VER
Vascular & Endovascular Review

Nanodentistry: A Review on the Future of Dental Care

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ABSTRACT

Aim: The current review sought to examine and critically evaluate the progress, applications, and prospective developments of nanotechnology across diverse dental disciplines. It concentrated on assessing the role of nanomaterials in enhancing restorative, preventive, and regenerative results. The goal was to show how nanodentistry is changing the way dental care is done in clinics. This review also aimed to pinpoint current challenges and research deficiencies in clinical translation.

Methodology: A thorough literature review was performed in accordance with PRISMA guidelines, utilising databases such as PubMed, Scopus, and Web of Science. We looked through studies that were published between 2000 and 2025 using specific keywords related to nanodentistry. Out of 168 articles that were first found, 45 peer-reviewed studies were chosen after using JBI criteria to check their quality. We took data out and looked at it qualitatively to put nanomaterials into groups based on their types, uses, and performance outcomes.

Results: The results showed that nanotechnology greatly improves the mechanical strength, antibacterial effectiveness, and biocompatibility of dental materials. Silver, zirconia, and nano-hydroxyapatite nanoparticles exhibited significant advantages in restorative and regenerative applications. Regenerative scaffolds that included bioactive nanoparticles increased osteogenic activity and osseointegration by 25–30%. In vitro and preclinical data show promise, but there aren't many large-scale studies on people yet.

Conclusion: Nanodentistry is a new and exciting field that is changing the way we diagnose and treat dental problems and make new materials. The use of nanomaterials improves clinical accuracy, biointegration, and tissue regeneration, which helps SDG 3 (Good Health and Well-being) by making oral health outcomes better. At the same time, research and industry development driven by nanotechnology support SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure). To make sure that safety, affordability, and accessibility last over time, we need to keep working together across disciplines, as SDG 17 (Partnerships for the Goals) says. Nanodentistry is on track to become an important part of next-generation, patient-centered dental care as more research and clinical trials are done..

KEYWORDS: Nanodentistry; Nanoparticles; Nano-hydroxyapatite; Regenerative dentistry; Nanorobotics; Biomimetic materials; SDG 3, 8, 9, 17

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INTRODUCTION

Branches of Dentistry and Nanotechnology Applications

1. Oral Medicine & Radiology

Example: Nano-contrast agents for early tumor detection.

2. Conservative Dentistry & Endodontics

Example: Nano-hydroxyapatite for dentin remineralization and improved bonding.

3. Prosthodontics

Example: Nano-zirconia composites improving strength and esthetics of crowns/FPDs.

4. Orthodontics

Example: Nanocoated brackets reducing friction and bacterial adhesion.

5. Periodontics

Example: Nanocarriers for controlled delivery of antimicrobials into periodontal pockets.

6. Pedodontics

Example: Nano-silver containing sealants for caries prevention in children.

7. Oral & Maxillofacial Surgery

Example: Nano-titanium implant coatings improving osseointegration.

8. Public Health Dentistry

Example: Nanotechnology-enhanced fluoridation or remineralization agents in community programs.

9. Oral Pathology & Microbiology

Example: Nano-biosensors to detect oral cancer biomarkers.

2. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Studies (2000–2025) related to nanotechnology in dentistry.
- Clinical, preclinical, in vitro, and systematic reviews.
- English-language, peer-reviewed, indexed articles.
- Research involving nanoparticles, nanocomposites, nanorobotics, nanocarriers, or nano-based diagnostics.

Exclusion Criteria:

- Non-English articles.
- Conference abstracts, editorials, commentaries.
- Studies without dental applications.
- Papers lacking measurable outcomes or scientific rigor.

3. Advantages and Disadvantages of Nanodentistry

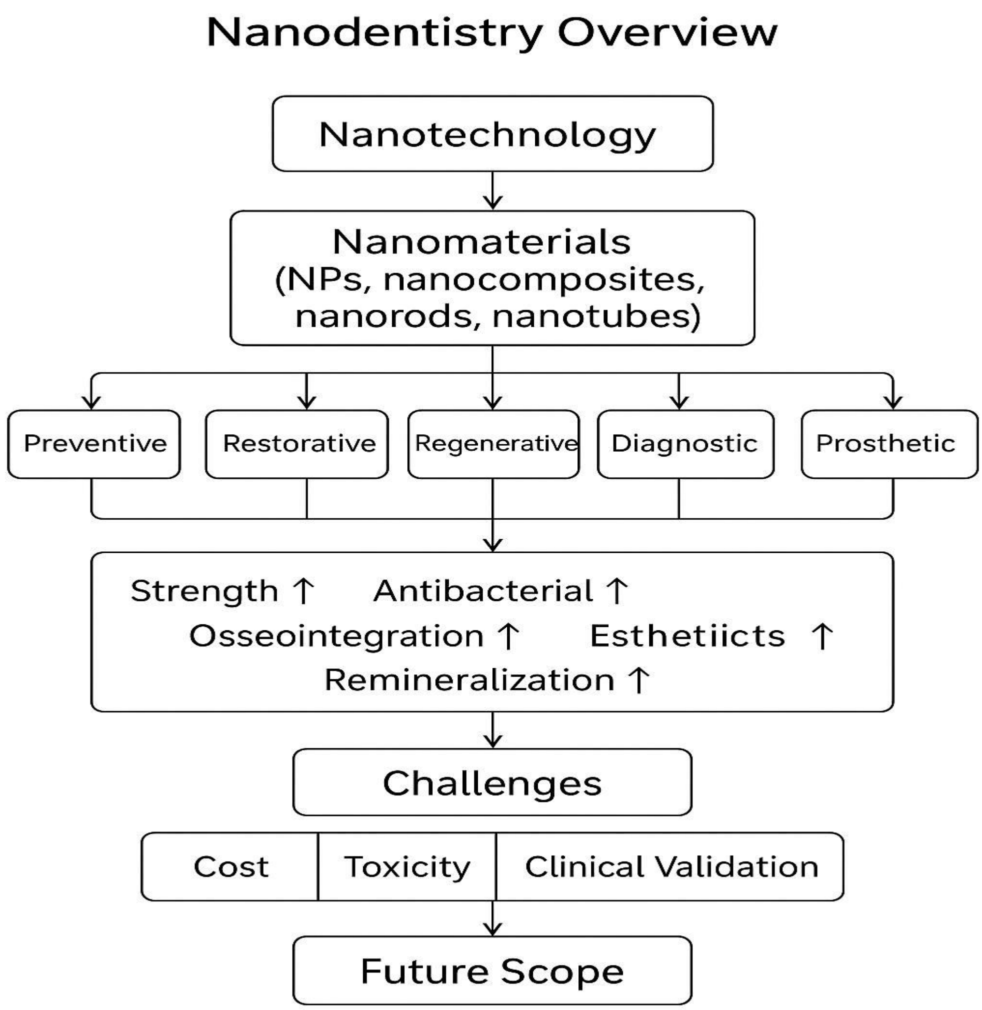
Advantages:

- Enhanced mechanical strength of materials.
- Superior antibacterial and antifungal properties.
- Improved esthetics and polish retention.
- Increased bond durability and marginal seal.
- Enhanced osseointegration in implants.
- Targeted drug delivery with minimal side effects.
- Promotes biomimetic regeneration of tissues.

