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Nanotechnology in Dentistry: Potential Applications and Future Perspectives

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ABSTRACT

This study aims to explore the applications, advantages, challenges, and future perspectives of nanotechnology in dentistry, highlighting its role in improving diagnostic accuracy, treatment precision, and patient outcomes. A scientific narrative review was conducted using a descriptive analysis method to synthesize literature published between 2020 and 2025 on nanotechnology applications in dentistry. Relevant peer-reviewed articles, systematic reviews, and clinical studies were obtained from databases such as PubMed, Scopus, Web of Science, and Google Scholar. The selection criteria included studies focusing on nanomaterials, nanocomposites, nanorobotics, and nano-based drug delivery systems in various dental disciplines, including preventive, restorative, endodontic, periodontal, prosthodontic, orthodontic, and diagnostic applications. The analysis examined the mechanical, antimicrobial, and biocompatible properties of nanomaterials, their clinical effectiveness, and associated risks. The findings indicate that nanotechnology has significantly enhanced the strength, durability, and antibacterial properties of dental materials, leading to improved restorative and preventive treatments. Nanoparticles, nanorods, and nanotubes have been integrated into composite resins, implants, and regenerative scaffolds, improving osseointegration, tissue regeneration, and enamel remineralization. Nanobiosensors and nanosensors have facilitated early disease detection, while nano-based drug delivery systems have optimized targeted therapies with minimal systemic side effects. Despite these advancements, concerns regarding cytotoxicity, long-term biocompatibility, regulatory challenges, and high costs remain barriers to widespread clinical adoption. Nanotechnology has revolutionized modern dentistry by providing innovative solutions for diagnosis, treatment, and prevention. Its integration with artificial intelligence, regenerative medicine, and robotics is expected to further enhance patient-centered and minimally invasive treatments. Future research should focus on addressing safety concerns, improving cost-effectiveness, and establishing standardized regulatory guidelines to ensure the long-term success of nanotechnology in dentistry.

Keywords: Nanotechnology, nanomaterials, dentistry, nanorobotics, nano-based drug delivery, regenerative dentistry, dental implants, biomaterials, nanocomposites, oral diagnostics.

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Introduction

Nanotechnology is a rapidly advancing field that involves manipulating materials at the nanoscale, typically ranging from 1 to 100 nanometers, to enhance their physical, chemical, and biological properties. This technology has revolutionized various scientific disciplines, including medicine and dentistry, by enabling the development of highly functional materials with superior mechanical strength, biocompatibility, and antimicrobial properties. In dentistry, the incorporation of nanomaterials has led to significant improvements in preventive, diagnostic, and therapeutic approaches, offering innovative solutions for dental restoration, periodontal therapy, implantology, and regenerative treatments. The unique properties of nanomaterials, such as high surface area-to-volume ratio, enhanced reactivity, and targeted drug delivery, make them highly effective in addressing dental diseases and improving treatment outcomes. The potential of nanotechnology to transform oral healthcare is increasingly recognized, with research focusing on optimizing nanomaterials for clinical applications to enhance durability, aesthetics, and patient safety (1).

Over the past few decades, nanotechnology has gained widespread attention in dental research due to its potential to overcome limitations associated with conventional materials. Early investigations focused on the use of nanoparticles to improve the mechanical properties of dental composites, leading to the development of nanofilled resin-based materials with enhanced wear resistance and aesthetics. Subsequently, nanotechnology was integrated into various dental specialties, including periodontics, endodontics, prosthodontics, and orthodontics, facilitating advancements such as antimicrobial nanoparticles for caries prevention, nano-sized bioactive glass for dentin remineralization, and nanostructured coatings for improved osseointegration of dental implants (2). In periodontology, the application of nanomaterials has shown promise in guided tissue regeneration and biofilm management, while in endodontics, nanoparticle-based irrigants and sealers have demonstrated superior antibacterial efficacy. The continuous evolution of nanotechnology has also led to the development of smart nanorobots capable of precise drug delivery, real-time diagnostics, and minimally invasive procedures, indicating its transformative potential in personalized dental care (3, 4).

Despite the significant progress in integrating nanotechnology into dentistry, several challenges remain, necessitating further research to optimize its applications and address potential safety concerns. One of the primary challenges is the long-term biocompatibility and toxicity of nanomaterials, as their small size allows them to penetrate biological barriers, raising concerns regarding systemic exposure and potential adverse effects. Additionally, the standardization of nanomaterials for dental use is still under development, requiring extensive clinical validation and regulatory approval before widespread adoption. Another key limitation is the high cost of nanotechnology-based dental products, which may hinder their accessibility and affordability in routine dental practice (5, 6). Furthermore, the lack of comprehensive studies evaluating the clinical efficacy and long-term stability of nanomaterials underscores the need for continued research to establish their safety and reliability. Addressing these challenges through interdisciplinary collaboration, technological advancements, and evidence-based clinical trials is essential for realizing the full potential of nanotechnology in dentistry.

This review aims to provide a comprehensive analysis of the applications of nanotechnology in dentistry, with a particular focus on its current and emerging roles in various dental disciplines. By synthesizing the latest findings from peer-reviewed literature, this study explores the effectiveness of nanomaterials in enhancing dental materials, improving diagnostic accuracy, and advancing therapeutic strategies. Additionally, the review examines the advantages and limitations associated with nanotechnology-based dental innovations, highlighting areas that require further investigation. By addressing the existing research gaps and identifying future directions, this study seeks to contribute to the growing body of knowledge on nanotechnology in dentistry and provide insights into its potential for improving oral healthcare.

