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REVIEW

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Explore the most recent developments and upcoming outlooks in the field of dental nanomaterials

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Abstract

Background The rapid evolution of nanotechnology has fundamentally transformed both medical and dental fields. By harnessing nanomaterials, researchers have unlocked the ability to replicate natural tissue structures and properties, significantly enhancing integration processes. Notably, nanostructures have emerged as pivotal elements in oral medicine, particularly in combating dental caries and enhancing outcomes in dental implants and maxillofacial surgeries.

Main body of the abstract Nanostructures play multifaceted roles in oral health, promoting osseointegration and expediting healing processes in dental procedures. The impact of these materials extends to improving the adhesive strength and overall properties of dental composites. This review critically evaluates the influence of nanointerfaces on the longevity of dental restorations, exploring innovative nanotechnological interventions aimed at augmenting restoration durability. Furthermore, recent strides in nanodentistry are discussed, highlighting breakthroughs in oral health diagnostics, preventative strategies, and treatment modalities essential for achieving and sustaining optimal oral health.

Short conclusion Incorporating nanotechnology into dental practice presents exciting prospects for advancing oral healthcare. From enhancing restoration durability to revolutionizing diagnostics and treatments, nanotechnology offers transformative solutions that hold significant promise for the future of oral health management.

Keywords Nanotechnology, Nanodentistry, Nanocomposite, Nanointerfaces

1 Background

The term "nano" has its roots in the Greek word "nanos," which means "very small" and is used to describe the nanoscale, typically ranging from 1 to 100 nm. This scale is considered ideal for working with tiny particles and materials. The concept of nanotechnology was first introduced by Richard Feynman in his 1959 lecture at Caltech. In this lecture, he delved into the realm of information at a minuscule scale, foreshadowing the inevitable integration of small robots and computers [1].

Nanodentistry is a cutting-edge area that offers new possibilities for improving dental treatments and procedures. It leverages nanoparticles to enhance dental materials, resulting in improved translucency, wear resistance, and osseointegration. Future nanotechnology-based local anesthetics may involve dental robots suspended in a colloidal solution, offering temporary pain relief through localized anesthesia. These nanosized particles enable

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precise delivery and excellent sealing of irregular surfaces. Materials such as hydroxyapatite, which is created with nanotechnology, exhibit biocompatibility, bioactivity, and antimicrobial properties. Nanosized instruments, such as suture needles and tweezers, provide strength and corrosion resistance for cellular-level surgeries. Furthermore, nanocoated archwires and brackets reduce friction in orthodontics, while the potential use of nanorobots in dentifrices could help remove plaque and prevent oral diseases. In addition, tiny nanoparticles known as quantum dots can be employed for cancer detection by binding to cancer cells [2].

Dentistry may explore various avenues for potential treatment opportunities, such as employing distinct methodologies. One approach involves the assembly of particles by combining atomic elements, known as the bottom-up approach. This technique has applications in local anesthetics, orthodontic treatment, and the diagnosis and treatment of oral cancer. On the other hand, the top-down approach involves the use of equipment to mechanically fabricate nanoscale objects. This method is employed in the creation of nanocomposites, impression materials, and bone replacement materials. Notably, nanoparticles have recently been utilized in the development of new dental materials to enhance their antibacterial properties [3, 4].

Nanodentistry represents an evolving field that introduces cutting-edge clinical tools and devices for advanced oral healthcare. Nanotechnology holds the potential to offer substantial benefits to the field of dentistry, spanning from experimental studies in the laboratory to real-world clinical use. (Fig. 1) [5].

2 Unraveling the potential of nanoscales

2.1 Understanding nanoscale dimensions

Typically, any substance designated as a nanomaterial falls within the range of 1 to 100 nm in size, and its characteristics are expected to be distinctively improved compared to those of the corresponding bulk materials [6]. The nanoscale does not merely serve as an intermediate stage between the molecular and macroscopic, but rather, it is dimensionally purposefully tailored for the acquisition, manipulation, and transmission of chemical-based information [7].

The term 'pars' in Latin, meaning 'part,' aptly captures the essence of nanoparticle fabrication. NPs can be fashioned using either a top-down or bottom-up approach, with each method focusing on manipulating and assembling individual parts on a nanoscale. Furthermore, the synthesis techniques for nanoparticles are contingent upon the material category to which the particle pertains, whether it is a metal, ceramic, or polymer. Understanding this foundational concept of 'part' in nanoparticle formation is a key to mastering the intricate processes involved in nanotechnology. However, it is crucial to note that this principle of manipulating and assembling individual parts on the nanoscale is not limited to engineered materials but also plays an essential role in shaping the

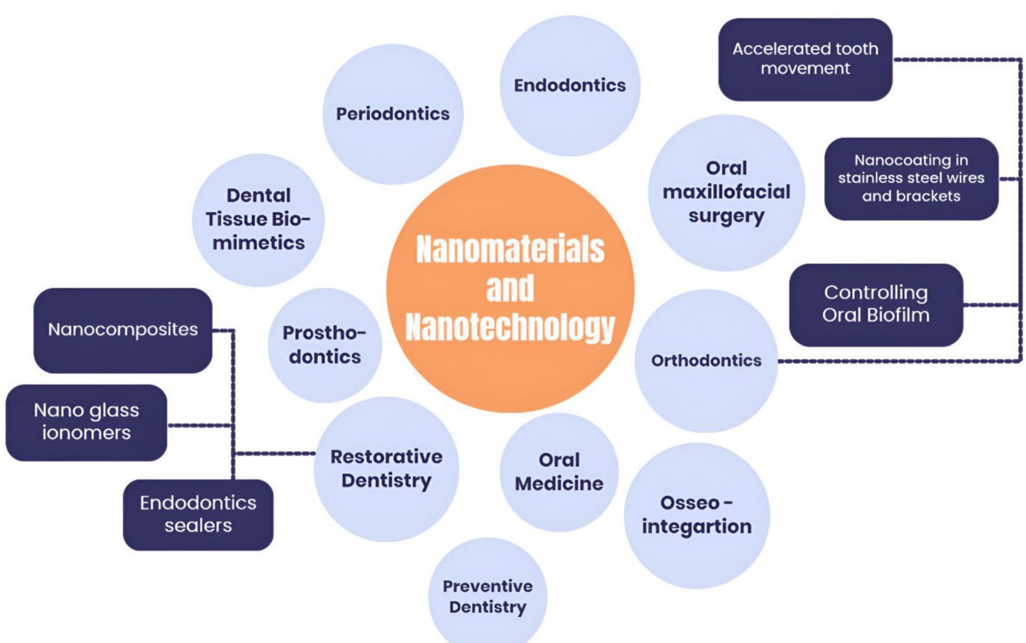

Fig. 1 Shows the wide range of applications of nanomaterials and nanotechnology in various fields of dentistry [1]