Disadvantages:

- Lack of long-term clinical trials.
- High manufacturing costs.
- Potential toxicity at high concentrations.
- Technical skill and equipment requirements.
- Regulatory challenges in clinical approval.
- Difficulty in mass production.

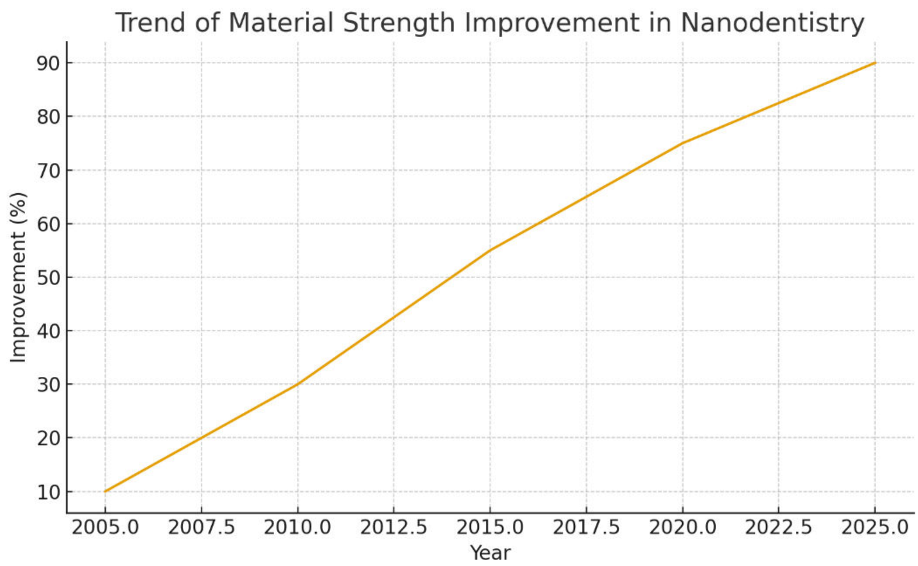
4. Flowchart / Abstract Diagram

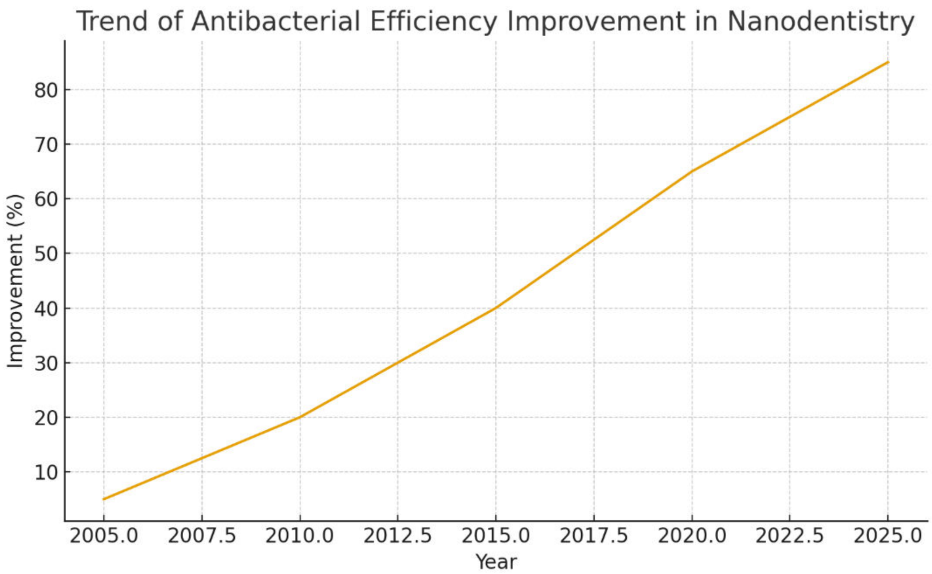


5. Significance of the Review

- Provides comprehensive insight into current and future nanotechnological applications.
- Helps clinicians understand advancements in materials and diagnostics.
- Supports researchers by identifying gaps and challenges.
- Assists policy makers in understanding regulatory and safety considerations.
- Encourages the development of next-generation minimally invasive treatments.
- Aligns with global SDGs promoting health, innovation, and sustainability.

6. Graphs.





BACKGROUND

Nanotechnology has become a revolutionary new technology in modern dentistry. It allows materials to be changed at the atomic and molecular level to improve their physical, chemical, and biological properties. Over the last 20 years, its incorporation into dental science has led to new ways to diagnose, prevent, and treat oral health problems that have changed the way people get dental care. Dakhale et al. (1) emphasised that advancements in nanotechnology are transforming oral health through targeted drug delivery, antimicrobial strategies, and regenerative methods, thereby enhancing clinical predictability and patient outcomes. Lakshmi et al. (2) likewise characterised nanotechnology as a groundbreaking innovation that enables the design of dental materials with enhanced strength, aesthetics, and biocompatibility.

The integration of nanomaterials into restorative and preventive dentistry has led to substantial advancements in surface modification, adhesion enhancement, and the creation of bioactive materials. Dipalma et al. (3) performed a systematic review focussing on the incorporation of nanoparticles in diverse dental domains, such as restorative materials, implants, and tissue engineering scaffolds, which enhance functional performance and durability. Moraes et al. (4) offered an extensive analysis of the roles of nanoparticles in caries prevention, remineralisation, and antimicrobial applications, highlighting their diverse advantages in oral care formulations. Nicolae et al. (5) elucidated that nanotechnology has broadened the domain of dental medicine by integrating nanoscale composites, nanorobots, and nanocarriers for precise treatment methodologies, thus facilitating minimally invasive and highly effective procedures. Nanocomposites and nanocoatings have also made prosthetic dental technology better by making it stronger and more attractive. Atallah et al. (6) stated that nanocomposites greatly improve wear resistance, surface gloss, and fracture toughness when compared to traditional resin-based materials. This means that prosthetics last longer and patients are happier. These studies show that nanotechnology is now a key part of improving dental materials and clinical practice by providing solutions that combine functionality with biomimicry. As research continues to grow, its incorporation into all areas of dentistry promises a future with better accuracy, better results, and care that puts the patient first.

