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Latest Trends in Surface Modification for Dental Implantology: Innovative– Developments and Analytical Applications.

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Abstract

The success of dental implantation depends primarily on one critical factor—osseointegration. As clinical demands grow and patient expectations rise, innovations in implant surface modifications are redefining standards in implant dentistry. This review dives into the latest biological, chemical, and nanotechnological surface treatments engineered to enhance bone-implant integration, accelerate healing, and minimize bacterial colonization. From bioactive coatings with growth factors and peptides to advanced nanostructures created via anodization, laser ablation, and ion deposition, each technique is explored for its clinical impact and potential. Novel hybrid surfaces, incorporating antibacterial agents like silver nanoparticles and controlled drug delivery systems, promise improved biocompatibility and long-term implant stability. Electrochemical and chemical approaches such as acid etching and hydroxyapatite layering also provide versatile and cost-effective methods to optimize surface topography and bioactivity. While early outcomes are promising, this review underscores the need for large-scale, long-term human trials to establish efficacy and safety across diverse patient populations. As we enter an era of personalized and precision implantology, combining cutting-edge materials science with clinical insight offers an exciting path forward in ensuring long-lasting, predictable outcomes in dental implant therapy.

Keywords: Osseointegration, Nanotechnology, Bioactive coatings, Surface modification, Titanium implants, Antibacterial surfaces, Anodization, Dental implants

Introduction:

Dental implants have become a widely accepted solution for rehabilitating edentulous spaces due to their high success rates and long-term functionality. However, the success of an implant is highly dependent on its ability to integrate with surrounding bone tissue, a process known as osseointegration. The nature of the implant surface plays a pivotal role in modulating cellular responses and enhancing bone-to-implant contact (BIC) during healing and long-term stability [1].

To improve osseointegration, a wide array of surface modification techniques has been developed. These include mechanical treatments (e.g., grit blasting and machining), chemical etching, plasma spraying, anodization, and biological coatings that aim to enhance bioactivity and cellular affinity [2]. These modifications not only influence surface roughness but also alter the chemical composition and wettability of the implant surface, thereby affecting protein adsorption, osteoblast attachment, and subsequent bone remodeling [3].

Recent advancements in nano-engineering and bio-functional coatings have further improved early-stage osseointegration by mimicking the natural bone environment. These innovations are particularly significant in medically compromised patients, where rapid and robust healing is critical [4].

Mechanical Surface Modifications of Implants

An increase in world population and life expectancy has led to increased relevance of dental implants in today's world. Many strategies to improve the survival rates focusing primarily on the composition of implant material and shape have been investigated widely. Mechanical surface treatments include various techniques that modify the morphology or surface structures of the implants. These techniques include sandblasting, peening, surface coating methods and laser surface engineering. The primary aim of these techniques is to improve the biocompatibility and long-term stability of implants [5,6,7].

The latest trends in surface modifications of implants are sandblasting, acid etching, plasma spraying and machine grit blasting. The use of these techniques changes the free surface energy, chemical composition and roughness which may increase osseointegration [8,9].

Sandblasting technique

Sandblasting is one of the most currently commercialized methods of surface modification which uses particles of various diameters. It has the advantage of both topography and wettability [10,11]. This technique involves use of pressured air steam to the titanium implant surface which in turn creates a macro roughness. Sandblasting has been considered a key treatment to modify implant surfaces with osseo-inductive activity, and to increase the contact angles for the improvement of hydrophilic behavior for osteoblasts adsorption [12].

Acid Etching

The acid-etching erosion takes place after sandblasting and the whole process is considered as the reference surface treatment. Usually, strong acid solutions, such Nitric Acid are used to remove the oxide layer and other contaminants from implant surfaces creating pits and craters [13]. Acid Etching creates homogenous surface irregularities which ultimately result in improved bioadhesion [14].

Plasma Spraying

Plasma Spraying is one of the most common methods which involves heating powders of different substances like calcium phosphate to a high temperature and then projected onto rough implant surfaces to form coatings [15]. This technique increases the surface area of the implant by providing roughness to the implant surface [16].

Machine Grit Blasting

Machine grit blasting is one of the most frequent methods of surface alterations in which hard particles like alumina are added to the implant surface to make it rough [17]. The main advantage of this technique is that it improves adhesion and proliferation of osteoblasts [18].

