

Review

From Nano to Smile: Applications, Innovations, and the Future of Nanotechnology in Dentistry—A Scoping Review

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Abstract

Background/Objectives: Nanotechnology has become a transformative area in modern dentistry, providing new opportunities for better diagnosis, targeted drug delivery, improved restorative materials, antimicrobial treatments, and tissue regeneration. This scoping review outlines the scope, key developments, and future directions of nanotechnology use across all dental specialties, highlights emerging innovations, and identifies major translational challenges and research priorities. **Methods:** This review followed the Joanna Briggs Institute (JBI) methodology for scoping reviews and adhered to the PRISMA-ScR guidelines. These guidelines, originally by Arksey and O'Malley (2005) and later updated by Levac et al. (2010) and Peters et al. (2020, 2021), guided the process. The Population, Concept, and Context (PCC) framework guided the eligibility criteria. Included studies were primary research or reviews reporting nanotechnology applications in any dental specialty, published in English, with no date restriction. Excluded were non-peer-reviewed sources, conference abstracts without full text, studies unrelated to dental applications, and non-English publications. A comprehensive literature search was conducted across PubMed/MEDLINE, Scopus, and Web of Science. After screening titles and abstracts and reviewing full texts, 133 studies were included. **Results:** The included studies covered a wide range of fields such as restorative dentistry, implantology, periodontology, endodontics, drug delivery, tissue regeneration, oral diagnostics, antimicrobial applications, prosthodontics, orthodontics, and emerging technologies like nanorobotics and graphene-based systems. The most commonly reported nanomaterials were silver nanoparticles (AgNPs), calcium phosphate nanoparticles (CaP NPs), and polymeric nanoparticles such as PLGA and chitosan. Additionally, there was a notable increase in publications starting from 2019. **Conclusions:** Nanotechnology offers transformative possibilities in every area of dentistry. Nonetheless, challenges such as nanotoxicology safety, regulatory alignment, and effective clinical application need resolution. Essential steps include standardized characterization, gathering long-term safety data, and establishing international regulatory standards to ensure safe adoption of nano dentistry.

Keywords: nanotechnology; dentistry; nanoparticles; nanomaterials; scoping review; nanostomatology; antimicrobial; drug delivery; tissue regeneration; nano-dentistry



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1. Introduction

Nanotechnology, which involves designing, synthesizing, and applying materials and devices at scales of 1–100 nm, has become one of the most transformative scientific paradigms of the 21st century [1,2]. Its rapid and varied adoption in dentistry has profoundly transformed the way dental materials, diagnostics, and treatments are developed, operated, and applied therapeutically [3–10].

Oral diseases like dental caries and periodontal disease remain a major global health challenge, affecting billions worldwide [11]. Nanotechnology provides mechanistic solutions to long-standing clinical issues, such as nanocomposite resins with improved mechanical and aesthetic features [12,13]; nanostructured implant surfaces that promote better user integration [14,15]; nano-enabled drug delivery systems for targeted periodontal and endodontic treatments [16,17]; and gold nanoparticle biosensors for early detection of oral cancer [18,19].

The influence of nanotechnology in dentistry covers all major specialties. In restoration, nanocomposite resins, which are nano-remineralizing agents, have revolutionized caries management [12,13,20,21]. In implantology, nanostructured surfaces are used, and antibacterial nanocoatings help prevent osseointegration failure and peri-implantitis [14,22,23]. In periodontology and endodontics, nanodrug delivery systems and regenerative scaffolds have expanded therapeutic options [16,17,24]. Emerging innovations, including nanorobotics, graphene-based nanomaterials, and smart, responsive systems, represent the future of nano dentistry [7,25–28].

Despite these advances, the field faces key challenges. Concerns about nanotoxicology, including genotoxicity, cytotoxicity, and environmental impacts, require thorough safety assessments [29–31]. Regulatory frameworks for nanomedicines are inconsistent and fragmented across regions [32–34]. The gap between laboratory breakthroughs and clinical application remains substantial [35,36]. Importantly, nanomaterials are not only additive but also reactive, thereby improving both mechanical and antimicrobial properties; for instance, they can be used to create dental materials via stereolithography for restorative dentistry [37].

Scoping reviews are ideal for mapping the emerging, diverse landscape of nanodentistry, helping researchers identify evidence gaps and trends in research priorities [38–42]. While previous scoping reviews have addressed particular facets of nanotechnology in dentistry, the present review uniquely synthesizes evidence from 133 studies across all major dental specialties using JBI-compliant methodology, thereby demonstrating a broader and more comprehensive contribution to the scientific literature. This review aims to (1) map nanotechnology applications across dental fields; (2) identify new innovations in nanomaterial designs; (3) evaluate safety and toxicity evidence; (4) review regulatory and translational hurdles; and (5) outline future research directions.

2. Material and Methods

2.1. Study Design

This scoping review followed the Joanna Briggs Institute (JBI) methodology for scoping reviews and adhered to the PRISMA-ScR guidelines, based on the Arksey and O'Malley (2005) framework, updated by Levac et al. (2010), and further refined by Peters et al. [42–47]. Reporting adhered to the PRISMA-ScR checklist for systematic reviews and meta-analyses. The flow diagram illustrating the PRISMA-ScR process is shown in Figure 1. A search was conducted from database inception to April 2026 with no restriction on publication date.