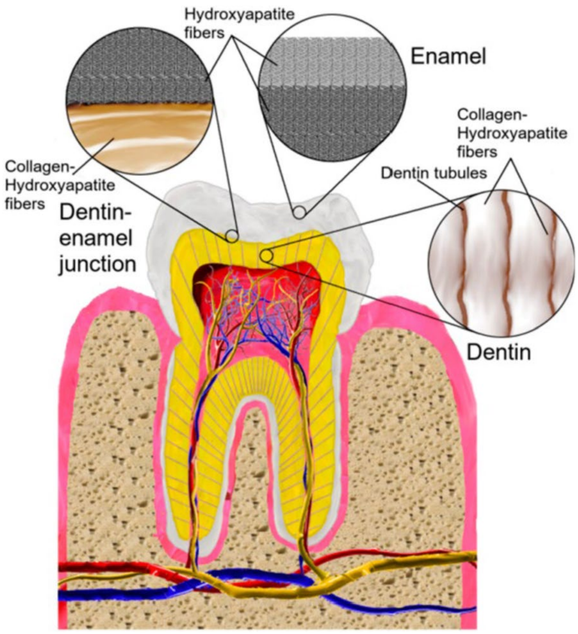

Fig. 2 Shows a detailed view of the tooth nanostructure, where densely packed hydroxyapatite crystals, the main component of enamel, form rod-like structures. These crystals extend into the dentin and are also present at the dentinoenamel junction, contributing to the overall strength and hardness of the tooth [11]

intricate nanostructures found in biological materials such as teeth (Fig. 2).

The creation of nanoparticles can occur through solid-, liquid-, or gas-phase methods. The choice of synthesis method impacts the nanoparticle shape, resulting in either irregular or uniform forms, and determines the breadth or precision of the particle size distribution. To produce ceramic nanoparticles using the traditional top-down approach, one typically employs very fine grinding or colloid milling techniques. In the case of ball mills, steel or similar balls rotate within a hollow cylinder, effectively crushing the material through a combination of impact and attrition. In contrast, a ring and ball mill are composed of two distinct rings separated by a series of large balls, functioning much like a thrust bearing, which crushes the material positioned between them. Alternatively, attrition mills reduce the size of solid particles through the vigorous agitation of a slurry containing the material to be milled and coarse grinding media. These mills are frequently utilized in the creation of ceramic nanoparticles, resulting in sizes as small as a few tens of nanometers [8].

2.2 Unprecedented properties of the nanomaterials

Specifically, ultrasmall nanoparticles measuring less than 10 nm display distinctive characteristics in contrast to larger bulk particles. Furthermore, reducing the size significantly changes the optical, electrical, and magnetic properties of nanomaterials. Among the array of unique features, the fundamental attributes can be fine-tuned by adjusting the sizes and shapes of these materials. The surface areas of nanomaterials are consistently considerably larger than those of their bulk counterparts, and this trait applies universally to all nanomaterials. Notably, the magnetic behavior of elements can undergo a transformation on the nanoscale. Even nonmagnetic elements can develop magnetic properties at this level. The quantum effects are more pronounced at the nanoscale, although the precise size at which these effects manifest is contingent on the specific semiconductor material. Due to the inherent nature of nanomaterials, exceptional thermal and electrical conductivity can be observed at the nanoscale, surpassing the performance of bulk materials. Nanomaterials show exceptional mechanical characteristics not present in their larger-scale counterparts. Additionally, steric attributes, such as hollow spheres, offer heightened selectivity for precise drug transport and controlled release. Nanodrug delivery systems (DDSs) have been designed with the aim of enhancing drug effectiveness while mitigating the toxicity of the loaded drugs. However, only a limited number of these systems have found practical applications in clinical settings. Furthermore, certain nanomaterials demonstrate remarkable abilities to combat viral, bacterial, and fungal infections, making them promising candidates for treating diseases caused by pathogens [9]. The utilization of nanoparticles (NPs) as catalysts represents a rapidly advancing domain in the realm of chemical catalysis. Compared with their bulk counterparts, NP catalysts have been shown to exhibit significantly improved or entirely new catalytic attributes, including improved reactivity and selectivity. The catalytic properties of these NPs are contingent upon factors such as their size, shape, composition, interparticle spacing, oxidation state, and support [10].

The adoption of nanotechnology offers numerous advantages to patients. It frequently enables more potent treatments, primarily through the implementation of targeted drug delivery systems. This approach enhances the drug concentration at the intended site of action while minimizing systemic side effects. In the field of regenerative medicine, nanotechnology plays a substantial role, significantly shortening recovery periods. The use of highly biocompatible materials speeds up tissue regeneration processes. Collectively, these factors foster the development of personalized therapies tailored to precisely meet a patient's diagnostic needs [11].

Various types of nanomaterials can be categorized by their dimensions: zero-dimensional, one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanostructures. These materials have applications in the fields of medicine and dentistry, particularly for the early diagnosis of disease. One-dimensional nanostructures are referred to as sheets, two-dimensional nanostructures take the form of nanotubes and nanowires, and three-dimensional nanostructures include quantum dots [5]. Additionally, nanomaterials can be classified based on their origin. They can either be natural nanomaterials originating from natural processes such as biological species or human activities or synthetic (engineering) nanomaterials. Synthetic nanomaterials are created through mechanical grinding, engine emissions, or synthesis methods involving physical, chemical, biological, or hybrid approaches [3].

3 Nanoparticles in restorative dentistry

3.1 Nanocomposite resins for enhanced durability

The integration of nanoparticles has revolutionized the development of modified nanocomposites, ushering in a new era of enhanced physical and mechanical properties. Extensive research has firmly established that the key determinants for elevating the performance of composite resins lie in both the quantity and uniform dispersion of nanoparticles. This crucial advancement arises from the dual effect of reducing the particle size while concurrently augmenting the filler volume, resulting in a discernible increase in the surface hardness and compressive strength of the composite. Prominent materials such as the 3M Filtek One Bulk Fill Restorative and the Ivoclar Vivadent Tetric EvoCeram Bulk Fill illustrate this transformative trend. These examples stand as a testament to the strategic integration of nanoparticles, which underpins the heightened attributes exhibited by these advanced composite resins. Bulk-fill composites demonstrate minimal shrinkage stress while polymerizing and display satisfactory deformation behavior under loading, indicating high dimensional stability. Moreover, the wear resistance of bulk-fill composite resins was found to be significantly greater than that of conventional composite resins, as indicated by a p value less than 0.05 [12, 13]. Similarly, the Kuraray Noritake KATANA™ Avencia Block and Tokuyama Estelite Bulk Fill Flow serve as compelling demonstrations of this paradigm shift, demonstrating the broad applicability and effectiveness of nanoparticle-based enhancements. A study conducted by researchers revealed that the Bulk Fill variant under investigation comprises filler particles with both regular and spherical shapes embedded within a matrix. This particular composition demonstrated enhanced bonding capabilities and polymerization, potentially leading to an overall improvement in adhesive strength [14, 15].