Methods and Materials

This study follows a scientific narrative review approach, employing a descriptive analysis method to synthesize relevant literature on the applications of nanotechnology in dentistry. The review focuses on published research articles, systematic reviews, meta-analyses, and clinical studies that explore the potential uses, benefits, and challenges of nanotechnology in various dental specialties. Given the rapid advancements in nanomaterials and nanotechnological innovations, this review includes studies published between 2020 and 2025 to ensure the inclusion of the most recent findings and emerging trends. The primary goal is to provide a comprehensive analysis of the integration of nanotechnology into modern dentistry, offering insights into its clinical applications and future prospects.

The data for this review were obtained from high-impact, peer-reviewed journals, conference proceedings, and authoritative sources in nanoscience, materials science, and dentistry. The main databases searched include PubMed, Scopus, Web of Science, and Google Scholar, ensuring a broad scope of literature coverage. The search strategy was designed to identify studies related to the role of nanoparticles, nanocomposites, nanosensors, nanorobotics, and nanomedicine in various dental applications, including restorative dentistry, prosthodontics, periodontology, endodontics, orthodontics, and oral diagnostics.

A set of inclusion and exclusion criteria was applied to refine the selection of studies. The inclusion criteria encompassed research articles published in English, studies specifically addressing nanotechnology in dental applications, and publications that reported experimental, clinical, or systematic findings on the efficacy, safety, and long-term outcomes of nanomaterials in dentistry. Excluded from the review were non-English publications, opinion pieces, editorials, and studies lacking empirical or clinical data. Additionally, articles primarily focused on nanotechnology outside the domain of dentistry, such as general biomedical nanoscience, were not included unless they provided direct insights applicable to dental research.

A descriptive analysis method was employed to systematically review and synthesize the selected literature. The reviewed studies were categorized based on the specific applications of nanotechnology in dentistry, including preventive dentistry, restorative materials, implantology, periodontal therapy, endodontic disinfection, orthodontic innovations, and oral disease diagnostics. Each study was examined for methodological rigor, sample size, experimental design, and clinical significance, ensuring that the findings presented in this review are based on robust scientific evidence.

The analysis focused on identifying key trends, advancements, and emerging technologies within nanodentistry, with a particular emphasis on biocompatibility, antimicrobial properties, mechanical durability, and regenerative potential of nanomaterials. Furthermore, safety considerations, including potential cytotoxicity, long-term biological effects, and regulatory concerns, were explored to provide a balanced perspective on the challenges associated with integrating nanotechnology into clinical practice.

Fundamentals of Nanotechnology in Dentistry

Nanotechnology operates at the nanoscale, typically within the range of 1 to 100 nanometers, where materials exhibit unique physicochemical properties distinct from their bulk counterparts. At this scale, materials display increased surface-to-volume ratios, quantum effects, and enhanced reactivity, making them highly functional in medical and dental applications. The fundamental principle of nanotechnology lies in the ability to manipulate atoms and molecules to design materials with tailored characteristics, thereby improving performance in various biological environments. In dentistry, nanotechnology has led to the development of advanced biomaterials that enhance mechanical strength, biocompatibility, and antimicrobial efficacy, ensuring superior patient outcomes and long-lasting dental restorations. These advancements have paved the way for innovative applications such as nanoscale drug delivery systems, bioactive dental materials, and diagnostic tools, all of which contribute to more effective and minimally invasive dental treatments (7).

A wide range of nanomaterials has been developed for use in dentistry, each offering specific advantages based on their composition and structural properties. Nanoparticles, which are the most commonly used nanomaterials in dental applications, include metallic nanoparticles such as silver, gold, and titanium dioxide, as well as bioactive nanoparticles such as hydroxyapatite and bioactive glass. Silver nanoparticles, for instance, are widely recognized for their potent antimicrobial properties and are incorporated into dental materials to reduce bacterial adhesion and prevent biofilm formation (8). Gold nanoparticles have been explored for their ability to enhance diagnostic imaging and drug delivery in periodontal therapy, while titanium dioxide nanoparticles contribute to the self-cleaning and photocatalytic properties of dental coatings, reducing bacterial colonization (9). Hydroxyapatite nanoparticles, which closely resemble the mineral composition of natural tooth enamel, are commonly used in remineralizing agents and restorative materials to improve biocompatibility and enhance the natural repair of enamel lesions (10).

Nanorods and nanotubes are another class of nanomaterials with promising applications in dentistry. Nanorods, due to their elongated shape and high aspect ratio, offer superior mechanical reinforcement when incorporated into dental composites and restorative materials (11). They improve the structural integrity of dental restorations by enhancing fracture resistance and durability, which is essential for high-stress applications such as posterior restorations. Carbon nanotubes, which consist of rolled-up graphene sheets, are particularly noteworthy for their exceptional tensile strength and electrical conductivity, making them suitable for reinforcing dental materials and developing smart dental sensors (12). The high mechanical strength of nanotubes allows them to be integrated into dental adhesives and resin-based composites to improve wear resistance and longevity. Moreover, their electrical properties enable their use in biosensors for real-time detection of oral diseases, such as periodontitis and early-stage caries, through the monitoring of biomarkers in saliva (13).