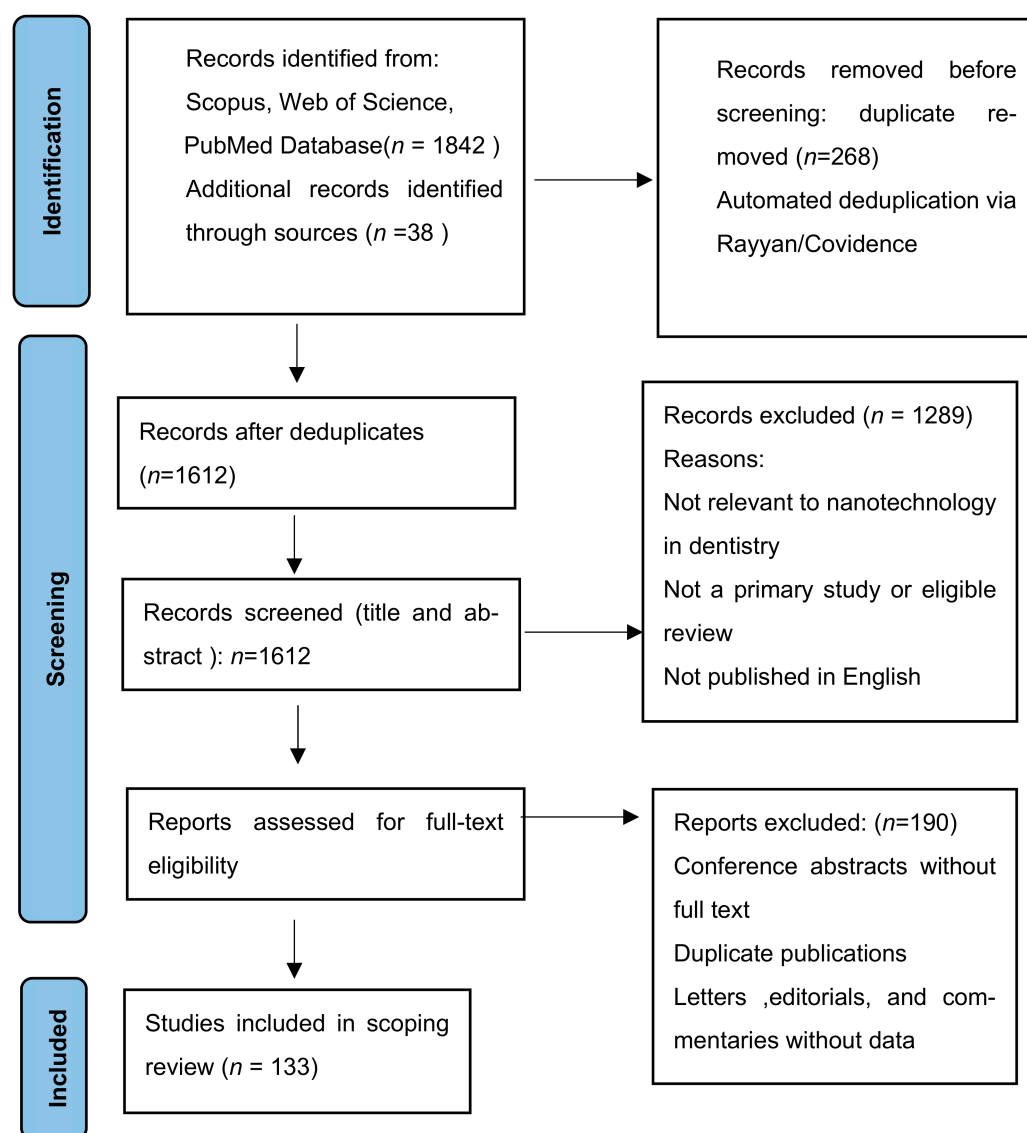


Figure 1. PRISMA ScR flow diagram.

2.2. Research Questions

The main research questions were as follows:

1. Which nanotechnology applications have been documented in various dental specialties?
2. What innovations are emerging in nanomaterial design in dentistry?
3. What are the primary translational challenges and prospects for nanotechnology in dentistry?

2.3. Eligibility Criteria

PCC Framework:

Population (P): dental patients, oral tissues and experimental models related to oral health.

Concept (C): applications, innovations, and materials in nanotechnology, such as nanoparticles, nanocomposites, nanocoatings, nanodevices, nanoscale drug delivery systems, nanosensors, and tissue engineering scaffolds using nanomaterials.

Context (C): dentistry and oral health care encompass all specialties and settings, including clinical practice, laboratory research, preclinical studies, and educational contexts.

Inclusion criteria: studies that report on the application, development, or clinical translation of nanotechnology or nanomaterials in any dental specialty or oral health

setting; original research, reviews, systematic reviews, and scoping reviews; published in English; with no restriction on publication date.

Exclusion criteria: studies unrelated to dentistry or oral health; conference abstracts lacking full text access; research focusing solely on non-dental biomedical applications without dental relevance; duplicate studies.

2.4. Search Strategy

The full Boolean search strings for PubMed/MEDLINE, Scopus, and Web of Science are provided in the Supplementary File. Such terms combined keywords such as “nanotechnology”, “nanoparticles”, “nano -dentistry”, “nanodentistry”, “dental,” “dentistry”, and “oral health”, as well as specific specialties like “implant”, “periodontal”, “endodontic”, “restorative”, “orthodontic”, “prosthodontics”. Boolean operators (AND, OR) were utilized. There was no restriction on publication date. A search was conducted from database inception to April 2026. Studies were screened using Rayyan systematic review management software for title/abstract and full-text screening.

2.5. Study Selection

Two independent reviewers screened titles and abstracts, then full texts. Disagreements were resolved through consensus or a third reviewer. This process is outlined in the PRISMA-ScR Flow diagram (Figure 1). Records were excluded at title and abstract screening if they did not relate to nanotechnology applications in dentistry, were non-English, or were duplicates; the number excluded per reason is detailed in Figure 1. At full-text review, exclusions were made for non-peer-reviewed sources (e.g., theses, grey literature without peer review), studies with insufficient methodological detail, and studies outside the scope of dental applications. The 38 additional records were identified through manual cross-referencing of included studies’ reference lists, targeted Google Scholar searches using nanotechnology-in-dentistry terms, and grey literature sources.