Chemical and Electrochemical Modifications to Dental Implants

The quest to enhance the success and longevity of dental implants has led to significant advancements in surface modifications. Among these, chemical and electrochemical modifications stand out for their ability to improve osseointegration and antibacterial properties.

Chemical Modifications to Dental Implants

Chemical modifications involve altering the surface properties of dental implants using various chemical agents. These modifications aim to enhance biocompatibility and promote bone growth thus enhancing osseointegration and reduce bacterial adhesion. Chemical modifications include:

Acid Etching

Acid etching is a widely used technique where implants are treated with strong acids such as hydrochloric or sulfuric acid. This process creates a roughened surface, which has been shown to enhance the initial mechanical stability and promote better osseointegration by increasing the surface area for bone-to-implant contact [19].

Surface Coatings

Surface coatings, such as hydroxyapatite (HA) and calcium phosphate, are applied to the implant surface to mimic the mineral component of bone. These coatings can significantly enhance bone integration and provide a bioactive surface that encourages bone growth [20].

Silane Coupling Agents

Silane coupling agents are organic compounds containing silicon atoms and act as a bridge linking two dissimilar materials. Silane coupling agents are used to create a bond between the implant surface and organic molecules, improving the adhesion of polymer-based coatings. This technique has been shown to improve the mechanical stability and longevity of dental implants [21].

Electrochemical Modifications to Dental Implants

Electrochemical modifications involve altering the implant surface through electrochemical processes such as anodization and electrochemical deposition. These techniques can create highly controlled surface features that enhance implant performance.

Anodization

Anodization is an electrochemical process that creates a thick oxide layer on the surface of titanium implants. This layer increases corrosion resistance and biocompatibility. Studies have shown that anodized surfaces can promote better osseointegration and provide antibacterial properties by incorporating elements like silver or zinc [22].

Electrochemical Deposition

Electrochemical deposition involves applying a thin layer of material onto the implant surface using an electric current. This technique allows for precise control over the thickness and composition of the coating. Commonly used materials include calcium phosphate and silver nanoparticles, which have been shown to enhance bone growth and provide antibacterial properties [23].

Comparative Analysis

Both chemical and electrochemical modifications offer unique advantages for enhancing dental implant performance. Chemical modifications, such as acid etching and surface coatings, are relatively simple and cost-efficient, providing immediate improvements in surface roughness and bioactivity. However, these techniques may lack the precision and control offered by electrochemical methods.

Electrochemical modifications, such as anodization and electrochemical deposition, allow for highly controlled and uniform surface alterations, resulting in enhanced osseointegration and antibacterial properties. These techniques can be more complex and costly but have superior long-term benefits compared to traditional chemical methods.

The advancements in chemical and electrochemical modifications have significantly improved the performance and longevity of dental implants. By enhancing the surface properties, these techniques promote better osseointegration, reduce bacterial adhesion, and improve mechanical stability. Future research should focus on combining these methods to optimize implant performance further.

Biological modification:

Bioactive Coating:

Bioactive molecules such as collagen, growth factors, and peptides improve osseointegration efficiently, which is of utmost importance in the initial stages of bone integration. These coatings modulate surrounding tissue via epigenetic signaling and are directly involved in the process of bone healing in osseointegration. [24]

Growth factors, in this instance BMP-2, are employed to improve osseointegration. However, it is required to optimize the concentrations and combinations for maximum outcomes. Various techniques, such as acid etching, granular radiation, and anodization, are utilized to develop sophisticated nanotechnological surfaces that improve osseointegration [25], [28].

Nanotechnology modification:

Techniques and Materials:

These nano functions can be created through methods like ion beam deposition and monolayer self-assembly. Additionally, hydroxyapatite coatings, deposited through processes like anodization, promote bone and implant interaction [25].

Impact on Osseointegration:

The application of both nanotechnology and biological modification is to enhance the contact between the implant surface and bone, thereby gaining a quicker and more powerful integration of bone [24], [26].

Clinical Effectiveness:

While many surface modifications exhibit high clinical effectiveness, more studies with human subjects are needed to directly compare the relative efficacy of the various techniques [26], [28].

