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Review Article

Nanotechnology in contemporary dentistry: a comprehensive review of current clinical applications, bioactive materials, and future perspectives

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ABSTRACT

This review explores the transformative shift in dentistry from biopassive materials to bioactive nanotechnology, addressing critical challenges such as polymerization shrinkage, secondary caries, and mechanical failure. Through a systematic search of PubMed, Scopus, Cochrane, and Google Scholar (2015–2026), the study evaluates the mechanisms and clinical efficacy of bioactive glass (BAG), nanohydroxyapatite (nHA), and calcium-phosphate scaffolds. Findings indicate that these nanomaterials outperform traditional composites by enabling deep biomimetic remineralization, providing Power of Hydrogen (pH)-responsive ion release, and reducing polymerization stress by up to 37% through advanced fillers like nanoclay. In clinical practice, nanotechnology enhances the polishability and wear resistance of restoratives, optimizes osseointegration via nanofeatured implant surfaces, and improves endodontic sealing through nanoparticle-enhanced sealers. The review concludes that the integration of smart stimuli-responsive systems, Artificial Intelligence (AI), and three-dimensional (3D) bioprinting is transitioning the field from prosthetic replacement to full biological tooth regeneration, establishing nanotechnology as the cornerstone of personalized, regenerative oral healthcare.

Keywords: Nanotechnology, Bioactivity, Nanocomposites, Osseointegration, Restorative, Biomimetics, Innovation

INTRODUCTION

Historical transition and current challenges

Dental materials are selected for their biocompatibility, durability, and aesthetic properties. A shift from biopassive replacements such as gold and amalgam to bioactive regenerative interfaces has been observed.[1,2] Challenges remain in ensuring universal biocompatibility and balancing mechanical strength with aesthetics.[2]

Mechanical and biological failure mechanisms

Restorative success is limited by material flaws. Light-curable composites, making up 70% of restorations, often show up to 7% polymerization shrinkage, causing marginal fissures, enamel fractures, and bacterial infiltration.[3]

Secondary caries, driven by microleakage at the tooth-material interface, is the main cause of failure, with success depending more on biofilm control than material properties.[4]

Aesthetic and structural limitations

Aesthetic stability is often reduced by extrinsic staining, especially in rough-surfaced materials.[5] Ceramics require a trade-off between translucent but brittle glass-matrix systems and tough but opaque zirconia.[6] In implantology, failures stem from slow osseointegration or peri-implantitis, emphasizing the need for surface treatments that enhance healing and resist bacterial colonization.[7]

The integration of nanotechnology

The "era of nanotechnology" in dentistry involves manipulating matter at 1–100 nm scales.[8] Replacing passive fillers with active nanoparticles enhances mechanical, optical, and biological properties, improving restoration longevity and tissue regeneration.[9,10]

Future trajectories and biomimetic innovation

The future of dentistry centers on nanotechnology and smart materials responsive to power of hydrogen (pH) or temperature, alongside artificial intelligence (AI)-guided bioprinting and tissue engineering for personalized tooth replacement, with a growing shift toward biomimetic, sustainable materials requiring long-term clinical validation.[1]

Objectives

The objectives were to evaluate the mechanisms and clinical shift toward bioactive nanomaterials, to examine current clinical applications in restorative, endodontic, and implant dentistry, to assess nanomaterial efficacy in overcoming shrinkage, microleakage, and secondary caries and to identify future trajectories in smart materials, AI, and bioprinting.

METHODS

To develop this literature review, a comprehensive systematic search was conducted using databases such as PubMed, Scopus, Cochrane Library, and Google Scholar. The search strategy utilized targeted keywords and Boolean operators, including: “nanotechnology” OR “nanofillers” OR “nanocomposites” AND “bioactivity” AND “biomimetics” OR “biomimetic integration” AND “restorative dentistry” OR “implant dentistry” AND “dental science innovations.”

The search was primarily limited to articles published between 2015 and 2026, though earlier seminal works were included if they provided foundational knowledge on bioactive filler mechanisms or the initial development of biomimetic standards.

Articles were selected based on their rigorous assessment of mechanical and biological properties, their evaluation of clinical efficacy in restorative and implant procedures, and their focus on the seamless integration of synthetic materials with host tissues.