2.6. Data Extraction and Charting

Data were collected using a standardized form capturing authors, publication year, study design, dental specialty, nanomaterial type(s), key findings, and translation status. Translation status was defined as the stage of evidence translation, classified as in vitro, preclinical (in vivo), or clinical. The data were then summarized both narratively and quantitatively within each domain.

3. Results

3.1. Overview of Included Studies

After the search and screening process, 133 studies were selected for this scoping review. There categorized into 12 thematic areas (see Figure 2). The most commonly reported domains include restorative dentistry ($n = 22$), implantology ($n = 18$), and drug delivery systems ($n = 16$). A total of 14 different nanomaterial types were identified, with silver nanoparticles (AgNPs, $n = 28$), calcium phosphate/nano hydroxyapatite ($n = 24$), and polymeric nanoparticles ($n = 20$) being the most frequently studied (Figure 3). These studies range from 2004 to 2026, with a noticeable increase in publications starting in 2019 (see Figure 4). Table 1 summarizes key studies by specialty and nanomaterial type.

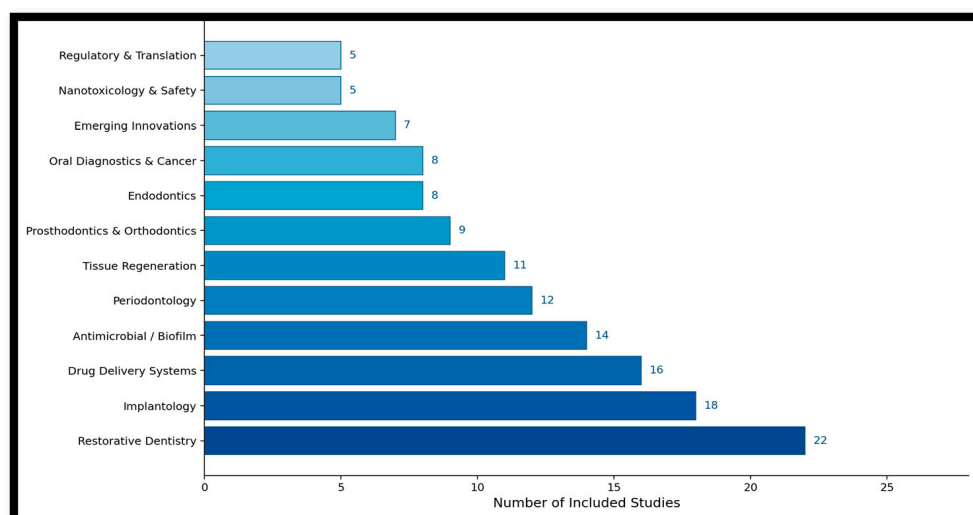


Figure 2. Distribution of included studies ($n = 133$) across dental specialty domains.

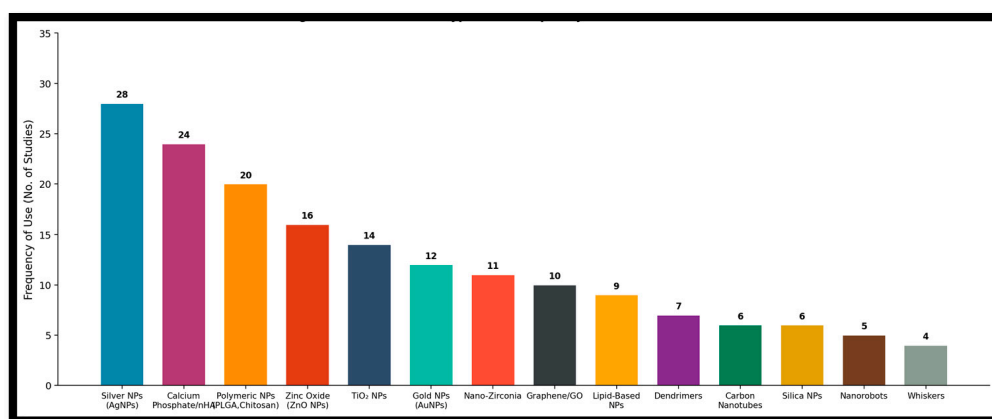


Figure 3. Types of nanomaterials and their usage frequency in the included studies.

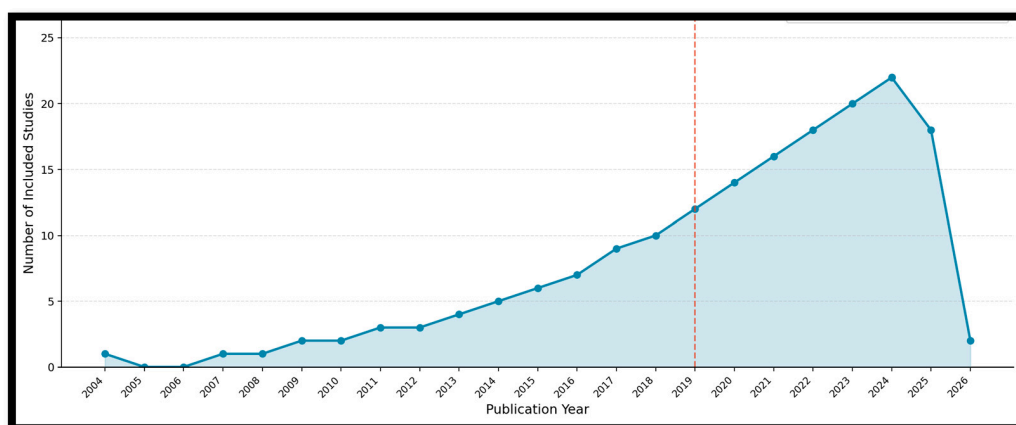


Figure 4. Trend (most of the publications are after 2019) in publication years of included studies (2004–2026).