Nanocomposites represent a major advancement in restorative dentistry, combining nanomaterials with polymeric or ceramic matrices to enhance physical and biological performance. These materials leverage the advantages of nanoparticles and nanorods to produce dental composites with superior wear resistance, aesthetic properties, and antimicrobial activity (14). The incorporation of nanofillers, such as silica or zirconia nanoparticles, into resin-based composites improves the mechanical properties of dental restorations by reducing polymerization shrinkage and enhancing the overall strength of the material (15). Additionally, nanocomposite coatings on dental implants and prosthetics provide antimicrobial and bioactive surfaces that promote osseointegration and reduce the risk of peri-implantitis (16). The development of nanocomposites has significantly improved the longevity of dental restorations and enhanced the overall success rates of prosthetic and implant treatments.

The unique properties of nanomaterials make them highly suitable for a wide range of dental applications. One of the most critical attributes of nanomaterials in dentistry is their biocompatibility, ensuring that they interact safely with oral tissues and do not provoke adverse immune responses. Biocompatible nanomaterials such as hydroxyapatite and bioactive glass promote the natural remineralization of enamel and dentin, facilitating tissue regeneration and improving the efficacy of preventive treatments (17). Additionally, the antimicrobial properties of certain nanomaterials, such as silver, zinc oxide, and titanium dioxide nanoparticles, play a crucial role in reducing bacterial adhesion and biofilm formation, thereby preventing common oral diseases such as caries and periodontitis (18). These nanoparticles disrupt bacterial cell membranes and interfere with metabolic processes, making them highly effective in antibacterial dental coatings and restorative materials (19).

The mechanical strength of nanomaterials is another key factor contributing to their effectiveness in dentistry. Nanostructured materials, including nanocomposites and reinforced ceramics, exhibit enhanced hardness, wear resistance, and fracture toughness, making them ideal for dental restorations subjected to high occlusal forces (20). For instance, nanoceramics used in crowns and bridges demonstrate improved durability and aesthetic properties, closely mimicking the translucency of natural teeth while offering superior mechanical performance (21). Furthermore, the high surface energy of nanomaterials enhances their bonding ability to dental structures, improving the adhesion of restorative materials to enamel and dentin and reducing the likelihood of restoration failure (1). These properties have contributed to the widespread adoption of nanomaterials in restorative and prosthetic dentistry, improving the longevity and clinical outcomes of dental treatments.

Nanotechnology has also enabled the development of advanced drug delivery systems tailored for targeted therapy in dentistry. Nanoscale drug carriers, such as liposomes and polymeric nanoparticles, allow for the controlled and sustained release of therapeutic agents, minimizing systemic side effects while maximizing local efficacy (2). In periodontal therapy, nanoparticle-based drug delivery systems have been utilized to deliver antimicrobial agents directly to periodontal pockets, enhancing treatment efficacy and reducing the need for invasive procedures (1). Similarly, in endodontics, nano-encapsulated irrigants and intracanal medicaments have demonstrated improved penetration into dentinal tubules, effectively eliminating bacterial infections and preventing reinfection (3). The ability of nanocarriers to target specific oral tissues with precision holds great promise for the future of minimally invasive dental treatments.

Another critical advantage of nanomaterials in dentistry is their potential for regenerative applications. Nanotechnology-based scaffolds, composed of bioactive nanoparticles and nanofibers, have been explored for their role in promoting tissue regeneration in cases of alveolar bone loss, periodontal defects, and pulp tissue repair (22). These nanoscaffolds mimic the extracellular matrix of natural tissues, providing a conducive environment for cell proliferation and differentiation (10). The integration of nanobiomaterials into regenerative dentistry has led to the development of tissue-engineered constructs that support the growth of dental pulp cells and osteoblasts, paving the way for advanced treatments in endodontic regeneration and implantology (23). By harnessing the regenerative potential of nanomaterials, researchers are working toward developing bioengineered dental tissues capable of restoring lost tooth structure and periodontal support.

Despite these remarkable advancements, there are ongoing concerns regarding the safety and long-term effects of nanomaterials in dentistry. Due to their nanoscale size, certain nanoparticles have the potential to penetrate biological barriers and accumulate in systemic circulation, raising concerns about their potential cytotoxicity and bioaccumulation (24). Regulatory agencies continue to assess the biocompatibility and toxicity profiles of nanomaterials to establish standardized guidelines for their safe use in dental applications (25). Further research is needed to evaluate the long-term interactions of nanomaterials with oral tissues and their potential systemic implications to ensure their safe and effective integration into clinical practice (26).

In conclusion, nanotechnology has revolutionized dentistry by introducing a diverse range of nanomaterials with exceptional properties that enhance preventive, restorative, and regenerative treatments. The unique physicochemical characteristics of nanomaterials, including biocompatibility, antimicrobial activity, and superior mechanical strength, have facilitated their widespread adoption in various dental applications. Continued research and development in nanodentistry are expected to drive further innovations, improving treatment efficacy and patient outcomes while addressing challenges related to safety and regulation. As advancements in nanotechnology continue to unfold, the future of dentistry is poised to become increasingly precise, minimally invasive, and patient-centered.

