REVIEW ARTICLE

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Nanotechnology in Dentistry: Current Applications, Challenges, and Future Perspectives: A Narrative Review

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Abstract

Nanotechnology has emerged as a transformative force in modern dentistry, offering novel solutions for prevention, diagnosis, restoration, and regeneration. This review synthesizes recent advances in nanomaterials and nanosystems applied across dental specialities, restorative dentistry, endodontics, periodontics, prosthodontics, implantology, oral surgery, and diagnostics. Important innovations include antimicrobial and self-healing resin composites, nano-enabled implant surface modifications, nano-drug delivery, and quantum-dot-based imaging. Key challenges are toxicity, biocompatibility, regulatory barriers, high manufacturing costs, and limited long-term clinical evidence. Nanotechnology holds significant clinical potential in dentistry; however, its successful translation into safe, effective, and widely accessible treatments requires rigorous translational and clinical trials, strict ethical oversight, and scalable manufacturing processes.

Keywords: Nanotechnology, Nanodentistry, Nanocomposites, Smart dental materials, Nanorobots, Implant drug delivery, Regenerative dentistry.

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1. Introduction

Nanotechnology refers to engineering materials or devices at the nanoscale (usually <100 nm), where unique physical, chemical, optical, and biological properties can emerge. In dentistry, this enables improvements in material performance, antimicrobial behaviour, and interactions with biological tissues [1].

The concept of nanodentistry emerged in the early 2000s, inspired by advances in nanomedicine and biomaterials. Early ideas included nano-fillers in composites, nanoparticle antimicrobial agents, and theoretical nanorobots for cleaning or repair. Over time, many in vitro studies, animal models, and some clinical or observational trials have tested these technologies. Systematic reviews in recent years have collated these developments [2-4].

Nanotechnology plays an important role in modern dentistry, and it can improve diagnosis (e.g., nano sensors or imaging probes), enhance preventive measures (antimicrobials, remineralization), improve restorative materials (durability, esthetics), reduce invasiveness, and enable regeneration of dental tissues (bone, pulp, enamel [5]. The objective of this review is to provide a comprehensive summary of current applications of nanotechnology in dentistry, a critical assessment of their advantages and limitations, and a discussion of future directions that may facilitate the translation of these technologies from laboratory research to clinical practice.

2. Classification of nanomaterials based on type and function

Nanomaterials are increasingly integrated into dentistry due to their unique physicochemical properties, nanoscale dimensions, and multifunctional capabilities. These materials can be classified based on their type and functional applications, each offering distinct advantages in restorative, preventive, regenerative, and diagnostic dentistry [6-8]. Various nanomaterials, their key properties, and applications are presented in Table 1.

Table 1. Various Nanomaterials and dental applications

Nanomaterial Type	Typical Composition / Example	Key Properties	Dental Application
Silver nanoparticles	Ag NP	Strong, broad-spectrum antimicrobial activity	Caries prevention: coatings for restorations and implants
Nano-hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$ nanoscale	Biomimetic remineralization, white colour, good biocompatibility	Enamel repair: desensitizing pastes
TiO_2 nanoparticles	Titanium dioxide NP	Photocatalytic antimicrobial, UV stability	Implant coatings, whitening agents, and antimicrobial surfaces
Self-healing microcapsules with nanoparticle modifications	Polymer microcapsules loaded with healing agents + NP	Ability to repair microcracks, reduce secondary caries	Restorative composites (resins)
Quantum dots	E.g., CdSe, ZnS	Fluorescence, size-tunable emission, imaging contrast	Diagnostic probes, biofilm imaging, and early disease detection

2.1 Based on type

- Nanoparticles: Metal (E.g., silver, gold), metal oxides (e.g., ZnO, TiO_2), polymeric nanoparticles, and others.
- Nanotubes: Carbon nanotubes, functionalized for dental applications.
- Nanofibers: Nanofibrous scaffolds for tissue engineering and regenerative dentistry.
- Nanocomposites: Composites containing nano-fillers to enhance mechanical, optical, or biological properties.
- Quantum dots: Fluorescent nanoparticles used as imaging probes for diagnostics.
- Nanoclays and Nanogels: For controlled drug delivery, scaffolding, and material reinforcement.

