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Review

Nanotechnology in Dental Restorative Materials: Advances, Challenges, and Future Directions Toward Precision Nanomedicine

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Abstract

Background: Nanotechnology has reshaped dental materials by enabling nanoscale control of composition and interfaces, yielding surface-dominated reactivity and bioactive functions that can outperform conventional restoratives. However, routine clinical translation remains limited, and precision applications are still emerging. This review examines synthesis principles and their integration into restorative materials, emphasizing performance gains, limitations, and future opportunities. **Main body:** A narrative synthesis was conducted integrating fundamental nanoscience, synthesis strategies (top-down, bottom-up, green or bio-inspired, hybrid, and emerging microfluidic, laser-assisted, and nanomaterial-enabled additive manufacturing routes), and evidence across ceramics, resin composites, glass ionomer cements, dental adhesives, denture base resins, and 3D-printing polymers. Reported benefits arise from mechanisms such as nanofiller-mediated crack deflection, densification and microstructural refinement, improved optical behavior through reduced light scattering, and therapeutic activity via ion release, photocatalysis, and bioactive interfacial mineralization. Applications include nanostructured ceramics for improved toughness, nanofilled composites for durability and esthetics, nanoparticle-modified glass ionomers with strengthened matrices and antibiofilm activity, and bioactive adhesives that support antimicrobial action and calcium phosphate based remineralization. Persistent barriers include nanoparticle agglomeration, dispersion and viscosity trade-offs, batch-to-batch variability, long-term hydrolytic or thermal aging instability, incomplete biosafety datasets, and regulatory and scale-up constraints. **Conclusion:** Nanotechnology is moving restorative dentistry from passive replacement toward multifunctional, safer, and patient-adaptable materials. Advancing toward precision nanomedicine will require standardized synthesis and characterization, scalable manufacturing, rigorous toxicology, and longitudinal clinical trials, together with greener synthesis and smart, stimuli-responsive systems integrated into digital workflows such as (three-dimensional) 3D printing.

Keywords: nanotechnology; dental restorative materials; nanocomposites; glass ionomer cement; precision nanomedicine

1. Introduction

In the mid-20th century, Richard P. Feynman, often regarded as the father of nanotechnology, outlined the vast potential of manipulating matter at the atomic scale in his visionary lecture “*There’s Plenty of Room at the Bottom*” [1].

Nanotechnology is broadly defined as the design, synthesis, and application of materials or devices with at least one dimension between 1 and 100 nm. At this scale, materials exhibit unique physical, chemical, and biological properties that are absent in their bulk counterparts. These properties include increased surface reactivity, size-dependent optical or electrical behavior, and enhanced mechanical performance, which make nanomaterials particularly attractive for biomedical applications [3,4].

A widely accepted general definition of a nanomaterial is a material with at least one dimension smaller than 100 nm, emphasizing size and structure [2]. A more rigorous definition goes beyond structure alone and also considers the emergence of unique size-dependent properties that do not exist in the bulk counterpart. This perspective is particularly relevant to materials scientists, as it highlights the importance of establishing structure–property relationships at the nanoscale [2].

In dentistry, nanotechnology offers opportunities to improve restorative materials by addressing persistent challenges such as polymerization shrinkage in composites [5], insufficient bond durability of adhesives [6], brittleness of ceramics [7], corrosion of metals [8], and secondary caries at restoration margins [5]. Nanomaterials, whether in the form of nanoparticles, nanofillers, nanoclusters, or nanostructured coatings, have been integrated into dental systems to enhance aesthetics, durability, antimicrobial activity, and biocompatibility.

This review critically explores the synthesis strategies and clinical applications of nanomaterials in restorative dentistry, focusing on ceramics, polymers (composites, glass ionomer cements, adhesives), and metals. Particular attention is given to translational challenges and future directions toward precision nanomedicine, where restorative materials can be customized to patient-specific needs through smart, bioactive, and sustainable nanotechnologies.

2. Strategies for Creating Nanostructures and Nanosized Materials

The synthesis of nanostructures can generally be categorized into top–down, bottom–up, green (bio-inspired), hybrid, and emerging approaches. Each strategy presents unique advantages and limitations, with specific implications for dental applications.