Included studies are those specifically addressing bioactive filler mechanisms, clinical outcomes of nanotechnology-based interventions, and innovations in dental materials that promote remineralization or biological emulation, including both patient-centered outcomes and practitioner-focused technical assessments.

BIOACTIVE NANOMATERIALS

Specific materials

Bioactive glass

Dixit et al reported that bioactive glass (BAG) enhances remineralization, antibacterial activity, and tissue regeneration, supporting its versatile clinical use across preventive, restorative, endodontic, and periodontal dentistry.[12]

It was found by Thomas et al that BAG supports remineralization, antimicrobial activity, and tissue regeneration, highlighting its versatility and regenerative potential in dentistry.[12]

Similarly, Sawant and Pawar described BAG as biocompatible, promoting hard-tissue repair and antimicrobial effects, noting clinical success depends on particle size, composition, and standardized protocols.[13]

Nanohydroxyapatite

It was found by Pushpalatha et al that nanohydroxyapatite (nHA) improves remineralization, tubule sealing, and composite strength, but high cost and lack of standardization limit its clinical use.[14]

Gennai demonstrated that nHA enhances enamel remineralization, dentin desensitization, and bone integration, supporting its safe and versatile use as an alternative dental material.[15]

Moreover, Izzetti et al showed that nHA treats hypersensitivity, remineralizes enamel, and supports bone regeneration, concluding that its biomimetic, non-toxic nature makes it a superior dental biomaterial.[16]

Anil et al indicated that nHA deeply penetrates enamel to reverse early decay, concluding it is a self-sufficient, non-toxic alternative to fluoride that forms acid-resistant synthetic enamel without fluorosis risk.[17]

Calcium/phosphate

Mishchenko et al demonstrated that three-dimensional (3D)-printed calcium/phosphate (Ca/P)–polymer scaffolds support bone formation and overcome ceramic brittleness, concluding they are effective off-the-shelf alternatives to autologous bone grafts.[18]

Also, Devadiga et al showed that Ca/P agents achieve intratubular remineralization and increase microhardness, concluding that they provide superior bioactive repair for hypersensitivity and acid resistance.[19]

It was evidenced by Rujiraprasert et al that Ca/P ceramics can mimic natural enamel structure and hardness, concluding that they are a next-generation restorative material that restores true tooth function and aesthetics.[20]

Likewise, Lee et al showed that nanostructured Ca/P cements induce odontoblast differentiation through nanotopography-driven cell signaling, make them superior pulp-capping materials.[21]

Mechanism of ion release

It was demonstrated by Garoushi et al that bioactive restoratives provide sustained, rechargeable ion release that reduces secondary caries, render them suitable for high-caries-risk patients.[22]

Venkataiah et al reported that bioactive resin cements show pH-responsive calcium and phosphate release, forming a smart, self-adjusting barrier that protects margins and prevents secondary caries.[23]

Raszewski et al reported that bioactive endodontic and restorative materials sustain calcium ion release in acidic conditions, buffering acidity, inhibiting bacteria, and promoting mineralized barrier formation for superior root canal sealing and deep restorations.[24]

Par et al showed that BAG–filled resin composites release sufficient ions to induce hydroxyapatite formation, acting as an active mineralizing materials that biologically seal margins and reduce secondary caries.[25]

CLINICAL APPLICATIONS

Restorative dentistry

Polishability

Zhang et al showed that nanofilled composites maintain superior smoothness and gloss over time compared to nanohybrids, which render them preferable for long-term aesthetic anterior restorations.[26]

Tyagi et al showed that nanofilled composites achieve higher hardness and smoother surfaces than microhybrids and nanohybrids with multi-step polishing. They offer superior mechanical stability and aesthetic durability.[27]

On the other hand, Fidan and Çankaya found that nanohybrids resist staining better than microhybrids, and longer polishing significantly improves color stability. Nanohybrids offer superior long-term aesthetics when properly polished.[28]

Abo-Eldahab and Kamel showed that suprananofilled composites resist staining better than nanofills, concluding that three-step polishing is essential to preserve color stability in high-stain-risk cases.[29]