2.2 Based on function

- Restorative dentistry: Strengthening dental materials, adhesives, and fillings.
- Antimicrobial agents: Agents to prevent or eliminate biofilms and pathogens.
- Regenerative dentistry: Scaffolds, cell carriers, and systems for growth factor delivery.
- Diagnostic/imaging dentistry: Sensors, contrast agents, and tools for early disease detection.

3. Current applications in dentistry

Nanomaterials have found wide-ranging applications in various fields of dentistry due to their unique physicochemical properties, including a high surface-to-volume ratio, enhanced mechanical strength, and superior bioactivity. These properties enable their use in multiple dental applications, ranging from restorative materials and preventive treatments to diagnostic and imaging technologies, ultimately improving the performance, durability, and functionality of dental therapies (Figure 1).

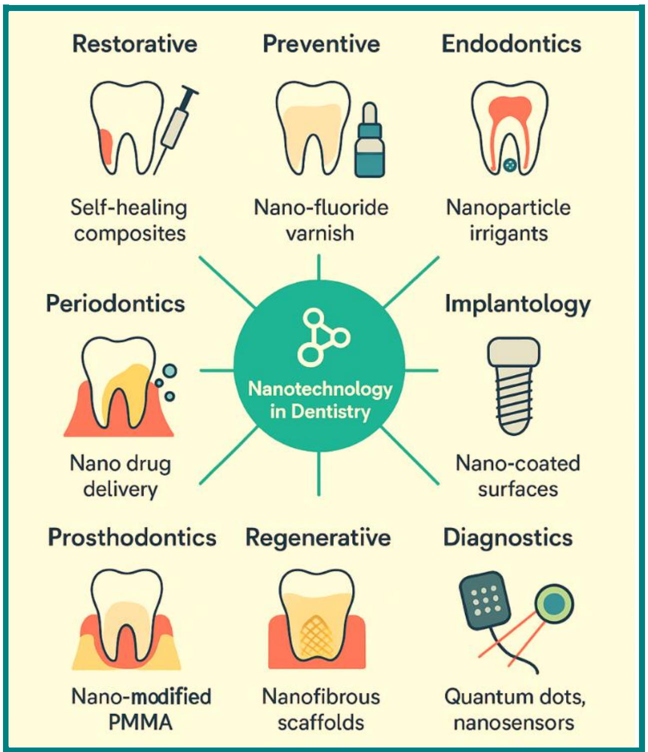

Figure 1. Application of nanotechnology across dental specialities

3.1 Restorative dentistry

Novel antimicrobial and self-healing resin composites have been developed by incorporating nanoparticle-modified self-healing microcapsules into the resin matrix. At an optimal capsule mass fraction of approximately 10%, these composites exhibit high bacteriostatic activity (around 80%) and effective self-healing efficiency (approximately 66%), while maintaining acceptable mechanical properties and cytocompatibility [9]. Nano-fillers continue to improve aesthetics, polishability, and reduce shrinkage [10]. Silver-based nanomaterials have gained significant attention in recent years due to their potent and broad-spectrum antimicrobial properties. According to Wang *et al.*, silver-based biomaterials (AgBMs) demonstrate multiple antibacterial mechanisms, including disruption of microbial cell membranes, damage to genetic material, interference with enzymatic activity, and contact killing effects [9]. The incorporation of nanotechnology has greatly enhanced the therapeutic potential of these materials by increasing surface reactivity, improving ion release control, and minimizing cytotoxicity [11].

3.2 Preventive dentistry

Systematic reviews show that agents such as casein phosphopeptide-amorphous calcium phosphate (CPP-ACP), combined with stannous fluoride and nano-sized sodium trimetaphosphate, significantly promote enamel remineralisation compared to standard treatments [4]. Nano-silver fluoride and nano silver particles are also in trials for caries arrest and prevention. Cheng *et al.* developed nanocomposites and adhesives incorporating silver nanoparticles (NAg), quaternary ammonium methacrylates (QAMs), and amorphous calcium phosphate nanoparticles (NACP) to achieve dual antibacterial and remineralizing effects [11]. NAg provided antimicrobial action against biofilms, while NACP released calcium and phosphate ions, promoting remineralization and acid neutralization. Other nanoparticles, such as zinc oxide (ZnO), titania (TiO_2), and polyethylenimine, have also shown promise in enhancing the antibacterial performance of dental materials, highlighting nanotechnology's potential in restorative and preventive dentistry [11].

