REVIEW ARTICLE

Advancements in Nanotechnology for Enhancing Dental Implant Integration and Root Regeneration

Negar Khaneshi[1], Mitra Rostami[2], Mina Sadat Mirkhani[3], Ali Izadi[4,5], Ava Rowshani[5,6], Mohammad Hasanzadeh Bidgoli[7*]

[1] *School of dentistry, Hamedan University of Medical Sciences, Hamedan, Iran.*

[2] *School of dentistry, Tehran University of Medical Sciences, Tehran, Iran.*

[3] *Independent Dental Researcher, USA.*

[4] *University of New England, Biddeford, ME, USA.*

[5] *Kerman University of Medical Sciences, Kerman, Iran.*

[6] *UCLA School of Dentistry, Los Angeles, USA.*

[7] *Department of Oral and Maxillofacial Surgery, Dental Faculty, Mashhad University of Medical Sciences, Mashhad, Iran.*

ARTICLE INFO

Article History:
Received 20 Sep 2025
Accepted 27 Nov 2025
Published 01 Dec 2025

Keywords:
Nanotechnology
Dental Implants
Implant Integration
Osseointegration
Root Regeneration

ABSTRACT

This review comprehensively explores the transformative role of nanotechnology in advancing dental implant integration and root regeneration. It highlights how nanoscale modifications of implant surfaces and incorporation of nanomaterials enhance osseointegration by promoting osteoblast adhesion and mimicking natural bone processes. The review discusses surface engineering techniques, antimicrobial nanoparticle coatings, and their clinical implications in infection control and implant longevity. Furthermore, it examines nanotechnology-driven approaches to root regeneration, including biomimetic scaffolds, stem cell delivery, and controlled growth factor release, which collectively stimulate effective tissue repair and regeneration. Advanced therapeutic strategies such as gene therapy using nanocarriers and smart nanomaterials offer promising directions for precision and multifunctionality in dental treatments. The review also addresses critical challenges related to safety, biocompatibility, regulation, and cost-effectiveness that must be overcome for clinical translation. Ultimately, it provides a forward-looking perspective on integrating nanotechnology with emerging biomedical technologies to revolutionize dental care, improve clinical outcomes, and promote sustainable practices.

How to cite this article
Khaneshi N., Rostami M., Mirkhani M.S., Izadi A., Rowshani A., Hasanzadeh Bidgoli M.. Advancements in Nanotechnology for Enhancing Dental Implant Integration and Root Regeneration. Nanomed Res J, 2025; 10(4): 360-367. DOI: 10.22034/nmrj.2025.04.004

INTRODUCTION

The field of dental implantology and root regeneration faces significant challenges, primarily due to the complex biological processes involved in achieving successful osseointegration and tissue regeneration. Traditional dental implants often struggle with issues such as inadequate osseointegration, implant-related infections, and limited regenerative capabilities. Nanotechnology has emerged as a promising solution to these challenges, offering innovative approaches to enhance the integration and functionality of dental implants. This review aims to explore the advancements in nanotechnology that are transforming dental implant integration and root regeneration, highlighting the scope and objectives of this evolving field.

The success of dental implants largely depends on osseointegration, which is the direct structural and functional connection between the implant surface and surrounding bone. Achieving this is

* Corresponding Author Email: *Mhmd.hassanzade2023@gmail.com*

challenging due to the need for precise control over the biological interactions at the implant interface [1, 2]. Implant-related infections and the need for materials with high biocompatibility are significant hurdles. Titanium and its alloys, while commonly used, can still face issues related to long-term success due to these factors [3, 4]. Traditional materials and methods often fall short in promoting effective root regeneration, necessitating innovative approaches to stimulate tissue growth and integration[5, 6].

Nanotechnology enables the modification of implant surfaces at the nanoscale, enhancing osseointegration by improving osteoblast adhesion and mimicking natural bone formation processes [7-9]. In addition, nanoparticle coatings can impart antimicrobial properties to implants, reducing the risk of infections and improving long-term outcomes[10]. Also, the incorporation of nanomaterials in dental applications has been shown to improve biocompatibility and stimulate tissue regeneration, offering a promising alternative to conventional materials [5, 11-13].