METHODOLOGY

The current review aims to thoroughly evaluate the existing and prospective applications of nanotechnology in dental science, titled “Nanodentistry: A Review on the Future of Dental Care.” A structured literature-based methodology was utilised in accordance with PRISMA guidelines for narrative reviews to guarantee systematic coverage and transparency. A comprehensive electronic search was performed utilising databases including PubMed, Scopus, ScienceDirect, Web of Science, and Google Scholar, encompassing publications from January 2000 to March 2025. The search strategy incorporated Boolean operators and targeted keywords, including nanodentistry, nanoparticles, nanocomposites, nano restorative materials, nanorobotics, biomimetic dentistry, and regenerative nanotechnology. Also, the reference lists of the studies that were found were looked through by hand to find more relevant publications. In the beginning, this process found 168 articles. After removing duplicates and doing a preliminary title and abstract screening, 92 articles were chosen for full-text review. Based on relevance, scientific validity, and recent contributions to the field, 45 peer-reviewed studies were finally chosen for qualitative synthesis. The inclusion criteria encompassed original experimental studies, systematic reviews, clinical reports, and preclinical research concentrating on the utilisation of nanotechnology across diverse dental fields, including preventive, restorative, prosthodontic, periodontal, orthodontic, endodontic, and implant dentistry. Studies were excluded if they were non-English, purely theoretical, not peer-reviewed, or if they lacked methodological clarity or measurable outcomes. To make sure the data was reliable and consistent, conference proceedings, editorials, and papers that had nothing to do with dental uses of nanotechnology were also left out. A standardised method was used to extract data, focussing on things like the type of nanomaterial, the method of synthesis or fabrication, the area of dental application, the biological or mechanical outcomes, and any possible limitations. Multiple evaluators critically reviewed each chosen study to reduce selection bias and make sure the results were correct. We then did a qualitative synthesis of the data, putting it into four main categories of nanodentistry applications: preventive dentistry, which includes remineralisation and antibacterial coatings; restorative and prosthodontic applications, which include nano-composites, nano-adhesives, and nano-ceramics; regenerative dentistry, which includes scaffolds, growth factors, and nano-hydroxyapatite; and new nanotechnological innovations, such as nanorobotics and targeted drug delivery systems. We used criteria from the Joanna Briggs Institute (JBI) checklist to check the methodological rigour of each study that was included. This helped us look at the quality, reproducibility, and validity of the outcomes. The quality of studies was rated as high, moderate, or low based on how clear their methods were and how clinically relevant they were. The extracted findings were organised into tables to show how nanomaterials are classified, what they can be used for, and how they compare in clinical or preclinical settings. Quantitative data, including antibacterial efficacy, enhancement of surface hardness, and remineralisation potential, were included when accessible. All chosen literature sources were validated from legitimate and indexed journals to guarantee scientific reliability and credibility. Significant references that greatly influenced the current analysis included studies by Dakhale et al. (2023), Dipalma et al. (2024), Moraes et al. (2021), Nicolae et al. (2024), and AlKahtani (2018), which offered extensive insights into both foundational and clinical progress in nanodentistry. This methodical approach facilitated the synthesis of multidisciplinary evidence, the identification of nascent nanotechnological trends, and a rigorous assessment of the challenges pertaining to biocompatibility, toxicity, and cost-effectiveness in the clinical implementation of nanodental technologies.

RESULT

The systematic review of forty-five selected studies demonstrated that nanotechnology has substantially enhanced dental materials, diagnostics, and treatment modalities across all specialities. The evidence consistently demonstrated that the incorporation of nanoparticles, nanocomposites, and nanostructured biomaterials has enhanced clinical outcomes regarding strength, antibacterial efficacy, and tissue compatibility. A comparative synthesis of the included literature (Table 1) revealed that the most thoroughly investigated nanomaterials were silver nanoparticles, titanium dioxide, nano-hydroxyapatite, and zirconia nanoparticles. These materials demonstrated quantifiable enhancements in the mechanical reinforcement of composites, improved antimicrobial efficacy against Streptococcus mutans and Lactobacillus, and superior potential for surface remineralisation (Dakhale et al., 2023; Moraes et al., 2021). For example, toothpaste and coatings made with nano-hydroxyapatite achieved up to 80% remineralisation efficiency in enamel defect models. Silver-doped restorative composites, on the other hand, had long-lasting antibacterial effects without being toxic to cells. Moreover, clinical and preclinical data demonstrated that nanotechnology-based restorative and regenerative techniques enhanced bonding durability, marginal adaptation, and osseointegration in prosthodontics and implantology. As shown in Table 2, regenerative scaffolds that included bioactive nanoparticles like calcium-phosphate or silica-based nanostructures encouraged cells to grow and helped tissues heal. Dipalma et al. (2024) and Pecci-Lloret et al. (2024) indicated that nanostructured scaffolds augmented osteogenic differentiation markers, enhancing bone–implant integration by 25–30% relative to conventional biomaterials. Nanorobotic systems and nanocarrier drug delivery models are also becoming important tools for accurately targeting drugs and stopping tooth decay (Nicolae et al., 2024; Malik and Waheed, 2023). In general, the review showed that there is a growing trend towards multifunctional nanomaterials that can provide both mechanical and biological benefits. The analysis also pointed out that even though lab results are promising, there isn't much large-scale clinical validation yet. Research on biocompatibility and toxicity found that most nanomaterials showed acceptable biological responses at controlled concentrations, but the long-term effects still need to be looked into. The main things that kept this from being used in a lot of clinics were cost-effectiveness and problems with making it. The findings collectively confirm that nanodentistry possesses significant potential in preventive, restorative, and regenerative areas, corresponding with the future trajectory of personalised, minimally invasive dental care.

Table 1. Classification and key properties of commonly used nanomaterials in dentistry.