2.1. Top–Down Approaches

Top–down strategies start with bulk materials that are progressively reduced to the nanoscale using external physical or chemical forces [9]. Common techniques for fabricating and modifying materials at the nanoscale include mechanical milling or attrition, which involves grinding materials into nanosized powders [10]. Lithography methods such as photolithography, electron-beam lithography, and nanoimprinting are used to create precise nanoscale patterns [11]. Etching techniques, including chemical etching and plasma or reactive ion etching (RIE), remove material at the nanoscale to produce roughened or patterned features [12]. Laser ablation utilizes pulsed laser irradiation to generate nanoparticles or nanocoatings [13].

Ion beam milling and focused ion beam (FIB) techniques allow for precision surface modification and nanoscale sculpting [14]. Additionally, high-energy processes like arc discharge and sputtering are employed to generate nanoparticles under energetic conditions [15]. These diverse methods enable the controlled production and manipulation of nanomaterials for various applications. Plasma etching enhances adhesion to enamel and dentin, while laser ablation and ion-beam modifications create nano roughened titanium implant surfaces that promote osseointegration [16]. Despite their ability to yield well-defined nanostructures, top–down methods are energy-intensive, costly, and often introduce surface defects or limited size control [17].

2.2. Bottom–Up Approaches

Bottom–up methods build nanostructures by assembling atoms, ions, or molecules, often emulating natural self-assembly processes [18]. Techniques in this category include chemical vapor deposition (CVD) and atomic layer deposition (ALD), which enable precise growth of thin films [19].

Sol–gel synthesis offers a versatile wet chemistry approach for producing oxides and bioactive glasses [20], while hydrothermal and solvothermal methods allow controlled crystal growth under high-pressure conditions [21]. Scalable production of oxide nanoparticles such as SiO₂ and TiO₂ can be achieved through spray pyrolysis and flame synthesis [22].

Micelle and templating methods are employed to fabricate porous nanostructures, and self-assembly alongside supramolecular chemistry facilitates the spontaneous organization of molecules into ordered nanoscale architectures [23]. These bottom–up techniques provide fine control over nanomaterial composition and structure for advanced applications. Sol–gel-derived bioactive glasses are used in restorative systems[24], CVD coatings enhance implant integration, and templating strategies enable porous hydroxyapatite scaffolds for regenerative dentistry [25]. These methods provide superior control over particle size, shape, and chemistry but require sophisticated equipment, strict reaction conditions, and may involve toxic reagents.

2.3. Green or Bio-Inspired Synthesis

Green synthesis utilizes biological extracts or biomolecules as reducing and stabilizing agents, offering an eco-friendly alternative to conventional methods [5]. This approach includes plant extract–mediated synthesis using sources such as aloe vera, neem, and grapefruit seed [5]. Additionally, microbial-assisted synthesis employs bacteria or fungi to produce nanoparticles, while enzyme-mediated processes use specific enzymes to facilitate nanoparticle formation [26].

These green synthesis techniques provide sustainable and environmentally benign routes for producing nanomaterials [5]. Green-synthesized Titanium Dioxide nanoparticles (TiO₂NPs) using grapefruit seed extracts have shown antimicrobial potential in composites [5]. Biocompatibility, sustainability, and regulatory acceptance [5]. Challenges include variability in nanoparticle size, stability, and reproducibility [27].

2.4. Hybrid Approaches

Hybrid strategies combine elements of both top–down and bottom–up methods, thereby integrating their respective advantages [28]. Examples include lithography followed by self-assembly, mechanical milling combined with surface functionalization, and etching processes coupled with sol–gel coating [29]. In dentistry, such approaches have been particularly valuable; hybrid nanocomposites exhibit enhanced mechanical strength and bioactivity [30], while surface-engineered implants with sol–gel-derived nanocoatings demonstrate superior osseointegration [31]. However, despite these advantages, hybrid techniques remain complex, costly, and often require multi-step integration, which limits their widespread adoption in clinical material production.

2.5. Emerging Approaches

New frontiers in nanomaterial synthesis aim for precision, scalability, and compatibility with digital workflows. Microfluidic-assisted nanoparticle synthesis – highly uniform, reproducible particles [32]. Laser-assisted synthesis in liquids – nanoparticle generation without chemical precursors [33]. 3D printing with nanomaterials – integration of nanoscale fillers into additive manufacturing [34].