This review delves into the various applications of nanotechnology in dental implantology, including surface engineering techniques such as coating, patterning, and functionalization and assesses the clinical outcomes associated with nanotechnology-enhanced dental implants, focusing on improvements in osseointegration, infection control, and tissue regeneration.

By examining current research and technological advancements, the review will identify future directions and potential innovations in the field, such as the use of stimuli-responsive and multifunctional implant surfaces.

FUNDAMENTALS IN NANOTECHNOLOGY IN DENTISTRY

Nanotechnology has emerged as a transformative force in dentistry, offering innovative solutions for dental implants and root regeneration. By leveraging the unique properties of nanomaterials, dental professionals can enhance the integration of implants and promote effective root regeneration. This section explores the fundamental concepts of nanotechnology in dentistry, the types of nanomaterials used, and recent advancements in the field.

Nanotechnology involves manipulating materials at the nanoscale (1 to 100 nanometers) to exploit their unique physical and chemical properties for various applications, including dentistry [14, 15]. In dentistry, nanotechnology is applied to improve the mechanical properties, biocompatibility, and aesthetic qualities of dental materials. It is used in areas such as implantology, orthodontics, restorative dentistry, and endodontics [16, 17]. Nanomaterials can mimic the mechanical and structural properties of natural tissues, promoting biointegration and enhancing the performance of dental treatments[15, 18].

Types of Nanomaterials Used in Dental Implants and Root Regeneration

Titanium and titanium alloys are commonly used in dental implants due to their strength and biocompatibility. Nanotechnology enhances their surface properties to improve osseointegration [7, 8]. Zirconia, known for its aesthetic appeal and strength, is used in ceramic-based implants. Nanotechnology can modify its surface to enhance integration with bone tissue[8]. Hydroxyapatite and bioglass are used for their bioactive properties, promoting bone growth and integration. They are often used in coatings for implants and in root regeneration applications[15, 19]. Silver nanoparticles**,** known for their antimicrobial properties, are used to prevent infections around implants and in endodontic treatments [14, 20]. Carbon-based nanomaterials Including carbon nanotubes and graphene, these materials offer excellent mechanical properties and can be functionalized to improve biocompatibility and osseointegration [21].

Advancements in Nanotechnology for Enhancing Dental Implant Integration and Root Regeneration

Advancements in nanotechnology have significantly enhanced dental implant integration and root regeneration through several innovative approaches. Surface modifications such as plasma spraying, sputtering, and anodic oxidation enable nanoscale alteration of implant surfaces, improving their interaction with bone tissue and promoting superior osseointegration [8, 21]. Nanotubular structures on these surfaces facilitate controlled drug delivery, aiding healing and minimizing infection risk[21]. Integrating nanotechnology with tissue engineering techniques enhances root regeneration by supporting the growth of new dental tissues[7]. Additionally, antimicrobial nanoparticle coatings on implants provide sustained protection against infections such as peri-implantitis, thus improving the long-term success of dental implants[11].

NANOTECHNOLOGY FOR DENTAL IMPLANT INTEGRATION

Nanotechnology has significantly advanced dental implantology by improving osseointegration, durability, and infection prevention, primarily through nanoscale modifications of implant surfaces to promote better integration with bone tissue [7, 22]. Techniques such as sandblasting, acid etching, and laser processing create nanostructured surfaces that enhance cell adhesion and bone-implant contact, leading to improved mechanical stability [8, 23]. Nanostructured coatings like titanium dioxide nanotubes and other nanocomposites provide a conducive environment for bone cell proliferation and differentiation [24, 25], while also serving as reservoirs for bioactive molecules such as growth factors and antibiotics to boost tissue integration and reduce infection risks [3, 24]. Incorporating antimicrobial agents like silver nanoparticles and chitosan into nanocoatings has effectively prevented biofilm formation and peri-implantitis, which are critical for the long-term success of dental implants [3, 16, 23, 24]. Additionally, nanotechnology improves the mechanical properties and corrosion resistance of implants, thereby extending their lifespan [3, 8], and nanoscale modifications facilitate better biological interactions, reducing the risk of immune rejection and enhancing overall biocompatibility [7, 26].

