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Nanotechnology and Its Application in Restorative Dentistry: A Narrative Review

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Abstract

Background

Nanotechnology has emerged as an important field in contemporary restorative dentistry because manipulation of materials at the nanoscale can modify their mechanical, optical, antimicrobial, remineralizing, and biological properties. Nanoparticles and nanostructured materials have been incorporated into resin composites, adhesive systems, glass ionomer cements, remineralizing materials, liners, coatings, and other restorative biomaterials. These modifications are intended not only to improve the physical performance and esthetics of restorations but also to develop multifunctional materials capable of controlling biofilm formation and promoting mineral recovery at the tooth–restoration interface.

Objective

This narrative review summarizes the principles of nanotechnology relevant to restorative dentistry and critically discusses the principal applications of nanomaterials in resin composites, adhesive systems, glass ionomer cements, antimicrobial restoratives, remineralizing materials, and emerging bioactive restorative systems. Current limitations, safety considerations, clinical evidence, and future directions are also addressed.

Methods

A narrative literature search was conducted using PubMed/MEDLINE and relevant peer-reviewed literature. Search terms included combinations of nanotechnology, nanomaterials, nanoparticles, restorative dentistry, dental composites, dental adhesives, glass ionomer cement, nanohydroxyapatite, silver nanoparticles, antibacterial restorative materials, and remineralization. Original investigations, systematic reviews, clinical studies, and relevant narrative reviews were considered, with emphasis on literature concerning restorative applications and clinically relevant outcomes.

Results

Nanotechnology has contributed substantially to the development of nanofilled and nanohybrid resin composites with favorable polishability, optical properties, wear resistance, and mechanical behavior. Metallic and metal-oxide nanoparticles such as silver, zinc oxide, and titanium dioxide have demonstrated antimicrobial activity, whereas nano-hydroxyapatite, nanoparticles of amorphous calcium phosphate, and bioactive nanomaterials have demonstrated remineralizing potential. Nanoparticle modification of glass ionomer cements and dental adhesives may improve selected mechanical, antibacterial, and bioactive properties. Nevertheless, many therapeutic nanomaterials remain supported predominantly by laboratory evidence, and improvements demonstrated in vitro do not necessarily translate into superior long-term clinical performance.

Conclusion

Nanotechnology has expanded restorative dentistry from predominantly passive replacement of lost dental tissues toward multifunctional and potentially bioactive restorative systems. Nanocomposites are already established clinically, while antimicrobial, remineralizing, and regenerative nanomaterials represent promising future developments. Long-term randomized clinical trials, standardized testing protocols, and comprehensive biocompatibility assessments remain necessary before many experimental nanotechnologies can be recommended for routine clinical application.

Keywords: Nanotechnology; nanomaterials; nanoparticles; restorative dentistry; nanocomposites; dental adhesives; glass ionomer cement; nano-hydroxyapatite; remineralization; antimicrobial materials.

Introduction

Restorative dentistry aims to restore the structure, function, biological integrity, and appearance of teeth affected by dental caries, trauma, developmental abnor-

malities, or other forms of tissue loss. Contemporary restorative practice has increasingly shifted from extensive removal of dental tissues toward minimally invasive and biologically oriented approaches. This transition has stimulated the development of materials

capable of providing improved adhesion, mechanical durability, esthetics, bioactivity, and protection against recurrent disease.

Despite substantial improvements in resin-based composites and adhesive systems, restorative materials remain exposed to a challenging oral environment characterized by repeated mechanical loading, temperature fluctuations, moisture, enzymatic activity, dietary acids, and complex microbial biofilms. Degradation of the tooth–restoration interface, wear, fracture, loss of marginal integrity, and secondary caries therefore remain important causes of restoration failure.

Nanotechnology offers one approach to addressing these challenges. The term generally refers to the design, characterization, production, and application of structures with dimensions at the nanometer scale. Nanomaterials commonly have at least one dimension approximately within the 1–100 nm range, although the term is also applied more broadly to materials possessing nanoscale structural features. At this scale, materials may demonstrate physicochemical properties different from those of their bulk counterparts because of their high surface-area-to-volume ratio, altered surface energy, and size-dependent optical, mechanical, chemical, and biological behavior (Saunders, 2009).

