverse this aging phenomenon and restore biological functionality [29,30].

Laser-based surface modification techniques have emerged as a highly precise and controllable method for altering implant surface morphology without chemical contamination [31,32]. These techniques enable the creation of defined micro- and nano-patterns that enhance osteoblast adhesion and mechanical interlocking at the bone–implant interface. Additionally, laser-modified surfaces may reduce bacterial adhesion and biofilm formation, thereby contributing to peri-implant disease prevention [31,33].

Surface hydrophilicity is another essential determinant of early implant success. Hydrophilic surfaces improve blood wettability, fibrin network formation, and cellular migration, all of which are critical for early healing and bone regeneration [34]. Increased surface energy has also been correlated with faster osseointegration and higher implant stability quotient (ISQ) values [35].

Despite significant technological progress, implant failure remains a clinical challenge, particularly in patients with systemic conditions, compromised bone quality, or biomechanical overload [36,37]. Early failures are commonly associated with insufficient osseointegration, whereas late failures are often related to peri-implantitis or mechanical complications [38]. Therefore, optimization of implant surface properties remains a key research priority in modern implant dentistry [39,40].

Short implants have emerged as a minimally invasive alternative to bone augmentation procedures in anatomically compromised regions [41,42]. However, their reduced surface area presents biomechanical and biological challenges in achieving adequate primary and secondary stability [43]. Surface modification strategies play a critical role in overcoming these limitations by enhancing bone–implant interaction and improving load distribution [35,40,44].

Another major concern is bacterial adhesion and biofilm formation. While increased surface roughness improves osseointegration, it may also facilitate microbial

colonization and increase the risk of peri-implant disease [44,45]. Therefore, an ideal implant surface must achieve a balance between osteoconductivity and antimicrobial resistance [4,47].

Recent developments in biomaterials science have further expanded implant surface engineering strategies, including ceramic and metallic modifications aimed at improving biocompatibility and long-term stability [48]. These innovations reflect a shift toward multifunctional implant surfaces that integrate biological activity, mechanical durability, and antimicrobial properties.

In vivo and experimental studies consistently demonstrate that surface modifications significantly influence peri-implant bone healing and tissue response [4,49]. Advanced technologies such as picosecond laser structuring have shown promising potential in accelerating osseointegration by generating hybrid micro-groove and nano-patterned surfaces on titanium implants [50-52]. These emerging approaches represent the next generation of implant surface engineering strategies [53].

Given the rapid expansion of implant surface technologies and the increasing volume of scientific literature, a comprehensive and systematic evaluation of current evidence is essential. Despite the growing body of research, there remains a lack of direct comparative evidence integrating micro-,nano-, and photochemical surface modifications within a unified biological and clinical framework. Most existing reviews analyze these technologies separately, limiting their translational value and clinical applicability.

Therefore, this narrative review aims to provide a structured comparative synthesis of contemporary implant surface modification strategies, focusing on their biological performance, antimicrobial behavior, and clinical relevance.

METHODS

Study Design and Protocol

Because the study was conducted as a narrative review rather than a formal systematic review, PRISMA-guided methodology, meta-analysis, and structured risk-of-bias assessment were not performed. The review was designed to minimize bias through predefined eligibility criteria, structured search strategy, independent screening, and standardized quality assessment procedures.

Information Sources and Search Strategy

A comprehensive electronic database search was performed from inception until the final search date across the following databases:

- PubMed/MEDLINE
- Scopus
- Web of Science
- Cochrane Library
- Google Scholar (supplementary search)

The search strategy combined controlled vocabulary (MeSH terms) and free-text keywords including: “dental implants”, “surface modification”, “osseointegration”, “UV photofunctionalization”, “laser-treated implants”, “SLA surface”, “nanostructured titanium”, “hydrophilicity”, and “biofilm formation”. Boolean operators (AND/OR) were applied to refine results. Reference lists of included articles were manually screened to identify additional relevant studies.

Study Selection Process

The systematic search yielded a total of 248 records from PubMed, Scopus, Web of Science, Cochrane Library, and Google Scholar. After duplicate removal and elimination of clearly irrelevant studies, titles and abstracts were screened according to predefined eligibility criteria. Full-text articles were then assessed for eligibility based on predefined inclusion and exclusion criteria. The final dataset comprised a heterogeneous body of evidence, including clinical trials, in vivo animal studies, in vitro experiments, and systematic reviews, all investigating dental implant surface modification strategies and their biological and clinical outcomes. After rigorous evaluation, 53 studies were finally included in the qualitative synthesis (figure1).