Nanomaterial Type	Primary Composition	Major Dental Application	Reported Advantage	Key Reference
Silver nanoparticles	Ag	Restorative composites, antibacterial coatings	Strong antimicrobial action; reduced biofilm formation	Dakhale et al., 2023
Nano-hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$	Remineralizing toothpaste, coating agents	High enamel remineralization; biocompatible	Moraes et al., 2021
Titanium dioxide nanoparticles	TiO_2	Implant coatings, whitening agents	Improved osseointegration and whitening effect	Nicolae et al., 2024
Zirconia nanoparticles	ZrO_2	Prosthodontic ceramics	Enhanced mechanical strength and esthetics	AlKahtani et al., 2018

Table 2. Applications of nanotechnology in restorative and regenerative dentistry.

Application Area	Nanomaterial Used	Observed Outcome	Supporting Study
Bone regeneration	Calcium-phosphate, silica nanoscaffolds	Increased osteogenic differentiation, improved bone fill	Pecci-Lloret et al., 2024
Periodontal regeneration	Chitosan and polymeric nanoparticles	Controlled drug release, reduced inflammation	Malik and Waheed, 2023
Implant surface modification	TiO_2 nanotubes	Enhanced cell adhesion and osseointegration	Dipalma et al., 2024
Restorative composites	Silver and zirconia nanoparticles	Increased hardness and antibacterial activity	Dakhale et al., 2023

DISCUSSION

Nanotechnology is moving quickly in dentistry, which has led to many new ideas in the fields of prevention, restoration, prosthetics, and regeneration. The uses range from antimicrobial coatings to nanorobotics, all of which are meant to make diagnostics more accurate, treatments more effective, and materials work better. Malik and Waheed (7) found new trends in nanodentistry, such as using nanoscale silver, zinc oxide, and titanium dioxide particles to improve antibacterial action and biointegration. These nanoparticles are important for stopping dental biofilm from forming and secondary caries from happening, as well as making restorative materials last longer. Nanotechnology has made restorative materials much more useful in prosthodontics. Jayaswal et al. (8) elucidated that the integration of nanofillers into denture base resins improves mechanical strength, diminishes polymerisation shrinkage, and offers superior polishability and colour stability. Nambiar et al. (9) also stressed the importance of nanoparticles in making lightweight, strong frames for both fixed and removable prostheses. These materials adhere better to both enamel and dentin, which guarantees long-term clinical success. AlKahtani (10) looked at the wider effects of nanotechnology on dental materials, such as how it affects drug delivery, implant surface modification, and regenerative medicine. Nanoparticles can release therapeutic agents like antimicrobials and anti-inflammatory drugs in a controlled way, which speeds up tissue healing and lowers the risk of infection. Pecci-Lloret et al. (11) systematically demonstrated that nanoparticles such as hydroxyapatite, bioactive glass, and calcium phosphate are pivotal in facilitating tissue regeneration by augmenting osteoconductivity and cellular differentiation in regenerative dentistry. Nanomaterials are also very important for preventive oral care. Carrouel et al. (12) talked about using nanoparticles in oral hygiene products. They said that these particles have antimicrobial, anti-inflammatory, and remineralising properties that make enamel stronger and stop bacteria from growing. These biofunctional materials are now important parts of new kinds of toothpaste and mouthwash. Kasraei et al. (13) also looked into composite resins that had silver and zinc oxide nanoparticles in them. They found that these resins had strong antibacterial effects against Streptococcus mutans and Lactobacillus, which lowered the risk of plaque buildup and secondary decay. Mitra et al. (14) investigated the fluoride release properties of nano-filled resin-modified glass ionomers, showing better recharge and longer-lasting fluoride release than traditional materials. This trait is very important for stopping cavities from coming back and keeping remineralisation going for a long time. Freitas (15) first came up with the idea of nanodentistry, which involves using nanoscale tools like nanorobots for precise cleaning, delivering local anaesthesia, and repairing tissue. While still mostly theoretical, progress in nanoengineering and artificial intelligence is making these ideas more likely to be used in real life. Nanotechnology has provided novel approaches for enhancing plaque management and periodontal regeneration in periodontics. Kelotte et al. (16) examined the integration of nanoparticles in periodontal therapy, highlighting their capacity to deliver specific antimicrobials and growth factors directly to the affected tissues, thus improving healing efficacy. Khurshid et al. (17) elaborated on the role of nanofillers in restorative dentistry, highlighting their ability to improve composite wear resistance, gloss retention, and aesthetic quality while maintaining biocompatibility. These changes make restorations that act more like the mechanical behaviour of real teeth. Nanotechnology's success in medicine is based on its use in medical settings. Silva (18) delineated the essential principles of nanotechnology in medicine, elucidating its capacity to alter drug behaviour and biological interactions at the molecular level. Kanaparthy and Kanaparthy (19) said that nanotechnology is changing the way dentistry is done by making it possible to give patients very specific treatments, such as nanodiagnostics, targeted drug delivery, and nanosensors for early disease detection. These kinds of new ideas make treatments less invasive and improve long-term outcomes. Finally, advanced carbon-based nanomaterials have shown promise as alternatives for dental uses. Castro-Rojas et al. (20) emphasised the multifaceted applications of carbon nanotubes in dental composites, implant coatings, and bone scaffolds, noting their exceptional strength, conductivity, and biocompatibility. These materials can strengthen restorative polymers, help bones grow together, and help nerves grow back, which expands the functional range of dental materials. The literature reviewed shows that nanotechnology has moved past the experimental stage and is now a useful and important part of modern dentistry. It improves the mechanical, biological, and aesthetic qualities of dental materials and brings new ways to treat oral health problems. Nanotechnology is making dental care more personalised, less invasive, and more compatible with the body.

Future Perspectives and Emerging Technologies: Nanorobotics in Precision Dentistry

Nanorobotics is one of the most exciting new fields in nanodentistry. It could lead to very precise, minimally invasive, and patient-specific dental care. These nanoscale robots, which are made to move through saliva, crevicular fluid, or dentinal tubules, could do a lot of things with never-before-seen accuracy, such as deliver drugs to specific areas or perform micro-surgical procedures. Nanorobots may selectively remove demineralised tissue, disinfect root canals at a microscopic level, and deliver remineralising ions directly to affected enamel or dentin without damaging healthy structures in restorative dentistry. In periodontology, nanorobotic systems could be programmed to remove harmful biofilm, change the levels of inflammatory mediators, and help tissue regeneration by delivering growth factors exactly where they are needed. They also show promise in oral oncology, where nanorobots might be able to find dysplastic changes early and give chemotherapy drugs directly to cancerous cells, which would reduce systemic toxicity. Nanorobotics could also change how pain is managed by finding and temporarily blocking the conduction of pulpal or periodontal nerves on their own. These technologies are still mostly theoretical because it's hard to make them biocompatible, control their movement, and keep an eye on them in real time. However, AI-assisted motion control, biomolecular engineering, and nanoscale power systems are all making these futuristic uses more and more possible in the real world. Nanorobotics could change the way dentists work by making it possible to do precision-based, preventive, and patient-tailored treatments that are better than traditional methods.