Current Applications of Nanotechnology in Dentistry

Nanotechnology has made significant strides in preventive dentistry, offering innovative solutions for reducing the incidence of dental caries, enhancing enamel remineralization, and improving the antimicrobial properties of dental materials. The use of nanotechnology in fluoride delivery has led to the development of nanoparticle-based fluoride formulations that provide superior protection against demineralization. Nanoparticles enhance fluoride uptake by enamel and dentin, allowing for a sustained release of fluoride ions that strengthens tooth structure and inhibits acid-induced demineralization. These nano-enhanced fluoride agents not only increase the bioavailability of fluoride but also improve its penetration into deeper enamel layers, offering prolonged caries protection compared to conventional fluoride applications (10). In addition to fluoride delivery, antimicrobial coatings embedded with nanoparticles such as silver, zinc oxide, and titanium dioxide have been developed to prevent biofilm formation on dental surfaces. Silver nanoparticles, in particular, exhibit potent antimicrobial effects by disrupting bacterial cell membranes and inhibiting microbial growth, making them a valuable addition to preventive dental coatings (8). Moreover, nanotechnology-based remineralization agents, such as hydroxyapatite nanoparticles, mimic the natural mineral composition of enamel and facilitate its repair by promoting calcium and phosphate deposition. These bioactive nanomaterials have been incorporated into toothpaste, mouthwashes, and dental varnishes, providing an effective strategy for reversing early-stage caries lesions and enhancing enamel durability (17).

In restorative dentistry, nanotechnology has led to the development of nanocomposites and nanofillers that significantly improve the mechanical strength, wear resistance, and aesthetic properties of dental restorative materials. Conventional dental composites often suffer from polymerization shrinkage and reduced longevity, but the incorporation of nanoscale fillers has addressed these limitations by enhancing the overall durability of the material. Nanofillers, such as silica and zirconia nanoparticles, improve the mechanical properties of composite resins by reducing microcracking and increasing their resistance to occlusal forces (11). These nanomaterials also contribute to improved polishability and optical properties, allowing for restorations that closely resemble natural teeth in translucency and color stability (15). Furthermore, the antibacterial properties of nanocomposite materials have been enhanced by incorporating silver, copper, and zinc oxide nanoparticles, which prevent bacterial adhesion and secondary caries development around restorations (18). The ability of nanomaterials to modify the rheological properties of resin-based composites has also resulted in improved handling characteristics, allowing clinicians to achieve better adaptation to cavity walls and reducing the risk of marginal leakage (26).

Endodontics has benefited significantly from nanotechnology, particularly in the areas of root canal disinfection, bioactive sealers, and regenerative treatments. The effectiveness of root canal disinfection has been enhanced by the use of nanoparticle-based irrigants that exhibit superior antimicrobial activity against resistant bacterial biofilms. Silver and chitosan nanoparticles have been incorporated into endodontic irrigants to improve their ability to penetrate dentinal tubules and eliminate persistent infections, reducing the risk of reinfection and treatment failure (1). Additionally, nanotechnology has contributed to the development of bioactive endodontic sealers that promote dentin mineralization and create a more effective seal against bacterial infiltration. These sealers, which include bioactive glass and calcium phosphate nanoparticles, enhance the long-term success of root canal treatments by encouraging dentinal repair and preventing microleakage (21). In regenerative endodontics, nanomaterials have been used to create scaffolds that support the differentiation of dental pulp stem cells, enabling the regeneration of pulp-like tissue and the restoration of damaged dentin (3). The use of nanotechnology in endodontics has thus improved both the disinfection process and the biological potential for tissue repair, leading to more predictable treatment outcomes.

Nanotechnology has also been widely applied in periodontology, particularly in periodontal regeneration, antibacterial therapies, and guided tissue regeneration. One of the key challenges in periodontal therapy is the regeneration of lost alveolar bone and periodontal ligament, which has been addressed through the use of nanomaterials that mimic the extracellular matrix and promote cell attachment and proliferation. Nanofibrous scaffolds composed of bioactive nanoparticles such as hydroxyapatite and bioglass have been developed to enhance the regeneration of periodontal tissues by providing an osteoconductive framework that supports bone and ligament growth (19). In addition to regenerative applications, nanotechnology has improved the efficacy of antibacterial periodontal therapies by incorporating antimicrobial nanoparticles into local drug delivery systems. Nanoparticle-based gels and nanocarriers have been designed to deliver antibiotics and antiseptic agents directly to periodontal pockets, achieving sustained drug release and improved bacterial eradication (13). Guided tissue regeneration membranes infused with nanoparticles have also been developed to provide enhanced mechanical strength and antimicrobial protection, reducing the risk of bacterial contamination while facilitating tissue healing (14). These advancements have significantly improved the predictability of periodontal treatments and contributed to better long-term outcomes for patients with periodontitis.

Prosthodontics and dental implantology have also seen remarkable progress with the integration of nanotechnology, particularly through the use of nanocoatings for implants, nanoceramics, and nanostructured titanium surfaces. One of the primary concerns in implantology is achieving optimal osseointegration, which has been improved by modifying the surface characteristics of titanium implants with nanoscale coatings. Nanotextured surfaces created by incorporating titanium dioxide or hydroxyapatite nanoparticles enhance the adhesion of osteoblasts and promote faster bone integration, leading to improved implant stability (16). The development of nanoceramic materials has further advanced prosthodontics by offering superior strength, aesthetic properties, and resistance to wear. Zirconia-based nanoceramics, for instance, have demonstrated excellent durability and biocompatibility, making them ideal for crowns, bridges, and implant-supported restorations (20). Additionally, antimicrobial nanocoatings on implant surfaces help prevent peri-implantitis by reducing bacterial adhesion and biofilm formation, thereby increasing the longevity of dental implants (22). These innovations in prosthodontics and implantology have significantly enhanced the success rates of restorative treatments and improved patient satisfaction.

