



GRADUATION PROJECT

Degree in Dentistry

SURFACE TREATMENT OF TITANIUM IM- PLANTS, CLASSIFICATION AND CLINICAL IM- PLICATIONS

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RESUMEN

Introducción: Las modificaciones de la superficie de los implantes dentales de titanio han sido ampliamente desarrolladas para mejorar la interacción biológica entre el implante y los tejidos circundantes y aumentar la predictibilidad del tratamiento implantológico. En las últimas décadas, se han introducido diversos tratamientos de superficie para acelerar la osteointegración y optimizar los resultados clínicos.

Objetivos: El objetivo de este estudio fue revisar y analizar críticamente la literatura científica sobre los tratamientos de superficie de los implantes de titanio, centrándose en su evolución a lo largo del tiempo y evaluando cómo las diferentes tecnologías de superficie influyen en resultados clínicos como la osteointegración, la estabilidad del implante, la preservación ósea marginal y la respuesta de los tejidos blandos.

Métodos: Se realizó una revisión de la literatura utilizando las principales bases de datos científicos. Los estudios relevantes que evaluaban diferentes tratamientos de superficie de implantes de titanio fueron identificados y analizados según criterios de inclusión y exclusión predefinidos.

Resultados: Tras aplicar los criterios de selección, se incluyeron un total de 20 estudios en la revisión. Los resultados mostraron que las superficies de implantes moderadamente rugosas, especialmente aquellas obtenidas mediante técnicas de arenado y grabado ácido, siguen siendo el estándar clínico de referencia debido a su osteointegración predecible y a sus resultados favorables a largo plazo. Además, las nuevas tecnologías de superficie mostraron efectos biológicos prometedores, aunque no siempre se observaron ventajas clínicas consistentes.

Conclusiones: Las características de la superficie del implante influyen significativamente en los eventos biológicos tempranos en la interfaz hueso–implante y pueden mejorar la estabilidad inicial del implante. Sin embargo, los resultados clínicos a largo plazo entre las superficies modernas parecen ser en gran medida comparables. Se requieren más estudios clínicos bien diseñados a largo plazo para aclarar los posibles beneficios de las tecnologías de superficie avanzadas.

PALABRAS CLAVE

dentistry, dental implants, implant surface modification, osseointegration, implant stability

ABSTRACT

Introduction: Surface modifications of titanium dental implants have been widely developed to improve the biological interaction between the implant and surrounding tissues and to enhance the predictability of implant therapy. Over recent decades, several surface treatments have been introduced to accelerate osseointegration and optimise clinical outcomes.

Objectives: The aim of this study was to critically review and analyse the scientific literature on titanium implant surface treatments, focusing on their evolution over time and evaluating how different surface technologies influence clinical outcomes such as osseointegration, implant stability, marginal bone preservation, and soft-tissue response.

Methods: A literature review was conducted using the major scientific databases. Relevant studies evaluating different titanium implant surface treatments were identified and analysed according to predefined inclusion and exclusion criteria.

Results: After applying the selection criteria, a total of 20 studies were included in the review. The findings showed that moderately rough implant surfaces, particularly those produced through sandblasting and acid-etching techniques, remain the clinical reference standard due to their predictable osseointegration and favourable long-term outcomes. Additionally, emerging surface technologies demonstrated promising biological effects, although consistent clinical advantages were not always observed.

Conclusions: Implant surface characteristics significantly influence early biological events at the bone–implant interface and may enhance early implant stability. However, long-term clinical outcomes among modern implant surfaces appear broadly comparable. Further well-designed long-term clinical studies are required to clarify the potential benefits of advanced surface technologies.

KEYWORDS

Dentistry, Dental Implants, Implant Surface Treatment, Osseointegration, Implant Stability

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1. INTRODUCTION

1.1 Definition

Dental implants are biocompatible devices, usually manufactured from pure titanium or titanium alloys, which are surgically placed in the jawbone to support and retain dental prostheses through a direct bone–implant interface known as osseointegration. (1,2)

The surface treatment of titanium implants refers to all physical, chemical, or biological modifications applied to the implant surface to enhance its biological performance, improve osseointegration, promote soft-tissue attachment, and reduce healing time.(3–5)

These modifications can alter surface roughness, topography, chemical composition, and surface energy or wettability.

Surface modifications aim to enhance cell adhesion, protein adsorption, and bone formation at the implant–tissue interface. (3–5)

In recent years, implant surfaces have evolved from being mechanically optimized to becoming biologically active, capable of influencing soft-tissue behaviour, immune response, and bacterial colonization, which extends the idea of osseointegration beyond the notion of simple bone contact. (6)

1.2 Background of the Subject

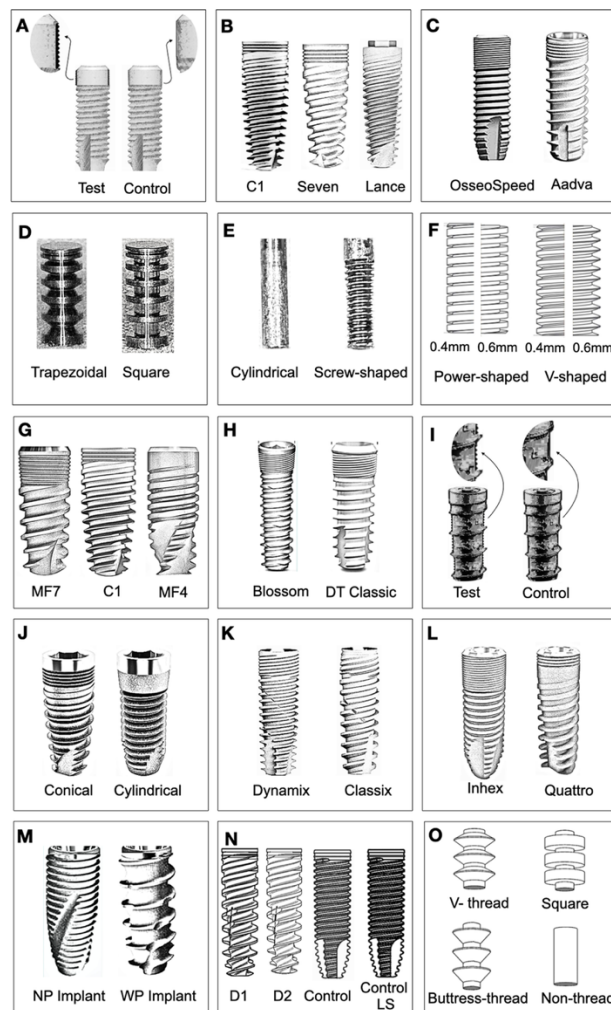


Fig.1 Macroscopic design of titanium dental implant (7)

Since the pioneering work of Brånemark and Albrektsson, titanium has become the material of choice for dental implants due to its favourable mechanical strength, corrosion resistance and high biocompatibility with the human body. (1,2)

Despite these advantages, the untreated titanium surface is biologically inert and does not inherently promote rapid bone healing.

This limitation has led to decades of research into surface modification techniques, trying to improve early stability, accelerate osseointegration, and increase long-term clinical success.