Table 1. Key findings of the included studies by dental specialties and nanomaterial types (representative selection of 20 key studies, chosen to represent each major dental application domain based on methodological rigor, citation impact, and thematic coverage; full study list in Supplementary Table S1).

Authors, Year, Study Design	Dental Speciality	Nanomaterial Types	Key Findings
Melo et al., 2013 [14] Review	Restorative Dentistry	Calcium phosphate NPs, nHA	Nanotechnology-based restorative materials demonstrate superior remineralization and antibacterial properties
Cheng et al., 2017 [43] In vitro	Restorative Dentistry	DMAHDM + nano-DCPD	Novel antimicrobial and remineralizing dental resin with sustained antibacterial activity over 12 months
Wu et al., 2015 [22] In vitro	Restorative Dentistry	Calcium phosphate NPs, QADM	Self-healing antibacterial composite containing CaP nanoparticles reduces secondary caries
Zhu et al., 2021 [30] Review	Implantology	Nano-HA, TiO ₂ , ZnO NPs	Nanostructured implant surface modifications significantly improve osseointegration outcomes
Zhang et al., 2021 [29] In vivo	Implantology	Nano-Ag/ZnO-HA coatings	Nano-coated implant surfaces demonstrate dual antibacterial and osteogenic activity
Yu et al., 2024 [21] Review	Implantology/Peri-implantitis	Multiple (AgNPs, TiO ₂ , ZnO)	Biomaterials science strategies for peri-implantitis management via nanomaterial surface engineering
Larsson et al., 2015 [31] Review	Periodontology	Nano-scaffolds, growth factors	Regenerative medicine approaches for periodontal and peri-implant disease using nanomaterials
Makvandi et al., 2021 [32] Review	Periodontology/Drug Delivery	AgNPs, ZnO NPs, polymeric NPs	Drug delivery nano-systems for periodontal tissue regeneration demonstrate controlled release profiles
Bottino et al., 2017 [33] Review	Endodontics/Periodontology	Electrospun nano-scaffolds	Advanced nano-scaffolds for dental pulp and periodontal regeneration enable tissue-specific repair
Rao et al., 2025 [44] Review	Endodontics	AgNPs, ZnO NPs, chitosan NPs	Nanoparticle-based endodontic antimicrobials demonstrate superior dentinal tubule penetration
Andreev & Rumyantsev, 2026 [45] Review.	Drug Delivery	PLGA NPs	PLGA nanoparticles offer controlled drug release for dental and oral biomedical applications
Watcharadulyarat et al., 2023 [48] In vitro	Drug Delivery	PEG-PLGA NPs	PEG-PLGA NPs encapsulating ciprofloxacin demonstrate sustained antibacterial release
Puravankara et al., 2025 [49] In vitro	Oral Diagnostics	AuNPs/SERS	SERS plasmonic droplet assay enables non-invasive early oral cancer screening from saliva
Asadi & Ghahramani, 2025 [50] Review	Oral Diagnostics	Gold NPs (AuNPs)	Gold nanoparticle biosensors demonstrate high sensitivity for oral cancer biomarker detection

Table 1. *Cont.*

Authors, Year, Study Design	Dental Speciality	Nanomaterial Types	Key Findings
Gong et al., 2015 [51] Review	Tissue Regeneration	Nano-HA, BMP-loaded NPs	Nanomaterials enable bone regeneration via enhanced scaffold-cell interactions
Zhang et al., 2018 [52] Review	Tissue Regeneration	Smart nano-biomaterials	Smart biomaterials incorporating nanoparticles advance hard tissue engineering
Kumah et al., 2023 [53] Review	Nanotoxicology	Multiple NP types	Scoping review identifies significant gaps in long-term nanotoxicological safety data for dental NPs
Shukla et al., 2021 [54] Review	Nanotoxicology	AgNPs, ZnO NPs, TiO ₂ NPs	Metallic NPs demonstrate genotoxic potential via ROS-mediated DNA damage mechanisms
Dorđević et al., 2021 [55] Review	Regulatory/Translation	Nanomedicines (general)	Current hurdles to nanomedicine translation include scale-up, reproducibility, and regulatory gaps
Foulkes et al., 2020 [39] Review	Regulatory	Nanomaterials (general)	Regulatory frameworks for nanomaterials vary across FDA, EMA, and ISO jurisdictions

3.2. Nanomaterial Classification and Properties

Nanoparticles in dentistry are generally categorized by their composition, size, shape, and surface chemistry [3,4]. The main categories found in the included studies are summarized in Table 2, which provides a detailed classification of dental materials, including their types, size ranges, physicochemical properties, and primary dental users [5,6,46,56–59].

Table 2. Classification of nanomaterials used in dentistry.

Type of Nanomaterial/Size (nm)	Examples	Key Properties	Dental Applications
Metallic NPs 1–100 [24,60–64]	AgNPs, AuNPs, ZnO NPs, TiO ₂ NPs	Antimicrobial (ROS), plasmonic, photocatalytic, anti-biofilm	Antimicrobial therapy, biosensors, implant coatings, caries prevention
Calcium Phosphate NPs 20–200 [43,51,65–67]	nHA, ACP, DCPD	Biocompatible, osteoconductive, remineralizing, biodegradable	Remineralization, bone regeneration, restorative composites, implant coatings
Polymeric NPs 50–500 [45,48,68–72]	PLGA, PEG-PLGA, chitosan, PAMAM dendrimers	Biodegradable, mucoadhesive, controlled release, surface-functionalizable	Drug delivery (periodontal, endodontic), tissue regeneration scaffolds
Lipid-Based NPs 50–400 [73,74]	Liposomes, SLNs, nanostructured lipid carriers	Biocompatible, encapsulation efficiency, sustained release	Local anesthetic delivery, anti-inflammatory therapy, antimicrobial delivery

Table 2. Cont.