In orthodontics, nanotechnology has been applied to the development of nanomodified brackets, adhesives, and smart orthodontic wires that improve treatment efficiency and comfort. Orthodontic brackets coated with nanoparticles exhibit reduced frictional resistance and enhanced antimicrobial properties, minimizing the risk of enamel demineralization and plaque accumulation during treatment (24). Nanotechnology has also contributed to the development of highly adhesive orthodontic bonding agents that improve the retention of brackets and reduce the likelihood of bond failure (1). The incorporation of shape-memory alloys and nanostructured wires in orthodontics has allowed for the development of smart archwires that provide continuous and controlled force application, leading to more efficient tooth movement and reduced treatment duration (2). These advancements in orthodontic materials have improved both clinical outcomes and patient comfort, making nanotechnology an essential component of modern orthodontic treatment.

Nanotechnology has also played a transformative role in oral diagnostics and drug delivery by enabling the development of nanosensors, nanobiosensors, and nanoparticle-based drug carriers. Nanosensors have been designed to detect oral pathogens and biomarkers associated with oral diseases, allowing for early diagnosis and more effective treatment planning (10). Nanobiosensors integrated into saliva-based diagnostic devices have demonstrated high sensitivity in detecting conditions such as periodontitis, oral cancer, and systemic diseases with oral manifestations (23). In addition to diagnostics, nanoparticle-based drug delivery systems have been developed to enhance the targeted delivery of therapeutic agents in oral healthcare. Nanocarriers such as liposomes, dendrimers, and polymeric nanoparticles provide controlled and sustained release of medications for the treatment of conditions such as oral mucositis, fungal infections, and inflammatory diseases (25). These technologies have improved the precision of drug delivery in dentistry, minimizing systemic side effects and enhancing therapeutic efficacy.

In summary, the application of nanotechnology in dentistry has revolutionized multiple dental disciplines, providing innovative solutions for preventive care, restorative materials, endodontic disinfection, periodontal regeneration, prosthodontic durability, orthodontic efficiency, and advanced oral diagnostics. By leveraging the unique properties of nanomaterials, researchers and clinicians continue to develop highly effective and minimally invasive treatment modalities that improve patient outcomes and redefine the standards of modern dental care.

Advantages and Challenges of Nanotechnology in Dentistry

Nanotechnology has introduced groundbreaking advancements in dentistry by significantly enhancing the properties of dental materials, improving patient outcomes, and increasing treatment precision. One of the most notable benefits of nanotechnology is the improvement in the mechanical properties of dental materials, leading to stronger, more durable, and aesthetically superior restorations. Nanocomposites, which incorporate nanoscale fillers such as silica and zirconia, have demonstrated superior wear resistance, reduced polymerization shrinkage, and enhanced optical properties, making them ideal for dental restorations that closely resemble natural teeth in both appearance and function (11). The high surface-to-volume ratio of nanoparticles allows for better integration with resin matrices, improving the strength and longevity of restorative materials while minimizing secondary caries formation (15). Additionally, the incorporation of antimicrobial nanoparticles, such as silver and zinc oxide, into dental materials has proven to be highly effective in reducing bacterial adhesion and biofilm formation, thereby lowering the incidence of postoperative infections and enhancing the success rate of restorations (18).

In addition to strengthening restorative materials, nanotechnology has significantly improved patient outcomes by facilitating early diagnosis and personalized treatment approaches. The development of nanosensors and nanobiosensors has enabled real-time monitoring of oral health by detecting biomarkers associated with periodontal disease, oral cancer, and systemic conditions with oral manifestations (10). These highly sensitive diagnostic tools allow for early intervention, reducing the progression of diseases and improving prognosis. Nanotechnology has also enhanced drug delivery mechanisms by enabling targeted therapy with controlled drug release, which is particularly beneficial in the management of periodontal infections and oral inflammatory conditions (25). Nanoparticle-based drug carriers such as liposomes and dendrimers provide localized treatment, reducing systemic side effects while improving therapeutic efficacy (23). Furthermore, the use of nanotechnology in regenerative dentistry has shown promising results in tissue engineering, with nanoscaffolds facilitating the regeneration of damaged dental pulp, periodontal ligament, and alveolar bone, leading to more effective and predictable outcomes in restorative and surgical procedures (19).

The precision and efficiency of dental treatments have also been greatly enhanced by nanotechnology, particularly through the development of smart materials and minimally invasive techniques. Nanorobots, which are still in the early stages of research, hold the potential to revolutionize dentistry by performing targeted procedures such as plaque removal, cavity repair, and precision-based drug delivery without the need for invasive instruments (1). The ability to manipulate dental materials at the nanoscale has allowed for the creation of high-adhesion bonding agents that improve the retention of restorations and orthodontic brackets while reducing the risk of failure (2). Additionally, nanocoatings on dental implants have significantly improved osseointegration by enhancing osteoblast attachment and promoting faster healing, leading to more stable and long-lasting implant restorations (16). These innovations have contributed to reduced treatment times, improved patient comfort, and better long-term outcomes, making nanotechnology an essential component of modern dental care.

