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Review Article

Nanotechnology in dentistry: mechanisms, clinical applications and translational status

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ABSTRACT

Nanomaterials in dentistry comprise a diverse group of material platforms rather than a single therapeutic category. This structured narrative review examined the principal nanomaterial classes used in dentistry, including calcium phosphate and nano-hydroxyapatite systems, bioactive glass and ion-releasing nanoparticles, metallic nanoparticles, metal-oxide nanoparticles, polymeric nanoparticles and nanogels, carbon-based nanomaterials, and hybrid multifunctional systems. A literature search of PubMed, Scopus, and Web of Science, and evidence was analyzed comparatively according to material class, mechanism of action, dental indications, and current evidence maturity across preventive-pediatric, prosthodontic, orthodontic, endodontic, periodontal, and implant-related applications. Overall, the findings suggest that nanomaterials used in dentistry do not represent a single level of clinical maturity. Mineral-based systems, particularly calcium phosphate and nano-hydroxyapatite, show the strongest clinically anchored evidence, especially for caries prevention in selected settings and dentin hypersensitivity relief, whereas evidence for white spot lesion improvement remains less robust and often short-term. By contrast, many antimicrobial, multifunctional, and implant-related nanomaterials remain supported mainly by laboratory or early translational data, with performance that is highly dependent on formulation, durability, and the balance between function and material stability. Future progress will depend on comparative studies that assess performance, durability, and long-term patient-relevant outcomes.

Keywords: Nanomaterials, Nano dentistry, Nano-hydroxyapatite, Calcium phosphate, Bioactive glass, Remineralization

INTRODUCTION

Nanotechnology has advanced from laboratory trials to a visible tool in the field of dentistry. Mineral-based systems, ion-releasing bioceramics, functional nanofillers, and nano-engineered implant surfaces share a nanoscale dimension.[1] The move toward bioactive and bioceramic materials reflects a broader shift from passive replacement toward materials designed to interact with the tooth–material interface and surrounding tissues in a

more functional way.[2,3] Among these material groups, calcium phosphate–based systems have attracted particular interest because they align closely with tooth mineral biology. Their appeal lies in biomimetic mineral deposition, tubule occlusion, and support of remineralization rather than reliance on purely antimicrobial action. This rationale has translated most clearly to dentin hypersensitivity, where systematic review evidence suggests that calcium phosphate formulations can reduce pain, although durability and formulation-dependent variability remain important considerations.[4]

In early enamel lesions, the picture is more nuanced. Recent evidence indicates that combinations such as nano-hydroxyapatite with fluoride may be promising, but outcomes remain dependent on lesion type, comparator, and study design rather than on the nanoscale alone.[5] At the same time, the expansion of nanomaterial design in dentistry extends well beyond remineralization. Nano-engineered restoratives, surface-active fillers, and implant-related surface modifications have broadened the therapeutic landscape, but they have also made interpretation more difficult because performance depends on much more than particle size.[6,7] Host matrix, release profile, dispersion quality, interfacial behavior, and target indication all influence whether a nanomaterial behaves as a useful bioactive system, a reinforcing additive, or merely a promising laboratory concept.

This is particularly relevant for implant surfaces, where nanoscale features may influence early biological events, yet the relationship between surface innovation and durable clinical advantage remains far from straightforward.[8] Examining nanomaterials makes it possible to distinguish biologically coherent and clinically advancing systems from those that remain more experimental, formulation-sensitive, or weakly validated. The purpose of the present review was therefore to examine the principal nanomaterial classes used in dentistry and to compare their mechanisms, applications, and relative translational maturity across dental specialties.

METHODS

Review design and scope

This article was developed as a structured narrative review of the principal nanomaterial classes used in dentistry and their reported therapeutic, preventive, and restorative roles. The review was designed to examine how distinct material platforms differ in mechanism, dental indication, and level of clinical maturity. The synthesis was therefore organized around major nanomaterial categories, including calcium phosphate and nano-hydroxyapatite systems, bioactive glass and other ion-releasing nanoparticles, metallic nanoparticles, metal-oxide nanoparticles, polymeric nanoparticles and nanogels, carbon-based nanomaterials, and hybrid or multifunctional nano-enabled systems.

Literature search and source selection

A search of the literature was undertaken in major biomedical databases, including PubMed/MEDLINE, Scopus, and Web of Science, with supplementary manual screening of the reference lists of relevant reviews and key primary studies.

The search strategy combined nanotechnology-related terms with material-specific terms and dental application terms in order to capture literature across material classes and specialties. Representative terms included nano-hydroxyapatite, calcium phosphate nanoparticles, bioactive glass, silver nanoparticles, zinc oxide nanoparticles, titanium dioxide nanoparticles, polymeric nanoparticles, nanogels, graphene, carbon nanotubes, hybrid nanomaterials, and multifunctional dental nanomaterials, each linked to dentistry-related terms such as caries, restorative dentistry, orthodontics, prosthodontics, endodontics, implantology, periodontology, prevention, and remineralization. The purpose of the search was to identify studies reporting benefit and capture evidence describing material-dependent limitations, including aging instability, mechanical compromise, biocompatibility concerns, and restricted clinical validation.