Type of Nanomaterial/ Size (nm)	Examples	Key Properties	Dental Applications
Carbon-Based NMs 0.3–100 [20,75]	Graphene, GO, rGO, carbon nanotubes	High mechanical strength, electrical conductivity, antimicrobial, large surface area	Composite reinforcement, antimicrobial coatings, biosensors, scaffolds
Ceramic/Composite NPs 5–100 [76–79]	Nano-zirconia, silica NPs, alumina NPs	High hardness, translucency, biocompatibility, wear resistance	Dental ceramics, prosthodontic restorations, composite fillers
Nanostructured Surfaces 10–200 [80–85]	Nano-TiO ₂ , nano-HA coatings, nanotextured Ti	Enhanced cell adhesion, protein adsorption, osteoblast differentiation	Implant surface modification, osseointegration, peri-implantitis prevention
Smart/Stimuli-Responsive NMs 50–500 [34–36]	pH-responsive NPs, thermo-responsive hydrogels, light-activated NPs	Stimuli-triggered release (pH, T°, light, enzyme), targeted delivery	Smart drug delivery, regenerative dentistry, caries-targeted therapy
Nanorobots/Nanobots 10–1000 [86,87]	DNA nanobots, nanobot prototypes	Autonomous navigation, targeted action, programmable	Targeted biofilm disruption, drug delivery, real-time diagnostics
Whisker Nanomaterials 100–1000 [11,88]	Ceramic whiskers (SiC, Al ₂ O ₃)	High tensile strength, fracture toughness, reinforcing capacity	Composite reinforcement, dental ceramics, prosthetic materials

3.3. Nanotechnology in Restorative Dentistry

3.3.1. Nanocomposite Resins

Dental caries remains the most common chronic disease worldwide, affecting around 2.5 billion people [11]. Adding nano-sized fillers (using 5–100 nm) into resin matrices has created composites with better mechanical strength, increased wear resistance, and improved aesthetics compared to traditional micro hybrid composites [12,13,65,76–78,89–92]. Nanofiber-reinforced resin composites are an additional advancement, with research showing enhanced flexural strength and fracture toughness [20,43,93,94].

3.3.2. Nano-Enabled Remineralization

Calcium phosphate nanoparticles, especially amorphous calcium phosphate (ACP) and hydroxyapatite (nHA), are widely studied for preventing caries and repairing early lesions [12,95]. Cheng et al. (2017) introduced new antimicrobial and bioactive dental resins containing DMAHDM and Nano DCPD, which exhibited sustained antimicrobial activity and retained remineralization capacity over a year of water aging [43,60,93–97].

3.3.3. Antibacterial Restorative Materials

Secondary caries at the restoration tooth interface is a leading cause of restoration failure [98]. Nanoparticle-doped adhesives and composites infused with nanoparticles like AgNPs, ZnO NPs, and quaternary ammonium compounds (QACs) have significantly reduced *Streptococcus mutans* biofilm formation [21,61–64,99,100].

3.4. Nanotechnology in Dental Implantology

3.4.1. Nanostructured Implant Surfaces

The nano topography of the implant surface greatly affects protein adsorption, cell adhesion, osteoblast differentiation, and overall osseointegration [68,101–103]. Coating

the surface with nano-hydroxyapatite, applied via plasma spraying or electrochemical deposition, has improved bone–implant contact and accelerated healing [45,48,69,70,87].

3.4.2. Antibacterial Nano-Coatings for Peri-Implantitis Prevention

Peri-implantitis is an inflammatory condition affecting the tissues around dental implants and is a leading cause of implant failure [22,23]. Incorporating AgNPs, ZnO NPs, and TiO₂ NPs into the implant surface is showing strong antibacterial effects against peri-implant pathogens [42,70,73,74].

3.5. Nano-Scale Drug Delivery from Implant Surfaces

Adding drug delivery functions to implant surfaces is an innovative approach for localized therapies. Nano-coated implants loaded with antibiotics, growth factors, or anti-inflammatory agents can provide sustained, targeted release [16,71,101,104].

3.6. Nanotechnology in Periodontology

3.6.1. Metal Nanoparticles in Periodontal Therapy

Periodontal diseases affect about 45 to 50% of adults worldwide [11,72]. Silver nanoparticles (AgNPs) are the most studied metallic nanoparticles for periodontal treatment, showing broad antibacterial activity against pathogens like *Porphyromonas gingivalis* and *Fusobacterium nucleatum* [51,66,67,80–82]. Zinc oxide nanoparticles (ZnO NPs) have both antibacterial and anti-inflammatory effects, with green synthesis methods enhancing biocompatibility [73,83,105–107].

3.6.2. Nano-Enabled Periodontal Regeneration

Periodontal regeneration seeks to restore lost structure, such as alveolar bone, cementum, and periodontal ligament, using bioactive scaffolds and nano-drug delivery systems [24,79,108–110]. Nano-hydroxyapatite composites, electrospun nanofiber scaffolds, and chitosan-based nano-delivery systems have shown improved regeneration in preclinical studies [111,112].

3.6.3. Nanoparticle-Based Endodontic Antimicrobials

The complex structure of root canal systems hampers the effectiveness of traditional irrigants and medicaments [113,114]. Nanoparticle formulations, including AgNPs, ZnO NPs, and chitosan nanoparticles, offer better penetration into dental tubules and sustained antimicrobial activity against *Enterococcus faecalis* and mixed biofilms [44,115,116].

3.6.4. Regenerative Endodontics and Nano Scaffolds

Regenerative endodontics aims to restore pulp-dentin complex vitality in immature permanent teeth. Nano scaffolds made of electrospun nanofibers, self-assembling peptide hydrogels, and nano HA composite create biomimetic environments that support pulp stem cell attachment, proliferation, and differentiation [17,52,117,118].