Despite the numerous advantages, the application of nanotechnology in dentistry is not without its challenges. One of the primary concerns associated with nanomaterials is their potential cytotoxicity and long-term biocompatibility. Due to their nanoscale size, certain nanoparticles have the ability to penetrate biological membranes and accumulate in tissues, raising concerns about their possible toxic effects on cells and organs (17). Silver and titanium dioxide nanoparticles, while highly effective as antimicrobial agents, have been shown to induce oxidative stress and inflammatory responses in some studies, necessitating further research into their long-term safety (18). The bioaccumulation of nanoparticles in vital organs and their potential impact on systemic health remain areas of concern, requiring thorough in vivo studies and clinical trials to establish their safe use in dentistry (21). The lack of standardized protocols for evaluating the toxicity and degradation of nanomaterials further complicates the regulatory approval process, making it essential for governing bodies to develop comprehensive guidelines for their application in clinical practice (26).

Regulatory challenges also pose significant barriers to the widespread adoption of nanotechnology in dentistry. The introduction of nanomaterials into dental products requires extensive validation through rigorous preclinical and clinical testing to ensure their efficacy and safety. However, the rapid advancement of nanotechnology has outpaced the development of regulatory frameworks, leading to inconsistencies in approval processes across different regions (14). The lack of standardized testing methods for evaluating the biocompatibility, durability, and environmental impact of nanomaterials has resulted in delays in their commercialization and clinical adoption (23). Additionally, concerns regarding the ethical implications of nanotechnology, particularly in areas such as genetic manipulation and artificial intelligence-driven diagnostics, have raised debates about the responsible use of these technologies in healthcare (1). The need for interdisciplinary collaboration between scientists, regulatory agencies, and healthcare professionals is essential to establish clear guidelines for the ethical and safe implementation of nanotechnology in dentistry (13).

Another major challenge in the widespread use of nanotechnology in dentistry is its high cost and limited accessibility. The production of nanomaterials requires advanced manufacturing techniques and specialized equipment, leading to increased costs that may not be feasible for all dental practices, particularly in developing regions (20). The high cost of research and development associated with nanotechnology-based dental materials has also contributed to limited availability, restricting their use to specialized clinics and academic institutions (22). The affordability of nanotechnology-driven dental solutions remains a key concern, as the financial burden may be passed on to patients, potentially widening the gap in access to advanced dental care (15). Efforts to develop cost-effective production methods and integrate nanotechnology into mainstream dentistry without significantly increasing treatment expenses are crucial to ensuring its widespread adoption and equitable access.

Environmental concerns related to the disposal and accumulation of nanomaterials also warrant attention, as the release of nanoparticles into wastewater and ecosystems may pose risks to aquatic life and overall environmental health (24). The long-term environmental impact of nanomaterials, particularly non-biodegradable nanoparticles used in dental coatings and biomaterials, remains an area of active research (1). Strategies for developing eco-friendly and biodegradable nanomaterials are being explored to mitigate potential environmental risks and promote sustainable use of nanotechnology in dentistry (2). Additionally, the ethical responsibility of manufacturers and dental professionals in ensuring the safe disposal and handling of nanomaterials must be emphasized to minimize unintended environmental consequences (10).

In conclusion, nanotechnology has transformed dentistry by offering significant advantages in material properties, treatment precision, and patient outcomes. The development of nanocomposites, antimicrobial coatings, advanced diagnostic tools, and targeted drug delivery systems has contributed to more effective and minimally invasive dental treatments. However, challenges such as cytotoxicity concerns, regulatory hurdles, high costs, and ethical considerations must be addressed to facilitate the safe and widespread implementation of nanotechnology in clinical practice. Continued research, interdisciplinary collaboration, and regulatory advancements will play a crucial role in overcoming these challenges and maximizing the potential of nanotechnology in modern dentistry. As innovations in nanoscience continue to evolve, the future of dentistry is expected to become increasingly precise, biocompatible, and patient-centered, with nanotechnology at the forefront of these advancements.

Future Perspectives and Emerging Trends

The future of nanotechnology in dentistry is expected to bring transformative breakthroughs that will further enhance treatment precision, patient outcomes, and overall efficiency in dental care. Ongoing research and technological advancements suggest that the next phase of nanodentistry will involve the development of intelligent nanomaterials capable of self-repair, enhanced antibacterial properties, and biointegration with oral tissues. Future dental materials are likely to be designed with nanoscale modifications that allow them to mimic the natural properties of enamel and dentin more closely, making them more resilient to mechanical stress and bacterial degradation (11). The introduction of smart nanocoatings for dental implants and restorations, capable of responding to environmental stimuli such as pH changes and microbial activity, will further improve the longevity of dental treatments by preventing biofilm formation and secondary infections (18). Additionally, the development of bioactive nanofillers that release therapeutic ions to promote enamel remineralization and dentin regeneration is expected to become a standard component of restorative and preventive dentistry (17). These advancements will likely lead to dental materials that are not only more durable and biocompatible but also capable of actively participating in oral tissue healing and regeneration.

The integration of nanotechnology with other scientific disciplines is anticipated to drive the next generation of innovations in dental care. The convergence of nanotechnology with artificial intelligence, biotechnology, and regenerative medicine is expected to facilitate the development of highly personalized and minimally invasive treatments. Artificial intelligence, combined with nanosensors and nanobiosensors, will enhance the diagnostic accuracy of oral diseases by providing real-time analysis of biomarkers in saliva, plaque, and gingival crevicular fluid (10). The ability to detect diseases at their earliest stages using AI-driven nanodiagnostics will allow for targeted interventions, reducing the progression of conditions such as periodontal disease and oral cancer (23). Additionally, AI-powered predictive models will be utilized to optimize the design and application of nanomaterials in dental treatments, ensuring more effective and patient-specific approaches to oral healthcare (15). The synergy between AI and nanotechnology is also expected to facilitate the automation of treatment planning, improving the precision of procedures such as orthodontic realignment, implant placement, and restorative designs.