3.3 Endodontics

Nanoparticle-based sealers and irrigants enhance penetration into dentinal tubules, improve disinfection, and reduce biofilm viability. Microrobots and magnetically controlled nanoparticles are being explored to reach complex canal anatomies, disrupt biofilms, and deliver therapeutic agents [12]. Raura *et al.* [12] reviewed the emerging role of nanoparticle technology in endodontics, emphasizing its potential to overcome microbial biofilm resistance within the root canal system. Various nanoparticles, including silver, chitosan, graphene, hydroxyapatite, titanium dioxide, zirconia, and bioactive glass, have demonstrated superior antimicrobial properties, enhanced bonding, and improved sealing ability when incorporated into endodontic sealers, obturating materials, irrigants, and intracanal medicaments. These materials not only aid in smear layer removal and disinfection but also contribute to bioactive and regenerative effects [12]. Wong *et al.* [13] discussed the translational potential of nanoparticles in endodontics, highlighting their unique physicochemical and antibacterial properties that can enhance disinfection, sealing, and regeneration within the root canal system. The authors noted that conventional endodontic materials often struggle with complete bacterial eradication and biofilm resistance; hence, nanoparticle-based irrigants and medicaments offer superior antimicrobial efficacy and deeper penetration into dentinal tubules. Functionalized nanoparticles, such as photosensitizer-linked variants, further improve root canal disinfection. Additionally, nanoparticle-incorporated sealers and obturation materials exhibit enhanced bonding, bioactivity, and mechanical performance. In regenerative endodontics, nanoparticles support controlled release of bioactive molecules and improve scaffold integration, offering promising directions for future biomimetic therapies [13].

3.4 Periodontics

Nanoparticles serve as local antimicrobial or anti-inflammatory delivery systems into periodontal pockets. Nanobiomaterials facilitate guided tissue regeneration; some studies using nanofibrous scaffolds have shown promising in vitro/animal results in regenerating alveolar bone and periodontal ligament. In addition, the advancement of nanosciences has made periodontal regeneration easier, resulting in more accurate predictions of its effects. It is encouraged that research be conducted into the full potential of nanosciences in dentistry and periodontics as a method of realising the field's bright future [14].

3.5 Prosthodontics

In prosthodontic treatments, which include both removable and fixed prostheses, nanotechnology has significantly enhanced material performance and clinical outcomes. The incorporation of nanoparticles into conventional materials such as polymethyl methacrylate (PMMA) and silicone elastomers has been reported to improve dimensional stability and tensile strength by reducing polymer chain mobility and enhancing filler-matrix interactions. In addition, nanoparticles such as silver, titanium dioxide, zinc oxide, and silica impart antimicrobial activity through ion release, reactive oxygen species generation, and surface contact-mediated mechanisms, thereby contributing to improved material longevity in dentures and maxillofacial prostheses. For example, TiO_2 nanotubes incorporated into PMMA nanocomposites exhibit strong antimicrobial effects, particularly against Candida species, thereby reducing microbial colonization and prosthetic-related infections. Furthermore, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has been modified at the nanoscale to address microstructural defects, enhancing its mechanical reliability and fracture resistance in fixed prosthodontic restorations [15].