Dentistry represents an attractive field for nanotechnology because natural dental tissues themselves possess hierarchical structures extending from the macroscopic to the nanoscale. Enamel is composed predominantly of highly organized hydroxyapatite crystallites, while dentin contains nanoscale mineral crystals embedded within a collagen-rich organic matrix. Consequently, nanoscale approaches provide opportunities not only for strengthening restorative materials but also for developing materials that interact more closely with the biological and mineral structures of teeth.

Nanotechnology has consequently been applied to resin composites, adhesive systems, glass ionomer cements (GICs), remineralizing agents, antibacterial materials, pulp-related biomaterials, ceramics, and regenerative strategies. Current applications range from commercially established nanofilled composites to experimental materials incorporating silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO-NPs), titanium dioxide nanoparticles (TiO₂-NPs), nano-hydroxyapatite (nHA), nanoparticles of amorphous calcium phosphate (NACP), bioactive glass nanoparticles, and polymeric nanoparticles.

However, the term “nano” should not automatically be interpreted as indicating superior clinical performance. Laboratory improvements in a material property may not translate into increased restoration survival, and inappropriate nanoparticle concentrations can adversely affect polymerization, esthetics, mechanical properties, or biological safety. Clinical evidence therefore needs to be distinguished carefully from experimental evidence.

The purpose of this narrative review is to provide an overview of nanotechnology and its major applications in restorative dentistry, with particular emphasis on nanocomposites, adhesives, glass ionomer cements, antimicrobial systems, remineralization, bioactivity, advantages, limitations, and future clinical developments.

Literature Search Strategy

A narrative literature review was undertaken using

PubMed/MEDLINE and reference lists of relevant peer-reviewed publications. The search focused on publications addressing nanotechnology and nanomaterials used in restorative dentistry.

Search terms included combinations of:

“nanotechnology AND restorative dentistry”; “nanomaterials AND dental restorations”; “nanoparticles AND dental composites”; “nanocomposites AND dentistry”; “nanoparticles AND dental adhesives”; “nanoparticles AND glass ionomer cement”; “silver nanoparticles AND restorative dentistry”; “nano-hydroxyapatite AND dentistry”; “amorphous calcium phosphate nanoparticles AND dental composite”; “antibacterial nanoparticles AND dental materials”; and “remineralization AND nanoparticles”.

Original laboratory investigations, clinical studies, systematic reviews, and relevant narrative reviews were considered. Greater emphasis was placed on studies directly addressing restorative applications and on systematic reviews or clinical investigations where these were available.

Nanotechnology and Nanomaterials

Nanotechnology involves the manipulation or utilization of matter at extremely small dimensions. Reduction of particles to the nanoscale substantially increases their surface area relative to their volume. This can alter surface reactivity, ion release, optical behavior, antimicrobial activity, and interaction with surrounding matrices.

Nanomaterials relevant to restorative dentistry may be broadly categorized into:

1. Inorganic nanoparticles – silica, zirconia, hydroxyapatite, amorphous calcium phosphate and bioactive glass.
2. Metallic nanoparticles – silver, gold and copper.
3. Metal-oxide nanoparticles – titanium dioxide, zinc oxide, magnesium oxide and zirconium oxide.
4. Carbon-based nanomaterials – carbon nanotubes, graphene-related materials and nanodiamonds.
5. Polymeric nanoparticles – including chitosan and quaternary ammonium-containing systems.
6. Nanoclusters and nanofibers – engineered structures designed to improve reinforcement or functional behavior.

The properties of a nanomaterial depend not simply on its chemical composition but also on particle size, morphology, surface treatment, distribution, concentration, aggregation, and interaction with the surrounding restorative matrix.

Applications of Nanotechnology in Restorative Dentistry

Nanocomposite Resins

Resin-based composites represent one of the most successful applications of nanotechnology in restorative dentistry.

Traditional composites contain an organic resin matrix reinforced by inorganic fillers. The size, concentration, composition, and distribution of these fillers substantially influence mechanical properties, polishability, wear behavior, viscosity, translucency, and esthetics.