Eligibility criteria

Articles were considered eligible when they examined a clearly defined nanomaterial or nano-enabled material platform used in a dental context and reported outcomes relevant to dental performance, biological activity, or clinical translation. Eligible studies included those addressing preventive, restorative, prosthodontic, orthodontic, endodontic, periodontal, or implant-related applications, provided that the nano-component was central to the intervention or material behavior under investigation. Studies were retained when they contributed meaningfully to understanding one of the nanomaterial classes covered in the review and when they reported outcomes such as remineralization, dentin hypersensitivity reduction, antimicrobial performance, mechanical behavior, surface modification, ion release, biocompatibility, durability, or clinically relevant translational findings.

Original laboratory studies, in situ studies, animal studies, clinical investigations, and evidence syntheses were all considered, provided they added interpretable evidence to the discussion of a specific material class. Articles were excluded if they focused exclusively on non-dental biomedical applications, discussed nanotechnology only in general conceptual terms without addressing a defined dental material platform, or were limited to synthesis chemistry or physicochemical characterization without clear dental relevance. Editorials, opinion pieces,

conference abstracts, and publications lacking sufficient methodological or outcome detail were also excluded.

Synthesis approach

The final synthesis was narrative in nature and was organized by nanomaterial class. Within each class, the literature was interpreted in relation to mechanism of action, representative dental indications, degree of clinical support, and major translational limitations. Greater interpretive weight was given to systematic reviews, meta-analyses, randomized clinical trials, and clinically oriented studies when available, whereas in vitro and proof-of-concept studies were used primarily to explain mechanisms and early performance trends.

NANOMATERIALS USED IN DENTISTRY

Nanotechnology in dentistry is not defined by a single material class. It includes mineral-based systems, metals and metal oxides, polymeric carriers, and hybrid formulations. Each group has different mechanisms, benefits, and failure modes. The same nano label can therefore describe interventions with very different clinical potential. Evidence quality varies by indication. Preventive applications have the most patient-level data. Antimicrobial and multifunctional restoratives remain dominated by laboratory studies. Many nano-enabled dental products are delivered chairside and may be mechanically modified intraorally. Yet, the most credible near-term exposure concern is not the nano label itself, but procedure-driven aerosol and splatter generation. Accordingly, the clinical relevance of nanomaterial safety is shaped by where in the workflow aerosols are produced and which controls reliably mitigate spread. Figure 1 summarizes common chairside procedures by relative aerosol risk and the primary mitigation controls most consistently recommended across infection-prevention guidance.

Clinical procedure	Relative aerosol risk	Primary controls
Finishing / polishing	**Moderate**	Wet polishing High-volume evacuation (HVE) Personal protective equipment (PPE)
Grinding / removal	**High**	Containment High-volume evacuation (HVE) Personal protective equipment (PPE)
Appliance / aligner adjustment	**Moderate**	Local suction Eye protection
Implant maintenance	**Low**	Low-speed polish Irrigation High-volume evacuation (HVE)

Figure 1: Procedure-based aerosol risk using nano-enabled dental products and primary controls in dental practice.

Calcium phosphate systems and nano-hydroxyapatite

Calcium phosphate nanomaterials are central to preventive nanodentistry because they target demineralization and remineralization directly. Their appeal is biologically plausible. Enamel and dentin are calcium phosphate–based tissues. Nano-scale particles may enhance surface deposition and mineral exchange due to higher surface area and closer interaction with enamel microdefects. The problem is not the rationale. The problem is consistency of clinical benefit and how it compares with fluoride-based standards. The most clinically important advance is that hydroxyapatite has been tested in long-duration randomized trials using patient-level endpoints. Paszyńska and colleagues conducted an 18-month double-blind randomized non-inferiority clinical trial in adults. A fluoride-free hydroxyapatite toothpaste was compared with a 1450-ppm fluoride toothpaste. The primary endpoint was the proportion of participants without an increase in DMFS. The design is important. It moves the evidence from surrogate outcomes toward real caries experience. The trial supports that hydroxyapatite can be clinically viable in this context. It does not prove superiority over fluoride. It supports non-inferior performance under the tested conditions.[9] This distinction matters because many papers imply that nano-hydroxyapatite is a “fluoride alternative” in a broad sense. The current clinical evidence supports a narrower conclusion. Hydroxyapatite can be effective, but it should not be presented as a replacement for fluoride across all risk profiles based on a limited number of trials. A systematic review and meta-analysis on clinical evidence for hydroxyapatite in caries prevention synthesized the emerging human literature and reinforced that the clinical signal is promising, while also reflecting that the evidence base is still developing.[10] White spot