3D-printed nanocomposites show promise for next-generation prosthetics and scaffolds [35]. Although still experimental, these approaches represent the future of nanotechnology in dentistry. A comparative summary of these strategies, including their definitions, common techniques, advantages, limitations, and examples in dentistry, is presented in Table 1.

Table 1. Strategies for Synthesizing Nanomaterials.

Strategy	Definition	Techniques	Advantages	Limitations	Examples in Dentistry
Top-down approach	Breaking down bulk materials into nanosized structures.	Ball milling, attrition, lithography, focused ion beam (FIB), etching (chemical/plasma), laser ablation, arc discharge.	Produces large quantities; relatively fast; well-defined patterns possible.	Limited control over particle size/shape may introduce defects; high energy cost.	Nanofillers for composites via milling; nanopatterned implant surfaces; plasma-treated enamel/dentin for bonding.
Bottom-up approach	Building nanostructures atom by atom or molecule by molecule.	Sol-gel, chemical vapor deposition (CVD), atomic layer deposition (ALD), hydrothermal/solvothermal, spray pyrolysis, flame synthesis, micelle/templating, self-assembly.	High precision; better control over size, morphology, and surface chemistry; scalable.	Requires precise control of conditions; equipment can be expensive.	Sol-gel bioactive glasses; CVD coatings on implants; templated porous hydroxyapatite scaffolds.
Green synthesis (bio-inspired)	Eco-friendly synthesis using plant extracts, microorganisms, or biomolecules as reducing and capping agents.	Plant extract-mediated synthesis, microbial-assisted synthesis, enzyme-mediated synthesis.	Non-toxic, biocompatible, sustainable, cost-effective.	Less control over uniformity; stability and reproducibility can vary.	AgNPs synthesized using Miswak or propolis extracts for antimicrobial composites; aloe vera-mediated ZnO nanoparticles; plant-extract hydroxyapatite for remineralization.
Hybrid approach	Combination of top-down and bottom-up techniques for optimized properties.	Etching + sol-gel coating; lithography + CVD; ball milling + surface functionalization.	Flexible; tailored structures with synergistic advantages.	More complex and costly; integration challenges.	Hybrid nanocomposites with high strength and bioactivity; surface-engineered implants with sol-gel derived nanocoatings.
Emerging approaches	Advanced synthesis strategies combining nanotechnology with modern fabrication.	Microfluidic-assisted synthesis, laser-assisted synthesis in liquids, nanomaterial-enhanced 3D printing.	Highly precise; reproducible; compatible with digital dentistry.	Still in early stages; limited large-scale adoption.	Customized nanocomposite prosthetics via 3D printing; microfluidic AgNPs for antimicrobial dental adhesives.

3. Unique Properties and Main Challenges of Nanoparticles Compared to Bulk Materials

When materials are reduced to the nanoscale, they exhibit physicochemical properties that are fundamentally different from their bulk counterparts [36]. These differences arise from two main factors: the increased surface area-to-volume ratio and the quantum confinement of electrons. Together, these effects produce distinctive optical, mechanical, chemical, and biological behaviors that make nanomaterials attractive for dental applications [37]. The unique nanoscale properties of materials have been exploited in multiple dental contexts:

- **Antimicrobial coatings** – Silver, zinc oxide and Titanium Dioxide nanoparticles incorporated into adhesives or composites inhibit bacterial growth at restoration margins [5].
- **Reinforcement of restorative materials** – Nanofillers enhance mechanical durability and improve esthetics in resin composites [5].
- **Bioactive systems** – Nano-hydroxyapatite and amorphous calcium phosphate promote remineralization of enamel and dentin [38].

- **Smart materials** – Quantum dot-based systems and pH-responsive nanoparticles are being developed for caries detection and targeted therapeutic release [39].

Despite the promising advances of nanotechnology in dental restorative materials, several challenges continue to hinder its full translation from laboratory research to clinical practice [37]. The key obstacles facing nanotechnology in dentistry revolve around manufacturing reproducibility, size control, biological safety, long-term validation, and regulatory approval [37]. Addressing these challenges requires collaborative efforts between material scientists, toxicologists, clinicians, and industry stakeholders. Ultimately, the transition of nanotechnology from the bench to the chairside will depend on achieving predictable, safe, and cost-effective solutions.