Nanocomposites incorporate nanoscale filler particles or nanostructured filler systems. Nanofilled composites may contain individual nanoparticles and nanoclusters, whereas nanohybrid composites combine nanosized particles with larger filler particles.

Potential advantages include improved:

- surface smoothness;
- polishability and polish retention;
- optical properties;
- filler loading;
- mechanical strength;
- hardness;
- wear resistance; and
- esthetic performance.

The very small filler particles permit the formation of smoother surfaces because the particles removed during finishing and wear are smaller than those in traditional macrofilled systems.

However, clinical evidence does not demonstrate that every nanocomposite is inherently superior to conventional hybrid composites. Alzraikat et al. (2018) reported that the mechanical properties of nanocomposites were generally comparable with hybrid composites and superior to microfilled composites for some characteristics. Importantly, clinical performance was broadly comparable with hybrid restorative materials.

Similarly, a systematic review by Angerame and De Biasi (2018) concluded that nanofilled and nanohybrid composites generally showed clinical behavior, marginal quality, and wear resistance similar to conventional microhybrid composites rather than clear clinical superiority.

A later systematic review and meta-analysis involving posterior restorations likewise found no significant differences between nanofilled/nanohybrid and hybrid composites in evaluated clinical parameters, including surface texture and color match (Maran et al., 2020).

Therefore, the principal clinically established contribution of nanotechnology to composite dentistry may be considered optimization of filler technology and favorable handling and esthetic characteristics rather than unequivocally longer restoration survival.

Nanotechnology in Dental Adhesives

The resin–dentin interface is one of the most vulnerable components of adhesive restorations. Water sorption, polymer hydrolysis, degradation of collagen, incomplete resin infiltration, polymerization stress, and bacterial activity can contribute to deterioration of the hybrid layer.

Nanoparticles have consequently been incorporated experimentally into primers and bonding agents to produce adhesives with additional mechanical, antimicrobial, and remineralizing functions.

Examples include:

- silver nanoparticles;
- nano-hydroxyapatite;
- amorphous calcium phosphate nanoparticles;
- zinc oxide nanoparticles;
- titanium dioxide nanoparticles;
- silica nanoparticles;
- quaternary ammonium nanoparticles; and
- bioactive glass nanoparticles.

Silver nanoparticles are particularly attractive because relatively small concentrations can produce antimicrobial effects. NACP-containing adhesives are being investigated because calcium and phosphate ion release could help remineralize demineralized tooth structure surrounding the adhesive interface.

Current research therefore aims to transform adhesives from materials that simply establish micromechanical bonding into multifunctional interfaces capable of resisting bacterial colonization and promoting mineral

recovery.

Nevertheless, much of this evidence remains laboratory-based. A recent review emphasized that nanoparticle-modified adhesive strategies demonstrate considerable antimicrobial and bioactive potential but that routine clinical applicability has not yet been demonstrated for many of these experimental systems.

Antibacterial Nanoparticles

One of the most extensively investigated applications of nanotechnology is the development of antibacterial restorative materials.

Conventional resin composites can accumulate bacterial biofilm, particularly around rough or defective restoration margins. If an antibacterial function can be incorporated without compromising the restorative material, it could potentially reduce bacterial colonization and secondary caries.

Silver Nanoparticles

Silver nanoparticles are among the most extensively investigated antimicrobial nanoparticles.

Their antibacterial mechanisms have been associated with:

- release of silver ions;
- interaction with bacterial cell membranes;
- increased membrane permeability;
- interference with intracellular proteins and enzymes;
- oxidative stress;
- interaction with microbial nucleic acids; and
- disruption of biofilm development.

AgNPs have been incorporated experimentally into composites, adhesives, primers, glass ionomer cements, and other dental materials.

An important advantage is their strong antimicrobial activity at relatively low concentrations. Excessive incorporation, however, may produce discoloration, nanoparticle aggregation, changes in polymerization, or adverse biological effects.

Therefore, an optimal balance between antibacterial activity and preservation of mechanical, optical, and biological properties is necessary.

Zinc Oxide Nanoparticles

ZnO nanoparticles demonstrate antimicrobial activity against several microorganisms and have therefore been investigated as additives to restorative composites and adhesives.