The most common surface treatment methods include: grit blasting, acid etching, anodization, plasma spraying, and various coatings. (3,4)

Early evidence demonstrated that roughened surfaces significantly increase bone–implant contact (BIC) and removal torque compared to machined surfaces (also called smooth implant), translating into an improved clinical stability and osseointegration. (3)

Today, it is well established that the surface design is a key factor for successful implantation, especially in protocols involving immediate or early loading, short implants, or compromised

bone conditions. These clinical situations are becoming increasingly common in contemporary implantology. (6,8)

Surface chemistry and roughness are important factors; however, implant macro-design also plays a significant role in clinical performance. Thread geometry, implant taper, platform switching, and collar design can influence primary stability, load distribution, and soft-tissue behaviour. Although surface modifications primarily target the biological interface, their effectiveness must be interpreted together with implant geometry, as both factors determine osseointegration and biomechanical success. For this reason, studies comparing different surface treatments often control for macro-design variables to isolate the true biological effect of the surface itself. (3,4,7)

Surface Treatment	Mechanism	Biological Effect	Clinical Advantages
Grit blasting	Mechanical abrasion with Al ₂ O ₃ /TiO ₂ particles	Creates micro-roughness, increases BIC	Improves early stability, widely used in commercial SLA
Acid etching	HCl/H ₂ SO ₄ or HF etching	Micro-pits, increased surface energy	Enhances osteoblast adhesion, synergistic with blasting
SLA (Sandblasted-Large grit + Acid etched)	Combination of blasting + etching	Moderately rough microtopography	Predictable osseointegration, >95% long-term survival
Anodization (e.g., TiUnite®)	Electrochemical oxidation	Thickened TiO ₂ , nano-/micro-porosity	Improves early bone response; good results in soft bone
Plasma spraying	High-temp deposition (e.g., HA)	Macro porous bioactive coating	Strong bone bonding; risk of coating delamination
Ion doping (Ca, Sr, Mg, Zn)	Incorporation of ions into oxide layer	Enhances osteogenic gene expression	Faster early BIC, promising in compromised bone
Hydrophilic / activated surfaces (e.g., SLActive)	Chemical modification + storage in saline	High surface energy, rapid protein adsorption	Faster transition to secondary stability
Laser microtexturing	Ultra-precise laser ablation	Controlled micro-grooves/nanopatterns	Soft-tissue sealing improvement
Graphene/carbon coatings	Deposition of carbon nanostructures	Osteogenic + antibacterial	Dual-function surfaces
UV / Plasma photofunctionalisation	Removal of hydrocarbons	Restores hydrophilicity, improves cell recruitment	Reduces biological aging of titanium

Table 1. summarizes the most common surface modification techniques applied to titanium dental implants and their biological rationale.(3–6,8–14)

1.3 Theoretical Framework

Surface treatments of titanium implants can influence biological performance by modifying several interrelated surface characteristics:

Topography and roughness: Micro- and nano-scale irregularities that enlarge surface area and enhance protein adsorption, osteoblast adhesion, and bone mechanical interlocking. (4,8)

Surface chemistry and composition: Alterations in the oxide layer, ion doping (Ca, Mg, Zn, Si), or application of bioactive coatings (hydroxyapatite, bio-glass, peptides) influence osteoblast behaviour, mineral deposition, and corrosion resistance. (9)

Surface energy and wettability: Hydrophilic or superhydrophilic surfaces improve initial blood wetting, fibrin network formation, and cellular recruitment, potentially shortening the healing phase and enhancing early osseointegration. (5,10)

Functional and bioactive coatings: Novel approaches introduce antibacterial agents, bioactive molecules, or nanostructures to create dual-function surfaces that simultaneously promote bone formation and resist bacterial colonisation. (11–13)

Together, these mechanisms represent a multidisciplinary framework combining materials science, cell biology, and clinical practice. The goal is not just to roughen the titanium, but to design surfaces that can actively influence biological processes to make healing faster and more predictable.

Recent studies have highlighted that osseointegration is not purely an osteoblastic or biomechanical phenomenon but rather a regulated immune-mediated process. (11)

After the implant placement, macrophages, neutrophils, and dendritic cells are the first cells to interact with the titanium surface. Their behaviour is strongly influenced by surface topography, chemistry, and surface energy. (11,15)

Some surface characteristics can promote a shift in macrophage polarization from a pro-inflammatory M1 phenotype toward a pro-healing M2 phenotype, which supports angiogenesis, extracellular matrix deposition, and osteoblastic differentiation. (3)

This immunomodulatory perspective expands the classical concept of osseointegration and suggests that optimized implant surfaces can actively guide the inflammatory response toward a regenerative pathway. Understanding how surface properties influence the early immune cascade is increasingly important as modern implantology aims to accelerate healing and improve the predictability of treatment outcomes. (5)

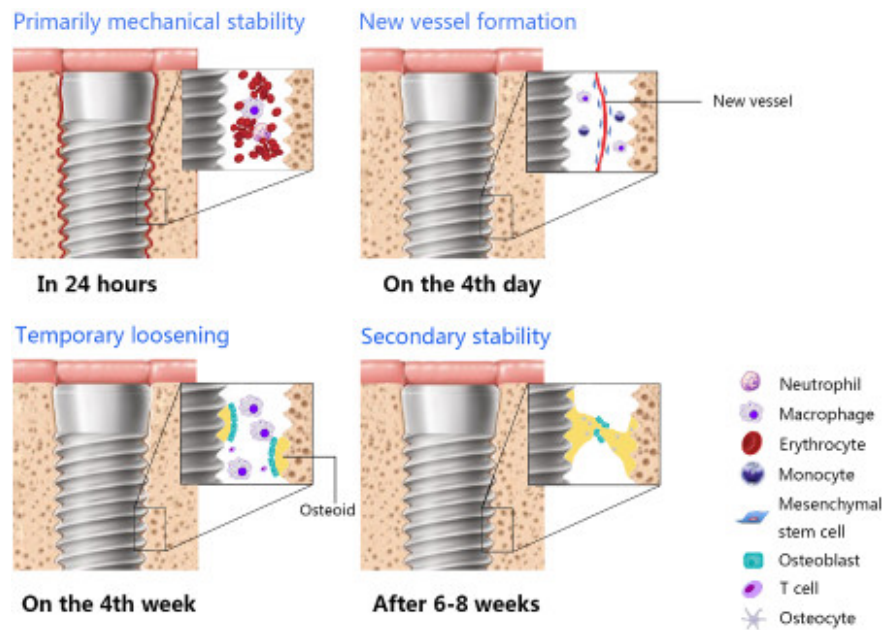


Fig.2 Biological phases of osseointegration showing the transition from primary mechanical stability to secondary biological stability (16)

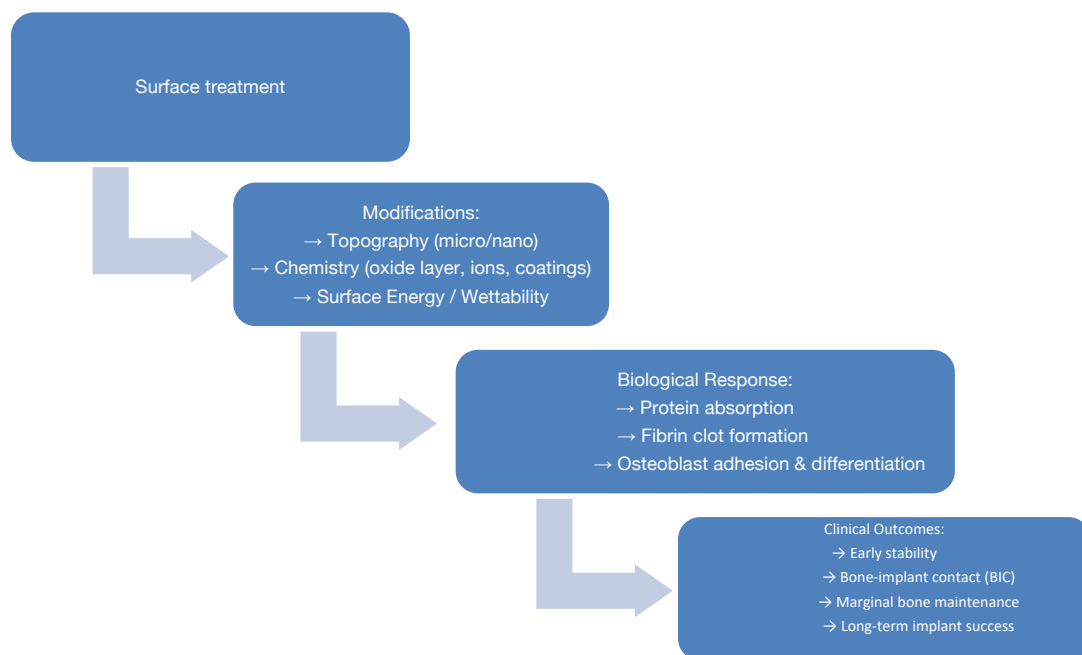


Table 2. Conceptual model illustrating the cascade from surface treatment to clinical outcomes.(5,8,17)

1.4 Current Status of the Subject

The evolution of surface technologies has produced a wide array of commercial implant surfaces with distinct topographies, chemistries, and biological behaviours.