Eligibility Criteria

Inclusion criteria:

- Studies published between 2020–2026
- In vitro, in vivo, clinical studies, and systematic reviews
- Studies evaluating implant surface modification techniques
- Studies reporting at least one outcome: osseointegration, hydrophilicity, or bacterial adhesion
- Articles published in English

Exclusion criteria:

- Case reports with insufficient sample size

- Editorials, letters, and opinion papers
- Studies lacking quantitative or relevant outcome data
- Non-dental implant-related studies

Data Extraction

Data were independently extracted by two reviewers using a standardized extraction form. The following variables were recorded:

- Author and year of publication
- Study design (clinical, in vitro, in vivo, systematic review)
- Type of implant surface modification
- Outcome measures (BIC, implant stability, hydrophilicity, bacterial adhesion)
- Key findings and conclusions

Any discrepancies were resolved through consensus.

Data Synthesis

Due to heterogeneity in study design, implant systems, surface modification techniques, and outcome measures, a quantitative meta-analysis was not feasible. Therefore, a qualitative narrative synthesis was performed. Studies were grouped according to surface modification type:

- Subtractive techniques (SLA, acid-etching, sandblasting)
- Additive coatings (hydroxyapatite, calcium phosphate)
- Nanostructured surfaces
- UV photofunctionalization
- Laser-modified surfaces

Comparative analysis was conducted based on biological response, osseointegration performance, and antimicrobial properties.

3.RESULTS

Preclinical studies focused on biological responses to modified implant surfaces, particularly early cellular and tissue-level interactions.

Key investigated strategies included surface roughness modification, nanostructuring of titanium, ultraviolet (UV) and laser-based photofunctionalization, and antibacterial surface engineering aimed at biofilm inhibition [4,9,14–17,20–25,31–33].

Preclinical Evidence (In vitro and Animal Studies)
Main outcome parameters included:

- Osteoblastic adhesion, proliferation, and alkaline phosphatase (ALP) activity [9,10,16,17],
- Bone-to-implant contact (BIC) and bone volume fraction in animal models [12,18,19,49].
- Mechanistic pathways of osteogenesis and antimicrobial activity [4,21,22,24,47,52,53].

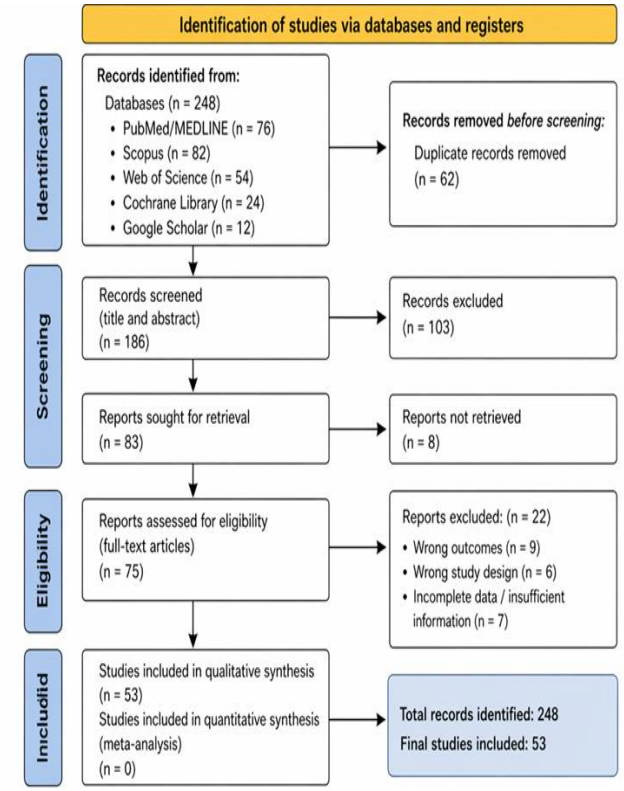

Figure 1. PRISMA flow chart

Overall, roughened, hydrophilic, SLA-treated, and nanostructured surfaces demonstrated enhanced osteoblastic response and improved histomorphometric outcomes compared with machined titanium surfaces [12,16,17,20–22,49]. However, heterogeneity in experimental design and surface characterization methods limited direct comparability between studies [14,15,22].