Potential mechanisms include:

- generation of reactive oxygen species;
- release of Zn^{2+} ions;
- disruption of bacterial membranes; and
- interference with cellular metabolism.

ZnO nanoparticles may additionally influence mechanical characteristics and biofilm formation. Nevertheless, their effects are concentration-dependent. Excessive nanoparticle loading can promote agglomeration and compromise mechanical or optical characteristics.

Metal-oxide nanoparticles therefore illustrate an important principle of nanorestorative research: increasing antimicrobial nanoparticle concentration does not necessarily result in a clinically better material.

Nanoparticles of Amorphous Calcium Phosphate

One of the most important emerging concepts in restorative nanotechnology is the development of materials capable of releasing remineralizing ions.

Nanoparticles of amorphous calcium phosphate are particularly promising because they can release calcium and phosphate ions into the surrounding environment.

Xu et al. developed experimental NACP-containing resin composites intended to combine structural restoration with caries-inhibitory activity.

When environmental pH decreases, increased calcium and phosphate ion release can potentially promote mineral recovery and reduce demineralization.

Experimental work has demonstrated remineralization of demineralized enamel using NACP-containing nanocomposites.

This approach represents an important conceptual change. Instead of functioning as a passive replacement for lost tooth tissue, a restoration may act as an ion reservoir that responds to cariogenic conditions.

Nano-Hydroxyapatite

Hydroxyapatite constitutes the principal mineral component of enamel and dentin. Nano-hydroxyapatite therefore has considerable appeal as a biomimetic dental material.

Reduction to nanoscale dimensions increases surface area and reactivity and may facilitate interaction with microscopic defects in dental hard tissues.

nHA has been investigated for:

- enamel remineralization;
- dentin remineralization;
- dentinal hypersensitivity management;
- incorporation into resin composites;
- modification of glass ionomer cements;
- dental adhesives; and
- bioactive restorative materials.

Its similarity to natural dental mineral makes nHA particularly attractive for biomimetic restorative dentistry. A comprehensive review by Juntavee et al. (2023) highlighted the increased solubility, surface energy, biocompatibility, and bioactivity associated with nanoscale hydroxyapatite compared with larger HA particles.

Nano-hydroxyapatite may deposit on demineralized surfaces and provide calcium and phosphate for mineral formation. Nevertheless, the effectiveness of remineralization depends on particle characteristics, concentration, lesion depth, exposure conditions, and the surrounding chemical environment.

Nanotechnology in Glass Ionomer Cements

Glass ionomer cements possess several desirable characteristics, including chemical adhesion to tooth structure, fluoride release, thermal compatibility, and relatively favorable biocompatibility. Their limitations include comparatively low fracture toughness, wear resistance, and strength.

Nanotechnology has therefore been investigated as a means of improving GIC properties.

Nanomaterials evaluated in GICs include:

- nano-hydroxyapatite;
- nano-fluoroapatite;
- silver nanoparticles;
- titanium dioxide nanoparticles;
- zinc oxide nanoparticles;
- zirconia nanoparticles;
- silica nanoparticles;
- alumina nanoparticles;
- magnesium oxide nanoparticles; and
- carbon-based nanostructures.

Nano-hydroxyapatite and related calcium-phosphate

particles may increase bioactivity while maintaining or enhancing selected mechanical properties.

Amin et al. (2021) reviewed nanostructure-modified GICs and found that several nanomaterials showed potential to improve mechanical properties and antibacterial activity. However, the authors emphasized that much of the available evidence was laboratory-based and that clinical translation remained limited.

A subsequent review similarly identified metallic, metal-oxide, apatitic, and multicomponent nanomaterials as promising GIC modifiers while emphasizing the need to optimize their concentration and demonstrate clinical benefits.

Nano-Ionomers

Commercial restorative technology has also produced resin-modified glass ionomer-based materials incorporating nanoscale fillers, often referred to as nano-ionomers.

The rationale is to combine the fluoride-releasing and adhesive characteristics associated with glass ionomer technology with improved polishability, esthetics, and mechanical behavior provided by resin and nanofiller technology.

These materials may be useful in selected low- to moderate-stress clinical situations, particularly where fluoride release and tooth-colored esthetics are desirable.