Moreover, products such as Dentsply Sirona Prime & Bond Active and VOCO GrandioSO Heavy Flow underscore the pervasive impact of nanoparticle technology across diverse formulations, reaffirming its pivotal role in increasing the performance of composite resins to new heights. This collective body of evidence highlights the critical importance of cement nanoparticle manipulation in crafting superior properties of composite materials, heralding a promising future for advanced material science [12, 16].

3.2 Nanoadhesives for seamless integration

Various studies and advancements in dental research have revealed promising advancements in dental adhesives, showing their potential to achieve robust bond strength through the incorporation of nanosized metal particles [17]. Within restorative dentistry, the adhesive layer assumes a critical role in tooth-colored restorations, effectively mitigating microleakage between the tooth and the restoration material subsequent to polymerization shrinkage. Notably, the nanobonded adhesive, whether applied in one or two layers, exhibited reduced microleakage. This phenomenon is attributed to elevated filler levels and diminished particle sizes in nanobonded adhesives [18].

The integration of dental adhesive systems into clinical practice has markedly enhanced seal adhesion to tooth structures, particularly dentin, a crucial determinant of sealing durability in restorative dentistry. These adhesive systems conventionally comprise three primary components: etchants, primers, and adhesives. The introduction of a filler into composites leads to a reduction in polycarboxylate content, resulting in fewer chemical bonds. This, in turn, is associated with weaker adhesion. The storage of cement in water for a period of two years leads to the release of fillers, thereby causing a reduction in micromechanical interactions. It is crucial to bear in mind that the addition of a filler to a composite material results in a decrease in the polycarboxylate content, leading to a lower quantity of chemical bonds. Consequently, this scenario is connected to a weakened adhesion. The removal of fillers with larger particle sizes leads to a notable decrease in mechanical adhesion. Simultaneously, such fillers possess a low surface-to-volume ratio, consequently reducing the quantity of monomers bound to dentin. As a result, the release of nanofillers from a nanofilled glass ionomer has a minimal impact on the adhesion strength. Notably, nanofillers boast a heightened surface-to-volume ratio, allowing their integration into cement with a greater abundance of binding material for the tooth monomers [11]. This enhancement underscores the potential for significant improvements in adhesion strength.

4 Nanotechnology in oral hygiene

4.1 Nanoinfused toothpaste

Nanoinfused toothpaste is at the forefront of a revolution in oral hygiene, employing microscopic warriors to wage an effective battle against plaque. These innovative formulations incorporate a diverse array of nanoactive materials, each bringing its own unique strengths to the forefront. For instance, calcium phosphate nanoparticles, especially nanohydroxyapatite (nHA), play a vital role in enhancing enamel strength, thereby promoting overall dental health. Nanohydroxyapatite, which closely resembles natural tooth enamel, facilitates remineralization, effectively fortifying teeth against decay. Metal nanoparticles, particularly in combating bacteria, have been a subject of extensive study. Gold nanoparticles have been found to have antibacterial properties, making them potentially useful in medical disinfection applications [19]. Additionally, they are known to generate reactive oxygen species (ROS) on the surface of oxides, aiding in resistance against a broad spectrum of microorganisms [20, 21]. Moreover, numerous other nanomaterials have been incorporated into toothpaste, and their properties and contributions are discussed in the table below.

Nanomaterials	Properties	References
Silica nanoparticles	SiO2 NPs in toothpaste offer superior plaque and stain removal due to their small size, enabling deep cleaning in tight spaces. Their high surface area efficiently binds and eliminates bacteria and debris from teeth and gums. Additionally, they enhance toothpaste texture for easier application and a more pleasant user experience	[22]
titanium dioxide nanoparticles	TiO2 NPs in toothpaste act as a whitening agent and offer ultraviolet (UV) protection. Their small size allows for deep cleaning between teeth. They also have a high surface area for UV absorption, safeguarding teeth and gums. Furthermore, they enhance the texture for easy application and a pleasant user experience	[22]
calcium carbonate nanoparticles	Toothpastes with calcium carbonate nanoparticles and 3% nanosized sodium trimetaphosphate promote remineralization of early carious lesions compared to conventional ones. The nanoparticles penetrate deeper into the tooth structure, providing more surface area for interaction. They also enhance the toothpaste's mechanical strength, leading to better cleaning and polishing	[23]
nanosized sodium trimetaphosphate	Nanosized trimetaphosphate boosts tooth remineralization, aiding in caries prevention and reversal. It also has antibacterial properties, lowering oral infection risk. Additionally, it forms a protective layer, guarding against demineralization and acid attacks	[24]
Selenium nanoparticles	Selenium nanoparticles in toothpaste have potent antimicrobial properties against cariogenic pathogens, preventing dental caries. They also act as antioxidants, shielding teeth, and gums from oxidative stress. These nanoparticles are biocompatible and cost-effective, making them appealing for dental care products	[25]
Chitosan nanoparticles	Chitosan nanoparticles in toothpaste offer antibacterial properties, reducing harmful bacteria and preventing plaque and cavities. They also have anti-inflammatory effects, reducing gum inflammation and preventing gum disease. Additionally, they effectively remineralize tooth enamel, strengthening teeth and preventing decay. Overall, adding chitosan nanoparticles to toothpaste can enhance oral health and prevent dental issues	[21]
Tricalcium phosphate nanoparticles	Tricalcium phosphate NPs, when added to toothpaste, acts as a bioactive agent, aiding in enamel remineralization, reducing sensitivity, and strengthening teeth to prevent cavities. Its antibacterial properties also lower the risk of oral infections, including gum disease	[26]

4.2 Targeted antimicrobial action for superior oral health

The introduction of nanoparticles within mouthwash formulations has ushered in a groundbreaking era of antimicrobial efficacy, as they hold great promise for enhancing oral hygiene. Among these remarkable nanoparticles, zein-coated magnesium oxide (MgO) nanoparticles have emerged as noteworthy contenders. In vitro studies have revealed their exceptional ability to combat a wide spectrum of oral microorganisms, including notorious pathogens such as *Streptococcus mutans*, *Staphylococcus aureus*, *Enterococcus faecalis*, and *Candida albicans*, when integrated into mouthwash [27]. Their demonstrated effectiveness in inhibiting the growth of these pathogenic species signifies a significant stride in the battle against common oral infections.