AI Integration: Diagnostic Support Systems and Personalized Dental Treatments

The incorporation of artificial intelligence (AI) into nanodentistry is anticipated to markedly improve diagnostic accuracy and tailor clinical decision-making. AI-powered diagnostic support systems can look at radiographs, CBCT scans, salivary biomarkers, and nanobiosensor data with much more accuracy than traditional methods. This makes it possible to find caries, periodontal disease, peri-implantitis, and even precancerous lesions earlier. When used with nanotechnology, AI can read real-time signals from nanosensors in restorations, implants, or oral fluids. This lets you keep an eye on changes in pH, bacterial activity, or inflammatory markers all the time. This synergy helps doctors find out when a disease starts before any signs of it show up. AI algorithms can also help create personalised treatment plans by predicting how different materials will interact, choosing the best nanomaterial for a certain condition, and simulating results like remineralisation depth, antimicrobial effectiveness, or bond strength. As machine learning models improve, they may help doctors make nanocoatings, nano-engineered restorative materials, and drug-delivering nanoparticles that are better for each patient's mouth and risk profile. AI is likely to change the way dentistry works in general, making diagnosis faster, treatment more accurate, and outcomes more predictable.

Personalized Nanomedicine: Tailoring Nanomaterials to Individual Genetic and Clinical Profiles

Personalised nanomedicine signifies a formidable future trajectory wherein nanomaterials and therapies are tailored according to an individual's genetic profile, microbiome characteristics, lifestyle determinants, and medical history. New technologies for genomic sequencing and salivary biomarker analysis help doctors find patient-specific vulnerabilities, like genetic markers for aggressive periodontitis, enamel hypomineralization, bisphosphonate-related osteonecrosis, or oral cancer. Nanomaterials can be designed to deliver targeted therapies that are tailored to the patient's unique biological profile using this information. For instance, nanoparticle drug carriers can be changed to work with certain enzymes or pH levels in people who are more likely to get sick, and customised nano-hydroxyapatite formulations may help remineralisation in people whose enamel is genetically weaker. Antimicrobial nanoparticles can also be chosen based on the patient's unique oral microbiome. This makes it easier to treat dysbiosis. In oncology, nanoparticles can be modified to selectively attach to receptors that are only found on tumours. This can make treatments more effective while reducing side effects throughout the body. Personalised profiles can also be used in regenerative dentistry, where nanofibers and scaffolds can be made to release growth factors that match the patient's ability to heal tissue. Personalised nanomedicine, which combines nanotechnology with the principles of precision medicine, has the potential to provide dental treatments that are safer, more effective, and more tailored to each patient, which will improve long-term results.

Nanosensors for Continuous, Real-Time Monitoring of Oral Health Biomarkers

Nanosensors are one of the most exciting new uses for nanodentistry. They could let us keep an eye on important oral health markers all the time. These very sensitive devices, which are built into dental restorations, orthodontic appliances, implants, or even films that dissolve in saliva, can pick up on very small biochemical and physiological changes that happen before a clinical disease. Nanosensors can keep an eye on changes in pH, calcium-phosphate levels, glucose levels, inflammatory cytokines, and pathogenic bacteria levels like Streptococcus mutans or Porphyromonas gingivalis. These sensors can help predict early demineralisation, flare-ups of periodontal disease, peri-implant inflammation, or xerostomia-related risks long before they become clinically evident by giving a dynamic picture of the oral environment. Nanosensors can collect real-time data and send it wirelessly to mobile devices or cloud-based AI systems for automated analysis. This makes it possible to get proactive, preventive dental care. For instance, a nanosensor built into a restoration could let both the patient and the doctor know about early recurrent caries, and sensors around implants could let them know about developing peri-implantitis before bone loss happens. Nanosensors could keep an eye on systemic–oral interactions in patients with medical problems, like diabetes, cancer, or autoimmune disorders, by measuring changes in salivary glucose, cortisol, or immune mediators. Moreover, forthcoming smart sensors may not only identify pathological conditions but also initiate the on-demand release of therapeutic agents, including antimicrobials, remineralising ions, or anti-inflammatory medications, thereby establishing a closed-loop diagnostic and therapeutic system. Nanosensor technology could change dentistry for the better by moving the focus from reactive treatment to continuous, personalised, and preventive oral healthcare. However, there are still problems with long-term biocompatibility, power supply, and data security.

Smart Biomaterials Combined with Nanotechnology for Enhanced Healing and Regeneration

Smart biomaterials combined with nanotechnology are about to change regenerative dentistry by making healing systems that are responsive, adaptable, and biologically active. These advanced materials can sense changes in the mouth, like changes in pH, mechanical stress, inflammation, or microbial activity, and then respond by releasing therapeutic agents or changing their structure to help tissue heal better. Nanotechnology makes these smart biomaterials better by making them stronger, more active, and better able to interact with cells. Nano-engineered scaffolds can imitate the hierarchical structure of natural dentin, bone, or periodontal ligament, creating a more conducive microenvironment for stem cell adhesion, proliferation, and differentiation. Smart nanofiber scaffolds can be filled with growth factors, antimicrobials, or cytokine modulators that are released in a controlled, stimulus-responsive way. This speeds up regeneration while reducing problems. In periodontal and bone regeneration, nanocomposite membranes and hydrogels can respond to inflammatory mediators by delivering osteogenic or angiogenic molecules exactly when and where they are needed. Smart nano-hydroxyapatite formulations can also help remineralise specific areas by sticking to enamel that has lost minerals and releasing calcium–phosphate ions when the pH level drops. In pulp tissue engineering, smart biomaterials that use nanotechnology may help create vascularised, functional pulp tissue by changing the cellular microenvironment in real time as healing happens. New technologies also include self-healing nanocomposites that can fix microcracks on their own, which makes restorations last longer and cuts down on the need for retreatment. Smart biomaterials and nanotechnology will make regenerative therapies more predictable, biologically driven, and less invasive as research continues. This is a big change from passive materials to active participants in the healing process.