However, nano-ionomers should not be assumed to possess all the properties of conventional GICs or resin composites simply because nanosized particles are incorporated. Their performance depends on their complete formulation.

Nanotechnology and Remineralization

Traditional restorative treatment removes irreversibly damaged tissue and replaces the missing volume with an artificial material. Contemporary minimally invasive dentistry increasingly emphasizes preservation and biological repair of demineralized tissue.

Nanotechnology supports this philosophy through remineralizing systems containing:

- nano-hydroxyapatite;
- NACP;
- nano-bioactive glass; and
- other calcium- and phosphate-releasing nanomaterials.

Calcium-phosphate nanoparticles may function as reservoirs capable of releasing ions under acidic conditions. The released ions can increase local mineral saturation and facilitate remineralization.

Research combining antibacterial nanoparticles with calcium-phosphate systems is particularly interesting. Such restoratives could theoretically suppress cariogenic biofilms while simultaneously encouraging remineralization.

Cheng et al. described this multifunctional concept using antibacterial and remineralizing composites and adhesives containing agents such as nanosilver and NACP.

These approaches could be particularly relevant at restoration margins, where biofilm accumulation, acid production, marginal defects, and recurrent caries frequently interact.

Nanotechnology and Esthetic Dentistry

Nanotechnology has also contributed to esthetic restorative dentistry.

Smaller fillers can reduce surface irregularities after

polishing. A smoother surface can enhance gloss and may reduce staining and plaque retention.

Nanoparticle engineering can additionally modify light transmission and scattering, helping manufacturers reproduce enamel-like translucency and natural tooth appearance.

Nanofilled and nanohybrid composites are therefore extensively used in both anterior and posterior restorations.

Nevertheless, clinical systematic reviews have not consistently demonstrated superior color match or surface texture for nanofilled/nanohybrid materials compared with modern hybrid composites.

Thus, nanoparticle technology contributes to excellent esthetic potential, but clinical performance remains dependent on the entire material formulation, restorative technique, finishing and polishing, patient factors, and clinical environment.

16. Mechanical Reinforcement

Nanoparticles can potentially strengthen restorative materials by occupying spaces between larger filler particles and improving filler packing.

Nanoparticles investigated for reinforcement include:

- nanosilica;
- zirconia;
- alumina;
- titanium dioxide;
- nano-hydroxyapatite;
- nanodiamonds;
- graphene derivatives; and
- carbon nanotubes.

Potential improvements include increased:

- flexural strength;
- compressive strength;
- fracture resistance;
- hardness;
- wear resistance; and
- fatigue behavior.

However, nanoparticle agglomeration represents a major problem. Nanoparticles possess high surface energy and tend to cluster. Agglomerated particles can behave as defects or stress-concentration sites and may actually weaken a restorative material.

Effective surface treatment, silanization, dispersion, and optimization of filler concentration are therefore essential.

Advantages of Nanotechnology in Restorative Dentistry

Potential advantages include:

- improved polishability;
- smoother restorative surfaces;
- favorable esthetics;
- improved optical characteristics;
- high filler loading;
- favorable wear behavior;
- enhanced selected mechanical properties;
- antimicrobial activity;
- reduced biofilm formation;
- calcium and phosphate ion release;
- potential remineralization;
- development of bioactive materials;
- biomimetic interaction with dental tissues; and
- potential development of multifunctional restorations.

The major advantage is therefore not merely reducing particle dimensions. Nanotechnology enables material designers to engineer surfaces and functions that are difficult to achieve with conventional fillers.

Limitations and Challenges

Despite promising findings, nanotechnology has several limitations.

Nanoparticle Agglomeration

Because nanoparticles possess high surface energy, they tend to aggregate. Poor dispersion may reduce mechanical performance and create defects within the material.

Concentration-Dependent Effects

Increasing nanoparticle concentration can enhance one property while compromising another. For example, antimicrobial activity may increase while bond strength, polymerization, translucency, or color stability deteriorates.

Esthetic Changes

Metallic nanoparticles, particularly silver, may produce discoloration at excessive concentrations.

Biological Safety

The small size and high biological reactivity responsible for many desirable properties also create concerns regarding cytotoxicity.