Another formidable nanoparticle to highlight is silver nanoparticles, which are renowned for their potent antimicrobial properties. Although not specifically tested within mouthwash formulations, in vivo studies conducted in rabbits have underscored their superiority over traditional chlorhexidine mouthwashes in terms of antimicrobial effectiveness. Furthermore, in vitro experiments have illuminated the bactericidal ability of silver nanoparticles, particularly against *S. mutans*, when they are employed as a mouthwash, suggesting their potential as a game-changing addition to oral care practices [28, 29].

Moreover, titanium dioxide (TiO2) nanoparticles have emerged as pivotal players in advancing oral hygiene. Mouthwash solutions enriched with TiO_2 nanoparticles have consistently demonstrated superior antibacterial activity against a range of oral pathogenic microorganisms in controlled in vitro settings. This underscores their capacity to offer heightened protection against prevalent oral health challenges when seamlessly integrated into mouthwash formulations. In summary, nanoparticles such as zein-coated MgO, silver, and TiO_2 are spearheading innovations in the realm of mouthwash development, ushering in a promising future of heightened antimicrobial oral care [30].

5 Clinical applications of nano-dental materials

Nanotechnology has evolved significantly, transitioning from a theoretical concept to being integrated into various areas of life, including dentistry. The principles of nanotechnology have revolutionized conventional dental technology, leading to a shift in research perspectives across dentistry domains such as prosthodontics and orthodontics. Dental practitioners primarily focus on preventive treatments for dental caries and periodontal disease. However, when teeth or periodontium are affected by infectious diseases, treatment aims to eliminate pathogens, remove decayed tissues, and provide durable oral cavity functionality (Fig. 3). Different approaches, such as top-down, bottom-up, biomimetic, and functional approaches, have been explored for each aspect.

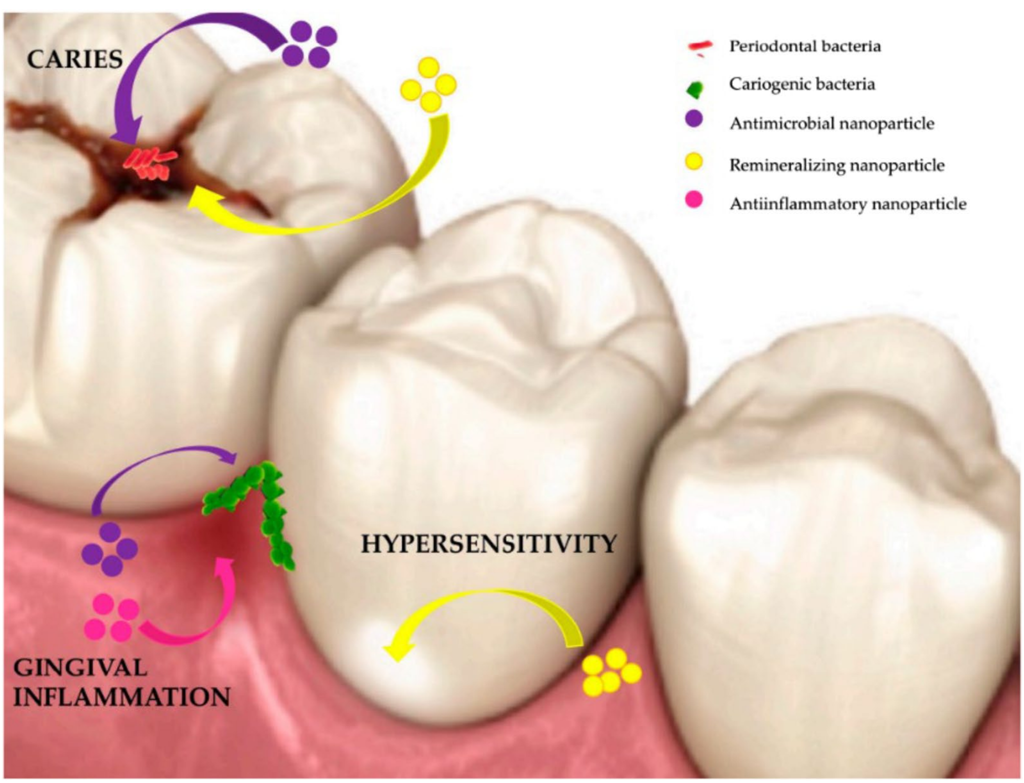

Fig. 3 Shows the potential of NPs in tackling various oral health problems, including cavities, gingivitis, and hypersensitivity [21]

6 Biocompatibility unveiled

6.1 Assessing nanomaterial interactions

Nanomaterials with inherent biocompatibility are engineered for use in various sectors of the food industry. By customizing their shape, density, and size, it becomes possible to synthesize biocompatible nanomaterials that offer reduced toxicity, minimized gastrointestinal effects, and bolstered immune responses. These tailored nanomaterials can selectively target specific organs and tissues, demonstrating compatibility with functional foods and nutraceuticals. Their versatility spans critical functions in food safety, processing, quality control, packaging, and labeling. This encompasses tasks such as detecting toxins and pathogens, producing biocompatible packaging, enhancing color, flavor, and aroma, creating edible films, and verifying the authenticity of food products [31, 32]. A groundbreaking solution, solution blow spinning (SBS), has revolutionized the fabrication of nanofiber materials, addressing the limitations of gelatin (GA) in food packaging. By incorporating nylon 66 (PA66), the mechanical properties and resistance to dissolution of gelatin films were significantly enhanced. These promising results highlight the potential of SBS for the rapid production of nanofibrous films for food packaging while demonstrating the versatility of PA66 in modifying gelatin films [33].

6.2 The potential risks of nanomaterials

The increasing use of nanomaterials calls for ongoing vigilance regarding their potential toxicity and exposure in diverse settings. Employing a scientific methodology that encompasses chemical, physical, and biological approaches, in tandem with engineering practices, allows for a thorough evaluation and control of nanomaterial toxicity. This evaluation takes into account key factors such as properties, structure, composition, and environmental and health impacts. In essence, having a comprehensive model for assessing and managing risks is vital for making well-informed decisions regarding nanomaterial applications [32].