Dental implant surface modification

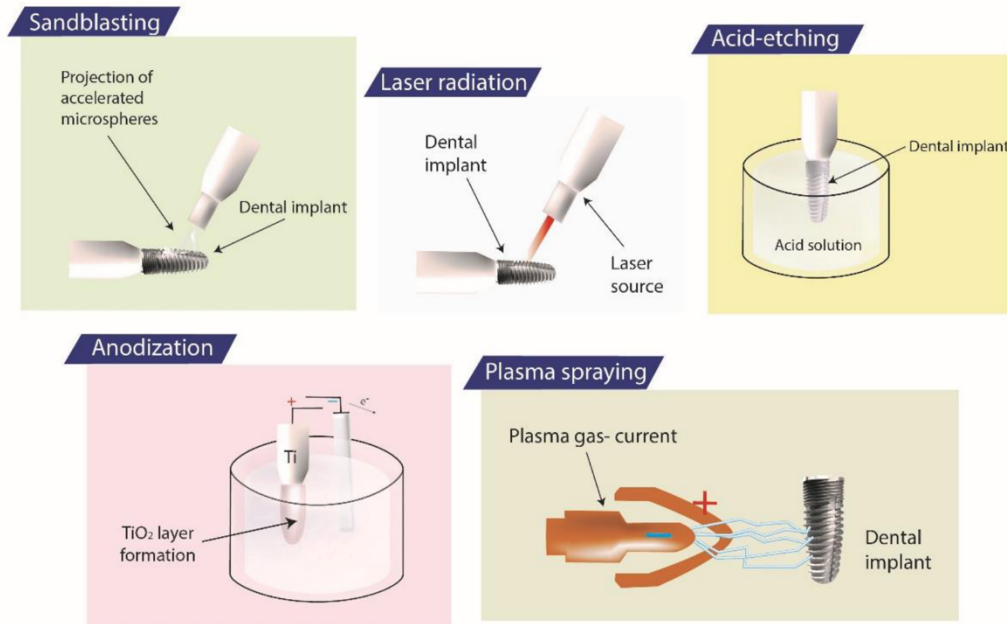


Fig 3. Mainstream engineering strategies in dental implantology

Conventional moderately rough surfaces, such as sand-blasted and acid-etched (SLA), are still the reference point for the clinical outcome, offering excellent long-term survival (>95% at 10 years) and predictable bone response. (3,4,6)

More recent long-term evidence confirms this trend: a 12-year clinical follow-up reported a survival rate of 96.1% with minimal MBL, reinforcing SLA as a highly reliable long-term implant surface. (18)

Long-term retrospective data further strengthen these findings: Buser et al. (2012) reported excellent 20-year outcomes for SLA implants, supporting their long-term predictability and stability.

However, recent innovations have expanded the field toward biofunctional and nanostructured designs that seek not only mechanical interlocking but also active biological stimulation. (11,12) Jimbo R. et al. (2011) highlighted that nanostructured implant surfaces enhance protein absorption, osteoblast differentiation, and bone-to-implant mechanical interlocking, reinforcing the rationale for next-generation nano-engineered surfaces. (19)

Hydrophilic and nano-structured surfaces (e.g., SLActive®, Ossean®, TiUnite®) have demonstrated improved early healing dynamics. Studies show enhanced initial stability and bone–implant contact within 2–8 weeks compared to conventional SLA surfaces. (5,9,10) Recent clinical trials further support this trend, reporting that chemically modified hydrophilic surfaces such as SLActive tend to recover implant stability earlier and show a faster transition from primary to secondary stability during the first 4 to 6 weeks of healing. (20,21)

However, changes in microroughness do not always translate into measurable clinical differences. A randomized clinical trial comparing two SLA surfaces with different roughness levels found no significant differences in stability, marginal bone loss, or soft-tissue parameters after one year, suggesting that microroughness alone may not meaningfully influence early outcomes.(22)

This view is consistent with the paradigm proposed by Albrektsson & Wennerberg (2004), who emphasized that implant success increasingly depends on surface chemistry and surface energy rather than roughness alone.

This interpretation is consistent with the theoretical framework described by Rupp et al., who demonstrated that wettability is governed not only by topography but also by surface chemistry and the energetic state of the titanium oxide layer. Early protein adsorption and clot formation depend primarily on surface energy rather than roughness, which explains why SLA surfaces with different microroughness profiles may behave similarly in vivo. (17)

Systematic reviews confirm these findings, but indicate that long-term differences in implant survival and marginal bone loss (MBL) are less pronounced once osseointegration is achieved.(12,23)

Emerging technologies should also be considered:

- Ion-doped and bioactive coatings (e.g., Ca, Sr, Mg, Zn) that modulate osteogenic cell behaviour and accelerate bone formation.(9,12)
- Graphene and carbon-based coatings, providing both osteogenic stimulation and anti-microbial properties.(13)
- Laser micro/nano-texturing and additive manufacturing (3D printing), which allow precise control over hierarchical roughness to mimic natural bone structure.(14,24)
- Plasma and UV photo functionalisation, improving surface energy and removing hydrocarbon contaminants, thus restoring hydrophilicity and enhancing cell adhesion.(25)

However, recent evidence shows that this hydrophilicity that we are trying to improve with plasma or UV is highly time-dependent.

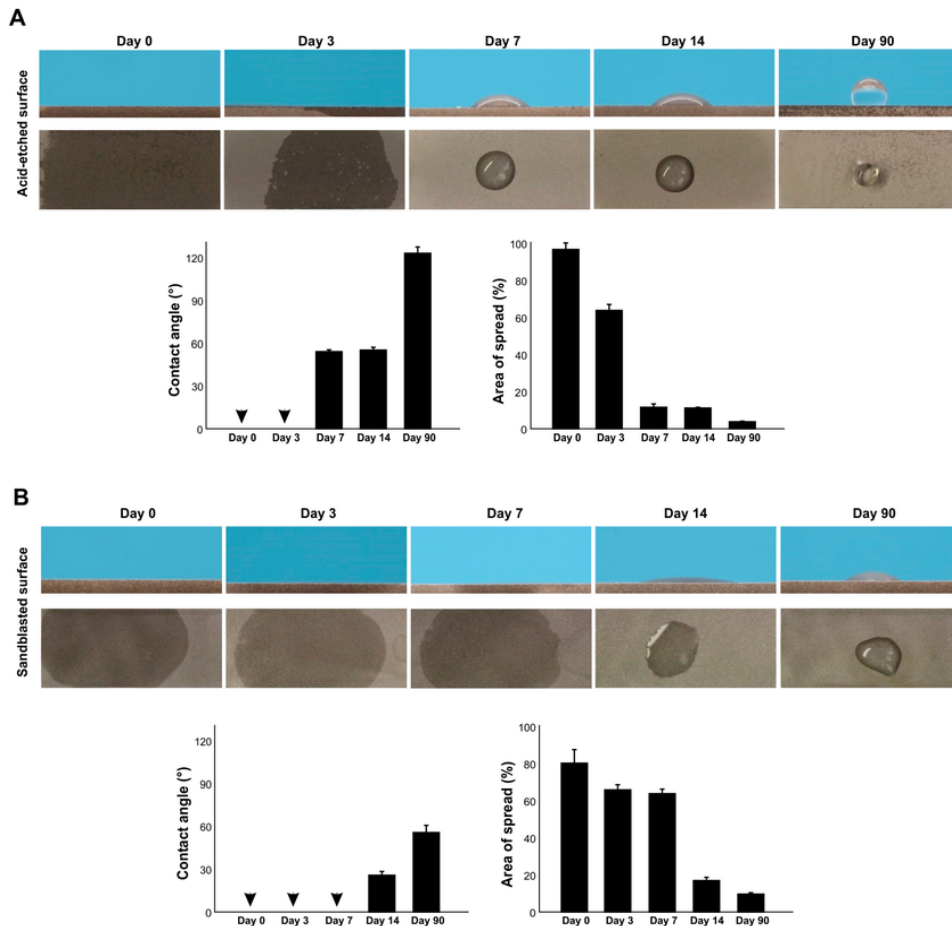


Fig.4 Time-dependent hydrophilicity loss “biological aging” of titanium surfaces caused by hydrocarbon accumulation (26)

Titanium surfaces progressively lose surface energy when stored in ambient air. Sometimes the storage in isotonic saline helps preserve wettability and supports cell interactions.(27)

Additional experimental work demonstrated that “fresh” titanium exhibits significantly higher surface energy and superior osteoblast attachment compared with titanium aged under ambient conditions, reinforcing the clinical relevance of biological aging. (28)

Further evidence clarifies the mechanisms underlying this biological aging process, describing a progressive physicochemical degradation of the titanium surface during storage.