Potential biological effects depend on:

- particle size;
- concentration;
- chemical composition;
- surface modification;
- ion release;
- duration of exposure; and
- ability of particles to migrate from the material.

Biocompatibility therefore requires assessment of the final restorative formulation rather than consideration of antimicrobial efficacy alone.

Lack of Standardization

Studies frequently use different nanoparticle sizes, concentrations, bacterial strains, aging conditions, restorative formulations, and experimental methods.

A systematic review of antibacterial nanoparticle-containing dental materials identified substantial heterogeneity among studies, highlighting the need for standardized research protocols.

Limited Long-Term Clinical Evidence

Perhaps the most important limitation is that many promising nano-enabled materials have been evaluated primarily in vitro.

Laboratory demonstrations of bacterial inhibition or ion release cannot establish that a material will reduce secondary caries or increase restoration longevity in patients.

Long-term randomized clinical studies are therefore essential.

Future Perspectives

Future restorative nanotechnology is likely to focus increasingly on smart, bioactive, and multifunctional materials rather than simply smaller fillers.

One promising direction involves pH-responsive restorative systems. Because cariogenic biofilms create acidic conditions, future materials may be engineered to increase calcium, phosphate, or antimicrobial ion release when environmental pH falls.

Another important field is biomimetic remineralization. Instead of merely filling a defect, nanomaterials may

eventually guide mineral deposition within demineralized dentin and enamel in ways resembling biological mineralization.

Nanotechnology may also contribute to controlled drug delivery. Nanocarriers could release antimicrobial, anti-inflammatory, remineralizing, or regenerative molecules at targeted locations.

Advanced nanomaterials such as graphene derivatives, nanodiamonds, carbon nanotubes, and functionalized polymeric nanoparticles are also being investigated as reinforcing or therapeutic components.

The development of self-healing restorative materials is another potential area. Micro- and nanoscale systems containing repair agents could theoretically respond to crack formation and prolong restoration service.

Artificial intelligence, digital material design, and computational modeling may further enable optimization of nanoparticle size, morphology, concentration, and distribution before materials undergo laboratory and clinical testing.

Nevertheless, future research should focus not only on demonstrating statistically significant laboratory improvements but on determining whether these technologies meaningfully improve patient-centered outcomes such as restoration survival, secondary-caries incidence, postoperative sensitivity, esthetic stability, and need for replacement.

Discussion

Nanotechnology has substantially influenced the evolution of restorative dental materials. Its most established application is the modification of composite filler systems, where nanoscale fillers can provide favorable polishability, surface characteristics, optical behavior, and mechanical performance.

However, the more transformative potential of nanotechnology lies in the development of restorations that actively interact with their environment.

Secondary caries remains an important challenge in restorative dentistry. Conventional restorative materials largely replace missing dental tissues without directly modifying the biological processes responsible for disease recurrence. Nanoparticle-containing systems could potentially address this limitation through antimicrobial and remineralizing functions.

Silver, zinc oxide, and titanium dioxide nanoparticles have demonstrated antimicrobial effects in experimental restorative systems. A systematic review and meta-analysis found improved antibacterial activity following nanoparticle incorporation, although substantial methodological heterogeneity was present. Similarly, NACP and nHA offer mechanisms for calcium-phosphate delivery and remineralization. Experimental NACP composites have demonstrated the capacity to release remineralizing ions and promote mineral recovery in demineralized enamel.

Nanotechnology has also been used to address limitations of GICs. Incorporation of nano-hydroxyapatite, metallic nanoparticles, metal oxides, and other nanostructures has produced encouraging laboratory improvements in mechanical or antimicrobial properties. Nevertheless, long-term clinical evidence for many such modifications remains inadequate.

These findings emphasize a central issue in nanodentistry: promising physicochemical behavior should not be equated with demonstrated clinical superiority.

For example, nanocomposites possess excellent prop-

erties and are widely used clinically, yet systematic clinical evidence indicates broadly comparable performance to modern hybrid composites rather than consistent superiority.

The next stage of restorative nanotechnology should therefore emphasize clinical translation. Future research requires well-designed randomized controlled trials, standardized nanoparticle characterization, appropriate aging protocols, clinically relevant biofilm models, toxicological evaluation, and long-term follow-up.