3.6 Implantology

Recent work focuses on nano-structured implant surface modifications to enhance osseointegration (surface roughness, coatings with bioactive ceramics or antibacterial agents), and drug delivery from implants to prevent peri-implantitis. Clinical observational studies support improved early-stage stability and reduced inflammation around nano-coated implants. According to Lavenus *et al.* [16], nanotechnology plays a pivotal role in improving osseointegration and long-term dental implant success by modulating early interactions between implant surfaces and key biological components involved in peri-implant tissue healing. Nanometer-scale surface properties, particularly chemistry and roughness, significantly influence protein adsorption, cell adhesion, and differentiation, leading to improved bone-to-implant contact. The review concluded that future nanometer-controlled surface designs, such as advanced nanostructured surface modifications and bioactive calcium phosphate (CaP) nanocrystal coatings, could enable precise regulation of peri-implant tissue responses by stimulating bone apposition and accelerating healing; these resorbable, biomimetic nanocoatings ultimately enhance the biological integration, stability, and long-term success of titanium implants [16].

3.7 Oral surgery/regenerative dentistry

Nanotechnology has emerged as a unifying platform in oral surgery and regenerative dentistry, as both disciplines aim to restore oral tissues while minimizing trauma and enhancing healing outcomes. In regenerative dentistry, nanofibrous scaffolds and nano-hydroxyapatite are widely utilized for bone and pulp regeneration due to their ability to mimic the native extracellular matrix and promote osteogenic and odontogenic differentiation. Additionally, nanoscale delivery systems for growth factors enable sustained and localized release, resulting in improved tissue repair and accelerated healing [17].

In oral surgery, nanotechnology is increasingly being applied to reduce the invasiveness of conventional surgical procedures while preserving tissue integrity. Advanced nanostructured materials and bioactive coatings are used to support postoperative regeneration and improve integration with surrounding tissues. Furthermore, emerging nanorobotic and nano system-based approaches are being explored for site-specific, tissue-level repair, bridging surgical intervention with regenerative outcomes.

Zinger *et al.* [17] introduced a novel nanotechnology-based strategy that exemplifies this convergence by developing proteolytic nanoparticles for controlled remodelling of oral connective tissue. Traditional surgical blades often cause nonspecific tissue damage, leading to prolonged healing and postoperative discomfort. To address this limitation, the authors engineered nanoparticles encapsulating collagenase in a deactivated state that becomes selectively activated by calcium ions naturally present in oral tissues. Upon activation, these nanoparticles facilitate targeted enzymatic cleavage of supracrestal collagen fibers, enabling precise tissue remodelling without mechanical incision. This controlled biochemical approach promoted periodontal and alveolar tissue repair, reduced surgical trauma, and minimized periodontal relapse [17]. Collectively, these advances illustrate how nanotechnology integrates regenerative principles into oral surgical practice, enabling less invasive, more targeted interventions that support natural healing processes and improve clinical outcomes.

3.8 Diagnostics and imaging

Quantum dots and fluorescent nanoparticles help visualize biofilms, detect early lesions, and aid in imaging of soft and hard tissue boundaries. Nanosensors exploring salivary biomarkers are under development for early disease detection. Calixto *et al.* [18] reviewed the role of nanotechnology-based drug delivery systems in the diagnosis and treatment of oral cancer, one of the most aggressive malignancies of the oral cavity and oropharynx.

Conventional therapies such as surgery, chemotherapy, and radiotherapy, though effective, often result in significant side effects and limited targeting efficiency. The authors highlighted that nanotechnology offers advanced diagnostic and therapeutic approaches by enabling the development of nanoscale carriers, including polymeric nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, gold nanoparticles, hydrogels, cyclodextrin complexes, and liquid crystal systems. These nanocarriers enhance drug solubility, bioavailability, and site-specific delivery, while also serving as imaging and diagnostic probes for early tumour detection. The integration of these multifunctional nanoplatforms holds promise for personalized and minimally invasive cancer management, improving both prognosis and patient quality of life [18]. Chen *et al*. [19] highlighted that traditional diagnostic techniques such as tissue biopsy, vital staining, and cytology are often invasive and limited in accuracy. In contrast, nanoparticle-based detection systems enable non-invasive, highly sensitive biomarker identification and molecular imaging at the nanoscale. Nanoparticles exhibit localized surface plasmon resonance and enhanced optical properties, improving imaging contrast and resolution, while their biocompatibility and surface functionalization allow precise targeting of tumour biomarkers [19].