lesions are often used to justify hydroxyapatite products in orthodontic patients. Here, the evidence is weaker and more fragile. A systematic review and meta-analysis concluded that nano-hydroxyapatite interventions showed promising remineralization effects on WSL compared with fluoride alone, but it also emphasized the limited number of clinical studies, short follow-up, and high risk of bias.[11] This is a repeated pattern in WSL research. Trials vary in lesion severity, measurement methods, and comparators. Short-term improvements in surface appearance do not always translate into durable changes in lesion activity. The field often reports improvement, but the clinical meaning depends on whether lesion progression is prevented after normal dietary and hygiene exposure. Dentin hypersensitivity is a stronger clinical target for nano-hydroxyapatite than WSL camouflage, because trials can directly measure symptoms. The highest level summary evidence is supportive. A systematic review and meta-analysis concluded that nHAP-containing agents reduce hypersensitivity in both at-home and in-office protocols when compared with other desensitizing agents or placebo. The authors still cautioned that the evidence was based on a small number of trials and that longer follow-up is needed.[12] This caution should be kept in the narrative. Hypersensitivity studies often have short observation periods. Many products show early effects that may not persist. Later randomized clinical studies are consistent with benefit and suggest possible dose effects. Amaechi and colleagues reported that nano-HAP toothpastes reduced dentin hypersensitivity symptoms, and that 15% nano-HAP performed better than 10% in their trial setting.[13] The key point is not that more is better. It is that concentration and formulation likely matter, which explains variability across commercial products. Calcium phosphate nanotechnology is often presented as remineralizing by default. That is not always true. Performance depends on solubility, particle size distribution, and the vehicle used to deliver the particles. It also depends on the competing chemistry of saliva and fluoride. Studies that show strong remineralization in artificial lesions can exaggerate expected outcomes in clinical lesions, where pellicle, plaque acids, and patient behavior dominate. Bioactive glass systems sit near the calcium phosphate domain because they act through ion release and apatite formation. They are not identical to hydroxyapatite, but the clinical logic overlaps. One recent study comparing varnish systems reported that fluoride-containing and nanosilver-containing bioactive glass varnishes achieved higher remineralization potential than some controls, based on microhardness and SEM/EDX outcomes.[14] This supports biological activity, but it also illustrates the translational gap. Many bioactive glass studies remain laboratory-based. Clinical adoption will require robust trials with lesion-level outcomes and durability.

Overall, calcium phosphate and nano-hydroxyapatite represent the most clinically anchored branch of nanodentistry. The evidence is strongest for caries prevention and hypersensitivity relief, because human trials and meta-analyses exist. The evidence is weaker for white spot lesion reversal and cosmetic change, because trials are fewer and more biased.

Bioactive glass and ion-releasing nanoparticles

Bioactive glass (BG) occupies a distinctive position in nanodentistry because it is designed to be chemically active in the oral environment. Its effect is not mainly based on filling space like inert fillers. It relies on controlled dissolution. BG releases calcium and phosphate ions and raises local pH, which can favor apatite formation on enamel and dentin surfaces. These mechanisms explain why BG has been repeatedly investigated for early lesion management, dentin hypersensitivity, and as an additive in restorative systems.[15] A major reason for the wide interest is that BG offers a plausible dual-action model. It can support remineralization through ion release and may also reduce cariogenic activity through alkalinization and altered bacterial metabolism. However, mechanistic plausibility has not translated uniformly across outcomes. The evidence is stronger for symptom-driven conditions such as hypersensitivity than for true caries prevention, where long-term behavior, diet, and fluoride exposure dominate. The literature on BG in caries-related indications shows a repeated pattern. Laboratory studies often report increased microhardness and mineral deposition on demineralized enamel or dentin. An in vitro study assessing fluoride-incorporated BG toothpaste reported remineralization effects on artificial subsurface lesions in primary teeth, which is consistent with the expected ion-release mechanism.[16] Yet these designs are limited by simplified lesions, controlled pH cycling, and the absence of mature plaque biofilms. They demonstrate potential, not clinical protection. The clinical translation question becomes clearer when long follow-up trials are available. A large double-blind randomized controlled trial in preschool children compared a fluoride-free 7.5% BG toothpaste to an 800-ppm fluoride toothpaste over 27 months for early childhood caries prevention. The study did not support BG as a straightforward replacement for fluoride in that setting. Caries progression remained substantial in both groups. The BG group showed slightly higher caries increments numerically, and the authors highlighted that a preventive agent performing no better than a low-fluoride comparator has limited public health value.[17] This trial is important because it directly challenges the common assumption that remineralization capability automatically leads to lower caries incidence. It also illustrates a second issue. BG efficacy may depend on formulation and context. A single concentration in one population cannot settle the question. Yet it sets a high bar for claims of anticaries superiority. The gap between remineralization and caries prevention is also reflected in evidence synthesis. A systematic review and meta-analysis comparing combined therapies (including BG-based approaches) with topical fluoride alone concluded that some combinations may improve remineralization of