Conclusion

Nanotechnology represents an important development in restorative dentistry and has contributed to substantial changes in the design and functionality of dental materials.

Nanofilled and nanohybrid composites provide excellent esthetic and mechanical properties and constitute the most clinically established application of nanotechnology in restorative dentistry. Nanoparticles are also increasingly being investigated in adhesives, glass ionomer cements, liners, coatings, and remineralizing restorative systems.

Metallic and metal-oxide nanoparticles, including silver, zinc oxide, and titanium dioxide, demonstrate considerable antimicrobial potential. Nano-hydroxyapatite, amorphous calcium phosphate nanoparticles, and bioactive glass nanoparticles offer promising approaches for remineralization and development of bioactive restorations.

The long-term objective of restorative nanotechnology is moving beyond the concept of an inert filling material toward multifunctional restorations capable of simultaneously restoring tooth structure, resisting bacterial colonization, releasing therapeutic ions, promoting remineralization, and protecting the tooth-restoration interface.

Nevertheless, the level of evidence varies substantially among applications. While nanocomposite technology is well established clinically, many antibacterial and remineralizing nanotechnologies remain predominantly supported by laboratory evidence. Their translation into routine practice will require standardized research methods, comprehensive toxicological assessment, and high-quality long-term clinical trials.

Nanotechnology should therefore be regarded not as a guarantee of superior restorative performance, but as a powerful platform for designing the next generation of biomimetic, bioactive, and disease-modifying restorative materials.

References

1. Alzraikat H, Burrow MF, Maghaireh GA and Taha NA (2018) Nanofilled resin composite properties and clinical performance: A review. *Operative Dentistry* 43(4): E173–E190. doi:10.2341/17-208-T.
2. Amin F, Rahman S, Khurshid Z, Zafar MS and Sefat F (2021) Effect of nanostructures on the properties of glass ionomer dental restoratives/cements: A comprehensive narrative review. *Materials* 14(21): 6260. doi:10.3390/ma14216260.
3. Angerame D and De Biasi M (2018) Do nanofilled/nanohybrid composites allow for better clinical performance of direct restorations than traditional microhybrid composites? A systematic review. *Operative Dentistry* 43(4): E191–E209. doi:10.2341/17-212-L.

4. Cheng L, Zhang K, Weir MD, Melo MAS, Zhou X and Xu HHK (2015) Nanotechnology strategies for antibacterial and remineralizing composites and adhesives to tackle dental caries. *Nanomedicine* 10(4): 627–641.
5. Juntavee A, Juntavee N and Sinagpulo AN (2023) Nanohydroxyapatite in dentistry: A comprehensive review. *Saudi Dental Journal* 35(6): 741–752. doi:10.1016/j.sdentj.2023.05.018.
6. Maran BM, de Geus JL, Gutiérrez MF, Heintze S, Tardem C, Barceleiro MO, Reis A and Loguercio AD (2020) Nanofilled/nanohybrid and hybrid resin-based composite in patients with direct restorations in posterior teeth: A systematic review and meta-analysis. *Journal of Dentistry* 99: 103407. doi:10.1016/j.jdent.2020.103407.
7. Marciano MA, Pereira JS, Antunes TBM and Palma PJ (2026) Applications of nanomaterials in restorative dentistry and endodontics: A narrative review. *Materials* 19(13): 2786. doi:10.3390/ma19132786.
8. Saunders SA (2009) Current practicality of nanotechnology in dentistry. Part 1: Focus on nanocomposite restoratives and biomimetics. *Clinical, Cosmetic and Investigational Dentistry* 1: 47–61.
9. Xu HHK, Moreau JL, Sun L and Chow LC (2011) Nanocomposite containing amorphous calcium phosphate nanoparticles for caries inhibition. *Dental Materials* 27(8): 762–769. doi:10.1016/j.dental.2011.03.016.
10. Xu HHK, Weir MD, Sun L, Moreau JL, Takagi S, Chow LC and Antonucci JM (2012) Strong nanocomposites with Ca, PO₄, and F release for caries inhibition. Related experimental work demonstrates the development of ion-releasing restorative nanomaterials and their potential for remineralization.