NANOTECHNOLOGY IN ROOT REGENERATION

Nanotechnology has significantly advanced the field of dental implant integration and root regeneration by offering innovative solutions for tissue engineering and regenerative therapies. This section of the review paper will explore the role of nanotechnology in root regeneration, focusing on its applications in promoting pulp and periodontal tissue regeneration, stem cell delivery, biomimetic scaffolds, and controlled release of growth factors and drugs.

Nanotechnology plays a pivotal role in advancing dental material performance and regenerative therapies. Incorporating nanoparticles enhances both the mechanical strength and antimicrobial properties of dental composites, which is vital for preventing reinfection and promoting the regeneration of pulp and periodontal tissues. Owing to their nanoscale dimensions, these particles can deeply penetrate dentinal tubules, offering superior antibacterial efficacy[27]. Additionally, nanohydroxyapatite and related nanomaterials integrated with scaffold systems have shown remarkable potential in improving periodontal regeneration by stimulating cellular adhesion, proliferation, and differentiation[28]. Beyond these structural benefits, nanotechnology-driven approaches also enable controlled drug delivery and guide stem cell differentiation, forming the foundation for successful pulp tissue regeneration[27].

Nanoparticles have emerged as efficient carriers for antibiotic delivery at low dosages, significantly improving antimicrobial efficacy while minimizing cytotoxicity and fostering an environment conducive to stem cell proliferation. Nanofibrous scaffolds further contribute by providing a supportive matrix that facilitates stem cell migration and growth, aiding in the regeneration of the pulp-dentin complex[29]. Moreover, integrating calcium phosphate nanoparticles into dental resin formulations has demonstrated promising effects in stimulating pulpal and periodontal ligament stem cells, thereby enhancing overall tissue regeneration and repair[30].

Biomimetic scaffolds engineered through nanotechnology are designed to replicate the structural and functional features of the extracellular matrix, thereby enhancing cell adhesion, proliferation, and differentiation essential for successful tissue regeneration[31]. Typically composed of polymeric nanofibers, these scaffolds mimic the natural matrix environment, supporting pulp tissue regeneration and promoting revascularization of periapical regions[28]. Furthermore, advanced three-dimensional constructs fabricated with nanomaterials serve as multifunctional systems that stimulate osteogenesis, angiogenesis, and biomineralization, making them highly promising for root tissue engineering applications[31].

Nanoporous carriers have shown great promise in enabling targeted and sustained delivery of therapeutic agents, thereby reinforcing structural stability and promoting effective tissue regeneration[32]. Nanotechnology-derived scaffolds and carriers, including polymeric nanoparticles and nanogels, offer advanced strategies for the controlled release of bioactive molecules that can stimulate alveolar bone and periodontal tissue repair[32]. Such regulated release systems enhance stem cell proliferation and support regeneration within the pulp-dentin

Table 1. Key Nanotechnology Approaches in Dental Implant Integration and Root

Nanotechnology Approach	Description	Key Benefits	Reference
Nanostructured Surface Coatings	Modification of implant surfaces at nanoscale level to enhance cell adhesion and osseointegration	Improved bone-implant contact and mechanical stability	(24)
Antimicrobial Nanoparticle Coatings	Use of nanoparticles like silver or zinc oxide to prevent bacterial colonization on implants	Reduced infection risk and implant failure	(33)
Biomimetic Nanoscaffolds	Nanoscale scaffolds designed to mimic natural extracellular matrix supporting root regeneration	Enhanced stem cell differentiation and tissue repair	(34)
Controlled Release Nanocarriers	Nanoparticles delivering growth factors or drugs in a controlled manner to implant sites	Targeted therapy promoting healing and regeneration	(35)
Gene Therapy via Nanocarriers	Nanomaterials used to deliver genes for local tissue engineering and regeneration	Precision modulation of cellular activities	(34)

complex, although a deeper understanding of these underlying biological mechanisms remains necessary[29]. Despite these advancements, significant challenges persist concerning the safety, toxicity, and long-term biocompatibility of nanoparticles. Continued research is crucial to address these limitations and to maximize the potential of nanotechnology in dental tissue engineering. Furthermore, integrating nanotechnological innovations with cutting-edge imaging and regenerative techniques may lead to more predictable and improved clinical outcomes in both endodontic and periodontic therapies[27, 32]. Table 1 summarizes nanotechnology approaches in dental implant integration and root.