Exposure to ambient air leads to the gradual accumulation of hydrocarbon contaminants on the oxide layer, reducing surface energy and impairing the initial biological response. (5,17)

This aging effect may delay osseointegration compared with freshly produced surfaces, which show significantly superior osteoblast attachment and spreading.

UV photofunctionalisation and non-thermal plasma activation can reverse biological aging by removing hydrocarbons and restoring the high-energy state of the surface. (25)

In vitro studies reveal that this reactivation occurs within seconds to minutes, although the restored hydrophilicity diminishes again with time unless implants are stored under controlled conditions or in saline solution. (27)

These next-generation surfaces may offer advantages in early loading, poor bone quality, and compromised patient profiles, but high-quality long-term evidence is still limited. Meta-analyses consistently conclude that the benefits of newer surfaces are most evident in early osseointegration rather than in overall survival after several years. (5,23,29)

Despite the considerable advances in implant surface technologies, uncertainties remain regarding their long-term clinical benefits and their impact on peri-implant tissue behaviour. Therefore, a comprehensive analysis of current surface modification strategies is required.

1.5 Justification

The rapid development of titanium implant surface technologies presents both significant opportunities and clinical challenges. Although numerous surface designs claim superior biological or clinical performance, the evidence supporting each remains fragmented and heterogeneous. A systematic review and critical analysis are therefore justified to synthesise the available data and clarify how various surface treatments influence key clinical outcomes such as osseointegration rate, implant survival, marginal bone loss, and soft-tissue health.

Additionally, understanding how innovations like hydrophilic, photo-functionalised, and nanostructured surfaces translate into clinical outcomes is vital for evidence-based practice.

Moreover, as implant dentistry increasingly moves toward immediate loading, short implants, and complex patient profiles, understanding the clinical impact of advanced surfaces is essential for evidence-based treatment planning.

This research aims to bridge the gap between surface engineering innovations and their clinical implications, helping clinicians and researchers discern which modern surface treatments truly translate into measurable improvements in patient outcomes.

2. OBJECTIVE

The main objective of this documentary research is to review and analyse the scientific literature on titanium implant surface treatments. Analysing their evolution over time and evaluating how the most recent surface technologies influence clinical outcomes. The study aims to determine, through the available evidence, which surface modifications demonstrate real advantages in osseointegration, implant stability, marginal bone preservation, and soft-tissue response.

3. MATERIAL AND METHODS

This work was designed as a systematised literature review, following the structure of a simplified systematic review and was conducted by a single reviewer. The main objective to apply this methodology was to ensure a transparent, reproducible, clear and a structured approach to the scientific literature. The study aimed to identify, select, and analyse primary scientific evidence evaluating different surface treatments applied to titanium dental implants and their clinical implications.

The primary aim was to examine and compare different surface treatments applied to titanium dental implants, evaluating their biological and clinical implications regarding osseointegration, implant stability, and long-term performance.

3.1 Research Question and PICO Framework

To give a precise focus to this review, the research question was structured according to the PICO methodology.

This method is widely used in evidence-based dentistry, as it facilitates the formulation of precise research questions and the development of an efficient search strategy.

The PICO approach made it possible to break down the topic into its essential analytical components, thus providing a clear focus for the research.

Based on the objectives of this work, the following research question was formulated:

“In patients receiving titanium dental implants, how do different surface treatments—compared to conventional SLA surfaces—affect osseointegration, implant stability, and long-term clinical outcomes?”

P(Patient/Problem):	I (Intervention):	C (Comparison):	O (Outcome):
Patients receiving titanium dental implants	Surface modifications applied to titanium implants (e.g., SLA, SLActive, anodization, coatings, hydrophilic activation)	Conventional machined surfaces or alternative surface treatments	Osseointegration rate, early and secondary stability, marginal bone loss, and overall implant survival

Table 3. Working table for designing the research question.

The PICO format allowed the identification of the essential concepts and guided the selection of keywords and eligibility criteria.

3.2 Eligibility criteria

Before starting the search process, specific inclusion and exclusion criteria were formulated to avoid selection bias. These criteria were based on the scope of the review.

Inclusion criteria:

- Primary research articles, including:
 - in vivo human studies
 - in vivo animal studies
 - in vitro studies involving biological interaction (e.g., osteoblasts, fibroblasts, stem cells)
 - clinical trials, controlled experiments, prospective or retrospective cohorts
- Studies evaluating titanium implant surfaces or coatings.
- Assessment of at least one clinical or biological outcome:
 - Bone-to-implant contact (BIC)
 - Implant stability (ISQ values)
 - Removal torque
 - Marginal bone loss (MBL)
 - Mineral apposition rate (MAR)
 - Survival or failure rates
- Publication in peer-reviewed journals ensuring scientific reliability.

- A 10-year restriction on publication date was applied for the Results and Discussion sections in order to be considered for the result and discussion
- No time restriction of publication for the introduction section
- Articles available in English

Exclusion criteria

- Systematic reviews, meta-analyses, narrative reviews
- Case reports, editorials, opinion papers, letters
- Studies without a comparison group
- In vitro studies analysing physical or chemical surface properties only (without any cellular or biological interaction)
- Temporary prostheses or implants made of non-titanium materials

All these criteria were selected to ensure that only relevant, comparable and scientifically robust studies were included

3.3 Sources of information

To guarantee a comprehensive literature collection and to avoid missing relevant publications, the search was conducted in the main biomedical databases to ensure a comprehensive retrieval of relevant literature. The following databases were consulted:

- **PubMed** (biomedical literature with MeSh indexing)
- **MEDLINE**

Only primary studies meeting the inclusion criteria were considered. Additional studies were identified through manual searches of reference lists of relevant articles.

The final search was performed between **October and November 2025**.

3.4 Search strategy

The search strategy integrated both controlled vocabulary (MeSH terms) and free-text keywords, ensuring sensitivity (capturing all potentially relevant studies) and specificity (retrieving only those truly related to the topic).

PICO Element	Free Terms	MeSH Terms
P – Patients	“Titanium dental implants”, “dental implants”, “implant dentistry”	Dental Implants
I – Intervention	“Surface treatment”, “surface modification”, “SLA”, “SLActive”, “nanostructured surface”, “bioactive coating”, “hydrophilic surface”, “anodized titanium”, “ion-doped surface”, “calcium-incorporated surface”, “UV-activated surface”, “plasma-treated implant”	Dental Implants / Surface Properties, Biocompatible Materials
C – Comparison	“Machined surface”, “conventional surface”, “smooth titanium”, “control surface”	(No specific MeSH — uses free terms)
O – Outcomes	“osseointegration”, “bone-implant contact”, “BIC”, “implant stability”, “ISQ”, “marginal bone loss”, “MBL”, “removal torque”, “implant survival”	Osseointegration, Bone Remodelling, Dental Implant-Abutment Design

Table 4. Working Table of Preliminary Search Terms in English

Boolean operators were used as follows:

- AND was used to combine different PICO concepts (e.g., titanium dental implants AND surface modification)
- OR to group synonyms or related terms (e.g., hydrophilic surface OR UV-activated implant)