4. Dental Restorative Materials Modified with Nanotechnology

Dental restorative materials represent one of the most active areas where nanotechnology has been applied, with the goal of enhancing mechanical performance, esthetics, bioactivity, and clinical longevity [40]. The incorporation of nanoscale modifications has been explored across virtually all classes of restorative materials, including ceramics, composites, glass ionomers, adhesives, and metals. Each category presents distinct challenges and opportunities, and the application of nanotechnology has yielded unique advances tailored to their specific limitations. Among these, ceramics and glass-ceramics have received particular attention due to their widespread clinical use and inherent brittleness, which nanotechnology seeks to address through microstructural refinement and functional surface engineering.

4.1. Dental Composites Modified with Nanotechnology

Since their introduction in the 1960s, composite resins have become the most widely used restorative materials due to their esthetics and minimally invasive application [5]. However, traditional composites face persistent drawbacks including polymerization shrinkage, limited wear resistance, surface roughening, and susceptibility to discoloration [41].

The evolution of composites has progressed from macrofilled to microfilled and hybrid systems, culminating in nanocomposites [42]. Nanotechnology represents a paradigm shift: by incorporating fillers in the 1–100 nm range, it enables high filler loading without compromising resin viscosity, thereby improving strength, optical properties, and surface smoothness [43].

The integration of nanotechnology into composite resins has markedly improved their mechanical properties, making them more suitable for demanding clinical conditions. Enhanced flexural and compressive strength, superior wear resistance, and increased fatigue tolerance provide nanocomposites with a clear advantage over earlier generations [44]. However, challenges such as polymerization shrinkage stress remain areas for continued innovation.

The rationale for adopting nanotechnology in composites therefore stems from its ability to address long-standing challenges in restorative dentistry. Specifically, nanofillers enable a balance between strength and esthetics that was not achievable with earlier filler technologies [45]. Furthermore, nanotechnology provides a platform for functional enhancements, such as the incorporation of bioactive or antimicrobial nanoparticles, expanding the role of composite resins beyond passive restoration toward active prevention of secondary caries and promotion of oral health [5].

Nanofillers in composite resins, classified as nanoparticles, nanoclusters, and nanohybrids, critically influence the performance of dental composites by enhancing physical, mechanical, and esthetic properties [46]. Nanoparticles (5–100 nm), such as silica and zirconia, offer improved polishability, gloss retention, and optical properties due to minimal light scattering, while reinforcing the resin matrix by inhibiting crack propagation [47]. However, their tendency to agglomerate can affect performance if not managed properly.

Nanoclusters are agglomerated nanoparticles forming porous structures that allow higher filler loading, balancing mechanical strength and esthetics; they fracture under stress into smaller particles,

maintaining surface smoothness [48]. Nanohybrids mix nanosized fillers with microfillers to combine bulk reinforcement and enhanced surface qualities, providing versatility and suitability for both anterior and posterior restorations with improved mechanical strength and esthetics.

Nanocomposite resins exhibit superior mechanical properties, higher flexural strength, modulus, compressive, tensile strength, and fatigue resistance, due to high filler loading, uniform stress distribution, and crack deflection mechanisms of nanoscale fillers [49]. They also demonstrate enhanced wear resistance and microhardness, crucial for posterior restorations, along with reduced polymerization shrinkage stress relative to conventional composites, although shrinkage remains a limitation [5].

Esthetically, nanocomposites achieve exceptional polishability, gloss retention, and translucency, mimicking natural enamel via minimal light scattering and refractive index matching, contributing to seamless shade blending and a “chameleon effect.”[50] Their dense nanoparticle packing reduces surface roughness and porosity, enhancing stain resistance and color stability, though vigilance remains necessary for discoloration from common dietary chromogens [51].

Overall, nanotechnology integrates the esthetic advantages of microfilled composites with the strength of hybrids, producing dental restorative materials that outperform earlier composites in durability and optical performance. Several experimental studies have confirmed the potential of nanofillers to improve composite performance. A summary of representative studies is provided in

Table 2. Representative studies on nanoparticle-modified dental composites.