6.3 Risk assessment and risk management of nanomaterial toxicity

Despite the multitude of advantages and beneficial uses of nanomaterials, numerous investigations have revealed the negative and damaging impacts of nanomaterials (NM) on living cells, the environment, and ecological balance. The most significant factors that can affect the potential toxicity of NPs are particle size, surface area, surface chemistry, surface charge, and zeta potential. These elements are necessary for nanoparticles to enter live cells, remain there, and cause biological harm. In this regard, it has been reported that lung tumors in rodent models can be induced by certain toxic nanoscale substances through mechanisms that resemble those observed with fine particles. These mechanisms involve DNA damage and heightened cell proliferation, which are linked to persistent irritation and chronic inflammation in the lungs. Additionally, it has been observed that carbon nanotubes exhibit a greater level of pulmonary toxicity in mice than does fine-scale carbon graphite. This toxicity is characterized by inflammation and the formation of granulomas. Additionally, the presence of metals in carbon nanotubes may also contribute to their toxic effects. Moreover, titanium dioxide has been demonstrated to induce lung tumors in various rat species. One potential approach to analyzing the dose–response relationship in rats could involve performing a quantitative risk assessment to evaluate the toxicity of TiO_2. Additionally, chronic pulmonary inflammation in rats and a proinflammatory effect in cultured human endothelial cells were identified as two other toxic impacts associated with TiO_2 exposure [34].

7 Nanosensors and diagnostics: unraveling oral health secrets

7.1 Nanoscale devices for early disease detection

Diverse types of nanoparticles, including fluorescent, magnetic, and metallic variants, have proven to be highly effective in the diagnosis of infectious diseases. Fluorescent nanoparticles function as sensitive and photostable probes capable of labeling multiple biological targets. These nanoparticles are easily synthesized through polymers that enhance the encapsulation of fluorophores, resulting in stable and versatile nanoparticles that outperform organic dyes. Additionally, the straightforward functionalization of fluorescent nanoparticles is facilitated by the presence of functional groups such as carboxylic acids, amines, and esters. Magnetic nanoparticles (MNPs) serve as contrast agents in magnetic resonance imaging (MRI) and have also found utility in the immunomagnetic separation of nucleic acids, proteins, and pathogens when conjugated with antibodies. The shape and magnetic properties of MNPs can be adjusted by varying synthesis parameters such as the timing of polymer addition, the temperature, and the use of specific capping agents and surface modifications. This flexibility enables the incorporation of functional groups for attaching various ligands, such as antibodies, proteins, and nucleic acids, to facilitate target identification and quantification [19, 35].

In dentistry, nanotechnology has diverse applications within the field, where nanomaterials are undergoing extensive research for the detection and diagnosis of oral conditions such as oral cancer, dental caries, periodontal disease, and halitosis. These nanomaterials encompass a range of options, such as metals and metal oxide nanoparticles, which serve as carriers or agents for enhancing MRI and ultrasound imaging; carbon nanotubes, which are employed in diagnosing deoxyribonucleic acid (DNA) transformation biomarkers and monitoring changes in protein structure; nanocore shells, which are utilized for contrast imaging in the detection of tumors; and 1D and 2D nanostructures [35, 36].

7.2 Biomarkers at the nanolevel

Harnessing saliva for tracking a patient's well-being and disease status is a coveted objective in the realms of health promotion and healthcare research [37].

Saliva has the potential to provide insights into a wide range of health and disease conditions within the body. Numerous research efforts have focused on the development of microfluidics and microelectromechanical systems for salivary diagnostics. These systems use small saliva samples and integrated detection techniques to conduct diagnostic assessments. For instance, elevated glucose levels in saliva can lead to an excess of lactic acid in plaque metabolism, increasing the risk of dental caries. Organic electrochemical transistors coated with platinum nanoparticles can selectively identify the presence of glucose and lactate in saliva. Various types of salivary biomarkers can be detected using nanoparticle-based biosensors. Through functionalization and chemical modifications of these nanoparticles, such as graphene and carbon nanotubes, hybrid compounds can be created to detect various substances in saliva. Additionally, magnetic nanoinclusions such as ferroferric nanoparticles, when combined with polymers, can enhance or convert them into sensing materials. Modifying the hydroxyl groups of nanoparticles with a silane-type coupling agent can result in novel sensing materials for periodontal disease [36].

8 Nanotechnology in endodontics: rooting for microscopic precision

8.1 Navigating root canals: nano-tools for optimal treatment

Endodontics, a specialized field in dentistry, delves into the intricate anatomy and physiology of the endodontium. It encompasses a comprehensive understanding of genetics, pathology, and epidemiology, as well as preventive measures, all of which converge in the effective treatment of endodontic and periapical ailments [38]. The effective cleaning and disinfection of intricate root canal networks are substantial difficulties during root canal treatments. Traditional methods frequently fail to thoroughly remove bacteria and debris, which results in treatment failure or reinfection [39]. A potential remedy for these restrictions is provided by nanotools. These pieces of equipment include incredibly tiny instruments and materials that were specially developed at the nanoscale to improve the accuracy and efficiency of root canal treatments. The combination of root canal treatments with nanotechnology has great potential to improve patient comfort and treatment results. The qualities of materials used in dentistry, such as durability, tissue regeneration, and antibacterial capabilities, can increase due to the growing diversity of nanoparticles (Fig. 4), including bioactive glass, zirconia, chitosan, hydroxyapatite, silver particles, and zinc oxide [38]. Moreover, nanotechnology has contributed to the development of imaging techniques that aid in the diagnosis and treatment planning of root canals. In imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI), nanoparticles can be utilized as contrast agents. By making the root canal system more visible, these contrast agents enable more precise determination of the level of infection and the location of anatomical features [38]. To evaluate the long-term effects of nanoparticles used in endodontic treatment, particularly their immunogenicity, biocompatibility, and/or biodegradability, more research must be performed in accordance with the high standards of evidence-based medicine (EBM), as well as careful follow-up after the end of treatment [38, 40].

8.2 Regenerative endodontics: nanoscaffolds for tissue engineering

A new area of dentistry called regenerative endodontics aims to regenerate sick or damaged tooth pulp and related tissues rather than eliminate them through conventional root canal therapy. By encouraging the development of new, healthy tissues, this procedure aims to restore tooth functionality and vitality [41]. Regenerative endodontics heavily relies on tissue engineering, and nanotechnology has emerged as a promising tool for creating nanoscaffolds that facilitate tissue regeneration [42]. A framework for cell attachment, development, and differentiation is provided by nanoscaffolds, which are three-dimensional structures formed of nanoscale materials that resemble the extracellular matrix in living organisms. Nanoscaffolds offer several advantages for tissue engineering in regenerative endodontics. First, because of how closely their nanoscale characteristics mirror the structure of real tissues, it is possible to precisely control the cellular activity and development of tissue. A high surface area-to-volume ratio of nanoscaffolds fosters cellular connections and improves nutrient exchange, both of which are crucial for tissue development and regeneration. In addition, nanoparticles incorporated into nanoscaffolds can impart unique functionalities [43]. To prevent infection and encourage a sterile environment for tissue