existing lesions, but they were not more effective at preventing caries incidence than fluoride monotherapy. The certainty was low and trial quality varied.[18] This supports a cautious interpretation. BG may add measurable mineral effects in controlled lesions, but prevention at the population level requires more than mineral deposition. White spot lesions around orthodontic brackets have also been used as a clinical argument for BG. Yet the best available synthesis suggests that benefit is not clearly superior to fluoride toothpaste. A systematic review and meta-analysis found no statistically significant difference between BG and fluoride toothpaste in white spot lesion remineralization, even though BG performed better than no treatment in pooled in vitro comparisons.[19] Many orthodontic nano-strategies reduce lesion depth in laboratory models, but the comparative advantage over standard fluoride exposure is often small, inconsistent, or absent. In contrast, the clinical case for BG is more persuasive in dentin hypersensitivity. Here the endpoint is symptom change, and short follow-up trials are informative. A randomized clinical trial reported that a toothpaste containing 5% fluorocalcium phosphosilicate (a BG-derived formulation) reduced hypersensitivity more than two comparator toothpastes over one month, using tactile and evaporative stimuli with pain scoring.[20] System-level syntheses support this general direction. A systematic review of randomized trials comparing BG-based desensitizers with controls concluded that both home and office products can reduce pain outcomes, although follow-up was short and trial designs differed.[21] A more recent systematic review focusing on BG-based hypersensitivity products reported consistent reductions in pain across clinical studies, while noting that follow-up typically ranged from 1 to 11 weeks.[22] A key limitation remains durability. Most hypersensitivity trials show early improvement, but fewer studies test whether relief persists for months under routine habits. Another area where ion release is used to justify benefit is antibacterial activity. BG can suppress growth and acid production in vitro, partly through pH elevation and ionic disruption. A study evaluated a bioactive glass-ceramic (HX-BGC) and reported antibacterial effects against cariogenic bacteria.[23] Strontium-doped BG systems have also been proposed to combine mineral effects with improved antibacterial behavior and material stability.[24] Yet the clinical relevance should not be overstated. The ECC prevention trial above shows that antibacterial potential and remineralization capacity do not necessarily translate into lower caries increments at scale, particularly when adherence, sugar exposure, and baseline risk are unfavorable.[17] Ion-releasing nanoparticles extend beyond BG into a broader class of therapeutic fillers. These include formulations designed to release fluoride, calcium, phosphate, or dopant ions such as zinc or silver. The intended advantage is a sustained local chemical effect without relying on patient compliance. The main limitation is control. Conventional BG compositions may release ions rapidly and lose activity over time. A review discussing BG roles in caries management emphasized that clinical translation remains limited and noted challenges such as rapid ion burst release and long-term stability.[25]

This is not a technical detail. It affects how long a material remains protective, and whether its effect can survive years of intraoral aging. Mesoporous bioactive glasses (MBGs) attempt to address this by increasing surface area and enabling more tunable release profiles. They are often discussed for implant-adjacent regeneration and local drug delivery, where the ability to load and release therapeutic agents becomes central. Experimental studies in this area support biological activity and drug carrier potential, but dental clinical evidence remains early.[26] This is a classic translational bottleneck in nanodentistry. Carrier performance is impressive in vitro, but clinical pathways require reproducible manufacturing and clear patient endpoints. BG and ion-releasing fillers are also increasingly incorporated into restorative materials under the label bioactive resin composites.

The logic is attractive. Ion release may support mineral recovery at margins and reduce bacterial activity. However, the antimicrobial and anticaries claims depend on whether the restorative remains mechanically stable and smooth after aging. A review assessing antimicrobial potential of bioactive resin composites highlighted the rationale and early evidence but reflects that clinical-level conclusions are still constrained by heterogeneity of materials and testing approaches.[27] This is why bioactive should be treated as a hypothesis, not a guarantee. A composite that releases ions but degrades faster can fail earlier, which undermines any theoretical anticaries advantage.

Overall, bioactive glass and ion-releasing nanoparticles represent one of the most rational nano-enabled strategies in dentistry because their mechanisms align with mineral biology. The most consistent clinical signal appears in dentin hypersensitivity. For caries prevention, the evidence is mixed, and large trials show that BG is not a simple substitute for fluoride in high-risk populations. The strongest future direction is not broader claims. It is better product standardization, longer follow-up, and head-to-head comparisons against guideline-level fluoride exposure, with outcomes that reflect real caries incidence rather than only surface changes.

Metallic nanoparticles

Metallic nanoparticles have been explored in dentistry mainly for antimicrobial control. Silver is the dominant example, followed by copper. Gold is used less as an antibacterial additive and more as a platform for diagnostics and therapeutic delivery. Across these metals, the same translational tension appears repeatedly. Antimicrobial effects are often strong in vitro. Mechanical stability and biocompatibility are more variable. Clinical evidence is limited. The broadest synthesis comes from a systematic review and meta-

analysis on metallic nanoparticle incorporation into restorative dental materials. It concluded that metals, especially silver and copper, commonly improve antimicrobial performance compared with unmodified controls. At the same time, several mechanical properties were reduced in a subset of formulations. The direction of effect depended on the material class and nanoparticle concentration. This is a consistent message across the literature.[28] Silver nanoparticles (AgNPs) are widely studied because they show broad-spectrum activity and are effective at low mass fractions. In restorative dentistry, AgNPs are typically added to resins, adhesives, or PMMA-based prosthetic polymers. The antibacterial rationale is clear, but translation requires activity in saliva-rich conditions. Li and colleagues used a plaque microcosm model to test bonding agents containing AgNPs, with and without a salivary pellicle layer. Antibacterial effects were retained even after pellicle coating. This supports the concept that AgNP-containing adhesives can remain active under clinically relevant surface conditioning. However, this remains laboratory biofilm evidence. It does not demonstrate fewer caries lesions or longer restoration survival in patients.[29]