This strategy ensured a balanced, systematic and comprehensive search

3.5 Article selection process

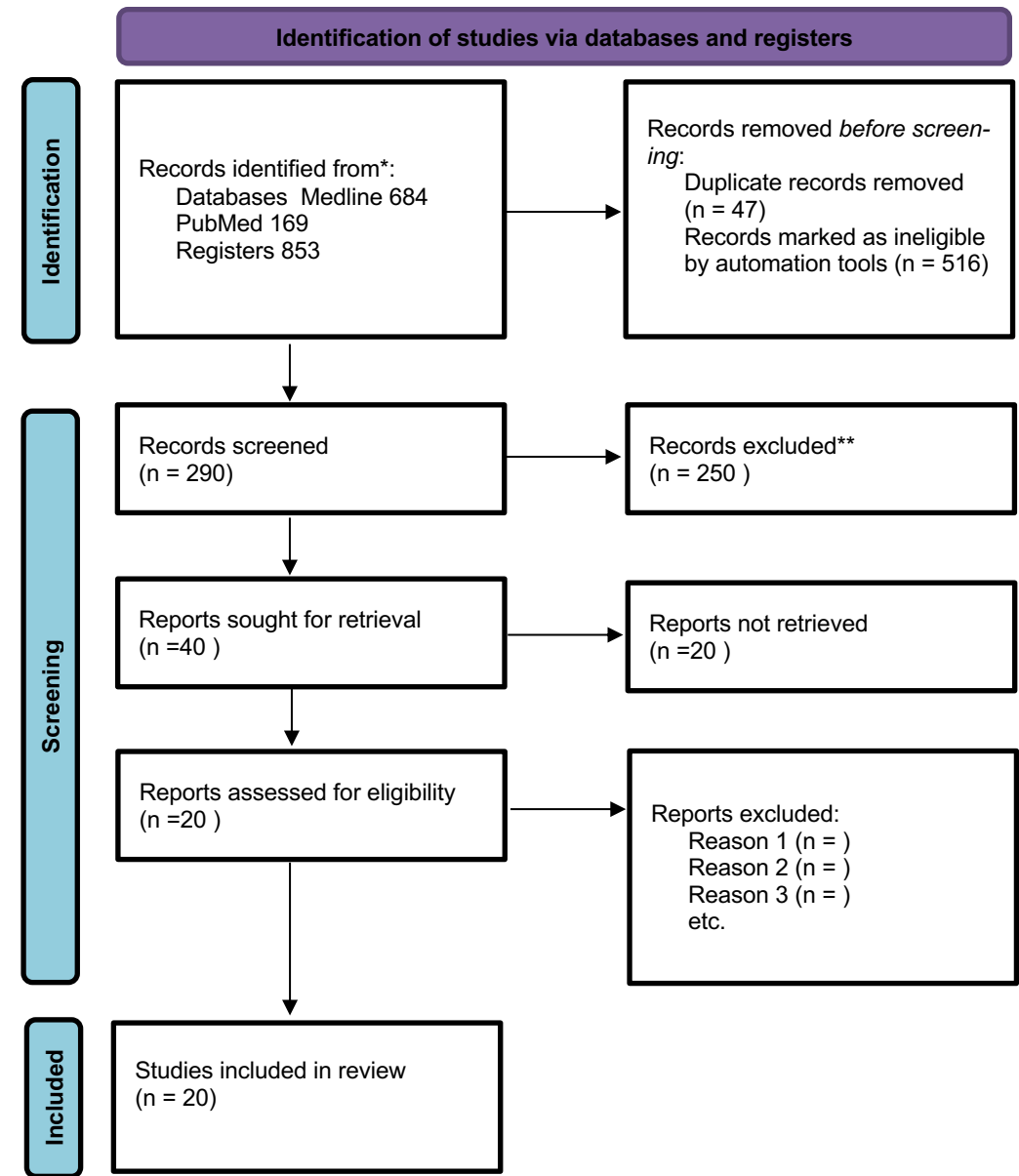


Table 5. *Prisma flow chart (30)*

The article selection was carried out in three stages:

1. Identification and removal of duplicates, using manual verification.
2. Title and abstract screening, excluding articles not meeting the eligibility criteria.
3. Full-text assessment, documenting the reason for exclusion when necessary.

Only studies fulfilling all inclusion criteria were incorporated into the final synthesis.

3.6 Data extraction

The data extraction was performed manually using structured tables. For each included study, the following data were extracted:

- Author and year
- Study design
- Sample characteristics
- Type of implant surface
- Comparison surface
- Methods of surface characterisation
- Biological or clinical outcomes (BIC, ISQ, MBL, torque values, MAR, survival rates)
- Main findings relevant to the research question

4. RESULTS

4.1 Overview of included studies

A total of twenty articles met the inclusion criteria previously established for this review. the selection included randomized clinical trials, long-terms follow-up studies, human histological analyses, preclinical in vivo experiments and selected in vitro biomechanical evaluations.

Study	Study Design	Model	Surface Comparison	Main Outcomes	Follow-up
Antal 2024	Randomized clinical trial	Human	CaP coating vs SBTC®	ISQ, Bone level	2 years
Carmo Filho 2018	Split-mouth RCT	Human	DAE / Nanotite / SLA / SLActive	ISQ, Insertion torque	91 days
Demetoglu 2021	Retrospective cohort	Human	RBM vs SLA	Survival rate	≥2–4 months
Jeon 2022	Randomized clinical trial	Human	SLA TG vs SLA CG	ISQ, MBL, Survival	1 year
Sayin Ozel 2021	Split-mouth RCT	Human	SLA vs SLActive	ISQ	12 weeks
Velasco-Ortega 2025	Long-term follow-up	Human	SLA	MBL, Survival	12 years
Zaheer 2024	Randomized clinical trial	Human	Control vs UVA vs UVC	ISQ	8 weeks
Makary 2023	Human histological study	Human	Machined vs SLA vs Ca-modified	BIC, BA	Early healing
Menhall 2024	Human histological study	Human	SLA	Mineral apposition rate	Early healing
Choi 2021	Randomized double-blind clinical trial	Human	UV-treated vs conventional implants	ISQ, Marginal bone level	1 year
Körmöcz 2021	Randomized clinical trial	Human	SA vs NH vs SLA	Implant stability (ISQ), Periotest	6 weeks
Canullo 2024	Controlled clinical trial	Human	Superhydrophilic bio-active surface vs moderately rough surface	ISQ, insertion torque, MBL	6 months
Barbosa 2021	Split mouth randomized controlled clinical trial	Human	Hydrophilic vs conventional sandblasted acid-etched implants	Implant stability (ISQ)	90 days
Pabst 2022	In vivo	Animal model	Ultrahydrophilic vs SA	BIC	1–4 weeks

Yang 2024	In vivo + in vitro	Rabbit tibia	HA vs SLA vs XPEED	BIC, Torque, Roughness	4 weeks
Sghaireen 2024	In vitro	Laboratory	Surface modifications	Tensile strength	Laboratory
Yadav 2025	In vitro	Laboratory	Surface treatments	BIC, Pull-out	Laboratory
Lee 2019	In vivo + in vitro study	Rabbit tibia	Machined vs UV-treated vs SLA	BIC, contact angle	Early healing
Lee 2025	In vivo + in vitro study	Rabbit / Beagle	MA vs SLA vs RBM vs HA	BIC, surface roughness	Early healing
Diaz-Sanchez 2020	In vivo experimental study	Dog radius	Grade IV vs Grade V titanium	BIC, removal torque	Early healing

Table 6: *The main characteristics of the included studies*

Clinical studies predominantly evaluated implant stability, marginal bone level changes, and survival rates (Antal, 2024; Jeon, 2022; Sayin Ozel, 2021; Velasco-Ortega, 2025; Zaheer, 2024; Barbosa 2021; Choi, 2021; Körmöczi, 2021; Canullo, 2024; Carmo Filho, 2018; Demetoglu, 2021). (18,21,22,31–38)

Histological and biomechanical investigations focused on bone-to-implant contact (BIC), bone area (BA), mineral apposition rate, removal torque, and tensile strength (Makary, 2023; Menhall, 2024; Lee, 2019; Lee, 2025; Yang & Hong, 2024; Pabst, 2022; Yadav, 2025; Sghaireen et al., 2024; Diaz-Sanchez, 2020). (39–47)

4.2 Clinical outcomes

Clinical studies primarily evaluated implant stability (ISQ), marginal bone loss, and implant survival, which are summarized in Table 7.

Across clinical investigations, implant survival rates were consistently high, generally exceeding 95–100%, regardless of the implant surface technology.