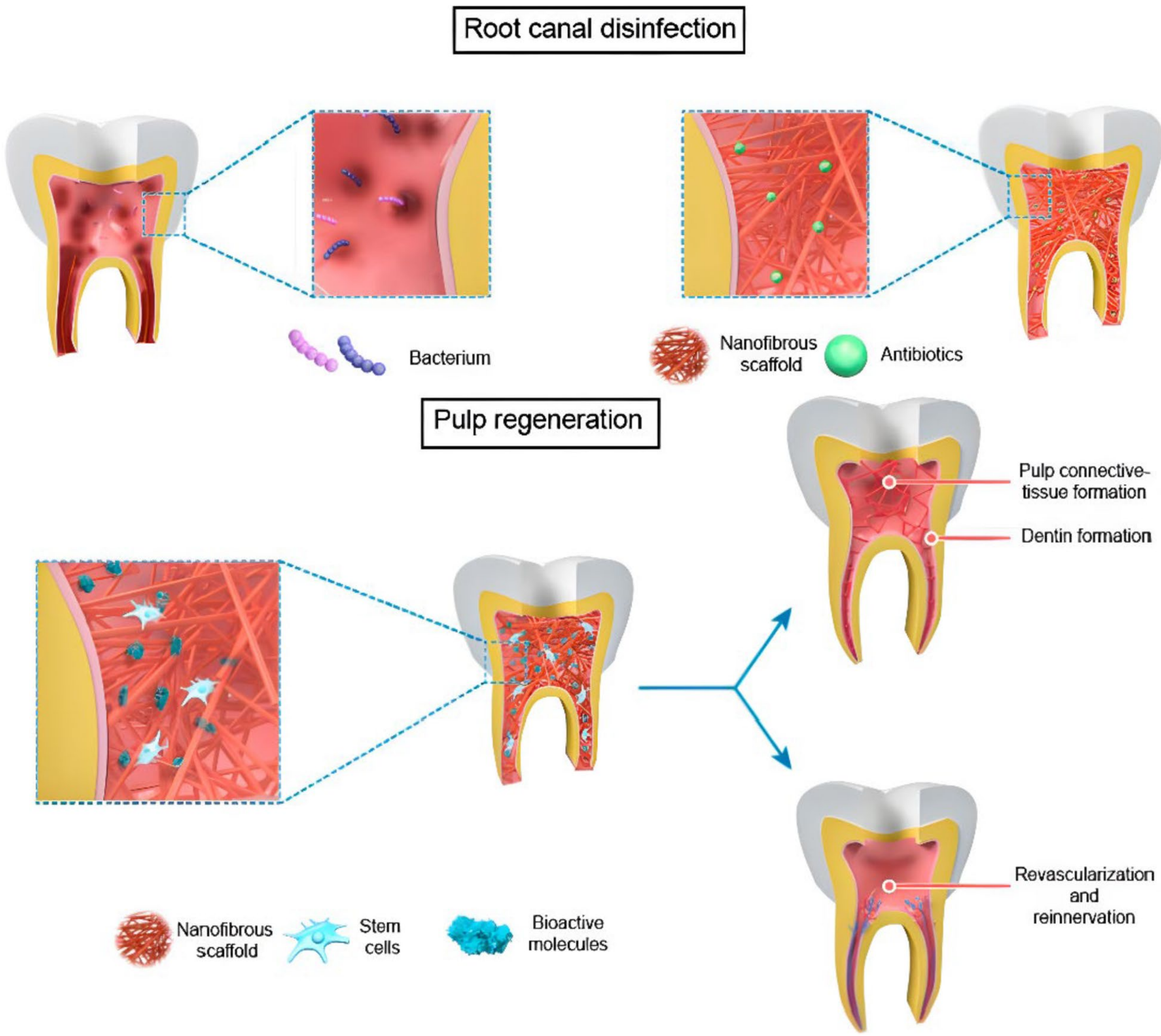

Fig. 4 Provides a closer look at the regenerative potential of nanofibrous scaffolds in endodontics. These intricate structures facilitate a 3D structure that mimics the natural extracellular matrix of the pulp, which helps guide the growth of new tissue. It precisely delivers bioactive molecules that can stimulate the differentiation of stem cells into dentin-forming cells and blood vessel cells [40]

regeneration, for example, antimicrobial compounds can be incorporated into nanoparticles and released as necessary. They can also be used as imaging tools to track the development of new tissue and evaluate the efficacy of treatments [44].

The future of dental therapy is bright thanks to regenerative endodontics, and nanoscaffolds are becoming important resources for tissue engineering in this area. The creation of scaffolds that encourage tissue regeneration and restore dental function is made possible by the precise control and distinctive characteristics of nanotechnology. The use of nanoscaffolds in regenerative endodontics will improve with further study and development, ultimately helping patients who require dental pulp and tissue regeneration.

9 Nanotechnology in periodontics: combatting gum disease at the nanofront

9.1 Nano-antimicrobials: targeted warfare against periodontal pathogens

Periodontitis, a chronic inflammatory disease, leads to the gradual deterioration of the supporting tissues around the teeth. This condition is primarily triggered by the colonization of harmful plaque biofilms in susceptible individuals. It is a prevalent dental problem worldwide and is now the leading cause of adult tooth loss. The standard treatment for periodontitis involves removing mineralized deposits and biofilms from tooth surfaces. Nonsurgical treatments have been shown to significantly improve clinical and microbiological indicators in individuals with periodontitis. However, even after these treatments, certain bacteria can persist on root surfaces. To address this issue, researchers have explored various approaches to combating periodontal bacteria since there is limited availability of new antibiotics. One promising avenue of research is the use of nanoparticles (NPs) [45]. Nanoantimicrobials provide numerous benefits in the management of gum disease. Through the utilization of nanoparticles, antimicrobial agents can be precisely directed to the periodontal pocket, which is the specific location where infection-causing bacteria reside. This targeted delivery approach enables a higher concentration of antimicrobial agents to be concentrated at the infection site, thereby enhancing their effectiveness while minimizing any potential harm to healthy tissues. Silver nanoparticles have garnered attention for their potential as antimicrobial agents against periodontal pathogens. These minuscule particles can disrupt the structure and functionality of bacterial cells, effectively impeding their growth and diminishing their harmful effects. Moreover, silver nanoparticles can penetrate bacterial cell walls, inducing changes in cell membranes and ultimately leading to cellular death (Fig. 5) [46]. Other types of nanoparticles, such as liposomes or polymeric nanoparticles, have also been investigated for their potential to deliver antimicrobial agents to periodontal pockets. These nanoparticles can encapsulate antimicrobial drugs and release them gradually, providing sustained antimicrobial activity [47, 48].