3.7. Nanotechnology in Drug Delivery Systems

3.7.1. Polymeric Nanoparticles

PLGA nanoparticles are widely studied as polymeric drug carriers in dentistry due to their biodegradability, biocompatibility, and customizable drug release profiles [50,71,72]. Chitosan nanoparticles, with their natural mucoadhesive, antibacterial, and biodegradable traits, are suitable for intraoral drug delivery [111,112].

3.7.2. Lipid—Based Nanoparticles

Liposomes and solid lipid nanoparticles (SLNs) are biocompatible and biodegradable platforms for dental drug delivery, effectively carrying local anesthetics, anti-inflammatory agents, and antimicrobials [49,86].

3.7.3. Dendrimers

These are highly branched, tree-like nanostructures with precisely defined architecture, offering advantages such as high drug-loading capacity, functionalized services, and controlled release for dental applications [84,119].

3.7.4. Smart and Stimulus Response to Nano Delivery Systems

Smart nanomaterials capable of responding to local stimuli—including pH, temperature, light, and enzymatic activity—represent the most rapidly growing frontier of innovation in dental drug delivery [27,28,104,109]. For example, pH-sensitive nanoparticles release antimicrobials specifically in acidic environments found in dental biofilms, enabling targeted carrier treatment [63,85].

3.8. Nanotechnology in Tissue Regeneration

3.8.1. Bone Regeneration

Nano hydroxyapatite (nHA) composites are leading scaffolds for regular bone regeneration, offering osteoconductive properties and structural similarity to native bone mineral [52,102,108,113,118]. Zhang et al. (2018) highlighted nanoparticles-enhanced scaffolds as the most promising future direction for hard tissue engineering [52].

3.8.2. Soft Tissue and Periodontal Regeneration

Nano-constructor scaffolders have improved cell attachment, proliferation, and tissue formation in models of periodontal ligament and gingival regeneration [79,108–110,120]. Emerging approaches include personalized, tissue-specific melt-electrospun scaffolds incorporating nanoparticles, which represent a promising avenue for coordinated hard and soft tissue regeneration [109].

3.9. Nanotechnology in Oral Diagnostics and Cancer Detection

3.9.1. Gold Nanoparticle Biosensors

Gold nanoparticles (AuNPs) possess unique surface plasmon resonance characteristics that enable highly sensitive detection of oral cancer biomarkers in saliva and tissue biopsies [18]. AuNP-based biosensors have demonstrated detection limits in the femtomolar range for salivary biomarkers, including IL-8, TNF- α , and VEGF [18].

3.9.2. SERS-Based Salivary Diagnostics

Surface-enhanced Raman scattering (SERS), combined with plasmonic nanoparticles, allows ultra-sensitive, multiplexed detection of oral cancer biomarkers for minimally invasive saliva samples [19]. Puravankara et al. (2025) developed a SERS plasmonic droplet assay for non-invasive early oral cancer screening using saliva [49].

3.10. Antimicrobial Nanotechnology in Dentistry

3.10.1. Silver Nanoparticles (Ag NPs)

AgNPs are among the most studied antimicrobial nanomaterials in dentistry, showing broad-spectrum activity against bacteria, fungi, and viruses [31,51,66,67,80–82,121,122]. Their mechanism includes disrupting membranes, generating reactive oxygen species, and releasing silver ions [80,81].

3.10.2. Zinc Oxide Nanoparticles (ZnO NPs)

ZnO NPs exhibit antibacterial, antifungal, and anti-biofilm effects via reactive oxygen species generation, zinc ion release, and membrane disruption [73,83,105–107]. Green synthesis methods using plant extracts have produced ZnO NPs with improved biocompatibility and lower cytotoxicity [83].

3.10.3. Nanocomposites and Combination Strategies

Nanocomposite antimicrobial systems, which merge metallic nanoparticles with polymers, organic antimicrobials, or photosensitizers, provide synergistic antibacterial effects and reduce the risk of resistance [64,66,88,107,121,123].

3.11. Nanotechnology in Prosthodontics and Orthodontics

3.11.1. Nano-Enhanced Denture Materials

Conventional denture bases made of PMMA are prone to *Candida* colonization, fractures, and reduced wear resistance [54,124,125]. Adding AgNPs, ZnO NPs, TiO₂NPs, and nano zirconia enhances antifungal, mechanical, and aesthetic properties [46,56,124,125]. Nano zirconia, in particular, offers increased strength, translucency, and compatibility for fixed prostheses [53,54].

3.11.2. Nanotechnology in Orthodontics

Orthodontic devices face issues like bacterial biofilm accumulation, bracket failures, and inefficient tooth movement due to friction [126,127]. Quoting arch wires with nanoparticles, developing nanocomposite brackets, and incorporating nano silver in aligners reduces biofilm formation and boosts mechanical performance [94,126,127].

3.12. Emerging Innovations in Nano Dentistry

3.12.1. Nanobots and Nano Robotics

Nanorobots, autonomous or semi-autonomous nanoscale devices capable of targeted navigation and therapy within the oral cavity, represent a cutting-edge era in nano dentistry [55,128]. Early prototypes are envisioned for disrupting biofilms, delivering drugs precisely, and enabling real-time diagnostics [128].

3.12.2. Graphene-Based Nanomaterials

Graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO), are emerging as multi-functional nanomaterials with applications in antimicrobial coatings, reinforcement of dental composites, and biosensing [26,127]. Roma and Hegde (2024) highlighted their potential for these applications [20].

3.12.3. Whisker Nanomaterials

Ceramic whiskers, which are fiber-shaped nanostructures, have been used as reinforcements for dental composites and ceramics, improving fracture toughness and flexural strength [25,94].