Study	Surface Comparison	ISQ (mean $\pm$ SD)	MBL (mm)	Survival (%)	Significant Difference	Main Finding
Antal 2024	CaP vs SBTC®	Progressive increase	≤ 1 mm	100%	No	Comparable stability between surfaces
Carmo Filho 2018	DAE / Nanotite / SLA / SLActive	Early differences $\rightarrow >75$ ISQ	NR	NR	Yes (early phase)	Different early stability curves but similar final stability
Demetoglu 2021	RBM vs SLA	NR	NR	96.06 vs 96.81	No	Surface type did not influence survival
Jeon 2022	SLA TG vs CG	$79.7 \pm 10.2 \rightarrow 82.9 \pm 10.0$	0.07 vs 0.00	100%	No	Comparable long-term stability between SLA surfaces
Sayin Ozel 2021	SLA vs SLActive	$70.0 \pm 0 \rightarrow 82.3 \pm 3.2$	NR	NR	No	Similar stability development in both surfaces
Velasco-Ortega 2025	SLA	NR	1.18 ± 0.64	96.1%	—	Long-term survival with limited bone loss
Zaheer 2024	Control vs UVA vs UVC	$62.1 / 65.2 / 69.3 \rightarrow 77.0 / 81.5 / 82.5$	NR	NR	Yes (early phase)	UV treatment improves early stability
Choi 2021	UV-treated vs conventional	Progressive increase	NR	NR	Yes (sub-group)	UV surfaces enhance stability in poor bone quality
Körmöczi 2021	SA vs NH vs SLA	Progressive increase	NR	NR	No	Comparable stability among modern rough surfaces

Canullo 2024	Superhydrophilic vs moderately rough	TG: 74.57±7.85 → 74.97±6.34	0.20–0.30	100%	Yes (early stability)	Bioactive surface maintains stability during early healing
Barbosa 2021	Hydrophilic vs conventional implants	Decrease at ~40 days → recovery at 90 days (≈76–78 ISQ)	NR	NR	No	Similar stability development in both surfaces

Table 7: clinical outcomes for different study

NR: not reported; ISQ: implant stability quotient; MBL: marginal bone loss; TG: test group; CG: control group.

4.2.1 Implant Stability (ISQ/RFA)

Across randomized clinical trials, implant stability values increased progressively during the healing period. Primary and secondary stability values remained within or above the commonly accepted “safe” range (ISQ ≥60–65), and no surface showed a destabilizing ISQ pattern over time.

Jeon et al. (2022) evaluated 55 patients and placed a total of 80 implants with two different roughness profiles, of which 75 were included in the follow-up. Mean primary stability values were 79.7 ± 10.2 ISQ in the test group and 79.9 ± 7.5 ISQ in the control group, increasing to 82.9 ± 10.0 and 83.2 ± 8.0 ISQ, respectively, after one year of follow-up, with no statistically significant differences between surfaces.(22)

Similarly, Sayin Ozel et al. (2021) analysed 50 implants, of which 25 with SLA surface and 25 SLActive observed progressive ISQ increases in both SLA and SLActive groups over 12 weeks, with mean ISQ values rising from approximately 70 at implant placement to 82.3 ± 3.2 at 12 weeks; and no significant difference between control and test groups. (21)

Zaheer et al. (2024) analysed 66 implants divided into three groups (control, UVA-treated, and UVC-treated). Baseline ISQ values were 62.1, 65.2, and 69.3, respectively. After 8 weeks, ISQ values increased significantly to 77.0 in the control group, 81.5 in the UVA group, and 82.5 in the UVC group. The UVA-treated group demonstrated significantly greater stability improvement compared with the control group ($p = 0.009$), while no statistically significant difference was observed between the UVC and control groups ($p = 0.191$). (32)

Hydrophilic implant surfaces were further investigated by Barbosa et al. (2021) in a split-mouth randomized controlled clinical trial including 30 patients receiving 60 implants placed in the posterior maxilla. Implant stability decreased during the early remodelling phase at approximately 40 days, followed by a recovery phase with increasing stability values at 90 days, reaching mean

ISQ values of approximately 76–78, with no statistically significant differences between hydrophilic and conventional surfaces.

More recent clinical evidence was provided by [Canullo et al. \(2024\)](#), who evaluated implants with a nano-superhydrophilic bioactive surface placed in 36 patients receiving 60 implants in D3–D4 bone. Baseline ISQ values were 74.57 ± 7.85 in the test group and 77.12 ± 5.83 in the control group. During early healing, bioactive implants maintained stable stability values (74.78 ± 7.31 at 30 days and 74.97 ± 6.34 at 45 days), whereas the control surfaces exhibited a reduction in stability (73.33 ± 6.13 and 73.44 ± 7.89). Differences in stability changes between baseline and follow-up were statistically significant ($p = 0.005$ and $p = 0.012$).⁽³⁶⁾

[Choi et al. \(2021\)](#) conducted a randomized double-blinded clinical trial investigating the effect of ultraviolet photofunctionalization on implant stability in the posterior maxilla. Fifty-seven implants were analysed after a one-year follow-up. Although no overall significant differences were observed between UV-treated and control implants, subgroup analysis demonstrated significantly greater increases in ISQ values at 4 weeks and 4 months in bone quality group III. These findings suggest that UV surface treatment may enhance early implant stability particularly in sites with compromised bone quality.⁽³⁴⁾

[Carmo Filho et al. \(2018\)](#) identified variations in early stability patterns among different roughened surfaces (Osseotite, Nanoite, SLA, SLActive), displayed slightly different ISQ trajectories between 35 and 56 days, but all groups showed ISQ means above 75 at 91 days and no clear long-term superiority of any specific surface.⁽³⁷⁾

[Körmöcz et al. \(2021\)](#) evaluated implant stability in a randomized clinical trial comparing sand-blasted-acid etched surfaces with hydroxyapatite-nanocoated implants under an early loading protocol. Implant stability increased significantly in all groups during healing, although no statistically significant differences were detected between the surface types, suggesting comparable clinical performance among contemporary roughened implant surfaces⁽³⁵⁾.

Overall, while early-phase differences were occasionally observed, no surface category consistently demonstrated long-term superiority in implant stability.

Collectively, these findings indicate that surface modifications may influence early stability dynamics, particularly during the first 4–8 weeks after implant placement, although long-term stability values tend to become comparable across different implant surface technologies.

4.2.2 Marginal Bone Loss (MBL)

Changes in marginal bone levels were reported less frequently and less uniformly reported than the ISQ values.

Jeon et al. (2022) observed minimal bone loss at 1 year (0.07 mm in the test group and 0.00 mm in the control group), without significant differences. (22)

In the long-term study by Velasco-Ortega et al. (2025), mean marginal bone loss after 12 years was 1.18 ± 0.64 mm, remaining within clinically acceptable thresholds. (18)

Also Canullo et al. (2024) reported minimal marginal bone loss after 6 months of follow-up, with values around 0.20 mm in the test group and 0.00 mm in the control group, without statistically significant differences between surfaces. (36)

Antal et al. (2024) conducted a RCT in which they analysed a total of 158 implants for 2 years follow up, the study compared CaP-based surface and a SBTC®. All implant successfully Osseo-integrated and were restored as planned. They found an increase in the ISQ value over 2-years in both group with no statistically significant difference. (31)

No consistent statistically significant superiority of a specific surface in maintaining marginal bone levels was demonstrated.

4.2.3 Implant Survival

Implant survival rates were uniformly high across clinical studies.

Jeon et al. (2022) reported a 100% implant survival rate at 1 year, further supporting the predictability of moderately rough SLA implant surfaces in clinical conditions. (22)

Antal et al. (2024) observed no implant loss during the 2-year follow-up period. (31)

In a large retrospective cohort, Demetoglu et al. (2021) reported survival rates of 96.06% for RBM surfaces and 96.81% for SLA surfaces without clinically meaningful differences. (38) Velasco-Ortega et al. (2025) reported a cumulative survival rate of 96.1% over 12 years for sand-blasted–acid-etched implants placed under an early loading protocol. (18)

Similarly, Canullo et al. (2024) reported 100% implant survival with no implant failures, confirming the high predictability of contemporary implant surfaces. (36)

Taken together, these findings suggest that implant survival is largely independent of specific surface modifications, provided that implants exhibit at least a moderately rough surface topography.