Clinical studies evaluated implant performance under functional loading conditions. Primary outcome measures included implant survival rate, marginal bone loss (MBL), implant stability quotient (ISQ), peri-implantitis incidence, and early versus delayed loading outcomes. Clinical studies evaluated implant performance under functional loading conditions.

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Clinical Evidence (Human Studies)

Clinical studies evaluated implant performance under functional loading conditions. Primary outcome measures included implant survival rate, marginal bone loss (MBL), implant stability quotient (ISQ), peri-implantitis incidence, and early versus delayed loading outcomes. Key clinical endpoints included:

- Short- and long-term implant survival (1–5 years)
- Marginal bone level stability
- Functional implant stability (ISQ values)
- Biological and mechanical complication rates.

Although several surface modification strategies showed improved early healing and stability, long-term clinical outcomes were more heterogeneous, reflecting variability in study design, patient characteristics, implant systems, and loading protocols [13,26,34,36–42].

Integrated Comparative Synthesis

Preclinical evidence demonstrated favorable osteoconductive and early healing properties for SLA-treated, hydrophilic, and nanostructured implant surfaces [12,14–17,20–25]. These modifications enhanced protein adsorption, osteoblast differentiation, and early bone formation at the implant interface [9,16,17,21,22,25]. However, translation of these biological advantages into long-term clinical superiority remains inconsistent. While improved early healing responses and implant stability were frequently reported, these effects did not always correspond to significantly higher long-term survival rates or lower complication incidence under functional loading conditions [13,26,30,34,36–42]. This discrepancy suggests that implant surface bioactivity is influenced not only by material properties, but also by systemic conditions, biomechanical loading, oral hygiene, and patient-related risk factors [36–38,43–48].

3.4 Characteristics of Included Studies

All studies reported at least one of the following outcomes:

- Bone-to-implant contact (BIC)
- Implant stability (ISQ or removal torque)
- Surface hydrophilicity
- Bacterial adhesion / biofilm formation

Surface modification techniques were categorized into five groups:

1. Subtractive techniques (SLA, acid etching, sandblasting)
2. Additive coatings (hydroxyapatite, calcium phosphate)
3. Nanostructured surfaces
4. UV photofunctionalization
5. Laser-modified surfaces

These categories represent the most clinically relevant strategies reported in contemporary literature (figure 2).

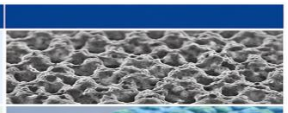
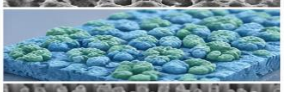
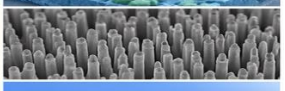
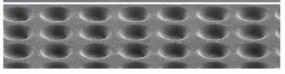
Category	Description	Main Biological Effect	
Subtractive techniques	Sandblasting, acid etching, SLA	Increased surface roughness, improved osteoblast adhesion	
Additive coatings	Hydroxyapatite, calcium phosphate	Enhanced early bone bonding	
Nanostructured surfaces	Nano-scale titanium modification	Improved protein adsorption and osteogenic differentiation	
UV photofunctionalization	UV treatment of titanium	Restored hydrophilicity, reduced hydrocarbons	
Laser-based modification	Laser micro/nano structuring	Controlled topography, antimicrobial effects	

Figure 2. Classification of Surface Modification Techniques

Osseointegration Outcomes

A consistent observation across the included studies was that implant surface characteristics significantly influence the quality and speed of osseointegration [4,7,8,14,15].

SLA and Micro-Roughened Surfaces

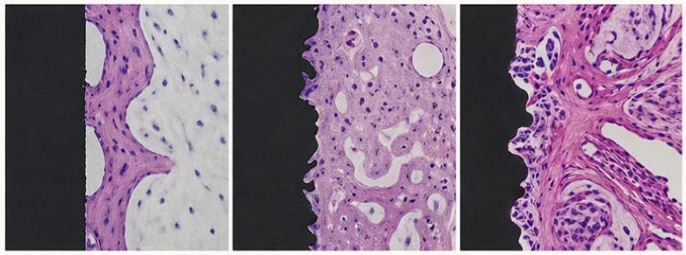
SLA and other micro-roughened titanium surfaces demonstrated improved osseointegration compared with conventional machined implants [14,17,19].