ADVANCED THERAPEUTIC APPROACHES

Advancements in nanotechnology have significantly impacted dental implant integration and root regeneration, offering innovative therapeutic approaches. These advancements are primarily driven by the development of nanotechnology-based gene therapy, smart nanomaterials, and recent innovations in nano-based regenerative dentistry. These approaches aim to enhance the effectiveness and precision of dental treatments, addressing the limitations of conventional methods and improving patient outcomes. The following sections explore these advanced therapeutic approaches in detail.

Nanotechnology-based gene therapy represents a promising frontier in dental tissue regeneration by using nanoparticles to deliver genetic material directly to specific cellular targets. The large surface area-to-volume ratio of nanoparticles significantly enhances gene loading capacity and facilitates efficient integration into host cells[36]. Through this approach, gene therapy can activate the expression of critical growth factors and regenerative proteins that drive tissue repair and improve healing outcomes within dental structures[37]. Additionally, employing nanocarriers for gene delivery enables precise, site-specific targeting while minimizing unintended biological interactions, thereby improving the safety and therapeutic efficacy of the treatment[38].

Smart nanomaterials are specially engineered to respond to environmental changes such as shifts in pH, temperature, or the presence of specific enzymes which enables precise, site-specific therapeutic action within the oral cavity[39, 40]. These advanced materials are capable of releasing therapeutic agents in response to pathological conditions like inflammation or infection, thereby localizing treatment and reducing the risk of systemic side effects. Among their practical applications, smart nanomaterials are utilized as antimicrobial coatings on dental implants, effectively preventing biofilm formation and lowering infection risks[40]. Their adaptive properties also allow for the controlled, on-demand release of drugs, which improves the therapeutic outcomes for periodontal disease and dental caries[41].

Recent innovations in regenerative dentistry are centered around the development of biomimetic nanostructures that closely replicate the architecture of natural dental tissues, thereby providing environments favorable for cell proliferation, differentiation, and migration all critical for effective tissue regeneration and integration with existing dental structures[38]. Advanced nanocomposite resins and bioceramics are increasingly applied in dental restorations, yielding improved mechanical performance and aesthetic outcomes for patients[36, 37]. The merging of nanotechnology with stem cell therapy represents a significant trend, further amplifying the regenerative potential of dental treatments and paving the way for the development of novel strategies that harness cellular and molecular mechanisms for tissue repair[37].

While these advancements in nanotechnology offer promising solutions for enhancing dental implant integration and root regeneration, challenges remain. Issues such as the long-term safety and biocompatibility of nanomaterials, regulatory hurdles, and the cost-effectiveness of these advanced therapies need to be addressed to facilitate their widespread adoption in clinical practice[27]. Ongoing research and development efforts are crucial to overcoming these challenges and realizing the full potential of nanotechnology in dentistry.

CLINICAL IMPLICATIONS AND CHALLENGES

Nanotechnology has significantly advanced the field of dental implants and root regeneration by enhancing the properties of materials used in these applications. The integration of nanomaterials into dental implants has improved osseointegration, which is the structural and functional connection between the implant and bone. This is achieved through nanoscale surface modifications that promote better osteoblast adhesion and bone formation, leading to improved implant stability and longevity[1, 3]. Additionally, nanotechnology has been applied in root regeneration, where nanomaterials mimic the mechanical and structural properties of native tissues, promoting biointegration and tissue regeneration[15].

Nanoscale modifications of titanium implants have significantly improved osseointegration by supporting osteoblast adhesion, thereby enhancing bone formation at the implant-tissue interface[2]. The introduction of nanoparticle coatings, such as silver or zinc oxide, has imparted antimicrobial properties to dental and orthopedic implants, effectively reducing the incidence of infections and supporting long-term implant success[1]. In addition, the use of nanomaterials in root regeneration allows for the precise imitation of native tissue characteristics, promoting more effective tissue repair and integration with surrounding biological structures. Collectively, these advances in nanotechnology not only foster the biological integration of implants but also address persistent clinical challenges such as infection and inadequate tissue regeneration[15].

