REVIEW ARTICLE

Nanotechnology in Restorative Dentistry: Its Applications and Efficacy

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ABSTRACT

Nanotechnology, defined as the manipulation of materials at the nanometer scale (1–100 nm), has introduced a paradigm shift in restorative dentistry by enabling the development of materials with enhanced mechanical, biological, and functional properties. Conventional restorative materials often fail due to polymerization shrinkage, wear, marginal leakage, and secondary caries. Nanotechnology-based restorative materials, including nanocomposites, nano-adhesives, nano-ionomers, antibacterial nanoparticles, and remineralizing agents, aim to overcome these limitations by interacting with tooth structure and oral tissues at the molecular level. This review critically evaluates the applications and efficacy of nanotechnology in restorative dentistry through a PRISMA-guided literature search. Evidence suggests that nano-enabled materials demonstrate superior mechanical properties, improved aesthetics, antibacterial potential, and bioactivity compared to conventional materials. However, long-term clinical evidence and standardized safety assessments remain limited. Further high-quality clinical trials are essential for widespread clinical translation.

KEYWORDS: Nanotechnology; Restorative Dentistry; Nanocomposites; Nano-adhesives; Antibacterial Nanoparticles; Dental Biomaterials

INTRODUCTION

Restorative dentistry aims to restore the form, function, aesthetics, and biological integrity of teeth affected by caries, trauma, developmental anomalies, or wear. Over the decades, restorative materials have evolved from gold and dental amalgam to resin-based composites and glass ionomer cements. Despite significant improvements, conventional restorative materials continue to exhibit inherent shortcomings such as polymerization shrinkage, marginal breakdown, postoperative sensitivity, wear, and susceptibility to secondary caries, which remains the primary cause of restoration failure (1,2).

The oral cavity presents a highly challenging environment for restorative materials, characterized by fluctuating temperatures, moisture, mechanical loading, chemical challenges, and a complex microbial ecosystem. Materials must therefore possess optimal mechanical strength, chemical stability, biocompatibility, and resistance to bacterial colonization while maintaining aesthetic integrity. Traditional approaches to material development have largely relied on macroscopic or microscopic modifications, which have reached a plateau in performance enhancement (3).

Nanotechnology has emerged as a revolutionary approach capable of addressing these limitations by engineering materials at the atomic and molecular scale. The term "nanotechnology" was first introduced by Norio Taniguchi in 1974 and later popularized in biomedical sciences. At the nanoscale, materials exhibit unique physicochemical properties, including increased surface area, enhanced reactivity, improved mechanical strength, and altered optical behavior (4).

In restorative dentistry, nanotechnology has enabled the development of nanocomposites with superior filler dispersion, nano-modified adhesive systems with enhanced bond durability, and bioactive materials capable of antibacterial action and remineralization. Nanoparticles such as silver, zinc oxide, titanium dioxide, and nano-hydroxyapatite have been incorporated into restorative materials to impart antibacterial and therapeutic properties (5–7).

The concept of restorative materials has thus shifted from passive replacement of lost tooth structure to biologically active systems that interact with the surrounding dental tissues. However, despite promising laboratory results, concerns remain regarding long-term clinical efficacy, biocompatibility, nanoparticle stability, and cost-effectiveness. This review synthesizes current evidence on nanotechnology applications in restorative dentistry and critically evaluates their efficacy and limitations.

AIM

To review and critically analyze the applications, mechanisms, and clinical efficacy of nanotechnology in restorative dentistry.

MATERIALS AND METHODS

Search Strategy (PRISMA Guidelines)

A comprehensive electronic search was conducted using PubMed, Scopus, and Web of Science databases for studies published up to December 2025. Search terms included: nanotechnology, nanocomposites, nanoparticles, restorative dentistry, nano-adhesives, antibacterial dental materials, and remineralizing nanoparticles.

Inclusion criteria

Randomized controlled trials
In vitro studies
In vivo studies
Systematic reviews related to nantechnology

Exclusion criteria

Non-English articles
Studies unrelated to restorative applications were excluded.
Articles lacking clear methodology, outcome measures, or efficacy data
Abstract-only publications without full-text availability

Results of Search (PRISMA)
Records identified: ~713
Records after duplicates removed:428
Records screened: 285
Full-text articles assessed: 73
Studies included in qualitative synthesis: 24
The selected studies focused on nanocomposites, nano-adhesives, antibacterial nanoparticles, remineralizing systems, and clinical performance of nano-modified restorative materials.

DISCUSSION

The integration of nanotechnology into restorative dentistry represents a fundamental shift from traditional passive restorative approaches toward biologically interactive and multifunctional materials. Unlike conventional restorative materials that primarily restore lost tooth structure, nano-enabled materials aim to enhance restoration longevity, biological compatibility, and therapeutic potential. This discussion critically evaluates the impact of nanotechnology across key domains.

Nanotechnology and Mechanical Reinforcement of Restorative Materials

Mechanical failure remains a major reason for restoration replacement, particularly in posterior teeth exposed to high occlusal loads. Nanocomposites have been developed to address this limitation by incorporating fillers in the nanometer range, either as discrete nanoparticles or as nanoclusters. These fillers allow higher filler loading with improved dispersion, leading to enhanced flexural strength, compressive strength, fracture toughness, and wear resistance compared to microhybrid composites (8,9).