4. Advantages and challenges of nanotechnology in dentistry

Nanotechnology has transformed dentistry by enhancing the mechanical, antimicrobial, and biological properties of dental materials. It improves the durability, aesthetics, and functionality of restorations, supports minimally invasive and patient-specific treatments, and enables diagnostic and targeted drug delivery for early disease detection and localized therapy (Table 2). However, challenges such as toxicity, regulatory and ethical issues, high costs, material stability, and limited long-term clinical data hinder its widespread clinical use (Table 2). Addressing these issues is essential to harnessing nanotechnology's potential in dental practice fully [20-24].

5. Future Directions

Based on recent literature and emerging technologies, the following areas are especially promising for future research and translation in nanotechnology in dentistry.

Table 2. Advantages and challenges of nanotechnology

Advantages	Challenges
Enhanced mechanical properties: Greater strength, wear resistance, reduced fracture risk, and better adhesion.	Toxicity & Biocompatibility: Potential nanoparticle toxicity (oxidative stress, inflammatory responses), especially with metals or metal oxides; long-term exposure effects unclear.
Antimicrobial activity & biocompatibility: Ability to kill or inhibit pathogens, reduce biofilm, while being compatible with host tissues when properly engineered.	Ethical & Regulatory Concerns: Regulatory frameworks for nanoparticles or nano-devices are often lagging; approval processes are not always well defined; patient safety, standards, and environmental concerns need attention.
Improved diagnosis & targeted therapy: More sensitive/early detection; ability to deliver therapeutic agents locally, reducing systemic side-effects.	Cost & Manufacturing Difficulties: High cost of nano-fabrication; ensuring reproducibility and consistency; scale-up from lab to industrial/commercial scale introduces variability.
Minimally invasive & patient-specific approaches: Smaller interventions; materials that mimic natural tooth tissues; potential for tailored therapies; less removal of healthy tissue.	Lack of Long-Term Clinical Data: Many studies are in vitro or animal models; human clinical trials with long follow-up are few; outcomes such as long-term durability, systemic effects, and cost-effectiveness are underreported.
	Stability, Aging, Degradation: Many nanomaterials may degrade or change properties over time (e.g., oxidation, leaching), which can affect functionality and safety.

5.2 Nanorobotic and active systems

Development of systems such as CalBots (magnetic nanobots) for deep dentinal tubule penetration to treat hypersensitivity by forming stable plugs. Microrobots capable of reaching complex dental anatomy for enhanced disinfection, drug delivery, biofilm disruption in endodontics and periodontal therapy. Nanozyme assemblies and catalytic particles for precisely targeting pathogens (including fungal infections) with minimal damage to human tissues [26].

5.3 Regenerative and personalized nanomedicine

Incorporation of stem cells, growth factors, and nanoscale scaffolds to regenerate dental pulp, periodontal ligament, alveolar bone, and even whole tooth structures. Tailoring materials to the patient's biological profile (genetics, microbiome, immunological status) for better integration and performance [27].

5.4 Integration with AI, Robotics, and Digital Workflows

The integration of artificial intelligence (AI), robotics, and digital workflows with nanotechnology is transforming the design, fabrication, and clinical application of advanced dental materials and therapies. AI- and machine learning–based approaches are increasingly employed to accelerate nanomaterial discovery and optimization by predicting nanoparticle physicochemical properties, biological interactions, toxicity profiles, and long-term performance. These data-driven models enable rational material design, reduce experimental trial-and-error, and support personalized treatment strategies by tailoring nanomaterials to patient-specific biological and mechanical requirements [28].

Digital workflows such as computer-aided design and manufacturing (CAD/CAM) and additive manufacturing are further enhanced through the incorporation of nano-additives, enabling the fabrication of customized restorations, scaffolds, and implant components with improved mechanical strength, bioactivity, and antimicrobial properties. Three-dimensional (3D) printing combined with nanocomposites allows precise control over micro- and nanoscale architecture, facilitating the creation of biomimetic structures that support tissue regeneration and functional integration [29].

Robotics and automation also play a growing role in translating nanotechnology into clinical practice. Robotic-assisted systems and programmable nano- or microrobotic devices are being explored for applications such as automated tooth cleaning, targeted biofilm disruption, and localized drug delivery.