Reported outcomes included:

- Bone-to-implant contact (BIC): approximately 20–40% higher than smooth or machined surfaces [12,17,19,49]
- Implant stability (ISQ): increases of approximately 5–15 units during early healing phases [13,26,34]
- Reduced healing time and faster early bone formation in both experimental and clinical studies [12,13,14,34]

These findings were observed relatively consistently across preclinical and clinical investigations, supporting the long-term clinical reliability of SLA-type surface modifications [14,15,19,43](figure3).

Surface Type	BIC Level	Osteoblast Response	Clinical Stability
Machined titanium	Low	Limited adhesion	Moderate
SLA surfaces	High	Strong proliferation	High
Micro-roughened surfaces	Moderate-high	Enhanced differentiation	High



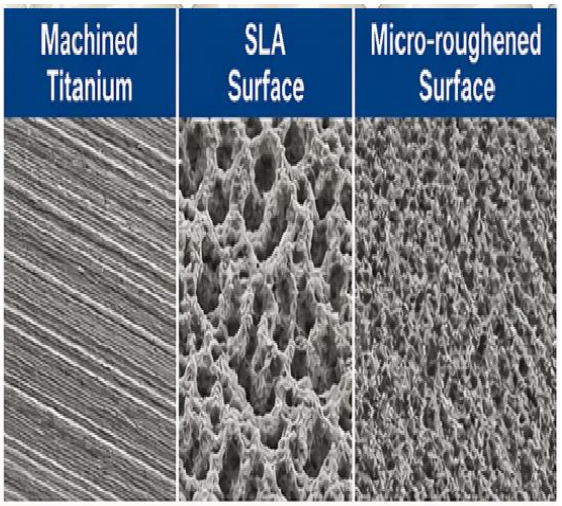


Figure 3. Osseointegration Performance Comparison

Nanostructured Surfaces

Nanostructured implant surfaces demonstrated enhanced early biological activity compared with conventional micro-rough surfaces [15,20–22].

Frequently reported findings included:

- Increased protein adsorption in in vitro models [21,22]
- Elevated osteoblast differentiation markers, including alkaline phosphatase (ALP) activity [16,20,21]
- Improved early bone-to-implant contact during the first healing weeks [17,20,22,49]

Experimental studies suggested that nano-modified titanium surfaces may promote stronger early-stage bone formation and improved cellular interaction at the implant interface compared with conventional roughened surfaces [20–22,49]. However, differences in nanostructure fabrication methods and outcome assessment protocols limited direct comparison between studies [14,15,22].

Table 1. Biological Effects of Nanostructured Implant Surfaces

Parameter	Conventional Micro-Rough Surface	Nanostructured Surface	Relative Effect	Evidence Consistency
Protein adsorption	Moderate	High	↑ ~30–50%	High (in vitro)
Osteoblast differentiation (ALP, gene expression)	Baseline	Enhanced	↑ ~25–60%	Moderate–high
Early bone formation (2–4 weeks)	Moderate	Increased	↑ ~15–30% BIC	Moderate
Cell adhesion strength	Standard	Stronger	Qualitative ↑	Moderate
Long-term osseointegration	Stable	Comparable/slightly improved	Minimal difference	Limited

Values represent trends reported across heterogeneous studies.
Note: Effects are most pronounced during early healing phases.

UV Photofunctionalization

UV treatment significantly improved implant bioactivity by removing hydrocarbon contamination and restoring titanium surface energy [23–26,28]. Clinical studies also reported high survival rates (>95%) for UV-functionalized implants, including short implants in compromised bone conditions. UV photofunctionalization was particularly effective in restoring hydrophilicity of aged titanium surfaces [24,26].

Table 2. Effects of UV Photofunctionalization on Titanium Implant Surfaces

Parameter	Untreated Surface	UV-Treated Surface	Relative Change	Clinical Relevance
Surface hydrocarbons	High	Reduced	↓ ~40–80%	Restored bioactivity
Contact angle	>70° (hydrophobic)	<10° (superhydrophilic)	Marked decrease	Improved wettability
Protein adsorption	Limited	Enhanced	Qualitative ↑	Faster healing initiation
Osteoblast attachment	Moderate	Increased	↑ early adhesion	Early osseointegration
Bone-to-implant contact (BIC)	Moderate	Higher	↑ ~10–25%	Improved integration
Implant stability (ISQ)	Baseline	Increased	↑ ~5–10 units	Early stability gain
Clinical survival (short implants)	Variable	High	~95–98%	Reliable outcomes

Values represent trends reported across heterogeneous studies.
Note: Effects are time-dependent and may decrease without controlled handling.