Wear resistance

Yilmaz et al showed that nanofill composites have the highest wear resistance and lowest roughness, which make them the most durable choice for occlusal surfaces under functional stress.[30]

Moreover, Dionysopoulos and Gerasimidou found that nanofill and nanohybrid composites resist wear better than microhybrids.[31]

Chen et al reported that nanofill and nanohybrid composites show lower wear and higher surface hardness than microhybrids, confirming that optimized nanofillers enhance restoration durability and long-term mechanical performance.[32]

In a comparative study, Asefi et al reported that innovative composite resins show higher wear resistance than conventional nano- and microfilled composites, supporting their superior durability and suitability for stress-bearing restorations.[33]

Implantology and osseointegration (OI)

It was demonstrated by Komatsu et al that nanofeatured implant surfaces enhance OI, cellular adhesion, and early bone healing versus conventional surfaces.[34]

Costa Filho et al demonstrated that titanium implants with micro–nano textured surfaces and strontium enhance OI, bone formation, and osteoblast activity, supporting improved stability and healing.[35]

Similarly, Sartoretto et al reported that nanostructured hydroxyapatite–coated implants enhance early OI in low-density bone by increasing bone-to-implant contact, new bone formation, and osteoblast activity, improving initial implant stability.[36]

Parnia et al showed that nanoparticle-coated titanium implants enhance OI and resist bacterial colonization, concluding they create a “sterile, pro-growth” surface.[37]

Endodontics

Wagih et al reported that nano-mineral trioxide aggregate (MTA) shows superior sealing and adaptability versus conventional MTA, supporting its use in endodontic surgery for improved marginal integrity and reduced microleakage.[38]

It was shown by Tiffany et al that nanoparticle-enhanced sealers penetrate microscopic canals, provide sustained antimicrobial action, and improve biocompatibility, making them “smart” materials that reduce microleakage and enhance obturation success.[39]

Moreover, Chandak et al demonstrated that nanoparticles in endodontics enhance antimicrobial activity, sealer penetration, and tissue regeneration, supporting improved treatment efficacy and long-term success.[40]

Tarek et al showed that bioceramic sealers with silver and chitosan nanoparticles enhance antimicrobial activity and bond strength. They provide a stronger mechanical and biological barrier against infection and sealer failure.[41]

OVERCOMING MATERIAL LIMITATIONS

Polymerization shrinkage

Campos et al showed that montmorillonite nanoclay reduces polymerization shrinkage and internal stress in composites, thereby improves marginal integrity and helps prevent restoration failure.[42]

Fronza et al showed that nanogel-grafted fillers reduce polymerization shrinkage stress by up to 37% without weakening composites, which improves bond stability and resistance to marginal leakage.[43]

Similarly, Alhussein et al demonstrated that bioactive nanocomposites with calcium fluoride exhibit antibacterial activity, ion release, and reduced polymerization shrinkage, supporting their use for durable, caries-resistant restorations.[44]

Masulili et al reported that nanoceramic composites show lower polymerization shrinkage than nanofilled composites, offering improved dimensional stability and potentially enhancing restoration longevity.[45]

Antimicrobial efficacy

Khalifa et al. showed that silver nanoparticles combat multidrug-resistant bacteria via multi-site mechanisms and synergize with antibiotics.[46]

Similarly, Song and Ge reported that antimicrobial nanoparticles in dental materials inhibit biofilms and secondary caries without compromising strength, supporting preventive, durable restorationst.[47] Ahmed et al demonstrated that gum Arabic–silver nanoparticles provide strong antimicrobial activity against oral pathogens with low cytotoxicity, which made them a safe, eco-friendly option for oral healthcare applications.[48] An interesting study by Ferrando-Magraner et al reported that silver, zinc oxide, and titanium dioxide nanoparticles in restorative materials enhance antibacterial activity against Streptococcus mutans, reducing bacterial colonization and secondary caries risk.[49]

BIOMIMETIC INNOVATION AND FUTURE PERSPECTIVES

Smart stimuli-responsive systems

Waghmode et al showed that bioactive restorative materials provide strong antibacterial activity, sustained fluoride release, hydroxyapatite formation, and reduced microleakage, made them superior over conventional resins.[50]