4.3 Histological and Biomechanical Outcomes

Study	Model	Surface Comparison	Key Outcome	Significant Difference?
Lee 2019	Rabbit tibia	Machined vs UV vs SLA	Higher early BIC in UV	Yes
Lee 2025	Rabbit/Beagle	MA vs SLA vs RBM vs HA	Highest BIC in HA (76.3%)	Yes
Makary 2023	Human histology	Machined vs SLA vs Ca-modified	SLA & Ca-modified > Machined (BIC/BA)	Yes
Menhall 2024	Human histology	SLA	Increased mineral apposition rate	Yes
Pabst 2022	In vivo	Ultrahydrophilic vs SA	Increased early BIC	Yes
Yang 2024	Rabbit tibia	HA vs SLA vs XPEED	Higher BIC and torque in XPEED/SLA	Yes
Yadav 2025	In vitro	Surface treatments	BIC up to 75.4±2.1%; pull-out up to 260.7±12.1 N	Yes
Sghaireen 2024	In vitro	Modified surfaces	Tensile strength up to 28.11±1.20 MPa	Yes
Diaz-Sanchez 2020	Dog radius	Grade IV vs Grade V	No significant differences	No
Carmo Filho 2018	Human	Four roughened surfaces	Insertion torque 42–45 Ncm	Yes (early stability pattern)

Table 8: Histological and biomechanical findings are summarized

Makary et al. (2023) conducted a split-mouth randomized human histologic study in the posterior maxilla, 35 mini-implants with machined, SLA and nanostructured calcium-incorporated (XPEED) surface at 4 and 6 weeks. Mean BIC increased in all the group (machined: 16.8%→29.0%;

SLA: 18.5%→33.7%; XPEED: 22.4%→38.6%), and also demonstrated significantly higher BIC and BA values in SLA and calcium-modified implants compared to machined surfaces during early healing in human histological samples.(39)

Menhall et al. (2024) reported higher mineral apposition rates around XPEED implants compared with SLA at 3 weeks (2.0±0.18 vs 1.5±0.10 µm/day) and 5 weeks (1.2±0.10 vs 1.1±0.10 µm/day), indicating an accelerated early bone-forming activity on nanostructured Ca-incorporated surfaces.(40)

Lee et al. (2019) reported significantly higher early BIC values in UV-treated implants compared to machined controls in a rabbit tibia model.(41)

Lee et al. (2025) observed the highest BIC percentages in hydroxyapatite-coated implants (76.3%) in animal models.(42)

Yang and Hong (2024) reported that nanostructured calcium-incorporated XPEED® and SLA implants in rabbit tibiae showed significantly higher BIC and removal torque values than conventional HA-coated controls after early healing, confirming a biomechanical advantage of Ca-incorporated nano-topographies over traditional HA.(43)

Pabst et al. (2022) also demonstrated increased early BIC in ultrahydrophilic surfaces compared to sandblasted controls.(44)

In vitro mechanical analyses by Yadav et al. (2025) and Sghaireen et al. (2024) showed increased pull-out strength and tensile strength in modified surfaces compared to controls.(45,46)

Diaz-Sanchez et al. (2020) found no significant differences in in vivo BIC between grade IV and grade V titanium implants with similar roughened surfaces in the dog radius. (47)

Carmo Filho et al. (2018) reported insertion torque values clustered around 42–45 N·cm for four commercially available roughened implant types, with only transient differences in early stability patterns despite distinct micro-topographies.(37)

However, most statistically significant differences were confined to early healing intervals or laboratory conditions.

4.4 Surface Physicochemical Characteristics

Several studies evaluated surface roughness and wettability parameters in association with biological outcomes.

Diaz-Sanchez et al. (2020) reported Ra values ranging between 0.19 and 0.35 μm depending on titanium grade and surface treatment, corresponding to smooth to slightly roughened surface.(47)

Jeon et al. (2022) described similar roughness values between the compared SLA groups (Ra approximately 3.1 μm)(22).

Wettability analysis revealed marked differences in contact angles between surfaces.

Yang and Hong (2024) demonstrated marked differences in contact angle between hydroxyapatite ($123.7 \pm 2.72^\circ$), SLA ($92.7 \pm 3.02^\circ$), and calcium-incorporated XPEED surfaces ($9.7 \pm 0.56^\circ$), confirming enhanced wettability of bioactive surfaces.(43)

Similarly, Lee et al. (2019) observed a shift from a more hydrophobic contact angle to a near-zero values after the UV-photofunctionalization, that show that after the treatment the titanium surface was more hydrophilic or it can be even called superhydrophilic state. (41)

Although physicochemical modifications were clearly measurable, the available clinical studies did not consistently demonstrate that these differences translated into superior long-term clinical outcomes.

4.5 Synthesis of Findings

The objective of this review was to determine whether contemporary titanium implant surface technologies provide real advantages in osseointegration, implant stability, marginal bone preservation, and clinical performance.

Across the twenty included studies, surface modifications such as increased hydrophilicity (e.g., UV treatment, ultrahydrophilic etching), calcium incorporation (XPEED® and related coatings), and calcium phosphate or hydroxyapatite coatings generally improved early biological responses and mechanical anchorage in experimental settings. Human and animal histology frequently showed higher early BIC, faster mineral apposition or greater early bone volume around these modified surfaces than around machined or conventional SLA surfaces. In vitro studies likewise demonstrated higher pull-out and tensile strengths for modified surfaces compared with machined controls.

When focusing on long-term outcomes, the results across studies appeared more consistent. Marginal bone loss remained low and clinically acceptable across all roughened and bioactive surfaces, and implant survival rates consistently exceeded 95% over follow-up periods ranging from 1 to 12 years, without robust evidence that any specific surface technology clearly outperforms established SLA-type surfaces.

Therefore, current evidence suggests that modern surface technologies enhance early osseointegration dynamics and may support early or immediate loading protocols in selected situations, but they have not yet demonstrate substantial, consistent long-term clinical advantages over conventional moderately rough titanium surfaces.

5. DISCUSSION

5.1 Principal findings of the review

The main objective of this review was to evaluate how titanium implant surfaces have evolved over the years and if the newer technologies about the surface modification really improve the clinical outcomes, in terms of: osseointegration, implant stability, marginal bone preservation and long-term implant survival.

A wide spectrum of surface modifications was investigated. These ranged from well-established moderately rough surfaces such as sandblasted–acid-etched (SLA) and resorbable blasting media (RBM), to more recent bioactive modifications including calcium-incorporated nanostructures, hydroxyapatite coatings, ultrahydrophilic surfaces and ultraviolet photofunctionalization. The evidence consistently suggests that the transition from early machined titanium implants to moderately rough surfaces represented the most important improvement in implant surface technology. Instead, the more contemporary bioactive modifications appear primarily designed to enhance the biological events occurring during the early healing phase rather than fundamentally altering long-term implant performance.

Experimental and histological studies included in this review frequently demonstrated enhanced early bone responses around modified surfaces. For example, increased bone-to-implant contact (BIC), faster mineral apposition rates and greater biomechanical anchorage were reported around calcium-modified, ultrahydrophilic and photofunctionalized surfaces in several studies (Makary et al.; Menhall et al.; Yang and Hong; Lee et al.; Pabst et al.; Yadav et al.; Sghaireen et al.). (39,40,42–46)

However, clinical studies evaluating implant survival, marginal bone levels and long-term stability generally reported comparable outcomes among modern moderately rough surfaces and more advanced bioactive modifications (Jeon et al.; Sayin Ozel et al.; Antal et al.; Velasco-Ortega et al.; Demetoglu et al.). (18,21,22,31,38)

This pattern suggests that surface technologies mainly influence the speed and dynamics of osseointegration, whereas the final clinical outcome is largely determined by other biological and biomechanical factors once osseointegration is established.

5.2 Osseointegration and implant stability

Implant stability reflects the mechanical and biological interaction between the implant surface and surrounding bone. Primary stability is determined mainly by bone density and surgical technique, while secondary stability results from new bone formation and remodelling at the bone–

implant interface. Surface characteristics can influence this transition by affecting protein adsorption, cell attachment and osteogenic activity.