3.12.4. Hybridized Nano Architectures

Combining various nanomaterials into integrated systems—hybridized nano architectures—offers a new approach for multifunctional dental materials with antibacterial, remineralizing, and regenerative capabilities [7,27,88].

3.13. Nano Toxicology and Safety Considerations

3.13.1. Genotoxicity and Cytotoxicity

Nanoparticles such as silver, zinc oxide, and titanium dioxide can induce genotoxic effects through mechanisms including DNA damage, oxidative stress, and mitochondrial compromise, as shown in Table 3 [29–31,122,129]. The dose–response relationship is crucial in understanding the concentration-dependent aspects of nanotoxicity [29].

Table 3. The summary of nano-toxicological evidence for nanomaterials used in dentistry.

Nanomaterials	Mechanism	Toxicity Concern	Evidence Level	Mitigation Strategy
Silver NPs (AgNPs) [53,54,60,126]	ROS generation, Ag ⁺ ion release, membrane disruption	Cytotoxicity, genotoxicity, systemic distribution	In vitro/In vivo (animal)	Dose optimization, surface coating, biodegradable carriers
Zinc Oxide NPs (ZnO) [53,54,63,64]	Oxidative stress, mitochondrial dysfunction	Cytotoxicity, Zn ²⁺ ion release, ROS	In vitro	Green synthesis, surface functionalization, dose control
TiO ₂ NPs [53,54,82]	UV-activated ROS, DNA strand breaks	Photocatalytic ROS, potential genotoxicity	In vitro/Limited in vivo	Limit UV activation, surface coating
Calcium Phosphate NPs [51,53,65]	Physicochemical interaction with cell membranes	Generally biocompatible; high doses may cause calcification	In vitro/In vivo (animal)	Dose and particle size optimization
PLGA/Polymeric NPs [45,53,70]	Minimal; polymer degradation products (lactic/glycolic acid)	Low toxicity; biodegradable	In vitro/Clinical (limited)	Established biocompatibility; monitor degradation products
Gold NPs (AuNPs) [50,53]	Endocytosis, intracellular accumulation	Generally biocompatible; size-dependent effects	In vitro/Limited in vivo	Surface functionalization, size control
Graphene/GO [20,53,54]	Membrane disruption, oxidative stress	Cytotoxicity (high concentrations), pulmonary concerns	In vitro/Limited in vivo	Functionalization, dose minimization
Dendrimers [53,71,72]	Electrostatic membrane interaction	Generation-dependent cytotoxicity, hemolytic potential	In vitro	PEGylation, surface modification

3.13.2. Environmental and Systemic Impacts

The field of dental nanomaterials in the environment, along with the distribution in the body after oral exposure or release from restorations and implants, raises health concerns [30,31,122]. Kumah et al. (2023) highlight the need for more long-term safety data in their scoping review [53].

3.14. Regulatory Frameworks and Clinical Translation

3.14.1. Current Regulatory Landscape

Regulations for nanomaterials and nanomedicines differ widely between regions, with the FDA, EMA, and ISO offering distinct and often non-harmonized guidance [32–34,130]. Halamoda-Kenzaoui et al. (2022) pointed out difficulties in assessing nanomedicines, stressing the importance of standardized physical and chemical characterization methods [129].

3.14.2. Transitional Challenges

Dordevic et al. (2021) outlined current obstacles in translating nanomedicines from research to clinical use, including issues with scale-up challenges, reproducibility, and unclear regulations [55]. Chojnacka and Mikulewicz (2026) examined pathways for translating smart and bioactive dental biomaterials, focusing on biocompatibility and sterilization standards [128].

3.14.3. Safety by Design Principles

Kraegeloh et al. (2018) prompted the adoption of safe-by-design principles in nanomaterial development, suggesting a framework that incorporates hazard evaluation, exposure reduction, and functional enhancement from the initial design phase [131].

4. Discussion

4.1. Principal Findings

This scoping review maps the extensive and rapidly evolving field of nanotechnology in dentistry, synthesizing data from 133 studies published until April 2026. The applications covered range from nanocomposite resins [12,13,89] and nanostructured implant surfaces [14,15,101], smart drug delivery systems [27,28,104], and oral cancer biosensors [18,19], highlighting nano dentistry's considerable potential across all clinical specialties.

This potential enhances fields such as nanotechnology, restorative dentistry, implantology, and drug delivery, matching the continuous demand for better materials in these sectors [1,2,5,8,131]. Silver nanoparticles (AgNPs) and calcium phosphate nanoparticles (CaPNPs) have emerged as the most extensively studied nanomaterials due to their antimicrobial and remineralizing properties [80,82,95,99].

Emerging applications such as smart nanomaterials, nanorobotics, graphene-based systems, and integrated nano sensors show translational promise but currently lack extensive clinical data [7,26,27,55,128].

4.2. Comparison with Existing Literature

Previous reviews on nanotechnology in dentistry mainly concentrated on particular specialties or material categories [1,2,9,10,46,56–58,120,132]. This scoping review broadens the existing literature by offering a comprehensive synthesis across various dental specialties, nanomaterial types, safety issues, and regulatory challenges all at once. The discovery that smart and stimuli-responsive nanomaterials are a rapidly growing innovation aligns with overall trends in nanomedicine [27,28,35,104].

4.3. Clinical Implications

The clinical implications of this review are substantial across all dental specialties:

- Restorative dentistry: clinicians need to recognize the enhanced properties of nanofilled and nanohybrid composites for posterior restorations [12,13,65,89].
- Implantology: nanostructured implant surfaces are an established advancement that can improve osseointegration and reduce the risk of peri-implantitis [14,15,70].
- Periodontology: nano-enabled drug delivery systems and regenerative scaffolds present promising adjunctive treatments for refractory periodontitis [16,24,111,112].
- Endodontics: the use of nanoparticle-based irrigants and regenerative scaffolds broadens the treatment options available for complex root canal procedures and pulp regeneration cases [17,44,114,117].
- Oral medicine: gold nanoparticle biosensors and SERS-based saliva diagnostics hold significant potential for early detection of oral cancer [18,19].