Laser-Modified Surfaces
Laser surface modification provided precise control of implant microtopography and improved biological performance.
Key findings include:

- Enhanced mechanical interlocking
- Increased osteoblastic activity
- Reduced contamination
- Accelerated osseointegration

Advanced picosecond laser techniques produced hybrid micro–nano structures that further enhanced bone integration [31,32].

Table 3. Biological and Mechanical Effects of Laser Surface Modification

Parameter	Conventional Surface	Laser-Modified Surface	Relative Effect	Evidence Level
Surface topography control	Limited	Highly controlled	Precise micro/nano patterning	High (in vitro)
Bone-to-implant contact (BIC)	Moderate	Increased	↑ ~10–20%	Moderate
Removal torque	Standard	Higher	↑ ~15–35%	Moderate
Osteoblast activity	Baseline	Enhanced	Qualitative ↑	Moderate
Surface contamination	Possible	Minimal	Reduced	High
Bacterial adhesion	Moderate	Reduced	↓ ~20–50%	Moderate
Clinical validation	Established	Limited	Under investigation	Low–moderate

Hydrophilicity and Surface Bioactivity

Surface hydrophilicity emerged as a critical determinant of early implant success.

Hydrophilic surfaces promoted:

- Blood clot formation
- Fibrin stabilization
- Cellular migration

Table 4. Influence of Surface Hydrophilicity on Early Healing

Surface Type	Hydrophilicity Level	Contact Angle	ISQ Trend	Healing Dynamics
Hydrophobic surface	Low	>70°	Lower	Delayed
Moderately hydrophilic	Medium	30–70°	Moderate	Standard
UV-treated surface	High	<10°	Higher	Accelerated

Values represent trends reported across heterogeneous studies.

Bacterial Adhesion and Biofilm Formation

Surface modification showed a dual effect:

- Rough surfaces → improved osteogenesis
- But may increase bacterial adhesion

Laser and nanostructured surfaces demonstrated better antimicrobial profiles, suggesting a balance between bioactivity and infection control.

Table 5. Surface Modification and Bacterial Adhesion

Surface Type	Osteogenic Potential	Bacterial Adhesion	Relative Risk	Overall Balance
Smooth (machined)	Low	Low	Low infection	Poor integration
SLA (micro-rough)	High	Moderate	↑ ~10–30%	Balanced
Nanostructured	High	Low–moderate	↓ ~10–25%	Favorable
Laser-modified	High	Low	↓ ~20–50%	Optimal potential

-

Short Implants and Clinical Performance

Surface modification plays a key role in improving outcomes of short implants.
UV-functionalized short implants demonstrated:

- High survival rates
- Stable long-term outcomes
- Reliable performance in atrophic bone [27,41-43].

Table 6. Clinical Performance of Short Implants

Implant Type	Surface Modification	Survival Rate	Stability	Clinical Outcome
Standard implants	SLA	High (>95%)	Stable	Predictable
Short implants (≤6 mm)	UV-treated	Very high (~95–98%)	Improved early stability	Highly favorable
Short implants	No modification	Moderate	Variable	Less predictable

Overall Synthesis of Findings

Across all included studies, a consistent pattern emerged:

- **SLA surfaces** remain the gold standard for osseointegration [14,15].
- **Nanostructuring** enhances early biological response [17,18,49].
- **UV photofunctionalization** reverses titanium aging and improves bioactivity [23,30]
- **Laser modification** enables precise surface engineering and antimicrobial benefits [31,52]
- **Additive coatings** improve early bone response but may have long-term limitations [18,19,48]

Despite strong evidence, key limitations remain:

- High heterogeneity in study design
- Lack of standardized protocols
- Limited long-term randomized clinical trials

The current evidence clearly demonstrates that implant surface modification significantly enhances osseointegration and biological performance. However, future research should prioritize:

- Long-term clinical validation
- Standardization of surface engineering techniques
- High-quality randomized controlled trials