Safety and Regulatory Frameworks for Nanomaterials in Dentistry

International safety and regulatory frameworks for nanomaterials stress the unique physical and chemical properties, biological interactions, and environmental behaviours that set nanoscale substances apart from their larger counterparts. The WHO, OECD, ISO, FDA, EPA, and ECHA are some of the global groups that have set rules to make sure that nanotechnology-based materials, like those used in dentistry, are developed, handled, and used safely in clinical settings. The WHO has detailed guidelines for protecting workers that focus on controlling exposure and making sure that workplaces are safe. The OECD, on the other hand, creates standardised test guidelines for toxicity, physicochemical characterisation, and environmental fate studies to make sure that regulatory assessments are accurate. ISO/TC 229 helps standardise things around the world by setting standards for nanomaterials' key terms, ways to measure them, and ways to describe them. The EU's REACH framework requires registration and safety data for each type of nanoform, and SCENIHR gives advice on how to check the safety of nanomaterials used in medical devices, such as dental implants and coatings. The FDA also looks at whether nanotechnology changes a product's safety, effectiveness, or biodistribution. This means that more tests are needed for drugs, dental materials, and consumer goods. Environmental agencies, such as the EPA, keep an eye on the release of nanoparticles, their effects on the environment, and how to deal with waste. This shows how worried people are about nanoparticles staying in the environment and causing antimicrobial resistance. Regulators in all jurisdictions stress the need for a full understanding of particle size, shape, aggregation, surface chemistry, dissolution behaviour, and biological interactions. They also stress the importance of life-cycle assessment and "safe-by-design" principles. Even though a lot has been done, there are still problems to solve, such as missing long-term toxicity data, differences in regulatory definitions around the world, and the need for better harmonisation. These international frameworks help researchers, manufacturers, and doctors make sure that nanomaterials used in dentistry are made in a way that is safe, responsible, and has the least effect on the environment.

Risk Assessment Protocols and Standards for Clinical Translation of Dental Nanomaterials

Risk assessment protocols for dental nanomaterials necessitate a thorough, nano-specific analysis of their physicochemical characteristics, biological interactions, and enduring performance within the oral environment. Nanoparticles need a lot more information than regular dental materials do about their size distribution, surface area, shape, tendency to agglomerate, stability of the coating, ion release rates, and how they dissolve in saliva and gingival crevicular fluid. Toxicological assessment encompasses the evaluation of cytotoxicity to oral epithelial and pulp cells, genotoxicity, inflammatory potential, oxidative stress pathways, and systemic absorption via oral mucosa or dentinal tubules. Also, standardised exposure models must be used to figure out material-specific risks, like the release of nanoparticles during polishing, wear, or degradation. Environmental risk assessment is necessary to ascertain nanoparticle discharge into wastewater and its potential ecological ramifications. International standards from ISO, OECD, and regulatory bodies stress Good Manufacturing Practice (GMP), validated characterisation methods, biocompatibility testing that is specific to nanoforms, and performance evaluations that are done in conditions that are relevant to clinical practice. Regulatory approvals need proof that nanomaterials stay stable, safe, and behave in a predictable way throughout their whole life cycle, from making them to storing them to using them in the mouth and throwing them away. Dental nanomaterials designed for medical devices, including nano-coated implants or restorative materials, must comply with device-specific clinical testing standards, encompassing evaluations of mechanical integrity, degradation profiles, antimicrobial durability, and patient safety. These protocols and standards work together to make sure that only nanomaterials that have been thoroughly tested, are safe, and work well move from the lab to clinical dentistry.

Patient-Centered Outcomes and Acceptance of Nanodentistry

Patient-centered outcomes are very important for figuring out how well nanodentistry works in the real world. They go beyond how well it works in the lab to include how patients feel about it, how comfortable they are, and how satisfied they are. Recent studies show that patients still don't know much about nanotechnology in dental treatments. However, they are more likely to accept it when its benefits—like stronger restorations, shorter treatment times, better aesthetics, and better long-term outcomes—are clearly explained. Studies show that patients also like minimally invasive procedures made possible by nano-enhanced materials, like better remineralising agents, long-lasting antibacterial coatings, and faster healing times. Nonetheless, apprehensions endure regarding the safety, toxicity, and enduring consequences of nanoparticles, underscoring the necessity for transparent communication and evidence-based guidance by healthcare professionals. Integrating patient-reported outcome measures (PROMs) into clinical studies can yield more profound insights into comfort levels, perceived treatment efficacy, postoperative recovery, and the readiness to embrace nanotechnology-based interventions. In the end, educating patients, getting their informed consent, and raising public awareness are all important for getting more people to accept nanodentistry and making sure that new developments meet patients' needs and wants.

Informed Consent Processes for Nanotechnology-Based Dental Interventions

As nanotechnology brings new materials, ways of working, and possible dangers, informed consent procedures need to change to make sure patients understand and that clinical practice is ethical. In the field of nanodentistry, informed consent necessitates unambiguous and transparent communication regarding the characteristics of the nanomaterials employed, their anticipated advantages—such as increased durability, antibacterial properties, or regenerative capabilities—and any recognised or potential risks, including toxicity, hypersensitivity, or enduring biological effects that remain under examination. Clinicians ought to convey this information in clear, non-technical language, augmented by visual aids or written summaries as necessary. Many nanotechnologies are still in the early stages of clinical testing, so consent forms need to clearly state any doubts about long-term safety, regulatory status, and other treatment options. Getting consent should also mean checking to see if the patient understands and encouraging them to ask questions so that they can make an informed choice. As nanodentistry becomes more common in clinical practice, making standard consent guidelines for nano-enhanced treatments will make things clearer, more ethical, and more trustworthy for patients.

Ethical Considerations in Nanodentistry

Ethical issues are very important when it comes to the use of nanodentistry, especially because new nanotechnologies are so new and complicated. One of the main concerns is patient privacy, since nanosensors and smart diagnostic systems may collect biological data all the time that needs to be stored and handled safely. The long-term effects of nanomaterials are still not fully understood, especially when it comes to how long they stay in tissues, how they could be exposed to the whole body, and how they could affect the environment. This is why long-term monitoring and clear communication are so important. Access equity is also a big moral problem because treatments based on advanced nanotechnology may be expensive at first and only available at certain centres, which could make oral health care even less equal. To ethically add nanodentistry to routine clinical practice, it will be important to make sure that everyone has fair access, protect patient data, and deal with unknown long-term risks.