Reference	Objective	Nanoparticles / Additives	Main Findings
[52]	To determine how incorporating nanoclay as a filler influences the flexural strength of fiber-reinforced composites (FRCs).	nanoclay fillers	nanoclay filler loading may enhance the flexural strength of FRCs.
[53]	To examine how silicon dioxide (SiO ₂) nanofibers affect the overall performance of dental composite materials.	silicon dioxide (SiO ₂) nanofibers	SiO ₂ nanofiber-containing Bis-GMA composite resins were envisioned as a promising choice to achieve long-term durable restorations in clinical therapies.
[54]	To compare and assess the mechanical properties of an experimental composite resin containing 2.5% titanium dioxide nanoparticles (TiO ₂ NPs) as a filler.	titanium dioxide nanoparticle (TiO ₂ NP)	the 2.5% TiO ₂ NP incorporated as filler in an experimental composite resin demonstrated higher mechanical properties compared to the conventional material.
[55]	To assess how adding zinc oxide nanoparticles to dental composites impacts their antimicrobial activity.	zinc oxide nanoparticles (ZnO-NPs)	zinc oxide nanoparticles (ZnO-NPs) blended at 10% (w/w) fraction into dental composites display antimicrobial activity .
[56]	To enhance the use and applicability of single-walled carbon nanotubes (SWCNTs) within dental resin-based composites (RBCs).	single-walled carbon nanotubes	The addition of modified SWCNTs improves the flexural strength of dental RBCs.
[57]	To investigate the antibacterial performance of a resin composite formulated with cross-linked quaternised polyethyleneimine (QPEI) nanoparticles.	cross-linked quaternised polyethyleneimine (QPEI) nanoparticles	PEI nanoparticles are highly promising in preventing bacterial recontamination when restoring teeth.
[58]	To employ a polylactic acid nanoscaffold loaded with CaO nanoparticles as a bioactive polymer component for dental resin composite applications.	CaO/polylactic acid nano scaffold	Nanotechnology as a novel technique has contributed to the use of nanoparticles in the organic resin matrix of dental composites at a nano-scale.
[59]	To examine how hydroxyapatite, zirconia, and glass nanoparticles affect wear behavior and microhardness of the organic matrix in an experimental dental composite resin.	nanoparticles of hydroxyapatite, zirconia, and glass	The inclusion of 32% nanohydroxyapatite, 27% of zirconia, and 19% of glass as filler into the experimental dental composite resin decreased the wear and increased the hardness.

[60]	To investigate mesoporous silica (MCM-41) coated with cerium oxide nanoparticles, and to evaluate its antibacterial effects and mechanical properties after incorporation into dental composite resin.	mesoporous silica coated with cerium oxide nanoparticles	The flexural strength exhibited a decreasing trend as the amount of cerium oxide nanoparticle-coated MCM-41 increased. However, the flexural strength and depth of cure values of the silane group met the ISO 4049 standard. Antibacterial properties increased with increasing amounts of cerium oxide nanoparticles. Although the mechanical properties decreased, silane treatment overcame this drawback. Hence, the cerium oxide nanoparticles coated on MCM-41 may be used for dental resin composite.
[61]	To determine the antibacterial efficacy of an experimental dental composite resin containing cerium oxide nanoparticles as filler particles.	cerium oxide nanoparticles	Integrating cerium oxide nanoparticles as fillers into dental composite resin can be promising in terms of antibacterial activity, provided furthermore study has to be conducted to examine other properties.
[62]	To evaluate how silver and calcium fluoride nanoparticles influence the antibacterial activity of composite resin against <i>Streptococcus mutans</i> .	silver and calcium fluoride nanoparticles	Composite resins containing 0.5% of AgNPs and 15% of CaF ₂ NPs exhibited a significantly lower antibacterial activity compared to the 1.5% and 1% of AgNPs with 15% of CaF ₂ NPs
[63]	To fabricate an experimental composite resin modified with grapefruit seed extract-mediated titanium dioxide nanoparticles (GSE-TiO ₂ NPs), and to assess its antibacterial activity along with its mechanical and physical properties.	Green TiO ₂ nanoparticles	Incorporating GSE-TiO ₂ NPs into composite resins enhances antibacterial activity, improves mechanical properties, and reduces polymerization shrinkage, suggesting a promising approach for developing advanced dental materials with integrated natural bioactive components.