The large surface area of nanoparticles enhances filler–matrix bonding, reducing stress concentration sites that initiate crack propagation. Additionally, nanocomposites demonstrate reduced polymerization shrinkage and shrinkage stress, which directly contributes to improved marginal integrity and reduced postoperative sensitivity (10). From a clinical perspective, these properties are critical in extending restoration lifespan and reducing the need for replacement.

However, nanoparticle agglomeration remains a technical challenge. Due to high surface energy, nanoparticles tend to cluster, which can compromise mechanical properties and handling characteristics. Surface treatment and silanization techniques have improved dispersion, but complete elimination of agglomeration remains difficult (11).

Optical Properties and Long-Term Aesthetic Stability

Aesthetic longevity is an increasingly important criterion in restorative dentistry. Nanocomposites exhibit superior optical properties because filler particles are smaller than the wavelength of visible light, allowing improved translucency, color matching, and depth of cure (9). This enables restorations that closely mimic natural enamel and dentin.

Unlike conventional composites that lose surface gloss due to filler plucking and surface degradation, nanocomposites maintain smoother surfaces over time. This not only improves aesthetics but also reduces plaque accumulation and surface staining, indirectly contributing to periodontal health.

Nano-Modified Adhesive Systems and Hybrid Layer Stability

The durability of adhesive restorations depends largely on the stability of the resin–dentin interface. Nano-modified adhesive systems have been developed to enhance infiltration into dentinal tubules and collagen fibrils, reinforcing the hybrid layer at the nanoscale (12,13).

Nanoparticles within adhesives may act as stress absorbers and fillers within the hybrid layer, reducing nanoleakage and improving resistance to hydrolytic degradation. This is particularly important given that enzymatic degradation of exposed collagen is a major cause of bond failure. Although laboratory studies demonstrate improved bond strength and durability, long-term clinical validation is still insufficient.

Antibacterial Nanoparticles and Secondary Caries Prevention

Secondary caries remains the leading cause of restoration failure worldwide. Conventional restorative materials are biologically inert and do not actively resist bacterial colonization. Nanotechnology introduces a proactive strategy through the incorporation of antibacterial nanoparticles such as silver, zinc oxide, and titanium dioxide (6,14).

These nanoparticles exert antibacterial effects through multiple mechanisms, including disruption of bacterial cell membranes, inhibition of enzymatic activity, and generation of reactive oxygen species. In vitro studies consistently show reduced Streptococcus mutans biofilm formation on nano-modified restorative materials.

Despite promising results, several concerns persist. Continuous antibacterial ion release may diminish over time, reducing long-term efficacy. Additionally, excessive nanoparticle release could pose cytotoxic risks to pulp tissues and surrounding oral mucosa. The balance between antibacterial efficacy and biological safety remains a critical research focus.

Bioactive and Remineralizing Nanomaterials

One of the most innovative contributions of nanotechnology to restorative dentistry is the development of bioactive materials capable of promoting remineralization. Nanoparticles such as nano-hydroxyapatite, amorphous calcium phosphate, and dicalcium phosphate anhydrous release calcium and phosphate ions, facilitating enamel and dentin remineralization adjacent to restorations (7,15).

These materials support the principles of minimally invasive dentistry by preserving affected but remineralizable tooth structure. Remineralizing nanomaterials may reduce the progression of secondary caries and improve the biological seal at restoration margins.

However, challenges include controlling ion release kinetics and maintaining adequate mechanical properties. Excessive ion release may weaken the resin matrix, highlighting the need for optimized formulations.

Clinical Performance and Translational Challenges

Short- and medium-term clinical studies indicate that nano-enabled restorative materials demonstrate acceptable survival rates, marginal adaptation, and patient satisfaction (16–18). However, heterogeneity in study design, materials tested, and outcome measures limits definitive conclusions regarding clinical superiority.

Translational challenges include higher material costs, technique sensitivity, and lack of clinician familiarity. Furthermore, regulatory frameworks for dental nanomaterials are still evolving, necessitating standardized evaluation protocols.

Biocompatibility, Safety, and Ethical Considerations

Although nanoparticles are generally embedded within resin matrices, wear and degradation may result in nanoparticle release. Current evidence suggests acceptable biocompatibility, but long-term systemic and pulpal effects are not fully understood (19,20).

Ethical considerations include patient safety, environmental impact, and informed consent when using emerging nanotechnologies. Rigorous toxicological and clinical studies are required to ensure safe implementation.

Future Directions in Nanorestorative Dentistry

Future research should focus on multifunctional nanomaterials that integrate mechanical strength, antibacterial action, remineralization, and self-healing capabilities. Advances in smart materials, nanorobotics, and controlled drug delivery systems may further revolutionize restorative dentistry (21–23). Integration with digital dentistry and artificial intelligence may optimize material selection and clinical outcomes.

CONCLUSION

Nanotechnology has significantly advanced restorative dentistry by enabling the development of materials with superior mechanical, aesthetic, antibacterial, and bioactive properties. While laboratory and early clinical data are promising, robust long-term clinical trials and comprehensive safety evaluations are essential before routine clinical adoption.

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