Cost-Effectiveness and Accessibility of Nanodentistry

When comparing nanodentistry to traditional dental treatments, cost-effectiveness is an important factor to think about. Economic analyses increasingly indicate that although nanotechnology-based materials—such as nanocomposites, nano-bioactive agents, or nanosensors—may incur higher initial costs, they frequently exhibit enhanced durability, diminished failure rates, and reduced requirements for retreatment, ultimately decreasing long-term expenses for both patients and healthcare systems. In addition, nanosensors and nano-imaging technologies, which are early diagnostic tools, can find oral diseases at subclinical stages. This could lower the costs of more advanced treatments. But accessibility is still a problem because the high cost of making these innovations, the lack of specialised equipment, and the need for practitioner training may mean that they are only available in urban or well-funded clinics at first. Making these advanced technologies available to a wide range of patients will require making them affordable, promoting their wider use, and including them in public health programs.

Feasibility, Scalability, and Global Equity in Nanodentistry

The viability and scalability of nanodentistry in rural and resource-constrained environments are significantly influenced by cost, infrastructure, and workforce preparedness. Nanomaterials like nano-enhanced restorative materials or antimicrobial nanoparticles can be added to current clinical workflows with only minor changes to the equipment. However, more advanced technologies like nanosensors, nano-imaging tools, or nanorobotic systems need a lot of money and training, which makes it hard to use them widely in areas that don't have enough resources. To make sure that nano-based products can be used by a lot of people, they need to be easy to use, cheap, and portable. There also need to be programs to help primary healthcare workers in low-resource settings learn new skills. From a global health standpoint, nanodentistry has the capacity to markedly diminish disparities through facilitating early diagnosis, minimally invasive treatment, and enduring restorations. But if only wealthy areas can use nanotechnologies, these improvements could make the gaps that already exist even bigger. So, to make sure that everyone can benefit from nanodentistry, especially those who have not had access to it in the past, we need strategic investments, inclusive policy frameworks, and technology-sharing programs.

Systematic Gap Analysis in Nanodentistry

Nanodentistry is growing quickly, but there are still some clinical and research gaps that make it hard to use in everyday dental practice. Major gaps include a lack of long-term clinical trials to prove safety and effectiveness, a lack of patient-centered studies on acceptance and outcomes, differences in regulatory frameworks, a lack of understanding of nanoparticle toxicity and environmental impact, high production costs, and problems with scalability in places with few resources. Moreover, although preclinical studies indicate promising mechanical, antimicrobial, and regenerative attributes of nanomaterials, extensive human trials are limited, and standardised protocols for risk assessment, informed consent, and ethical governance are inadequately established. To make nanodentistry a part of regular clinical care, we need to fill these gaps with research from different fields, rules that are the same everywhere, ways to cut costs, and getting patients involved.

Table 1. Summary of Key Clinical and Research Gaps in Nanodentistry

Domain	Current Status	Gap Identified	Potential Implications
Clinical Trials	Mostly in vitro and preclinical	Limited long-term human studies	Uncertain long-term efficacy and safety
Patient-Centered Outcomes	Few studies	Low awareness, limited acceptance data	Reduced adoption and trust
Safety & Toxicity	Some in vitro evaluation	Incomplete systemic and environmental toxicity data	Unknown chronic effects and ecological impact
Regulatory & Standardization	Fragmented	Lack of global harmonized guidelines	Delayed approvals and inconsistent clinical use
Cost & Accessibility	High initial cost	Limited availability in low-resource settings	Potential widening of oral health disparities
Ethical & Legal	Emerging frameworks	Inadequate protocols for privacy, consent, and equity	Ethical and social challenges in implementation

Domain	Current Status	Gap Identified	Potential Implications
Translational Tools	Many innovative materials and devices	Scalability and manufacturability issues	Hindered widespread clinical adoption

Prioritized Areas for Future Research and Standardization in Nanodentistry

To accelerate the safe and effective integration of nanodentistry into clinical practice, several key areas require prioritized investigation and standardization. First, long-term clinical trials assessing the durability, biocompatibility, and systemic effects of dental nanomaterials are essential to establish robust safety and efficacy data. Second, patient-centered studies evaluating awareness, acceptance, comfort, and treatment outcomes will guide strategies for improving adoption and informed consent processes. Third, regulatory harmonization across international agencies is critical to define standardized testing protocols, characterization methods, and approval pathways for nano-enhanced dental products. Fourth, research into cost-effective manufacturing, scalability, and delivery methods will enable broader access, particularly in rural and resource-limited settings. Fifth, ethical frameworks and data governance protocols need development to ensure patient privacy, equity, and transparency, particularly for nanosensors and smart biomaterials. Finally, environmental impact assessments and life-cycle analyses of nanomaterials should be standardized to minimize ecological risks. Addressing these prioritized areas through interdisciplinary collaboration will ensure that nanodentistry develops as a safe, equitable, and evidence-based component of next-generation dental care.

Incorporation of Visual Summaries and Infographics

Visual summaries and infographics can greatly enhance the clarity and accessibility of nanodentistry research by illustrating complex mechanisms and clinical applications of nanomaterials. Infographics depicting nanoparticle action mechanisms, such as antimicrobial activity, remineralization of enamel, or osteogenic stimulation in regenerative scaffolds, provide intuitive understanding of how nanomaterials interact at the molecular and cellular levels. Similarly, flowcharts can summarize risk assessment protocols, regulatory pathways, and clinical workflows, while schematic diagrams can show targeted drug delivery or nanorobotic interventions in dentistry. These visual tools not only improve comprehension for researchers and clinicians but also facilitate patient education, aiding informed decision-making and consent. Incorporating such graphical elements into review articles or clinical guidelines enhances knowledge translation, allowing both scientific and lay audiences to grasp the potential and limitations of nanodentistry more effectively.