4.2. Glass Ionomer Cements (GICs) Modified with Nanotechnology

Glass ionomer cements (GICs) remain integral to restorative dentistry due to their unique properties such as fluoride release, chemical adhesion to tooth structure, and biocompatibility, making them indispensable in pediatric dentistry, preventive applications, and atraumatic restorative treatment (ART) [64]. However, conventional GICs are limited by low strength, brittleness, poor wear resistance, and esthetic shortcomings [65]. Resin-modified GICs (RMGICs) partially addressed these issues, but concerns persist regarding polymerization shrinkage, hydrolytic degradation, and long-term durability [66]. The incorporation of nanotechnology into GIC formulations has emerged as a promising strategy to overcome these drawbacks while preserving their inherent advantages [67].

Various nanofillers have been investigated to enhance the performance of GICs [67]. Nano-hydroxyapatite (nHAp) acts as a biomimetic additive that promotes remineralization, strengthens chemical bonding with tooth structure, and improves mechanical properties [68]. Nano-silica (nSiO₂) serves as a reinforcing agent, reducing porosity within the matrix and improving both handling and durability [69]. Nano-titanium dioxide (nTiO₂) provides dual benefits of mechanical reinforcement and photocatalytic antibacterial activity, while also enhancing hardness and esthetics [70]. Silver nanoparticles (AgNPs) [71] and zinc oxide nanoparticles (nZnO) contribute potent antibacterial effects that help reduce secondary caries [72]. In addition, bioactive nanoparticles, including bioactive glass, calcium phosphate, and chitosan, promote remineralization, maintain or enhance fluoride release, and improve biocompatibility at the tooth-restoration interface [73].

Nanoparticle incorporation significantly enhances glass ionomer cement (GIC) performance across multiple domains. Mechanically, nanoparticles such as nano-hydroxyapatite (nHAp), nanosilica (nSiO₂), and nano-titanium dioxide (nTiO₂) improve compressive and flexural strength, microhardness, and resistance to crack propagation, strengthening the material for durable

restorations [74–76]. Antibacterial effects are notable with silver nanoparticles (AgNPs), zinc oxide (ZnO), and TiO₂, which reduce biofilm formation, benefiting particularly pediatric and high-carries-risk patients [75,77].

For remineralization, fluoride release is maintained or even enhanced, with nHAp and bioactive glass facilitating superior ion exchange and tissue remineralization [75]. Esthetically, nano-additives improve translucency and polishability, overcoming traditional GIC esthetic limitations by providing smoother, glossier surfaces similar to natural enamel. Regarding bonding, nHAp enhances interfacial adhesion to enamel and dentin and reduces microleakage, supporting restoration integrity and longevity [78].

Nanotechnology-modified GICs show potential to expand the use of these materials beyond traditional preventive settings into intermediate restorations and stress-bearing areas, particularly for pediatric, ART, and high-carries-risk patients [76]. Nonetheless, long-term clinical validation is still lacking, and issues related to nanoparticle safety, reproducibility, and cost-effectiveness remain unresolved. Future development should focus on multifunctional nanofillers that combine reinforcement, antibacterial activity, and remineralization in a single system.

A summary of representative studies is presented in Table 3, highlighting recent advances in green synthesis approaches, bioactive modifications, and multifunctional enhancements of GICs.

Table 3. Summary of studies on nanoparticle-modified glass ionomer cements (GICs).

Reference	Objective	Nanoparticles / Additives	Main Findings
[77]	Synthesized CuNPs using <i>Mentha longifolia</i> extract and incorporated into GIC	Green-synthesized CuNPs	Inhibited biofilm formation on dental implants
[74]	Produced low-cost TiO ₂ NPs from biowaste corn silky hair fibre and added to GIC	Biowaste-derived TiO ₂ NPs	5% addition significantly increased shear bond strength to enamel (4.93 ± 0.74 MPa, $p < 0.05$); confirmed sustainable elemental profile
[75]	Evaluated ChiPh and TMPnano incorporation into RMGIC	Nano-sized sodium trimetaphosphate (TMPnano)	0.25% ChiPh + 14% TMPnano improved mechanical strength, fluoride release, and antibacterial properties while maintaining cytocompatibility
[78]	Tested biocompatibility of green-synthesized nano-modified GIC in rats	Chitosan, TiO ₂ , ZrO ₂ , and nHAp	Demonstrated satisfactory biocompatibility with enhanced tissue repair and no systemic toxicity
[79]	Compared antibacterial, microhardness, and color stability of GIC with AgNPs and Ag@MoS ₂ nanocomposites after thermal aging	Green-synthesized Ag@MoS ₂ NC	Maintained antibacterial activity without compromising color or microhardness after aging
[80]	Assessed the effect of nano-ZrO ₂ on physical and mechanical properties of commercial GICs	Zirconium oxide nanoparticles	7 wt% improved flexural strength/modulus and water sorption; 2 wt% enhanced Vickers hardness