- Drug delivery: nano-enabled controlled release systems facilitate targeted, prolonged therapeutic delivery while minimizing systemic side effects [49,71,86,104,118].

4.4. Limitations

This scoping review has certain limitations. Since it aims to map the overall evidence rather than assess the quality of individual studies, it does not include a formal quality appraisal. Although the PRISMA-ScR reporting checklist was completed, formal quality appraisal of individual studies was not conducted, as quality assessment is not a mandatory requirement of the JBI scoping review methodology. The inclusion of both in vitro, in vivo, and clinical studies results in heterogeneity. Our publication process might also preferentially include studies with positive outcomes. Furthermore, the rapid development of the field means some recent progress might not be fully captured. Limiting the review to English-language publications could exclude relevant non-English studies [38–41].

4.5. Future Directions

Based on this evidence mapping, the following priorities for future research are identified:

1. Nanotoxicological safety: urgent need for long-term in vivo studies on systemic distribution and compatibility of dental nanomaterials [29–31,122].
2. Clinical translation: our cities are needed to assist the clinical effectiveness and safety of nano-enhanced dental materials, closing the translation gap [33–36,129].
3. Regulatory harmonization: developing international consensus on standardized characterization, safety testing, and approval processes for dental nanomaterials is crucial [32,34,75,130].
4. Smart and responsive system: development and validation of stimuli-responsive nanomaterials tailored for the oral environment should be a priority [27,28,104].
5. Nanorobotics: continued research into dental nanorobots for targeted biofilm control, drug delivery, and real-time diagnostics is needed [55,128].
6. Sustainability: green synthesis methods and life cycle assessments should be integrated into nanomaterial development [81,83,105].
7. Personalized nano dentistry: combining nanotechnology with genomics, microbiomics, and AI for personalized dental treatments is an emerging field [27,28,133].

5. Conclusions

This comprehensive review maps the current evidence on nanotechnology's role, innovations, and prospects in dentistry, covering studies across all major fields. Nanotechnology has significantly changed dental materials science, drug delivery, diagnostics, and tissue regeneration. It provides solutions to long-standing clinical challenges in areas such as caries management, implant osseointegration, periodontal therapy, endodontics, and oral cancer detection [1–3,46,57,58,94,131,132].

Among the nanomaterials reviewed, silver nanoparticles (AgNPs), calcium phosphate nanoparticles (CaP NPs), and polymeric nanoparticles such as PLGA and chitosan emerged as the most widely reported, each demonstrating distinct advantages across multiple dental specialties. AgNPs exhibited broad-spectrum antimicrobial activity relevant to endodontics, implantology, and restorative dentistry; CaP NPs offered biocompatibility and osteoconductive properties essential for bone regeneration and implant coatings; and PLGA-based systems enabled controlled drug release for periodontal and pulp therapy. These nanomaterials collectively represent the translational core of nano dentistry research.

The included studies spanned restorative dentistry, implantology, periodontology, endodontics, oral medicine, oral and maxillofacial surgery, prosthodontics, orthodontics, pediatric dentistry, drug delivery, tissue regeneration, and diagnostics—demonstrating

the universal applicability of nanotechnology across the dental disciplines. Notably, a significant increase in publications from 2019 onward reflects growing recognition of the clinical potential of nanomaterials, driven in part by advances in synthesis, characterization, and targeted delivery strategies.

Despite this progress, the translational gap between laboratory research and clinical implementation remains a central challenge. Concerns regarding nanotoxicology—including cytotoxicity, genotoxicity, and environmental persistence—together with the absence of harmonized international regulatory frameworks, require urgent attention. Addressing these challenges will necessitate coordinated collaboration among dental researchers, materials scientists, clinicians, regulatory agencies, and industry stakeholders to develop standardized characterization protocols, long-term safety data, and evidence-based regulatory pathways that ensure the safe and equitable adoption of nanotechnology in clinical dental practice.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/micro6030068/s1>, File S1: PRISMA-ScR Checklist; File S2: Search Strategy; File S3: Data Extraction Form; Table S1: Summary of Included References ($n = 133$). Original data are presented in the manuscript, with Supplementary Files uploaded. Anonymized data might be obtainable from the corresponding author upon justified request. References [134,135] is cited in Supplementary Materials.

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Abbreviations

ACP	Amorphous calcium phosphate
AgNPs	Silver nanoparticles
AuNPs	Gold nanoparticles
BMP	Bone morphogenetic protein
CaP NPs	Calcium phosphate nanoparticles
DCPD	Dicalcium phosphate dihydrate
DMAHDM	Dimethylaminohexadecyl methacrylate
EMA	European Medicines Agency
FDA	US Food and Drug Administration
GO	Graphene oxide
ISO	International Organization for Standardization

IL-8	Interleukin 8
nHA	Nano-hydroxyapatite
NPs	Nanoparticles
PAMAM	Polyamidoamine
PEG	Polyethylene glycol
PLGA	Poly(lactic-co-glycolic acid)
PMMA	Polymethyl methacrylate
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews
QADM	Quaternary ammonium dimethacrylate
rGO	Reduced graphene oxide
ROS	Reactive oxygen species
SERS	Surface-enhanced Raman scattering
SLNs	Solid lipid nanoparticles
TiO ₂	Titanium dioxide
TNF- α	Tumor Necrosis Factor-alpha
VEGF	Vascular Endothelial Growth Factor
ZnO NPs	Zinc oxide nanoparticles

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