In surgical contexts, robotic platforms integrated with nanoscale tools and imaging technologies offer enhanced precision, reduced operator variability, and minimally invasive intervention capabilities. Collectively, the convergence of AI, robotics, and digital dentistry with nanotechnology has the potential to improve treatment accuracy, efficiency, and patient outcomes while advancing personalized and predictive oral healthcare models [28,29].

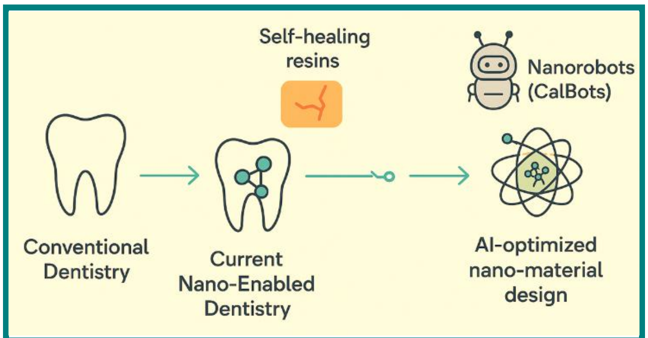

Figure 2. Future directions and innovations

5.5 Sustainability and green nanotechnology

Sustainability considerations are increasingly important in the development of dental and biomedical nanotechnologies. The use of biodegradable nanomaterials that safely degrade without producing toxic byproducts should be prioritized to minimize environmental and biological risks. In parallel, the adoption of eco-friendly and cost-effective synthesis strategies—such as green chemistry approaches and plant-based nanoparticle fabrication—can significantly reduce the environmental footprint of nanomaterial production. Furthermore, comprehensive life cycle assessments, encompassing raw material sourcing, synthesis, clinical application, and end-of-life disposal, are essential to ensure the long-term sustainability and responsible implementation of nanotechnologies [30].

5.6 Translational and clinical studies emphasis

To facilitate the clinical translation of nanotechnology-based dental materials and therapies, there is a critical need for well-designed, long-term randomized controlled trials in human populations. These studies should assess not only therapeutic efficacy but also safety, cost-effectiveness, and patient-reported outcomes such as comfort and satisfaction. In addition, standardisation of clinical outcome measures, including material durability, esthetic stability, and peri-tissue health, is essential to enable meaningful comparison across studies. Robust regulatory and ethical frameworks, coupled with post-market surveillance, are also necessary to ensure the safe and responsible implementation of nanotechnologies in clinical practice [31].

5.7 Multi-modal platforms

The development of multi-functional or multi-modal nanotechnology platforms represents a promising direction in advanced dental and biomedical applications. These materials and devices are designed to integrate multiple capabilities within a single system, such as combined diagnostic and therapeutic functions (theranostics), simultaneous antimicrobial and regenerative activity, or self-sensing and self-repair mechanisms. For example, quantum dot–based imaging agents can be engineered to simultaneously deliver therapeutic payloads, enabling real-time monitoring of treatment response. Similarly, sensor-embedded restorative materials capable of detecting changes in pH, bacterial load, or mechanical stress offer the potential for early diagnosis of material failure or disease progression. Such integrated platforms have the potential to enhance treatment precision, improve long-term clinical outcomes, and enable proactive, personalized dental care [32] (Figure 2).

6. Conclusion

Nanotechnology offers huge promise across many aspects of dentistry, from preventive care and restorative materials to diagnostics, regeneration, and patient-specific therapy. Recent advances such as self-healing resins, nanorobotic systems (e.g. CalBots), and multifunctional materials signal that we are moving closer to clinical utility. Nonetheless, challenges relating to safety, standardization, cost, long-term performance, and regulatory oversight remain. To translate these exciting developments into routine dental practice, multidisciplinary collaboration is essential, including materials science, bioengineering, clinical dentistry, ethical regulators, and industry partners. Future work should emphasize rigorous human clinical trials, scalable manufacturing, and sustainable practices so that nanodentistry becomes safe, effective, accessible, and beneficial for patients.

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