The application of nanotechnology in dentistry raises important safety, toxicity, and regulatory considerations. While nanomaterials offer numerous benefits, their small size and high reactivity can pose potential risks to human health. Concerns about cytotoxicity and long-term biocompatibility are significant barriers to the widespread clinical adoption of nanotechnology in dentistry[42]. Regulatory frameworks are still evolving to address these challenges, and there is a need for standardized guidelines to ensure the safe use of nanomaterials in dental applications[42].

Despite the transformative potential of nanomaterials in dental applications, their small size and high reactivity raise important cytotoxicity concerns that warrant comprehensive safety evaluations prior to clinical adoption. The absence of universally standardized regulations for nanomaterial use in dentistry further complicates their translation from research to practice, underscoring the need for clearly defined guidelines to ensure consistency and patient safety. Achieving long-term biocompatibility remains a central challenge, as it is critical to monitor and understand how these materials interact with biological tissues over extended periods. Addressing these safety and regulatory challenges is vital for the responsible integration of nanotechnology into routine dental care and for safeguarding public health[42].

Despite the promising advancements in nanotechnology for dental applications, several limitations and barriers hinder their clinical translation. High costs associated with the development and production of nanomaterials can limit their accessibility and widespread use[42]. Additionally, there are gaps in research, particularly in long-term in vivo studies, which are necessary to validate the clinical efficacy and safety of nanotechnology-enhanced dental implants.

Furthermore, the complexity of integrating nanotechnology with existing dental practices and the need for specialized training for dental professionals are significant barriers[3].

The integration of nanomaterials into dental implant technologies faces several significant barriers. Chief among these is the high cost of development and production, which restricts widespread accessibility and limits adoption, especially in resource-constrained settings[42]. In addition, there is a notable gap in long-term in vivo research needed to rigorously validate the clinical efficacy and safety of nanotechnology-enhanced implants. These clinical translation challenges are compounded by the necessity for specialized training and adaptation within dental practice, as the incorporation of nanotechnology often requires new skills and protocols beyond conventional methods. Overcoming these limitations will require continued research, economic consideration, and the establishment of robust educational programs to facilitate the responsible integration of nanotechnology into routine dental therapy[3].

While nanotechnology offers transformative potential for dental implants and root regeneration, addressing safety, regulatory, and cost-related challenges is crucial for its successful clinical translation. The development of standardized guidelines and further research into long-term effects will be essential to overcome these barriers and fully realize the benefits of nanotechnology in dentistry.

CONCLUSION AND FUTURE OUTLOOK

Recent advancements in nanotechnology have significantly enhanced the integration of dental implants and the regeneration of dental roots. The application of nanostructured surfaces and nanoparticles has improved osseointegration, bone regeneration, and the overall success of dental implants. These innovations have led to better clinical outcomes, including increased implant stability and reduced infection rates.

Nanoparticle-coated dental implants have made significant advances in osseointegration and bone regeneration, leading to as much as a 25% increase in bone density and a 20% improvement in implant stability according to recent studies. These surface modifications foster the attachment and activity of osteoblasts, thereby promoting robust bone formation at the implant interface. Additionally, the antimicrobial properties imparted by nanoparticles help to reduce the risk of infection and extend the longevity of dental restorations, with materials such as silver, gold, and graphene oxide showing particular effectiveness against bacterial colonization and biofilm formation. Furthermore, nano and biomaterial-based drug delivery systems provide controlled, sustained release of therapeutics, improving the management of post-implantation complications and enhancing overall clinical outcomes for dental patients. These advancements underscore the potential of nanotechnology to revolutionize dental implantology and endodontics, providing more effective and patient-friendly solutions.

The future of nanotechnology in dental applications is promising, with several areas poised for further exploration and development. Continued research is essential to address existing challenges and expand the scope of nanotechnology in dentistry.

While the benefits are clear, concerns about the long-term safety and biocompatibility of nanoparticles remain. Future research should focus on understanding and mitigating potential cytotoxic effects. Establishing standardized regulatory guidelines and improving cost-effectiveness are critical for the widespread adoption of nanotechnology in clinical practice. The integration of nanotechnology with artificial intelligence, regenerative medicine, and robotics could further enhance treatment precision and patient outcomes, paving the way for more personalized and minimally invasive dental care.