4.3. Dental Adhesive Systems Modified with Nanotechnology

Dental adhesives are critical in restorative dentistry because they establish durable bonding between tooth structures and restorative materials, ensuring retention, marginal integrity, and clinical longevity [81]. Despite their widespread use, conventional systems are limited by polymerization shrinkage induced stress, hydrolytic and enzymatic breakdown of the hybrid layer, and bacterial microleakage at the adhesive dentin interface, factors that collectively promote secondary caries and ultimately compromise restoration longevity [41]. Nanotechnology has been widely applied to overcome these shortcomings by enhancing the mechanical, chemical, and biological performance of adhesives [82].

Incorporating nanoparticles such as silica, nanoclays, zirconia, or hydroxyapatite has been shown to significantly reinforce adhesive matrices [83]. These nanofillers improve cohesive strength,

increase the modulus of elasticity, and reduce shrinkage stresses, thereby improving bond durability [83].

Secondary caries continues to be a leading contributor to failure of adhesive restorations [84]. Nanotechnology has enabled the incorporation of antimicrobial agents directly into adhesive systems without severely compromising their mechanical performance [85]. Silver and zinc oxide nanoparticles release antimicrobial ions, while chitosan-based nanostructures exhibit antibacterial effects against *Streptococcus mutans* [86]. Controlled release at therapeutic levels minimizes cytotoxicity and provides long-lasting antimicrobial activity at the adhesive–dentin interface, thereby reducing bacterial infiltration and prolonging restoration survival [87].

The degradation of exposed collagen fibrils within the hybrid layer is a critical factor in adhesive breakdown [88]. To address this, adhesives have been modified with remineralizing nanofillers such as amorphous calcium phosphate (NACP), nano-hydroxyapatite, and bioactive glass nanoparticles [89]. These additives release calcium and phosphate ions that support intrafibrillar mineralization, stabilize the hybrid layer, and resist enzymatic degradation [89]. The result is a bioactive adhesive interface that not only bonds but also contributes to the long-term preservation of tooth structure [64].

Nanoparticle-modified adhesives combine mechanical reinforcement, antimicrobial protection, and biomimetic remineralization, addressing nearly all major shortcomings of conventional systems. Nonetheless, challenges remain, including optimizing nanoparticle concentration to prevent agglomeration, maintaining viscosity and handling properties, and ensuring biocompatibility. Early clinical studies (Table 4) underscore the potential of nanotechnology to transform dental adhesives into multifunctional, long-lasting systems, though long-term in vivo evidence remains essential for widespread clinical adoption.

Table 4. Summary of recent studies on nanoparticle-modified dental adhesives.