Guidelines for Future Ventures:

Nanomaterials: Future application of nanomaterials is ushering in a new generation of implants that are not only going to be highly efficacious but also economical. [27], [29]. Zirconia Implants: Surface treatment of zirconia implants with processes like sandblasting and UV treatment enhances osseointegration by surface roughening and hydrophilicity. [30]

Hybrid and Novel Surface Treatments

Titanium and its alloys stand out as the most used materials in this field, largely due to their exceptional corrosion resistance, biocompatibility, and robust mechanical properties. However, there are certain drawbacks associated with traditional implants, that arise the need for modifications to their basic structure.

Firstly, titanium and its alloys offer many advantages, they are inherently bioinert, meaning they struggle to directly bond with bone tissue upon implantation. This is largely because they lack osteoconductive and osteoinductive properties, which are essential for facilitating bone growth and integration. Secondly, bacterial adhesion at the implant site can lead to infection-related complications, posing a serious challenge in implant success. Thirdly, the surface of the titanium implant is the critical interface with blood, cells, and tissues. The properties of this surface profoundly influence

the interaction with proteins and cells, which, in turn, can either support or hinder osseointegration—the process of the implant bonding with the bone. Therefore, the morphology, chemical composition, and antibacterial functionality of the implant surface are key factors in determining the overall success of the implant.
Hybrid and novel surface treatments for dental implants aim to enhance osseointegration and long-term performance by modifying the implant surface to improve bone-implant contact, reduce bacterial colonization, and promote faster healing.

Osseointegration Enhancement:

Sandblasting enhances osteoinductive activity and improves the hydrophilic properties necessary for osteoblast adsorption, supporting the integration of the implant with the surrounding bone tissue [12]. Titanium surfaces treated with an acid-etching process have shown promising results, including enhanced roughness and improved osteogenic response. This is attributed to the increased proliferation, adherence, and differentiation of osteogenic cells [31]. Due to their enhanced bioactivity and capability to load and release proteins and growth factors, TNTs (Titanium Nanotubes) present a highly promising approach for surface modification aimed at promoting osteogenesis, as demonstrated by numerous in vivo studies [32,2]. Nanostructured coatings such as calcium, calcium phosphate, and hydroxyapatite (HA) are applied to metal implants through methods like hydrothermal deposition or plasma spraying. By releasing calcium and phosphate ions, they promote the mineralization of surrounding tissues and aid in bone healing [33].

Antibacterial Properties:

Remarkable bacterial colonization inhibition was identified when silver nanoparticles were incorporated, which rendered excellent antibacterial properties, and also confirmed good bio-integration [34,35]. Aminoglycosides, particularly gentamicin, are commonly used antibiotics for coating titanium implants due to their heat stability and broad antibacterial activity. Other antibiotics that have been tested for use in implant coatings, especially in prosthetics, include carbenicillin, amoxicillin, cephalothin, cefamandole, vancomycin, and tobramycin [36]. Antimicrobial agents like silver, copper, and zinc incorporated via sol-gel processes create hybrid nanolayers that are biocompatible and non-infective [37].

Specific Techniques:

Anodization of dental implants creates a porous titanium oxide layer, which favors blood-clot retention [38], nano-roughness, and osseointegration [39]. Laser ablation techniques are employed to create micro- and nano-textured surfaces on titanium implants (Ti6Al4V), enhancing osseointegration by mimicking bone structures. This process boosts protein attachment, which in turn promotes better cell adhesion and wear resistance [40]. Thread geometries (e.g., V-shaped) achieve efficient stress distribution, improving implant stability and force distribution along the implant length [28].

Future Directions

Emerging research highlights the potential of epigenetic modulations through surface modifications to enhance bone healing during osseointegration. By creating biomimetic surfaces that replicate natural bone structures, we can significantly improve implant integration and long-term success. Furthermore, employing combination strategies that integrate various surface modification techniques and materials promises to optimize implant performance, offering a more effective approach to advancing dental implant technologies.

Clinical Implications and Future Directions of Surface Modifications in Dental Implants

Implant longevity and osseointegration have been greatly enhanced by the development of surface modification methods. Techniques like bioactive coatings and nanoparticle deposition have demonstrated encouraging therapeutic results. More research is needed to enhance these strategies even more and get over their shortcomings in terms of long-term stability and biocompatibility [41],[42].

The potential for surface bioactive alteration to enhance osseointegration and implant survival rates was demonstrated by a systematic review. The review states that bioactive coatings raise the bone-to-implant contact (BIC) by significant percentages, which translates into improved implant durability and decreased failure. According to the research, using bioactive modification on dental implants can result in better clinical outcomes, especially for patients with poor bone quality. Yet, the research calls for extended randomized controlled trials to establish the same benefits over the longer period [41].