By addressing these challenges, the dental field can fully harness the potential of nanotechnology, leading to unprecedented advancements in dental care and patient satisfaction.

While the advancements in nanotechnology for dental applications are significant, it is important to consider the broader context of these developments. The integration of nanotechnology into dental practices must be balanced with considerations of ethical implications, patient safety, and the potential environmental impact of nanomaterials. As the field progresses, interdisciplinary collaboration and comprehensive regulatory frameworks will be essential to ensure that the benefits of nanotechnology are realized in a responsible and sustainable manner.

ACKNOWLEDGEMENTS

The authors utilized artificial intelligence tools,

namely Perplexity.ai, to enhance the clarity and language quality of this manuscript throughout its preparation. All suggestions and content provided by the AI were thoroughly reviewed and revised by the authors, who take full responsibility for the accuracy and integrity of the final version.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

REFERENCES

1. Lavenus S, Louarn G, Layrolle P. Nanotechnology and dental implants. International journal of biomaterials. 2010;2010(1):915327. https://doi.org/10.1155/2010/915327
2. Khullar D, Duggal N, Kaur S. Nanotechnology: An upcoming frontier in implant dentistry. The Saint's International Dental Journal. 2015;1(2):86-90. https://doi.org/10.4103/2454-3160.177929
3. Zhang Y, Gulati K, Li Z, Di P, Liu Y. Dental implant nano-engineering: advances, limitations and future directions. Nanomaterials. 2021;11(10):2489. https://doi.org/10.3390/nano11102489
4. Tavazozadeh E, Shakour N, Mohajerani R, Farhadtouski K, Jamilian A, Nasiri K. Revolutionizing Nano-Orthodontic Diagnosis and Treatment through AI-Enhanced CBCT Image Analysis: New Frontiers in Deep Learning. Nanomedicine Research Journal. 2025;10(3):243-9.
5. Lima PDG, Lima LV, de Castro Bizarria G, da Silva ED, Angelim LM, Alves AFA, et al. Nanotecnologia Nos Materiais Odontológicos: Da Restauração À Regeneração Tecidual Dentinária. Revista Contemporânea. 2023;3(10):16901-21. https://doi.org/10.56083/RCV3N10-018
6. Meimandinezhad M, Bidhendi HM, Zadeh ET, Anzabi RM, Asadi H, Fathi A, et al. Comparison of different surface treatment methods on flexural strength and elasticity modules of quartz and glass fiber-based posts: A narrative review. Journal of Family Medicine and Primary Care. 2022;11(12):7616-20. https://doi.org/10.4103/jfmpc.jfmpc_239_21
7. Praveena C, Chaughule RS, Satyanarayana K. Nanotechnology in implant dentistry. Advances in Dental Implantology using Nanomaterials and Allied Technology Applications: Springer; 2020. p. 1-23. https://doi.org/10.1007/978-3-030-52207-0_1
8. Thomas B, Ramesh A. Nanotechnology in Dental Implantology. Nanomaterials in Dental Medicine: Springer; 2023. p. 159-75. https://doi.org/10.1007/978-981-19-8718-2_9
9. Ghazizadeh Y, Salehi Shadkami H, Madani F, Niknam S, Adabi M. Advances in cancer nanovaccines: a focus on colorectal cancer. Nanomedicine. 2025;20(9):1029-41. https://doi.org/10.1080/17435889.2025.2486930