Across the randomized clinical trials included in this review, implant stability values measured through resonance frequency analysis generally remained within the clinically accepted safe range throughout healing. Jeon et al. reported mean primary ISQ values close to 80 for both tested SLA implant groups, with secondary stability values increasing during follow-up to approximately 82–84 after one year. Importantly, no statistically significant differences were observed between the two SLA surface variants, suggesting that relatively small modifications in microtopography may not substantially influence the final stability achieved once osseointegration has occurred.(22)

Similar findings were reported by Sayin Ozel et al., who compared SLA implants with their hydrophilic SLActive surface. Although SLActive surfaces are designed to improve wettability and increase surface energy, both implant types demonstrated comparable stability trends over the 12-week healing period. ISQ values increased progressively in both groups, indicating successful osseointegration regardless of the specific surface treatment used.(21)

Several studies suggested that surface modifications can influence the early phase of osseointegration; for example, Zaheer et al. which investigated ultraviolet-treated implants reported a higher early ISQ values compared with the untreated control group. Ultraviolet photofunctionalization reduces the surface hydrocarbon contamination and so increases surface energy, creating a superhydrophilic titanium surface that may facilitate rapid protein adsorption and osteoblast attachment. This mechanism likely explains the improved early stability observed in the ultraviolet-treated implants.(32)

Makary et al. demonstrated significantly higher bone-to-implant contact and bone area values for SLA and calcium-incorporated implants compared with machined surfaces during early healing in human histological samples.(39)

Similar findings were also reported by Yang and Hong which observed higher BIC and removal torque values around calcium-incorporated XPEED surfaces compared with hydroxyapatite-coated implants in a rabbit tibia model. These findings indicate that nanostructured calcium incorporation may enhance osteoblastic activity and mineral deposition at the implant interface. (43)

Lee et al. also reported significantly higher early BIC values in ultraviolet-treated implants compared with machined titanium implants in a rabbit model, further supporting the hypothesis that improved surface energy and wettability can accelerate early bone formation. (42)

Pabst et al. observed similar results for ultrahydrophilic surfaces, which demonstrated increased early bone contact compared with conventional sandblasted implants.(44)

Despite these early biological advantages, the available clinical data indicate that the long-term level of implant stability achieved after healing is generally similar across different modern roughened surfaces. Carmo Filho et al., for example, compared four commercially available roughened implant surfaces and observed only transient differences in early stability patterns, while all implants ultimately reached comparable ISQ values after 91 days. These findings suggest that surface modifications primarily affect the rate of osseointegration, rather than the final degree of bone anchorage achieved.(37)

5.3 Marginal bone preservation and long-term performance

Marginal bone stability is one of the most relevant indicators of long-term implant success because progressive crestal bone loss may compromise both implant stability and peri-implant soft tissue support. Across the clinical studies included in this review, marginal bone loss remained consistently low regardless of the specific surface modification evaluated. Jeon et al. reported minimal marginal bone loss after one year, with mean values of approximately 0.07 mm in the test group and virtually no measurable bone loss in the control group. These values fall well below the generally accepted thresholds for implant success and suggest stable peri-implant bone conditions for both implant surfaces.(22)

Similarly, Antal et al. compared calcium-phosphate coated implants with implants featuring a smart bioactive trabecular coating (SBTC®) in a randomized clinical trial and reported progressive increases in implant stability during the two-year follow-up period without significant differences between surfaces. Both implant types successfully osseointegrated and were restored as planned, further confirming the predictable performance of contemporary rough titanium surfaces.(31)

Long-term observational data support these findings. Velasco-Ortega et al. reported a cumulative survival rate of approximately 96% and a mean marginal bone loss of 1.18 mm after twelve years for SLA implants placed under early loading conditions. These results demonstrate that moderately rough surfaces can maintain stable bone levels over extended periods of function.(18)

Comparable survival outcomes were also observed in the retrospective study by Demetoglu et al., who reported survival rates of approximately 96% for both RBM and SLA implants during early healing periods.(38) The absence of meaningful differences between these surfaces further supports the concept that modern rough titanium implants already achieve highly predictable long-term results.

Taken together, these clinical findings suggest that once a proven rough surface is used, the specific type of microstructural modification may play a relatively limited role in determining long-term clinical success. Instead, patient-related factors such as bone quality, systemic health, oral hygiene and prosthetic loading conditions are likely to exert a greater influence on long-term implant outcomes.

5.4 Surface physicochemical characteristics and biological response

Several studies included in this review investigated physicochemical properties of implant surfaces to better understand the biological mechanisms underlying osseointegration.

Surface roughness plays a fundamental role in bone–implant interaction because it increases the available surface area and facilitates mechanical interlocking between newly formed bone and the implant surface. Measurements reported by Diaz-Sanchez et al. indicated roughness values ranging between approximately 0.19 and 0.35 μm depending on titanium grade and surface treatment, corresponding to smooth to slightly rough surfaces. In contrast, the SLA implants investigated by Jeon et al. showed roughness values around 3 μm , consistent with moderately rough implant surfaces known to promote bone formation.(22,47)

Beyond surface roughness, wettability has emerged as an important determinant of early biological responses. Hydrophilic surfaces exhibit lower contact angles and higher surface energy, which facilitates protein adsorption and early cell adhesion. Yang and Hong demonstrated substantial differences in contact angle values between hydroxyapatite-coated surfaces, conventional SLA surfaces and calcium-incorporated XPEED implants. The latter showed extremely low contact angles, indicating markedly enhanced wettability and potentially greater biological activity.(43)

Similarly, Lee et al. reported that ultraviolet photofunctionalization can convert hydrophobic titanium surfaces into highly hydrophilic ones by removing surface hydrocarbons and increasing surface energy. This transformation leads to improved protein adsorption and osteoblast attachment, which may explain the enhanced early bone-implant contact observed in photofunctionalized implants.(42)

Although these physicochemical modifications clearly influence early cellular events, their translation into clinically significant long-term advantages remains uncertain. Most clinical studies included in this review did not demonstrate consistent improvements in implant survival or marginal bone preservation associated with these advanced surface treatments.

5.5 Clinical implications and limitations

From a clinical perspective, the findings of this review suggest that advanced implant surface technologies may provide the greatest benefit in situations where rapid osseointegration is required. Accelerated early bone formation may facilitate early or immediate loading protocols and may also be advantageous in sites characterized by reduced bone density or compromised healing potential.

However, in routine implant therapy involving adequate bone quality and conventional loading protocols, established moderately rough surfaces such as SLA continue to demonstrate excellent long-term outcomes. Under these conditions, factors such as surgical technique, implant positioning, prosthetic design and patient maintenance are likely to play a more decisive role in determining treatment success than the specific surface modification used.

Several limitations should also be considered when interpreting the results of this review. The included studies were heterogeneous in terms of study design, sample size and follow-up duration. Many clinical trials involved relatively small patient populations and observation periods shorter than five years, which limits the ability to detect subtle differences in long-term implant performance.

Furthermore, several of the strongest biological advantages associated with advanced surface technologies were observed in animal experiments or laboratory studies, which may not fully reproduce the complex biological and mechanical conditions present in clinical practice. Future research should therefore focus on well-designed randomized clinical trials directly comparing different implant surface technologies under standardized clinical conditions and with extended follow-up periods.

Such studies would help clarify whether specific patient groups, such as individuals with poor bone quality or those undergoing immediate loading protocols, may derive greater benefits from advanced bioactive implant surfaces.

6. CONCLUSIONS

The present review aimed to analyse the evolution of titanium implant surface treatments and to evaluate how different surface modifications influence relevant clinical outcomes, including osseointegration, implant stability, marginal bone preservation, and soft-tissue response. Based on the available evidence, implant surface characteristics play a significant role in the biological interaction between the implant and surrounding tissues. Moderately rough titanium surfaces, particularly those produced through sandblasting and acid-etching techniques, remain the clinical reference standard due to their predictable osseointegration and favourable long-term outcomes. Surface modifications such as chemically modified hydrophilic surfaces and nanostructured designs appear to enhance early biological events at the bone–implant interface and may contribute to improved early implant stability during the healing phase. However, once osseointegration has been achieved, differences in long-term outcomes such as implant survival and marginal bone loss among modern implant surfaces appear to be less pronounced. In addition, emerging surface technologies aim to optimise not only bone response but also the interaction with surrounding soft tissues and the modulation of early biological processes. Nevertheless, the available literature remains heterogeneous in terms of study design, surface technologies, and follow-up duration. Therefore, further well-designed randomized clinical trials with standardized methodologies and longer follow-up periods are required to better clarify the long-term clinical benefits of advanced implant surface modifications.

7. SUSTAINABILITY

According to the Royal Decree 822/2021 the sustainability is an important component of university project, it shows ethical responsibility and awareness of the long-term impact in scientific work. This research on surface treatments for titanium dental implants explores sustainability from ethical, social, economic, and environmental viewpoints. The aim is to identify surface modifications that improve osseointegration and extend implant longevity. Longer-lasting implants support economic sustainability by reducing the need for replacements. Environmentally, greater durability lowers titanium use and decreases clinical waste. Socially, better clinical outcomes improve patients' oral health, comfort, and quality of life.

Overall, this project aligns with the United Nations Sustainable Development Goals, reflecting an ethical commitment to sustainable progress in dentistry.

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