One of the most innovative methods for altering the surface of implants is nanotechnology. The application of dental implants coated with nanoparticles and their potential to enhance angiogenesis and bone regeneration were investigated in a scoping study. Although more research is required for practical use, the results indicate that these surface alterations can improve osseointegration and allow for early implant loading. Despite these advantages, questions about the long-term effects of nanoparticles on general health and potential inflammatory responses remain unanswered and require more research [42].

Other surface modification procedures have been evaluated in additional studies to enhance osseointegration and reduce complications. Studies have reviewed procedures such as surface texturing, chemical treatment, and use of bioactive molecules to promote implant integration and longevity. While these processes are promising, large-scale clinical trials must be conducted to identify their safety and efficacy profiles. [43,44,45].

In this regard, perfecting such surface modification techniques for optimal clinical effectiveness and safety in a biocompatible manner is part of the future of implant dentistry. Combining nanoparticle technology with the bioactive coating could have a synergistic effect that improves tissue compatibility and mechanical stability. To evaluate long-term durability and create uniform procedural protocols for utilization, larger clinical trials must be conducted. To further advance the wider clinical application of these novel surface alterations, it is imperative to coordinate the regulatory approval process and address cost considerations. [41,42,44].

Conclusion

In summary, cutting-edge surface treatments—such as nanotechnology and bioactive coatings—are revolutionizing the field of dental implantology. These innovations are designed to enhance osseointegration by creating a more favorable environment for bone growth at the implant interface. By improving cellular adhesion, accelerating early bone healing, and mimicking natural biological conditions, these advanced surfaces significantly boost implant stability and success rates, particularly in patients with poor bone quality.

Nanostructured surfaces influence cellular responses at the nanoscale, enhancing osteoblast activity and promoting faster integration. Meanwhile, bioactive coatings, including calcium phosphate and hydroxyapatite, actively stimulate bone regeneration and provide a chemically conducive surface for bone bonding.

However, despite their clear potential, these technologies require robust validation. Long-term, large-scale clinical trials are crucial to confirm their safety, effectiveness, and consistency across diverse patient populations. While initial results are promising, more comprehensive evidence is needed to establish their routine use in clinical practice.

With ongoing research and development, these surface modifications have the power to reshape the future of implant dentistry. By aligning implant design more closely with biological processes, they promise improved outcomes, reduced healing time, and greater predictability—setting new standards in patient care and implant success.

References:

1. Brånemark PI, Hansson BO, Adell R, Breine U, Lindström J, Hallén O, Ohman A. Osseointegrated implants in the treatment of the edentulous jaw. Experience from 10 years. *Scand J Plast Reconstr Surg Suppl.* 1977; 16:1–132.
2. Albrektsson T, Wennerberg A. Oral implant surfaces: Part 1—review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. *Int J Prosthodont.* 2004;17(5):536–543.
3. Buser D, Broggini N, Wieland M, Schenk RK, Denzer AJ, Cochran DL, Steinemann SG. Enhanced bone apposition to a chemically modified SLA titanium surface. *J Dent Res.* 2004;83(7):529–533.
4. Cochran DL. A comparison of endosseous dental implant surfaces. *J Periodontol.* 1999;70(12):1523–1539.
5. Arifvianto B, Suyitno. Surface modification of titanium using steel slag ball and shot blasting treatment for biomedical implant applications. *Int J Miner Metall Mater.* 2013; 20:788–795.
6. Cervino G, Fiorillo L, Iannello G, Santonocito D, Risitano G, Cicciù M. Sandblasted and acid etched titanium dental implant surfaces: Systematic review and confocal microscopy evaluation. *Materials.* 2019; 12:1763.
7. Darimont GL, Cloots R, Heinen E, Seidel L, Legrand R. In vivo behaviour of hydroxyapatite coatings on titanium implants: A quantitative study in the rabbit. *Biomaterials.* 2002; 23:2569–2575.
8. Simões IG, Dos Reis AC, Da Costa Valente ML. Analysis of the influence of surface treatment by high-power laser irradiation on the surface properties of titanium dental implants: A systematic review. *J Prosthet Dent.* 2023; 129:863–870.
9. Nimbalkar S, Dhatrak P, Gherde C, Joshi S. A review article on factors affecting bone loss in dental implants. *Mater Today Proc.* 2021; 43:970–976. doi: 10.1016/j.matpr.2020.07.428.
10. Rupp F, Liang L, Geis-Gerstorfer J, Scheideler L, Hüttig F. Surface characteristics of dental implants: A review. *Dent Mater.* 2018; 34:40–57. doi: 10.1016/j.dental.2017.09.007.
11. Smeets R, Stadlinger B, Schwarz F, Beck-Broichsitter B, Jung O, Precht C, Kloss F, Gröbe A, Heiland M, Ebker T. Impact of dental implant surface modifications on osseointegration. *Biomed Res Int.* 2016; 2016:1–16. doi:10.1155/2016/6285620.
12. Gil J, Pérez R, Herrero-Climent M, Rizo-Gorrita M, Torres-Lagares D, Gutierrez JL. Benefits of residual aluminum oxide for sand blasting titanium dental implants: Osseointegration and bactericidal effects. *Materials.* 2021; 15:178. doi:10.3390/ma15010178.
13. Garg H, Bedi G, Garg A. Implant surface modifications: A review. *J Clin Diagn Res.* 2012; 6:319–324.
14. Barfeie A, Wilson J, Rees J. Implant surface characteristics and their effect on osseointegration. *Br Dent J.* 2015;218: E9. doi: 10.1038/sj.bdj.2015.171.
15. De Jonge LT, Leeuwenburgh SC, Wolke JG, Jansen JA. Organic-inorganic surface modifications for titanium implant surfaces. *Pharm Res.* 2008; 25:2357–2369. doi:10.1007/s11095-008-9617-0.
16. Le Guéhennec L, Soueidan A, Layrolle P, Amouriq Y. Surface treatments of titanium dental implants for rapid osseointegration. *Dent Mater.* 2007; 23:844–854. doi: 10.1016/j.dental.2006.06.025.
17. Searson LJ. History and development of dental implants. In: Narim L, Wilson HF, editors. *Implantology in general dental practice*. Chicago: Quintessence Publishing Co; 2005. p. 19–41.
18. Gupta A, Dhanraj M, Sivagami G. Status of surface treatment in endosseous implant: a literary overview. *Indian J Dent Res.* 2010; 21:433–438. doi:10.4103/0970-9290.70805.
19. Albrektsson T, Brånemark PI, Hansson HA, Lindström J. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthop Scand.* 1981;52(2):155–170.
20. Le Guéhennec L, Soueidan A, Layrolle P, Amouriq Y. Surface treatments of titanium dental implants for rapid osseointegration. *Dent Mater.* 2007;23(7):844–854.