In prosthodontics, AgNPs are mainly used to target Candida and mixed biofilms on PMMA dentures. A systematic review and meta-analysis of in vitro studies evaluated AgNP-based antimicrobial PMMA resins. The pooled results indicated antimicrobial improvement, but the studies varied widely in particle synthesis, concentrations, and testing methods. Mechanical and physical trade-offs were not uniform. This heterogeneity makes it difficult to define an effective and safe dose that generalizes across products.[30] A review focusing on AgNPs as additives to PMMA reached a similar conclusion, emphasizing antimicrobial benefit while highlighting the need to balance it against material performance and safety.[31] Copper nanoparticles have gained attention as a lower-cost antibacterial alternative with strong antimicrobial mechanisms. A review summarized copper nanoparticle applications across dental materials and emphasized their dual potential to enhance antimicrobial activity while influencing physicomechanical properties. However, it also highlighted the same critical dependency on concentration and formulation. Copper can be beneficial in one matrix and harmful in another.[32] Importantly, translation has moved slightly beyond bench testing in this area. An in situ study evaluated a universal adhesive containing copper nanoparticles and reported antimicrobial effects under oral exposure conditions. This type of design matters because it places the material into the complex oral environment rather than simplified media. Even so, in situ antimicrobial signals still need confirmation through patient-level outcomes such as reduced lesion formation or improved restoration longevity.[33] Gold nanoparticles sit in a different evidence space. Their major strength is not direct bacterial killing. It is their optical and surface chemistry properties, which support biosensing, imaging, and drug delivery. A review mapped proposed dental uses of gold nanoparticles across bone regeneration, periodontology, implantology, caries-related concepts, and oral cancer diagnostics. It also noted that the field lacks mature evidence synthesis at the systematic-review level, which reflects how fragmented the primary literature remains.[34] At present, gold nanoparticles contribute more to "technology development" than to routine dental materials with established clinical endpoints. Across metallic nanoparticles, the most consistent barrier to readiness is not lack of antimicrobial effect. It is the instability of the benefit once mechanical durability, esthetics, aging, and host safety are considered together. A meta-analysis on metallic nanoparticle incorporation makes this explicit. Antimicrobial benefit is common. Mechanical penalties are also common, and not predictable without studying each formulation separately.[28] This is why metallic nanoparticles should not be discussed as a single clinical solution. They represent a design tool. Their value depends on whether antimicrobial improvement is retained in saliva-conditioned biofilms, without sacrificing long-term function.

Metal-oxide nanoparticles

Metal-oxide nanoparticles are among the most studied nano additives in dentistry because they combine antimicrobial potential with physicochemical stability. Their antimicrobial mechanisms are usually linked to oxidative stress, surface reactivity, and (in some cases) photocatalysis. This creates a predictable trade-off. When antibacterial potency increases, biocompatibility and material performance can become more fragile. Clinical translation therefore depends on dose, exposure conditions, and long-term stability. Titanium dioxide (TiO_2) is the clearest example of this dual profile. It is widely described as biocompatible, chemically stable, and antimicrobial, yet there is still no consensus on how to optimize its antimicrobial activity without compromising performance. A review emphasized that antimicrobial efficacy remains highly dependent on particle characteristics and modification strategies.[35] This uncertainty is not academic. It becomes obvious when TiO_2 is moved into real appliances. In a randomized controlled clinical trial, 1% TiO_2 nanoparticles were incorporated into the acrylic baseplates of twin-block functional appliances. The test group showed reduced bacterial colony counts under the baseplate compared with controls, with statistically significant differences appearing after four and six months.[36] The signal is encouraging, but the endpoint is microbiological. It does not confirm fewer lesions, less gingivitis, or better clinical outcomes. The sample size was also small. Photocatalysis is often presented as the "solution" that upgrades TiO_2 from passive to highly antimicrobial. In reality, it introduces a clinical constraint: activation conditions. A study on TiO_2-coated clear aligners showed that antimicrobial effects were achieved when samples were activated with UVA light. It also showed a realistic trade-off. Higher TiO_2 concentration modestly increased

microhardness but reduced optical transparency, with 4% TiO_2 showing a significant decrease in clarity.[37] This is a common weakness of TiO_2 translation. The antimicrobial story becomes strongest under light activation, while clinical acceptability is constrained by aesthetics and practical delivery of appropriate light exposure. Zinc oxide (ZnO) is often positioned as a more straightforward antimicrobial oxide because it can show antibacterial activity without relying on photonic activation. It is therefore heavily investigated in orthodontic and restorative contexts. The most valuable evidence comes from clinical designs rather than bench studies. A randomized split-mouth trial evaluated ZnO nanoparticle-coated elastomeric modules in orthodontic patients over one year. The coated side showed lower S. mutans signal at one year and lower laser fluorescence values, suggesting reduced demineralization.[38] Yet the same paper documented a major durability concern. Coating integrity was stable only for about two weeks, with delamination and discontinuity reported after that period. This is a key translational friction point. The antimicrobial benefit may be clinically modest, and the coating may not persist long enough to justify the complexity, unless the coating can be stabilized or renewed. In restorative dentistry, ZnO is often used as a modifier to enhance antibacterial behavior and potentially influence adhesion or mechanical performance. A study reported that adding mesoporous ZnO nanoparticles to resin-modified glass ionomer cement improved adhesion to enamel and dentin at 5 wt%, but the results were concentration-dependent.[39]