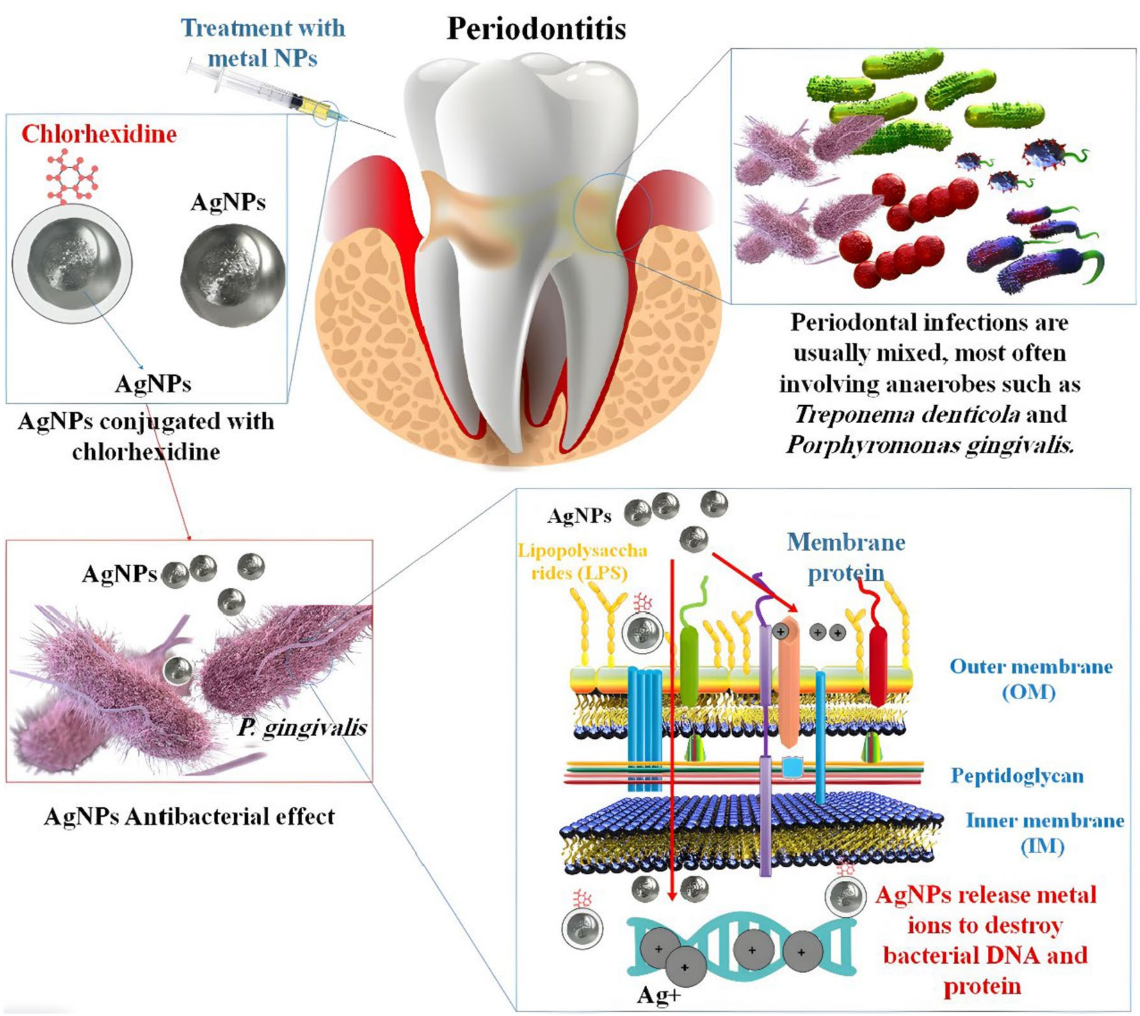

Fig. 5 Shows a diagram illustrating the antibacterial mechanisms of AgNPs in periodontitis. Both AgNPs and the released Ag + ions serve as effective antibacterial agents. AgNPs-CHX, which possess both antibacterial and anti-inflammatory properties, present a potential therapeutic avenue for periodontitis [42]

9.2 Tissue engineering for periodontal regeneration: a nano-approach

Tissue engineering has emerged as a promising field focused on restoring the health and function of periodontal tissues, which include the gums, periodontal ligament, and alveolar bone. Periodontal regeneration is essential for effectively managing infections and achieving functional restoration. In this context, nanomaterials have attracted increasing attention due to their remarkable physical and chemical properties, as well as their antibacterial capabilities, which make them highly relevant for promoting tissue regeneration. Efforts have been directed toward employing regenerative therapies, such as guided tissue/bone regeneration (GTR/GBR), in the realm of periodontal regeneration. GTR membranes, which function as scaffolds, play a pivotal role in creating a conducive three-dimensional (3D) environment. This environment supports cell attachment, proliferation, and differentiation, thereby contributing significantly to the regeneration of periodontal tissues.

One particularly intriguing avenue of research involves nanocomposite scaffolds composed of electrospun nanofibers. These scaffolds have garnered substantial attention due to their ability to mimic the natural extracellular matrix (ECM). These scaffolds not only enhance cell survival but also improve flowability, making them highly promising tools for periodontal regeneration [49, 50].