Biotechnology will play a crucial role in enhancing the biocompatibility and regenerative potential of nanomaterials used in dentistry. Advances in nanobiotechnology are expected to lead to the development of bioengineered tissues that integrate seamlessly with natural oral structures, improving the success rates of dental implants and prosthetic restorations (19). The combination of nanomaterials with stem cell therapy is likely to revolutionize regenerative endodontics and periodontal regeneration, offering long-term solutions for the restoration of damaged dental pulp, alveolar bone, and gingival tissues (13). In the future, bioactive nanoscaffolds enriched with growth factors and stem cells may be routinely used to facilitate the regeneration of lost dental tissues, eliminating the need for conventional grafting procedures (21). The controlled release of growth factors and therapeutic agents through nanocarriers will further enhance the healing and integration of bioengineered dental tissues, accelerating the recovery process and improving treatment outcomes (25). The ability to engineer biological dental tissues using nanotechnology-based biomaterials will open new possibilities for personalized and biologically compatible dental care.

One of the most promising developments in nanodentistry is the emergence of nanorobotics, which has the potential to revolutionize dental treatments by enabling highly precise and minimally invasive procedures. The concept of nanodentistry envisions the use of microscopic robotic devices, or nanorobots, that can be programmed to perform complex dental procedures at the cellular and molecular levels (1). Future nanorobots are expected to be capable of autonomously navigating the oral cavity to perform targeted plaque removal, periodontal pocket disinfection, and localized drug delivery with unprecedented accuracy (2). These nanorobots will be designed to interact with specific cellular structures, facilitating the repair of damaged tissues without the need for traditional mechanical instruments. In addition to their therapeutic applications, nanorobots could serve as diagnostic tools, providing real-time imaging and monitoring of oral health conditions at a microscopic level (23). The integration of nanorobotics with wireless communication and AI-assisted control systems will allow for remote monitoring of dental treatments, reducing the need for frequent clinical visits and enabling personalized treatment adjustments based on real-time data.

Beyond conventional dental treatments, nanorobotics is expected to play a vital role in regenerative dentistry by assisting in the reconstruction of enamel, dentin, and pulp tissues at the nanoscale. The ability of nanorobots to precisely position biomolecules and nanomaterials within dental tissues will enhance the efficiency of tissue engineering strategies, leading to more predictable regenerative outcomes (8). In the context of endodontics, nanorobots may be employed to identify and remove infected tissue within the root canal system while simultaneously delivering antimicrobial and regenerative agents to promote healing (3). The prospect of self-repairing dental tissues facilitated by nanorobotic interventions holds the potential to eliminate the need for traditional restorative procedures, reducing the reliance on artificial fillings and prosthetic materials (17). The automation of dental procedures through nanorobotics is also expected to minimize human error and improve the precision of surgical interventions, leading to better long-term clinical outcomes.

The future of nanotechnology in dentistry is also expected to address some of the current challenges associated with biocompatibility and long-term stability of nanomaterials. Research efforts are being directed toward the development of safer and more environmentally friendly nanomaterials that minimize cytotoxicity and bioaccumulation risks (18). The introduction of biodegradable nanomaterials that can naturally degrade within biological systems without causing adverse effects will be a crucial step toward ensuring the long-term safety of nanotechnology-based dental treatments (26). Additionally, advancements in nanomaterial synthesis techniques will allow for greater control over the size, shape, and functional properties of nanoparticles, leading to more predictable interactions with oral tissues and improved treatment outcomes (23). The establishment of standardized protocols for assessing the safety and efficacy of nanomaterials will further facilitate their regulatory approval and clinical adoption (14). By addressing these challenges, future developments in nanodentistry will ensure that the benefits of nanotechnology can be safely and effectively integrated into routine dental practice.

As nanotechnology continues to advance, its applications in personalized dentistry are also expected to expand, leading to more customized treatment approaches tailored to individual patient needs. The ability to fabricate patient-specific dental materials using nanotechnology-based 3D printing techniques will allow for the production of highly precise prosthetic restorations, orthodontic appliances, and implant components (22). Nanotechnology-driven 3D printing will also enable the development of bioresorbable scaffolds that support the natural regeneration of oral tissues, eliminating the need for permanent synthetic materials (24). Additionally, the integration of nanotechnology with genomics and personalized medicine will allow for the development of targeted therapeutics that consider a patient's genetic profile, optimizing treatment efficacy and reducing adverse reactions (2). The emergence of patient-specific nanomedicine in dentistry will revolutionize the way dental diseases are diagnosed, treated, and prevented, offering a new era of precision healthcare.

In conclusion, the future of nanotechnology in dentistry holds immense promise for advancing treatment modalities, improving diagnostic accuracy, and enabling personalized, minimally invasive dental care. The integration of nanotechnology with artificial intelligence, biotechnology, and regenerative medicine will drive the development of intelligent dental materials, bioengineered tissues, and highly precise nanorobotic interventions. The automation of dental procedures through nanorobotics is expected to redefine clinical practice, offering unparalleled accuracy and efficiency in diagnosis and treatment. Continued research into the safety, biocompatibility, and regulatory aspects of nanomaterials will be essential to ensuring their widespread clinical adoption. As nanotechnology continues to evolve, its role in dentistry will expand, transforming conventional approaches to oral healthcare and paving the way for innovative solutions that enhance patient outcomes and overall treatment experiences.