This concentration dependence should be treated as the rule, not the exception. More broadly, nanomaterial performance should be understood as an emergent property of formulation and use context rather than a fixed property of the material label itself. It reflects the same pattern seen across nanofillers: low–moderate loading may help, while higher loading can increase defects, roughness, or polymer disruption. Mechanistic work also supports that ZnO can inhibit S. mutans biofilm behavior and clarifies plausible modes of action.[40] The limitation remains external validity. Many studies rely on single-species models and short exposure windows. Cerium oxide (CeO_2) has gained attention because it is mechanistically different from TiO_2 and ZnO. "Nano-ceria" is often described as redox-active with antioxidant behavior, which makes it attractive when researchers want antimicrobial or anti-inflammatory potential without purely relying on oxidative damage. A review summarized biomedical and dental interest in CeO_2 nanoparticles, including antimicrobial and tissue-response modulation themes.[41] However, the dental evidence base is still dominated by preclinical designs and material-property testing. Clinical dentistry does not yet have the type of long-duration trials that exist for some preventive mineral systems. This makes CeO_2 a high-promise, low-maturity oxide at present. Iron oxide nanoparticles, Fe_3O_4 and related forms, represent a more translationally interesting direction because they are increasingly framed as nanozymes rather than passive fillers. A strong example is ferumoxytol, an FDA-approved iron oxide nanoparticle formulation. A study showed that ferumoxytol combined with stannous fluoride produced synergy that inhibited both biofilm accumulation and enamel damage more effectively than either agent alone. The combination was reported to be highly effective in vivo, even at four times lower concentrations, without adverse effects on host tissues or the oral microbiome.[42]

This is notable because it aligns with what dentistry actually needs: concurrent control of biofilm biology and mineral loss. It also illustrates a realistic pathway for translation, since both components are already known in biomedical or oral health contexts. The limitation is that this remains a specialized formulation strategy, not a routine dental material used chairside. Overall, metal-oxide nanoparticles show a repeated evidence structure. Antimicrobial effects are relatively easy to demonstrate. Durable clinical benefit is harder to prove. The most credible advances are those that show patient-relevant outcomes or clinically realistic exposure conditions. ZnO coatings in orthodontics and TiO_2 in functional appliances are steps in that direction, but both still face durability and endpoint limitations.[38] The strongest future studies will need to measure more than bacterial reduction. They must also report aging stability, surface roughness changes, release during wear, and clinically meaningful outcomes such as lesion incidence and restoration survival.

Polymeric nanoparticles and nanogels

Polymeric nanoparticles matter in dentistry for one main reason. They can act as carriers. This shifts the goal from "a material that kills bacteria" to "a system that keeps an active agent where it is needed, for long enough to matter". That distinction is important because many dental failures are driven by short contact time and poor penetration, not by lack of potent drugs. The strongest dental rationale is local therapy. Periodontal pockets, root canals, and mucosal lesions are all accessible sites where sustained delivery could reduce systemic exposure and improve effect. Yet most polymeric nanoparticle studies still report release curves in simplified media. This often overstates performance. Retention in crevicular fluid or diffusion through mature biofilms is harder than in buffer. In endodontics, the evidence base is large but inconsistent. A systematic review on antimicrobial polymeric nanoparticles in endodontics concluded that polymeric systems can improve antibacterial outcomes in preclinical models, but it also emphasized broad heterogeneity in formulations, outcomes, and study designs, which limits clinical inference.[43] A scoping review on multifunctional nanoparticles in endodontics reached a similar message. The field is expanding rapidly, but most evidence remains laboratory-driven, and clinical endpoints are rarely tested.[44] This gap is not a minor limitation. Root canal therapy fails clinically because of biofilm persistence in complex anatomy. Many

nanoparticle studies test planktonic bacteria or simplified biofilms, which inflates apparent success. Chitosan-based nanoparticles are a major subset of polymeric systems in dentistry. Their appeal is not only delivery. Chitosan is also inherently bioactive due to its cationic nature, which can disrupt bacterial membranes and improve adhesion to negatively charged surfaces. A narrative review in summarized chitosan applications across dental fields and reported that it included a substantial body of human clinical trials from the last decade, while also stressing variability in protocols and outcomes.[45] However, clinical presence does not mean uniform clinical maturity. Many human trials relate to formulations that are not strictly nanoparticle drug-carriers, so the evidence still needs careful separation by indication and product type. In regenerative endodontics and vital pulp therapy, chitosan systems look more convincing biologically than clinically. A systematic review focused on chitosan-based nanoparticles and biomaterials for pulp capping and regeneration reported consistent preclinical benefits, including enhanced cell viability, odontogenic differentiation, angiogenic signaling, and reparative dentin formation compared with conventional agents in the included studies.[46]