21. Buser D, Schenk RK, Steinemann S, Fiorellini JP, Fox CH, Stich H. Influence of surface characteristics on bone integration of titanium implants: A histomorphometric study in miniature pigs. *J Biomed Mater Res.* 1991;25(7):889–902.
22. Liu X, Chu PK, Ding C. Surface modification of titanium, titanium alloys, and related materials for biomedical applications. *Mater Sci Eng R Rep.* 2004;47(3–4):49–121.
23. Gulati K, Ramakrishna S, Aw MS, Atkins GJ, Findlay DM. Biocompatible surface modification of titanium implants with titanium dioxide nanotubes for enhanced osseointegration and localized drug delivery. *Appl Sci.* 2017;7(6):539.
24. Kunrath MF, Garaicoa-Pazmino C, Giraldo-Osorno PM, Haj Mustafa A, Dahlin C, Larsson L, Asa'ad F. Implant surface modifications and their impact on osseointegration and peri-implant diseases through epigenetic changes: A scoping review. J Periodontal Res. 2024 Dec;59(6):1095-1114. doi: 10.1111/jre.13273. Epub 2024 May 15. PMID: 38747072; PMCID: PMC11626700.
25. Alamoudi A. Nanoengineering and surface modifications of dental implants. Cureus. 2024 Jan 2;16(1): e51526. doi: 10.7759/cureus.
26. Ghasemi Bargi V, Shirmohamadi A, Sedighi M, Rahmanpour N, Alihosseini M, Sedighi M. Review of dental implant surface modifications. J Res Dent Sci. 2013;9(4):224-34.
27. Marasli C, Katifelis H, Gazouli M, Lagopati N. Nano-based approaches in surface modifications of dental implants: A literature review. Molecules. 2024 Jun 27;29(13):3061. doi: 10.3390/molecules29133061. PMID: 38999015; PMCID: PMC11243276.
28. Kligman S, Ren Z, Chung CH, Perillo MA, Chang YC, Koo H, Zheng Z, Li C. The impact of dental implant surface modifications on osseointegration and biofilm formation. J Clin Med. 2021 Apr 12;10(8):1641. doi: 10.3390/jcm10081641. PMID: 33921531; PMCID: PMC8070594.
29. Marasli C, Katifelis H, Gazouli M, Lagopati N. Nano-based approaches in surface modifications of dental implants: A literature review. Molecules. 2024 Jun 27;29(13):3061. doi: 10.3390/molecules29133061.
30. Sun L, Hong G. Surface modifications for zirconia dental implants: A review. Front Dent Med. 2021; 2:733242. doi: 10.3389/fdmed.2021.733242.
31. Ban S, Iwaya Y, Kono H, Sato H. Surface modification of titanium by etching in concentrated sulfuric acid. Dent Mater. 2006; 22:1115–1120.
32. Kurup A, Dhatrak P, Khasnis N. Surface modification techniques of titanium and titanium alloys for biomedical dental applications: A review. Mater Today Proc. 2021; 39:84–90.
33. Asensio G, Vázquez-Lasa B, Rojo L. Achievements in the topographic design of commercial titanium dental implants: Towards anti-peri-implantitis surfaces. J Clin Med. 2019; 8:1982.
34. Cheng H, Li Y, Huo K, et al. Long-lasting in vivo and in vitro antibacterial ability of nanostructured titania coating incorporated with silver nanoparticles. J Biomed Mater Res A. 2014;102(10):3488–3499.
35. Chen J, Mei ML, Li QL, et al. Mussel-inspired silver-nanoparticle coating on porous titanium surfaces to promote mineralization. RSC Adv. 2016;6(106):104025–104035.
36. Pan C, Zhou Z, Yu X. Coatings as the useful drug delivery system for the prevention of implant-related infections. J Orthop Surg Res. 2018; 13:220.
37. Škach J, Šlamborová I, Jelínek Šourková H, Exnar P, Gürlich R. Surface modification of artificial implants by hybrid nanolayers: Antimicrobial surface finishing and strength tests. Eur Surg Res. 2023 Dec 18;64(4):376–389.
38. Gong Z, Hu Y, Gao F, Quan L, Liu T, Gong T, Pan C. Effects of diameters and crystals of titanium dioxide nanotube arrays on blood compatibility and endothelial cell behaviors. Colloids Surf B Biointerfaces. 2019; 184:110521.
39. Pan C, Liu T, Zhang Z, Zhang X, Qiao X, Hu Y, Zhang Q, Yang Z. Preparation of chitosan-Zn2+ complex coating on polydopamine-modified TiO2 nanotubes to enhance osteoblast behaviors. Mater Lett. 2021; 282:128665.

40. Mesa-Restrepo A, Civantos A, Allain J, Patiño E, Alzate J, Balcázar N, Montes R, Pavón J, Rodríguez-Ortiz J, Torres Y. Synergistic effect of RhBMP-2 protein and nanotextured titanium alloy surface to improve osteogenic implant properties. Metals. 2021; 11:464.

41. Shayeb MA, Elfadil S, Abutayyem H, Shqaidef A, Marrapodi MM, Cicciù M, Minervini G. Bioactive surface modifications on dental implants: a systematic review and meta-analysis of osseointegration and longevity. Clin Oral Investig. 2024 Oct 11;28(11):592. doi: 10.1007/s00784-024-05958-y. PMID: 39392473; PMCID: PMC11469970.

42. Kumar R, Liu Y, Alotaibi A, Fernandes G. Application of nanoparticles as surface modifiers of dental implants for revascularization/regeneration of bone. BMC Oral Health. 2024;24(1):66.

43. Lee H, Park J, Chen L, Singh A. Dental implant bioactive surface modifications and their effects on osseointegration: a review. Biomark Res. 2016;4(1):1–8.

44. Zhou W, Song Y, Li D, Huang Q. Surface modified techniques and emerging functional coating of dental implants. Coatings. 2020;10(11):1012.

45. Garcia B, Romero M, Tanaka M, Iqbal Z. The impact of dental implant surface modifications on osseointegration and biofilm formation. J Clin Med. 2021;10(8):1641.