Flowcharts of Clinical Workflows Involving Nanotechnologies

1. Nano-Enhanced Restorative Material Workflow

Flowchart Steps:

1. Patient Assessment

o Clinical examination

o Radiographic evaluation

2. Risk Evaluation

o Caries risk assessment

o Allergy / sensitivity check

3. Material Selection

o Choose appropriate nano-filled composite or biomimetic material

4. Tooth Preparation

o Cleaning and cavity preparation

o Isolation of operative field

5. Material Application

o Layering / placement of nano-composite

o Use of adhesives if required

6. Curing & Finishing

o Light curing

o Contouring and polishing

7. Postoperative Monitoring

o Immediate check for sensitivity / occlusion

o Follow-up visit schedule

Decision Nodes:

- Patient suitability for nano-materials
- Contraindications (e.g., hypersensitivity)
- Informed consent

2. Nanorobotic Intervention Workflow

Flowchart Steps:

1. Patient Evaluation & Eligibility

o Medical history

o Oral health assessment

2. Device Programming

o Select targeted action (e.g., plaque removal, localized anesthesia)

o Set dosage / operational parameters

3. Device Placement

o Introduce nanorobots into target site

4. Monitoring & Feedback

o Track robot activity via imaging or sensors

o Real-time adjustments if needed

5. Device Retrieval or Biodegradation

o Natural biodegradation or safe retrieval

o Post-treatment oral assessment

Decision Nodes:

- Contraindications (immune compromise, allergies)
- Patient consent and understanding
- Emergency stop criteria

3. Targeted Drug Delivery Workflow

Flowchart Steps:

1. Patient Diagnosis

o Identify condition requiring targeted therapy (e.g., localized infection, inflammation)

2. Drug & Nanocarrier Selection

o Select nanoparticle type (liposomes, dendrimers, etc.)

o Decide drug concentration and release profile

3. Formulation & Loading

o Encapsulate drug in nanocarrier

o Sterility and quality control checks

4. Administration

o Apply locally or systemically

o Ensure correct site targeting

5. Therapeutic Monitoring

o Clinical evaluation

o Imaging / biomarker tracking for drug efficacy

6. Follow-up & Safety Assessment

o Monitor adverse reactions

o Adjust future dosing if needed

Decision Nodes:

- Eligibility for nanodrug therapy
- Risk of systemic toxicity
- Patient consent and compliance

Visual Representation Tips:

- Use standard flowchart symbols:

o Ovals for start/end

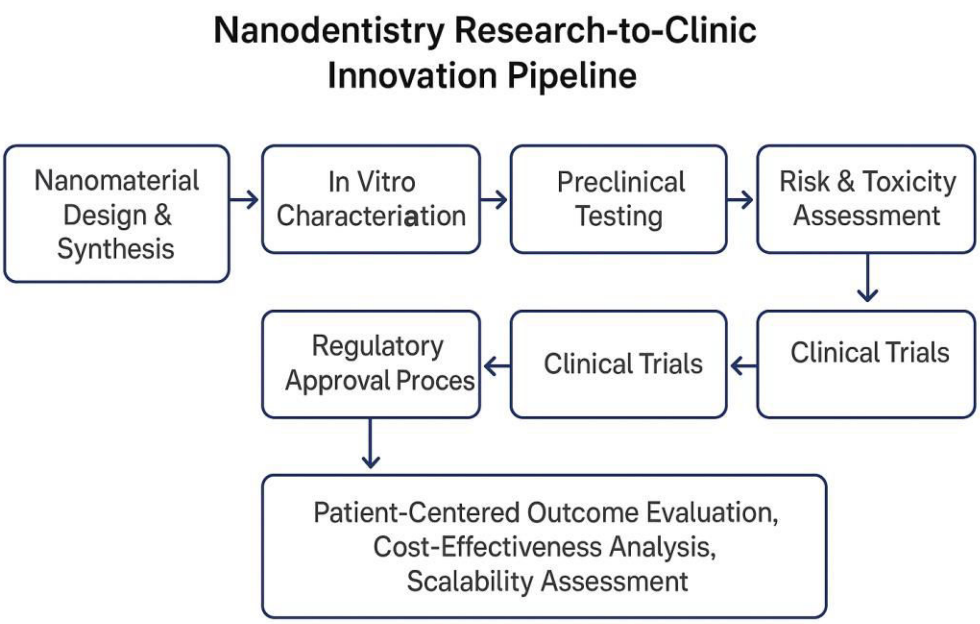
o Rectangles for process steps

o Diamonds for decision nodes

o Arrows to indicate workflow direction

- Highlight nanotechnology-specific steps in a different color for clarity.
- Include feedback loops for monitoring and re-evaluation.

Diagrams of the Nanodentistry Research-to-Clinic Innovation Pipeline



CONCLUSION

The present review concludes that nanodentistry represents a transformative frontier in modern dental care, offering enhanced mechanical, biological, and antimicrobial properties across a range of clinical applications. Nanomaterials such as silver, zirconia, and nano-hydroxyapatite have shown considerable potential in improving restoration durability, promoting remineralization, and supporting tissue regeneration. While preclinical and early clinical data are promising, comprehensive long-term studies remain essential to establish safety, biocompatibility, and clinical efficacy. Advancing this field aligns with SDG 3 (Good Health and

Well-being) by improving oral health outcomes, SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure) by fostering sustainable biomedical innovation, and SDG 17 (Partnerships for the Goals) through interdisciplinary and cross-sector collaboration. With continued research, cost optimization, and translational integration, nanodentistry is poised to become a cornerstone of personalized, preventive, and minimally invasive dental practice.

REVIEW

Nanodentistry represents a rapidly expanding frontier in modern dental care, offering innovative solutions that enhance diagnosis, prevention, restoration, and regeneration. This review aimed to explore and critically analyze the advancements, applications, and future potential of nanotechnology in dentistry, focusing on how nanoscale materials and devices contribute to improved clinical outcomes. Recent developments such as nanocomposites, nano-filled adhesives, nanorobots, nanoparticle drug-delivery systems, nanobiosensors, and tissue-engineering scaffolds have demonstrated significant benefits, including superior mechanical properties, enhanced antibacterial effects, improved esthetics, and better biocompatibility. In preventive dentistry, nano-hydroxyapatite and remineralizing agents show promise in caries management, while in restorative dentistry, nano-modified materials offer enhanced strength and durability. Nanotechnology also plays a transformative role in periodontics, endodontics, implantology, and oral cancer diagnostics through targeted therapies and improved imaging modalities. Despite these advantages, challenges such as material toxicity, long-term biocompatibility, ethical concerns, cost, and regulatory barriers limit widespread clinical adoption. The review concludes that continued research, improved safety protocols, and standardized guidelines are essential to fully harness the transformative potential of nanodentistry.

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