The limitation is obvious when viewed as translation. Most endpoints are cellular or histologic. Few studies test long-term clinical success under real contamination and loading conditions. This makes the category promising, but not practice-changing yet. Nanogels sit at the far end of polymer-based delivery systems. Their key advantage is swelling behavior and high water content, which can support loading of both hydrophilic and hydrophobic drugs, plus stimulus-responsive release in some designs. A review on chitosan-based nanogels described how polysaccharide nanogels can encapsulate small molecules, nucleic acids, and proteins while preserving biological features of the parent polymer.[47] The problem is dental readiness. Nanogels are often discussed as platforms, not as tested clinical interventions. Dental studies still tend to stop at antimicrobial activity or release kinetics. There are few trials that link nanogels to outcomes clinicians care about, such as reduced postoperative pain, higher healing rates, or fewer retreatments. Overall, polymeric nanoparticles and nanogels are best understood as enablers. They are not inherently better than conventional delivery. They become better only when they solve a clear problem: short contact time, poor retention, or toxicity from high local drug dosing. The next step for this field is not more "nanoparticle shows inhibition zones". It is comparative studies that test real biofilms, realistic aging, and clinically interpretable endpoints, using standardized reporting that allows replication.[43]

Carbon-based nanomaterials

Carbon-based nanomaterials have attracted attention because they combine high mechanical strength with surface tunability. In dentistry, they are mainly studied as reinforcement additives and as antibacterial surfaces. The evidence base is large, but it is still dominated by laboratory work. Human outcome studies are rare. Graphene and graphene oxide (GO) are the most discussed members of this group. They are usually added at low concentrations to resins or polymers to improve strength and reduce microbial adhesion. Antimicrobial claims for graphene are common, but the quality of evidence varies.

A scoping review on graphene's antimicrobial effect in dentistry described broad antibacterial activity across studies and suggested potential roles in polymer composites and drug-loading systems.[48] The limitation is that most studies use simplified bacterial models and short exposure times. These conditions do not replicate salivary pellicle formation or mature polymicrobial biofilms. This makes overinterpretation likely. Prosthodontic polymers provide a useful example of where carbon materials may help, but with clear constraints. A review of graphene-incorporated nanofillers in prosthodontic polymers summarized improvements in mechanical behavior at low loading and raised the core translational issue: dispersion quality and interfacial bonding determine whether graphene reinforces the polymer or creates defects.[49] This is a recurring reason why results differ across studies even when "graphene" is the same label. Carbon nanotubes (CNTs) are studied for reinforcement and, less commonly, for antibacterial effects. Their theoretical appeal is strong because CNTs can increase stiffness and fracture resistance in polymer matrices. A review focusing on CNTs in restorative dentistry described reinforcement benefits and antimicrobial potential, but also highlighted persistent barriers such as dispersion difficulty and safety concerns that restrict routine clinical adoption.[50] In practice, CNT systems often show performance gains only when processing quality is high, which is difficult to standardize at scale. Nanodiamonds are often viewed as the most biocompatible carbon nanomaterial in dental applications. Their role is mainly reinforcement, with some studies suggesting reduced bacterial adhesion as an added benefit. Short-term antibacterial reduction does not predict long-term plaque behavior, and short-term strength does not guarantee performance after aging and water sorption. Carbon-based coatings are also discussed for implant applications. Here the primary aim is surface stability, corrosion resistance, and tissue response. An updated review of carbon-based bioactive coatings for dental implants summarized diamond-like carbon, silicon carbide, CNT, and graphene-based options and emphasized that these coatings can improve mechanical stability and biocompatibility in experimental settings.[51] The remaining uncertainty is clinical impact. The field still lacks consistent long-term evidence linking carbon-based coatings to lower peri-implantitis rates or better survival outcomes. Across carbon-based systems, biocompatibility is the decisive issue. Toxicity is not uniform across materials. It depends on surface

chemistry, oxidation state, impurities, and dose. A toxicity-focused assessment of graphene derivatives highlighted that graphene oxide can show more concerning toxicity signals than high-purity graphene forms, reinforcing that "graphene" cannot be treated as one safe category.[52] Overall, carbon-based nanomaterials are scientifically active and technically versatile. Their current dental evidence supports potential reinforcement benefits and plausible antibacterial effects in controlled settings. It does not yet support broad clinical claims. The critical gap remains long-term performance under oral aging and patient-level outcome testing. Viewed across the material classes discussed, this uneven translational readiness can be understood as a maturity gradient in which mineral-based systems are the most clinically anchored, selected ion-releasing and metallic/metal-oxide systems occupy an intermediate zone, and more complex multifunctional systems remain most constrained by formulation-related material trade-offs. As illustrated in Figure 2, the translational maturity of dental nanomaterials follows a gradient, with mineral-based systems being the most clinically anchored, selected ion-releasing and metallic/metal-oxide systems occupying an intermediate position, and more complex multifunctional systems remaining most constrained by material-related trade-offs.