Reference	Objective	Nanoparticles / Additives	Main Findings
[90]	Evaluate effect of adhesive loaded with 0.2% Cu and 5% ZnO NPs on adhesive properties and enzymatic activity at the hybrid layer in an ex vivo randomized clinical model.	0.2% Copper (Cu) NPs + 5% Zinc Oxide (ZnO) NPs	Reduced nanoleakage and gelatinolytic activity at the hybrid layer without compromising adhesive properties.
[91]	Assess CAD surface conditioners and effect of 1% Sep-NPs in experimental adhesive on Ra, SBS, DC, and rheological properties.	Sepiolite NPs (1%)	CAD conditioning with PA and FS laser improved surface roughness and adhesion. Modified adhesive (1% Sep-NPs) decreased DC and rheological properties.
[92]	Assess antimicrobial activity, μ TBS, and DC of adhesive modified with photoactivated RB (0.5%) and RB-doped TiO ₂ NPs (2% and 5%) on CAD.	Photoactivated Rose Bengal (RB)-doped TiO ₂ NPs (2%, 5%)	5% RB-TiO ₂ NP adhesive showed lowest <i>S. mutans</i> survival and highest bond strength. DC decreased with higher NP concentration.
[93]	Evaluate dentin bonding agents incorporated with AgNPs, ZnONPs, and RSVNPs on shear bond strength.	Silver NPs, Zinc Oxide NPs, Resveratrol NPs	RSV-NPs provided anti-cariogenic effects without significantly affecting mechanical properties. AgNPs and ZnONPs maintained bond strength. Further optimization required.
[94]	To evaluate the degree of conversion (DC) and shear bond strength (SBS) of an experimental adhesive (EA), either unmodified or supplemented with 1% cerium oxide (CeO ₂) nanoparticles, for bonding metallic brackets to enamel prepared using three distinct conditioning protocols: riboflavin activated photodynamic therapy (RF), Er,Cr:YSGG laser treatment (ECY), and phosphoric acid etching (PA).	Cerium oxide (CeO ₂)-NPs	Riboflavin activated photodynamic therapy (RF activated PDT) may serve as an alternative to 37% phosphoric acid (PA) for enamel conditioning during metallic bracket bonding. Incorporating 1% CeO ₂ nanoparticles into the experimental adhesive enhances shear bond strength (SBS) regardless of the conditioning method used. However, adding 1% CeO ₂ nanoparticles does not produce a statistically significant change in the degree of conversion (DC) compared with the unmodified experimental adhesive.

5. Future Directions

The integration of nanotechnology into dental restorative materials is rapidly advancing, yet several critical avenues remain for exploration to fully realize its clinical potential and translate laboratory innovations into routine dental practice.

- **Multifunctional Nanofillers and Smart Materials**

Future research should prioritize the development of multifunctional nanofillers that simultaneously provide mechanical reinforcement, antimicrobial protection, and bioactive remineralization to address multiple clinical challenges in a single restorative system. Stimuli-responsive “smart” nanomaterials capable of releasing therapeutic agents on demand—triggered by pH changes, enzymatic activity, or bacterial presence—represent a promising frontier for precision dental care and active intervention at restoration margins.

- **Green and Sustainable Nanomaterial Synthesis**

To ensure biocompatibility, environmental sustainability, and regulatory acceptance, expanding eco-friendly green synthesis approaches that utilize plant extracts, microbial systems, or enzyme-mediated methods is crucial. These sustainable techniques can reduce toxic reagents, improve reproducibility, and facilitate safer clinical translation of nanomaterials in dentistry.

- **Digital Integration and 3D Printing**

Combining nanotechnology with digital dentistry and additive manufacturing offers opportunities for patient-specific restorative solutions with precise nano-engineered architectures. The advancement of 3D-printed nanocomposites, tailored prosthetics, and scaffold materials can revolutionize personalized dental restorations with superior functional and esthetic outcomes.

- **Long-Term Clinical Validation and Safety Assessment**

Robust, longitudinal clinical trials are imperative to evaluate the long-term safety, durability, and efficacy of nanotechnology-enhanced restorative materials under diverse oral environments and patient populations. Comprehensive toxicological and biocompatibility studies must accompany these efforts to address biosafety concerns and facilitate regulatory approval pathways.

- **Overcoming Manufacturing and Translational Challenges**

Further optimization of nanomaterial synthesis protocols is needed to improve batch-to-batch reproducibility, control nanoparticle size and dispersion, and minimize agglomeration in complex dental formulations. Bridging collaborative efforts between material scientists, clinicians, and industry stakeholders will accelerate translation from bench to chairside while balancing cost-effectiveness.

6. Conclusions

Nanotechnology has revolutionized dental restorative materials by enhancing their strength, esthetics, antibacterial properties, and bioactivity across various platforms including ceramics, composites, adhesives, glass ionomer cements, and 3D-printed polymers. However, clinical adoption is still hindered by challenges in reproducibility, biosafety, regulatory approval, and cost. The future of precision nanomedicine in dentistry depends on developing multifunctional nanofillers that combine reinforcement with antibacterial and remineralizing effects, adopting green synthesis for safer materials, integrating nanotechnology with digital workflows and 3D printing for personalized restorations, and creating smart, stimuli-responsive systems for targeted therapeutic delivery. This marks a shift from passive restorations to active, patient-specific, and sustainable biomaterials, bridging innovation with practical clinical application.

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