10. Chaughule RS, Dashaputra R. Advances in dental implantology using nanomaterials and allied technology applications: Springer; 2021. https://doi.org/10.1007/978-3-030-52207-0
11. Dakhale R, Paul P, Achanta A, Ahuja KP, Meshram M, Meshram Sr M. Nanotechnology innovations transforming oral health care and dentistry: a review. Cureus. 2023;15(10). https://doi.org/10.7759/cureus.46423
12. Seifi N, Mansoori R, Khoshbakht Marvi P, Niknam S, Zarrinnahad H, Amini N, et al. Anti-cancerous effect and biological evaluation of green synthesized Selenium nanoparticles on MCF-7 breast cancer and HUVEC cell lines. Nanomedicine Research Journal. 2023;8(4):373-82.
13. Naghinezhad J, Moradpanah S, Khodakarim N, Hamblin MR, Rezaeeyan H. Nanodrug-based modulation of platelet-leukocyte interactions in ovarian cancer: a new frontier in targeted therapy. Cancer Nanotechnology. 2025;16(1):37. https://doi.org/10.1186/s12645-025-00340-3
14. Jain S, Singla M. Application of nanotechnology in clinical dentistry type of manuscript. International Dental Journal of Students' Research. 2023;11(4). https://doi.org/10.18231/j.idjsr.2023.031
15. Shashirekha G, Jena A, Mohapatra S. Nanotechnology in dentistry: Clinical applications, benefits, and hazards. Compendium of continuing education in dentistry (Jamesburg, NJ: 1995). 2017;38(5):e1-e4.
16. Dipalma G, Inchingolo AD, Guglielmo M, Morolla R, Palumbo I, Riccaldo L, et al. Nanotechnology and its application in dentistry: a systematic review of recent advances and innovations. Journal of Clinical Medicine. 2024;13(17):5268. https://doi.org/10.3390/jcm13175268
17. Gauba K, Gupta A, Sharda S. Nanotechnology in Dentistry. Biomedical Translational Research: Drug Design and Discovery: Springer; 2022. p. 141-52. https://doi.org/10.1007/978-981-16-9232-1_10
18. Sadeghzade A, Ghanbari M, Malmir S, Mohammadikhah M, Purtaji B, Namazikhah M, et al. Artificial Intelligence and Nanotechnology in Oral and Maxillofacial Cancer: A Review of Diagnosis and Treatment Advances. Nanomedicine Research Journal. 2025;10(3):202-9.
19. Zafar MS, Alnazzawi AA, Alrahabi M, Fareed MA, Najeeb S, Khurshid Z. Nanotechnology and nanomaterials in dentistry. Advanced Dental Biomaterials: Elsevier; 2019. p. 477-505. https://doi.org/10.1016/B978-0-08-102476-8.00018-9
20. Afkhami F, Chen Y, Walsh LJ, Peters OA, Xu C. Application of nanomaterials in endodontics. BME frontiers. 2024;5:0043. https://doi.org/10.34133/bmef.0043
21. Bokobza L. On the use of nanoparticles in dental implants. Materials. 2024;17(13):3191. https://doi.org/10.3390/ma17133191
22. Alamoudi A. Nanoengineering and surface modifications of dental implants. Cureus. 2024;16(1). https://doi.org/10.7759/cureus.51526
23. El-Sherif RM, Abdel-Fattah A, Fahmy AH, Soliman ZR, Ali FN, Mehanna S. The role of nanotechnology in enhancing dental implant performance. Nanotechnology and Applied Sciences Journal. 2025;1(2):49-59. https://doi.org/10.21608/nasj.2025.408751.1011
24. Marasli C, Katifelis H, Gazouli M, Lagopati N. Nano-based approaches in surface modifications of dental implants: a literature review. Molecules. 2024;29(13):3061. https://doi.org/10.3390/molecules29133061
25. Aung LM, Renn T-Y, Lin JC-Y, Salamanca E, Wu Y-F, Pan Y-H, et al. Nanorough Surface of Fibronectin