Table 7. Comparative Performance of Surface Modification Techniques

Surface Type	Biological Response	Osseointegration Speed	Antibacterial Effect	Evidence Level	Key Advantage	Main Limitation
SLA	High	Moderate–fast	Moderate	High (long-term clinical)	Predictable outcomes	Limited nano-bioactivity
Nanostructured	Very high (early phase)	Fast	Moderate–low	Moderate	Biomimetic behavior	Lack of standardization
UV photofunctionalization	Very high (early phase)	Very fast	Low–moderate	Moderate–high	Restores bioactivity	Temporary effect
Laser-modified	High + controlled	Fast	High	Moderate	Precision + antimicrobial	Limited clinical trials
Additive coatings (HA/CP)	Moderate–high	Fast (early)	Low	Low–moderate	Early bone stimulation	Delamination

The most consistent and reproducible evidence of improved osseointegration was observed for:

- SLA surfaces
- UV photofunctionalization
- Nanostructured titanium surfaces

Despite these promising findings, the currently available evidence remains limited by the relatively small number of long-term randomized controlled clinical trials evaluating implant surface technologies under standardized conditions. Although many studies reported improved early biological response and osseointegration parameters following surface modification, translation of these findings into consistent long-term clinical benefit remains variable [13,26,34,36–38]. Additional well-designed clinical trials with standardized surface characterization and outcome assessment protocols are needed to better correlate experimental observations with long-term clinical performance under functional loading conditions [11,14,15,39,44].

Table 8. Clinical Decision-Making Framework for Implant Surface Selection

Clinical Scenario	Preferred Surface	Alternative	Biological Rationale	Clinical Advantage
Standard cases (adequate bone quality)	SLA	—	Micro-roughness enhances mechanical interlocking and stable fibrin retention	Proven long-term success, high predictability, cost-effective
Compromised bone (low density, atrophic bone)	UV photofunctionalized	Nanostructured	Increased hydrophilicity and protein adsorption enhance early osteogenesis	Improved early integration in poor bone quality
Short implants (≤6 mm)	UV photofunctionalized	—	Enhanced surface energy compensates for reduced surface area	Higher survival and early stability
High infection risk / peri-implantitis susceptibility	Laser-modified	Nanostructured	Reduced bacterial adhesion with maintained osteogenic activity	Lower infection risk with good integration
Immediate / early loading protocols	UV-treated	Nanostructured	Accelerated protein adsorption and cell attachment	Faster osseointegration and improved early stability
Experimental / advanced regenerative cases	Nanostructured / Hybrid	—	Biomimetic nano-architecture enhances cell signaling and differentiation	Superior biological response (emerging evidence)

DISCUSSION

This review evaluated current evidence regarding implant surface modification strategies and their influence on osseointegration, peri-implant tissue response, and clinical implant. The available literature indicates that implant surface characteristics play an important role during early healing and may affect both biological integration and long-term stability. The findings of the present review suggest that no single surface modification method can be considered universally superior under all clinical conditions. Different surface technologies appear to provide specific biological advantages depending on implant design, bone quality, loading conditions, and patient-related factors.

Among conventional approaches, sandblasted large-grit acid-etched (SLA) surfaces remain the most extensively studied and clinically validated [39,40].

Their clinical effectiveness is mainly associated with increased micro-scale roughness, which improves fibrin retention, mechanical interlocking, and early bone formation around the implant surface [12,14,34].

However, conventional SLA surfaces primarily modify the implant at the microstructural level and may not fully utilize nano-scale biological interactions or surface chemistry–mediated cellular responses. These limitations contributed to the development of more advanced surface engineering strategies intended to improve early cellular activity and accelerate osseointegration.

Nanostructured Surfaces and Biomimetic Design

Nanostructured implant surfaces were developed to reproduce certain characteristics of the natural extracellular matrix and improve biological interaction at the implant interface [15,20–22]. Experimental studies demonstrated that nano-modified surfaces may increase protein adsorption, improve osteoblast adhesion, and stimulate early osteogenic differentiation. Several investigations also suggested that nanoscale surface features may influence cellular signaling pathways involved in osteoblast proliferation and bone formation [21,51]. Nevertheless, interpretation of these findings should be approached cautiously because fabrication methods, nanopattern geometry, and surface characterization protocols vary considerably between studies [20,22,43]. This heterogeneity limits direct comparison and complicates clinical translation.