Samir and Hussein demonstrated that Cention N and Activa Bioactive show an initial fluoride burst followed by sustained release, supporting long-term caries prevention and enamel remineralization in pediatric restorations.[51]

On the other hand, it was confirmed by El-Adl et al that bioactive restorative materials show an immediate fluoride burst within 24 hours, providing early cariostatic effects, especially beneficial for high-risk patients.[52]

Puspitasari et al reported that bioactive resins release more fluoride in acidic conditions, enhancing cariostatic effects and protecting teeth during acid challenges.[53]

AI and 3D bioprinting

Mayya et al showed that 3D-printed and hydrogel scaffolds mimic the pulp-dentin environment and deliver stem cells and growth factors, enabling full regenerative endodontics beyond conventional root canal therapy.[54]

Likewise, Smaida et al reported that 3D dental pulp models replicate the native microenvironment, supporting studies on cell behavior, vascularization, and biomaterial interactions, and serving as a platform for regenerative endodontic strategies.[55]

Chen and Wei reported that 3D printing enables precise, efficient fabrication of diverse dental restorations and appliances, enhancing customization and reducing time and waste.[56] Moreover, Chander and Gopi showed that 3D printing enables accurate, customizable prosthodontic restorations and guides, improving workflow and outcomes, with ongoing advances supporting fully personalized, high-precision care.[57]

Ostrovidov et al found that 3D bioprinting enables precise reconstruction of the dental alveolar complex, including pulp-dentin, supporting functional tooth regeneration while highlighting the need for long-term neurovascular integration.[58]

DISCUSSION

The literature confirms a paradigm shift from inert to bioactive materials, driven by nanotechnology. This transition addresses long-standing clinical failures in restorative, endodontic, and implant dentistry through three primary pillars: structural regeneration, functional durability, and smart bio-responsiveness.

Bioactive regeneration versus passive repair

The consensus across studies highlights BAG and nHA as superior to traditional materials.[11,12]

Mechanism

Unlike fluoride, which primarily provides surface protection, nHA enables deep enamel penetration and "biomimetic" repair.[17]

Hardness

Ca/P agents mimic natural tooth structure, successfully increasing microhardness and reversing early decay.[19,20]

Enhancing clinical longevity and aesthetics

Nanotechnology has significantly optimized the physical properties of composites.

Durability

Nanofilled composites offer superior polishability and wear resistance over traditional hybrids, ensuring long-term aesthetic stability in stress-bearing areas.[26,30]

The "smart" interface

Modern resins now feature pH-responsive ion release, where acidity triggers a mineral surge to buffer the environment and prevent secondary caries at the margins.[23,24]

Solving the "Achilles' heel": shrinkage and infection

Nanofillers are successfully mitigating the two leading causes of restoration failure.

Stress reduction

Innovations like nanoclay and nanogel-grafted fillers reduce polymerization shrinkage by up to 37%, preserving the marginal seal.[42,43]

Biofilm control

Integrating silver and zinc oxide nanoparticles creates a "sterile" environment, inhibiting bacterial colonization without weakening the physical restoration.[46,47]

Precision and future horizons

The integration of 3D bioprinting and AI is moving the field toward personalized regenerative medicine.

Complex repair

3D-printed scaffolds now mimic the pulp-dentin microenvironment, offering a viable path for full biological tooth regeneration beyond traditional root canals.[54,58]

Implantology

Nanofeatured and strontium-incorporated surfaces significantly accelerate OI and early bone healing, improving stability in low-density bone.[35,36]

CONCLUSION

Nanotechnology has catalyzed a shift from biopassive to bioactive dentistry, solving the critical failures of polymerization shrinkage, secondary caries, and mechanical wear. Through materials like BAG and nHA, dentistry has moved beyond passive filling to biomimetic remineralization and pH-responsive protection.

Furthermore, nanostructured surfaces in implantology and endodontics have optimized osseointegration and marginal sealing. As the field integrates AI-guided 3D bioprinting, the focus evolves from restorative replacement toward full biological regeneration, establishing nanotechnology as the gold standard for personalized, long-term oral health.

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