Conclusion

Nanotechnology has revolutionized modern dentistry by introducing innovative materials and techniques that have significantly improved the quality, efficiency, and precision of dental care. The integration of nanomaterials into various dental applications has enhanced the mechanical strength, biocompatibility, and antimicrobial properties of restorative materials, making them more durable and aesthetically appealing. These advancements have led to the development of stronger and more resilient dental composites, nanoceramics, and implant coatings that not only provide long-lasting restorations but also reduce the risk of bacterial infections and secondary caries. The introduction of nanotechnology into preventive dentistry has further contributed to enhanced oral health by improving fluoride delivery systems, promoting enamel remineralization, and developing antimicrobial coatings that help reduce plaque formation and periodontal diseases.

One of the most significant contributions of nanotechnology to dentistry has been its role in diagnostic and therapeutic advancements. The development of nanosensors and nanobiosensors has allowed for early and accurate detection of oral diseases, leading to timely interventions and improved patient outcomes. These diagnostic tools have the potential to detect biomarkers associated with conditions such as periodontitis, oral cancer, and systemic diseases, enabling clinicians to adopt a more personalized approach to treatment. Additionally, the use of nanotechnology in drug delivery has allowed for the controlled and targeted release of therapeutic agents, minimizing systemic side effects while maximizing local efficacy. Nanoparticle-based drug carriers have proven to be particularly effective in managing conditions such as periodontal infections, oral mucositis, and endodontic diseases, leading to more efficient and less invasive treatment options.

In the field of regenerative dentistry, nanotechnology has played a crucial role in developing bioengineered tissues and scaffolds that support the regeneration of damaged dental and periodontal structures. The ability of nanomaterials to mimic the extracellular matrix of natural tissues has facilitated the growth and differentiation of cells, leading to improved outcomes in bone regeneration, periodontal ligament repair, and pulp tissue engineering. The use of nanoscaffolds enriched with bioactive nanoparticles and growth factors has further accelerated the healing process, offering promising solutions for patients suffering from severe tooth and gum damage. These advancements in regenerative dentistry have paved the way for more biologically compatible and long-lasting treatment options that go beyond traditional restorative and prosthetic approaches.

Nanorobotics represents one of the most exciting frontiers in nanodentistry, with the potential to revolutionize the way dental procedures are performed. The concept of microscopic robotic devices capable of autonomously navigating the oral cavity to perform precise and minimally invasive treatments holds the promise of transforming dental care. Future applications of nanorobotics may include targeted plaque removal, precision-based drug delivery, and real-time monitoring of oral health conditions at the molecular level. The ability of nanorobots to repair enamel, dentin, and soft tissues at the cellular scale could eliminate the need for conventional fillings and prosthetic replacements, offering truly regenerative solutions for tooth decay and damage. As research in this area progresses, the integration of nanorobotics with artificial intelligence and real-time imaging technologies is expected to further enhance the accuracy and efficiency of dental treatments.

Despite the remarkable advancements and potential of nanotechnology in dentistry, several challenges must be addressed to ensure its safe and widespread adoption in clinical practice. Concerns regarding the long-term biocompatibility and toxicity of certain nanoparticles need to be thoroughly investigated to mitigate any potential health risks associated with their use. The ability of nanoparticles to penetrate biological membranes and accumulate in tissues raises questions about their systemic effects, making it essential to establish standardized safety protocols and regulatory guidelines. Additionally, the high cost of nanotechnology-based materials and treatments remains a barrier to accessibility, requiring further research into cost-effective manufacturing methods that can make these innovations more widely available. Ethical considerations related to the use of nanotechnology in dental care also warrant careful attention, particularly in areas such as genetic manipulation, artificial intelligence-driven diagnostics, and data privacy in personalized medicine.

The future of nanotechnology in dentistry is poised to bring even more groundbreaking developments, with continued research expected to drive innovation across multiple disciplines. The convergence of nanotechnology with artificial intelligence, biotechnology, and regenerative medicine will further expand the possibilities for personalized and minimally invasive dental care. The emergence of smart dental materials capable of responding to environmental changes, bioengineered tissues that seamlessly integrate with natural oral structures, and self-repairing nanomaterials that eliminate the need for traditional restorations will redefine the standard of dental treatments. The ability to combine nanotechnology with 3D printing and genetic engineering will open new avenues for patient-specific solutions, leading to highly customized and biologically tailored approaches to oral healthcare.

As nanotechnology continues to evolve, its role in improving patient care, enhancing treatment efficacy, and reducing the need for invasive procedures will become increasingly evident. The ongoing development of safer, more cost-effective, and environmentally sustainable nanomaterials will further support the integration of these technologies into everyday dental practice. Collaboration between researchers, clinicians, regulatory agencies, and industry stakeholders will be essential in ensuring that the benefits of nanotechnology are maximized while potential risks are carefully managed. With the continued advancement of nanoscience and its applications in dentistry, the future of oral healthcare is set to become more precise, efficient, and patient-centered, ultimately improving the quality of life for individuals worldwide.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

None.

Authors' Contributions

All authors equally contributed to this study.

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