Grafted Bioactive Zirconia Dental Implants by Using Glow Discharge Plasma Promotes Osseointegration in a Rabbit Model. International Journal of Nanomedicine. 2024:12615-31. https://doi.org/10.2147/IJN.S494580
26. Subramani K, Lavenus S, Rozé J, Louarn G, Layrolle P. Impact of nanotechnology on dental implants. Emerging nanotechnologies in dentistry. 2018:83-97. https://doi.org/10.1016/B978-0-12-812291-4.00005-4
27. Ivković U, Moreno-Rabié C, Mignon A, EzEldeen M, Jacobs R. Multifunctional nanoparticles in endodontics: applications, challenges, and future directions. Discover Nano. 2025;20(1):1-21. https://doi.org/10.1186/s11671-025-04314-7
28. Tao O, Wu DT, Pham HM, Pandey N, Tran SD. Nanomaterials in craniofacial tissue regeneration: A review. Applied Sciences. 2019;9(2):317. https://doi.org/10.3390/app9020317
29. Ramachandran VS, Radhakrishnan M, Ravindrran MB, Alagarsamy V, Palanisamy GS, Ravindrran MB. Functionalized nanoparticles: a paradigm shift in regenerative endodontic procedures. Cureus. 2022;14(12).
30. Reynolds MA, Zhao Z, Weir MD, Ma T, Liu J, Xu HH, et al. Nanopharmaceuticals in Alveolar Bone and Periodontal Regeneration. Nanopharmaceuticals in Regenerative Medicine. 2022:269-88. https://doi.org/10.1201/9781003153504-15
31. Huang M, Huang Y, Liu H, Tang Z, Chen Y, Huang Z, et al. Hydrogels for the treatment of oral and maxillofacial diseases: current research, challenges, and future directions. Biomaterials Science. 2022;10(22):6413-46. https://doi.org/10.1039/D2BM01036D
32. Alsuraifi A, Ayad R, Mohammed NAR, Al-Essa UI, Mohammed Z, Husam Y, et al. Endodontics at the Bio-Futuristic Frontier: Integrating High-Resolution Imaging, Regenerative Therapies, and Nanotechnology for Next-Generation Care. 2025. https://doi.org/10.20944/preprints202501.1077.v1
33. Tomsia AP, Launey ME, Lee JS, Mankani MH, Wegst UG, Saiz E. Nanotechnology approaches for better dental implants. The International journal of oral & maxillofacial implants. 2011;26(Suppl):25.
34. Ghodrati H, Goodarzi A, Golrokhian M, Fattahi F, Anzabi RM, Mohammadikhah M, et al. A narrative review of recent developments in osseointegration and anti-corrosion of titanium dental implants with nano surface. Bone Reports. 2025:101846. https://doi.org/10.1016/j.bonr.2025.101846
35. Yousif AAM. Advances in Biomaterials for Dental Implants: From Nanotechnology to Regenerative Medicine. Future Dental Research. 2024;2(2):28-38. https://doi.org/10.57238/fdr.2024.152576.1011
36. Xavier JR, Desai P, Varanasi VG, Al-Hashimi I, Gaharwar AK. Advanced nanomaterials: promises for improved dental tissue regeneration. Nanotechnology in endodontics: current and potential clinical applications. 2015:5-22. https://doi.org/10.1007/978-3-319-13575-5_2
37. Mitsiadis TA, Orsini G. Regenerative dentistry using stem cells and nanotechnology. Nanosci Nanotechnol Hum Health. 2017;13:263-92. https://doi.org/10.1002/9783527692057.ch13
38. Yazdanian M, Rahmani A, Tahmasebi E, Tebyanian H, Yazdanian A, Mosaddad SA. Current and advanced nanomaterials in dentistry as regeneration agents: an update. Mini Reviews in Medicinal Chemistry. 2021;21(7):899-918. https://doi.org/10.2174/1389557520666201124143449
39. Cui C, Yan J, Zhou L, Xu Y, Wang G, Wu X, et al. The Next Generation of Dental Treatments: Leveraging Smart-Responsive Nanomaterials for Unique Oral Environments. Materials Today Bio. 2025:102057. https://doi.org/10.1016/j.mtbio.2025.102057
40. Amiri R, Zarei F, Rezaei M. Theranostic Nanomaterials in Dentistry: Dual-Function Platforms for Diagnosis and Therapy. Journal of Oral and Dental Health Nexus. 2025;2(3):1-17. https://doi.org/10.61838/kman.jodhn.2.3.3
41. Yang Z, Han L, Guo Y, Jia L, Yin C, Xia Y. Nanotechnology in dental therapy and oral tissue regeneration. Nanotechnology in Regenerative Medicine and Drug Delivery Therapy: Springer; 2020. p. 91-189. https://doi.org/10.1007/978-981-15-5386-8_3
42. Cheraghiyan M. Nanotechnology in dentistry: Potential applications and future perspectives. Journal of Oral and Dental Health Nexus. 2025;2(1):1-13. https://doi.org/10.61838/kman.jodhn.2.1.1