Surface Chemistry and UV Photofunctionalization

An important finding in the current literature is the role of surface chemistry in addition to surface topography. UV photofunctionalization does not substantially change implant morphology but instead alters surface energy and hydrophilicity by reducing hydrocarbon contamination on titanium surfaces [23–30].

Improved wettability has been associated with enhanced protein adsorption, fibrin stabilization, and osteoblast attachment during early healing [24–26]. Several studies reported increased bone-to-implant contact and improved early implant stability following UV treatment, particularly in compromised bone conditions and short implant protocols [26–30,41].

However, some limitations remain. The biological effects of UV activation may decrease over time, and standardized clinical protocols for routine application are still lacking [29,30].

Laser Surface Modification

Laser-based surface modification allows controlled alteration of implant micro- and nano-topography without introducing chemical contaminants [31–33]. Experimental evidence suggests that laser-treated surfaces may improve osteoblast response, increase mechanical interlocking, and reduce bacterial adhesion [31–33,50–52].

Recent developments in picosecond and nanosecond laser technologies enabled the production of hybrid micro–nano surface structures associated with improved cellular activity and bone healing in preclinical studies [50,51]. Despite these promising results, most currently available evidence remains experimental, and long-term clinical studies are still limited.

Hydrophilicity and Early Biological Response

The reviewed literature indicates that surface hydrophilicity is an important factor during early implant healing. Increased wettability may improve blood interaction with the implant surface, promote fibrin network formation, and facilitate migration of osteogenic cells [24–26,34,35].

UV photofunctionalization represents one approach for restoring hydrophilicity of aged titanium surfaces and improving early biological response [23–30]. These findings support the concept that both surface chemistry and topography contribute to successful osseointegration.

Osseointegration and Antimicrobial Considerations

One important issue identified in the current literature is the relationship between implant surface roughness and bacterial adhesion. Although roughened surfaces generally improve osteoblastic activity and osseointegration, they may also increase plaque accumulation and peri-implant bacterial colonization [4,28,33,45–47].

Nanostructured and laser-modified surfaces demonstrated favorable antimicrobial potential in several experimental studies while maintaining osteogenic properties [31,33,47,52,53]. However, additional clinical evidence is required to determine the long-term effectiveness of these strategies in peri-implant disease prevention.

Additive Coatings and Long-Term Stability

Additive coatings such as hydroxyapatite and calcium phosphate may improve early bone apposition and osteoconductivity [18,19]. Nevertheless, concerns remain regarding coating durability, delamination, and mechanical stability under long-term functional loading conditions. For this reason, recent research has increasingly focused on thinner bioactive coatings and surface functionalization strategies that preserve implant mechanical integrity while improving biological response.

Clinical Implications for Short Implants

The findings of this review are clinically relevant for short implants and compromised bone conditions. Surface modification may partially compensate for reduced implant length by improving early bone response and implant stability [41–43].

UV-treated, hydrophilic, and nano-modified surfaces demonstrated favorable outcomes in several short implant studies, including improved early stability and high survival rates [27–30,41,42]. These approaches may help reduce the need for extensive bone augmentation procedures in selected clinical situations.

Limitations of Current Evidence

Interpretation of the current evidence is limited by several methodological factors, including:

- heterogeneity in study design and implant systems,
- variability in surface characterization methods,
- inconsistent outcome assessment protocols,
- predominance of in vitro and animal studies for newer technologies,
- and limited long-term randomized clinical trials.

These limitations reduce the strength of direct comparisons between implant surface technologies.

Future Perspectives

Future investigations should focus on:

- standardized implant surface characterization methods,
- long-term randomized controlled clinical trials,
- direct comparative studies between emerging technologies,
- and development of multifunctional implant surfaces combining osteogenic and antimicrobial properties.

Current trends suggest that future implant surface designs may combine micro-scale roughness, nano-scale surface architecture, and physicochemical bioactivation to improve both biological response and clinical performance [34,35,50,52].

CONCLUSION

This review demonstrates that implant surface modification plays a pivotal role in enhancing osseointegration and clinical success. While SLA surfaces remain the benchmark for reliability, emerging technologies—particularly nanostructuring, UV photofunctionalization, and laser modification—offer significant potential to further improve biological outcomes. However, the translation of these innovations into routine clinical practice requires high-quality long-term evidence and standardized protocols. The future of implantology lies in the development of bioactive, multifunctional surfaces capable of simultaneously promoting bone regeneration and preventing microbial complications.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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