10 Nanomaterials in orthodontics: straightening smiles with precision

10.1 Nanocoated brackets and wires: enhancing orthodontic efficiency

Orthodontic archwires play a pivotal role in applying precise mechanical forces through brackets, ultimately facilitating the correction of various dental issues such as misalignment, gaps, or crowding. Additionally, they serve the crucial function of maintaining teeth in their intended positions. Presently, these archwires are predominantly fashioned from base metal alloys, with stainless steel, NiTi, and beta-titanium alloy wires (composed of titanium, molybdenum, zirconium, and tin) emerging as the most widely utilized varieties. Within the realm of sliding mechanics, a significant consideration lies in the interaction between the wire and bracket, wherein friction becomes a prominent factor. Whenever two surfaces come into contact and engage in movement, friction naturally arises at the point of contact, resulting in resistance to the motion of teeth. The magnitude of this frictional force depends on the pressure applied to these surfaces and is dictated by the specific qualities of the surfaces involved, such as their smoothness, roughness, reactivity, or whether lubricants are used. Reducing these frictional forces between orthodontic wires and brackets has the potential to accelerate the desired tooth movement, ultimately leading to a shorter treatment duration [4]. Recently, nanoparticles have been applied in dry lubricants to reduce friction between orthodontic wires and brackets, ultimately improving the efficiency of tooth adjustment. For instance, inorganic fullerene-like nanoparticles made of tungsten sulfide (IF-WS2) serve as illustrative examples of dry lubricants, effectively acting as self-lubricating coatings on stainless steel orthodontic wires. Other options include changing the wire dimensions and structure, modifying bracket designs, or applying diverse coatings to wire surfaces to potentially reduce friction during sliding. These coatings have been implemented on the surface of brackets, stainless steel wires (SS), or nickel-titanium wires (NiTi) [5]. Throughout orthodontic treatment, microbial colonization of materials is virtually unavoidable. This is primarily due to the evident expansion of the surface available for retention, which results in an amplified buildup of bacterial plaque, increased bacterial presence, and potential enamel decalcification, leading to exacerbated bleeding issues. Furthermore, the irregular surfaces of orthodontic devices contribute to elevated bacterial plaque formation. Consequently, maintaining proper oral hygiene and self-cleansing becomes challenging. Over a six-week period, bacterial counts surged by approximately 30-fold, with heightened levels of *Streptococcus mutans*, *Staphylococcus aureus*, and Lactobacilli being observed [51]. Specifically, metal nanoparticles ranging in size from 1 to 10 nm have demonstrated remarkable antibacterial effects, with silver nanoparticles (AgNPs) being at the forefront of this discovery. Recent research has shown the outstanding antimicrobial properties of silver nanoparticles in combating a diverse range of microorganisms. Within the orthodontic domain, investigations have introduced AgNPs (measuring 17 nm) into orthodontic elastomeric modules, brackets, wires, and other components, testing them against various bacterial strains. The results suggest that orthodontic appliances incorporating AgNPs hold promise for reducing dental biofilm, consequently decreasing the risk of dental enamel demineralization during and after orthodontic treatments. Silver nanoparticles (AgNPs) have shown a notable capacity to hinder the attachment of *S. mutans* bacteria to the surfaces of orthodontic brackets and wires. Notably, the smaller AgNP variants exhibited statistically significant anti-adherence properties against *S. mutans*, outperforming both NiTi (nickel-titanium) and SS (stainless steel wires) [52].

11 Nanomaterials in prosthodontics

11.1 Nanomaterials enhance the implant surface

Several variables influence the success of dental implants, such as the integration of bone implants and the level of bacterial accumulation around them. Given that dental implants traverse both bone and gingiva, they are partially exposed to an oral environment supplemented with oral bacteria. The transgingival abutment of the implant serves as a crucial gateway for bacterial infiltration. Nanomaterials possess distinctive characteristics, making them highly suitable for the coating of dental implants [19, 53]. Studies have shown that titanium plates coated with nanosilver display antibacterial effects against *Staphylococcus aureus*, *Escherichia coli*, and Micrococcus lysodeicticus [53, 54].

11.2 Nanoceramics

Ceramic biomaterials present a practical solution because of their mechanical durability, biological effectiveness, and ability to interact harmoniously with the human body. Conventional ceramics are derived from natural sources such as clay, while contemporary ceramics consist of alumina, zirconia, hydroxyapatite, glass, and silicon carbide. The use of dental materials depends on various factors, such as chemical durability, mechanical resilience, aesthetics, and biocompatibility. The integration of nanoceramics in dental prosthetics has notably improved these characteristics, including longevity and performance, when contrasted with traditional ceramics [55]. Recently, there have been new advancements in dental materials with the introduction of polymer-infiltrated ceramic network (PICN) materials and composite resin nanoceramic blocks. These innovative CAD/CAM materials serve as alternatives to dense ceramics, providing not only the desirable characteristics of polymers such as lower brittleness and enhanced fracture resistance but also the aesthetic properties found in glass ceramics [56].

12 Future horizons: nanotech's promise for next-gen dentistry

Nanotechnology in dentistry holds immense potential for transforming oral healthcare. This process involves manipulating and controlling materials on the nanoscale, enabling the creation of innovative materials, devices, and processes. Nanosensors and nanodevices can detect specific biomarkers or changes in the oral environment, enabling early detection of conditions such as tooth decay, gum disease, and oral cancer [57].

Nanomaterials can also improve dental restorations. The incorporation of nanocomposites into fillings, crowns, and bridges increases their strength, durability, and aesthetics. These nanocomposites can mimic the natural characteristics of teeth, resulting in more natural-looking and long-lasting dental restorations [58]. The use of intelligent dental materials is another significant research direction. Nanosensors implanted in dental materials can detect pH imbalances or bacterial activity, release therapeutic drugs or provide real-time monitoring of oral health. This allows for more individualized and focused therapeutic methods [59]. Nanotechnology also shows promise in regenerative dentistry. Nanomaterials can stimulate the growth of new bone, enamel, and dentin, promoting the regeneration of damaged or lost dental structures. This approach has the potential to revolutionize the treatment of conditions such as dental caries and tooth loss [60].

13 Conclusion

Nanotechnology currently has a limited impact on dentistry because it only employs available materials. However, ongoing investigations in the field will make possible developments that may seem impossible today. In the future, nanotechnology will help improve oral health by providing advanced restorative materials, new diagnostic and therapeutic techniques, and pharmacological approaches to enhance dental care.

Abbreviations

DDS	Drug-delivery systems
NPs	Nanoparticles
nHA	Nanohydroxyapatite
ROS	Reactive oxygen species
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
UV	Ultraviolet
MgO	Magnesium oxide
NM	Nanomaterials
MNPs	Magnetic nanoparticles
MRI	Magnetic resonance imaging
DNA	Deoxyribonucleic acid
1D	One-dimensional/one-dimension
2D	Two-dimensional/two-dimension
3D	Three-dimensional/three-dimension
CT	Computed tomography
EMB	Evidence-based medicine
AgNPs	Ag nanoparticles
CHX	Chlorhexidine
GTR/GBR	Guided tissue/bone regeneration
ECM	Extracellular matrix
NiTi	Nickel-titanium
IF-WS2	Inorganic fullerene-like nanoparticles made of tungsten sulfide
SS	Stainless steel

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Declarations

Ethics approval and consent to participate
As our submission is a research review paper, it does not involve original data collection or participation. Therefore, ethics approval and consent to participate are not applicable to this manuscript.

Consent for publication
Not applicable.

Competing interest
The authors declare that they have no competing interests relevant to this research review paper.

Use of AI-Assisted Readability Enhancement
We would like to inform that the utilization of AI-assisted tools in the preparation of this manuscript was strictly limited to enhancing its readability. At no point were AI technologies used to replace essential authorial responsibilities, such as the generation of scientific, educational, or medical insights, the formulation of scientific conclusions, or the making of clinical recommendations. The implementation of AI for readability enhancement was rigorously supervised under the discerning eye of human oversight and control.

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