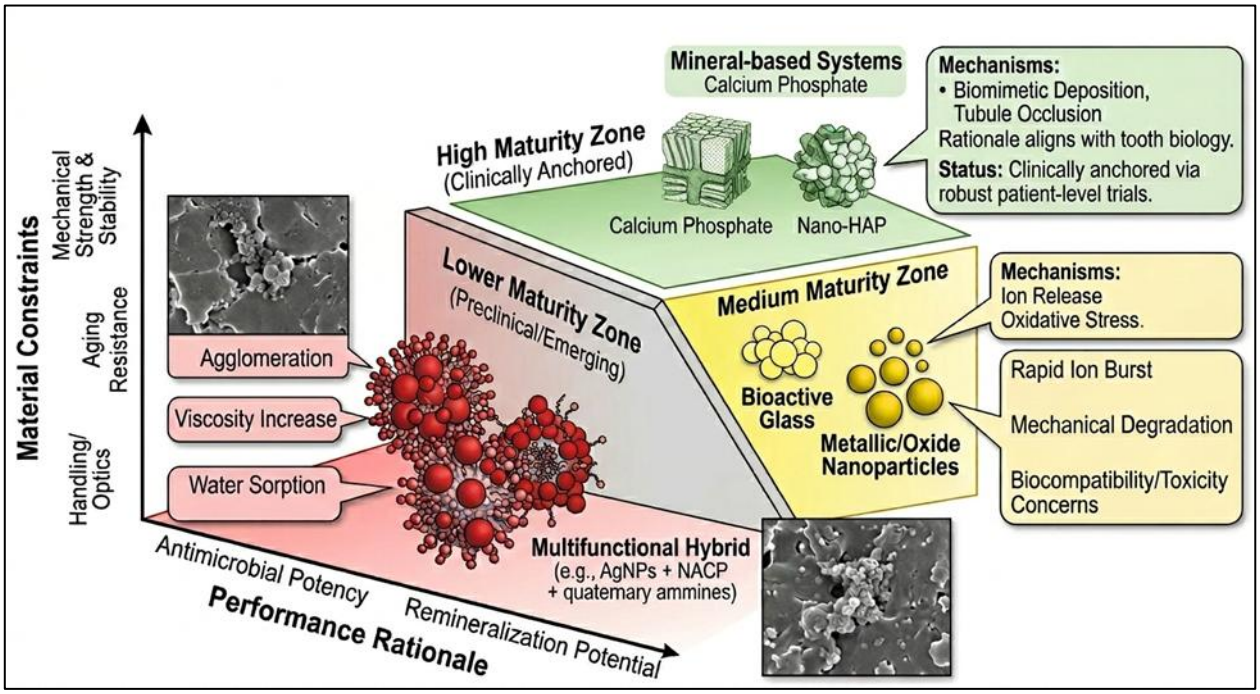

Figure 2: Conceptual maturity barrier model of dental nanomaterials across major material classes.

HYBRID AND MULTIFUNCTIONAL NANO-SYSTEMS

Hybrid nano-systems are built to solve a specific contradiction in dentistry. Restorations should be strong and durable. They should also resist biofilms and support mineral recovery at the margins. Most single-function materials cannot do both. This is why the field shifted from one nanoparticle, one effect toward multifunctional designs. The goal is not novelty. The goal is longer restoration survival. The strongest multifunctional concept in restorative dentistry is the antibacterial–remineralizing combination. It was developed to address secondary caries at the tooth–restoration interface. A classic example is adding silver nanoparticles for antibiofilm activity and amorphous calcium phosphate nanoparticles (NACP) for calcium/phosphate release. Melo et al incorporated both into a dental adhesive and showed two simultaneous outcomes: inhibition of plaque microcosm biofilms and preservation of dentin bond strength. The study mattered because it used a complex biofilm model, not only single-species bacteria. It also treated bonding performance as a core endpoint, not a side note.[53] Later work expanded the same idea using contact-killing chemistry instead of relying on metal release. Quaternary ammonium methacrylates were explored because they can provide long-term antibacterial surfaces through polymerized cationic groups. Zhang et al examined how quaternary ammonium chain length changes antibacterial behavior in a bonding agent, within a design space that also includes remineralizing NACP systems. This helped clarify a major design rule. Antibacterial potency rises with chemical tuning, but the formulation must still cure properly and remain stable in water.[54] The key limitation of early multifunctional designs was that "more functions" often meant "more compromise." Adding multiple fillers can increase viscosity, reduce depth of cure, and raise water sorption. These effects are clinically relevant because they accelerate degradation, staining, and marginal breakdown. A study that developed a multifunctional resin composite using nano-MgO and bioactive glass

(BAG) illustrates this tension. Antibacterial and remineralizing goals were pursued together, but depth of cure and water sorption increased as total filler loading increased. That trend is predictable, and it sets practical constraints on how far multifunctionality can be pushed.[55]

Figure 3: Overview of nanomaterial classes, mechanisms, applications, and translational status in dentistry.

Table 1: Clinical roles of nanotechnology across dental specialties.

Preventive-paediatric dentistry				
Domain	What nano-prevention is trying to solve	What seems to work best in practice	What looks promising but is not settled	Why findings differ across papers
Enamel remineralization and early caries control	Mineral loss begins before cavitation. Standard prevention may be insufficient in high-risk exposure.	Mineral-based nano systems fit prevention because they target the lesion directly. They align with enamel biology.	Added value beyond fluoride depends on patient risk and how the product is used. Combination strategies may help some settings more than others.	Different baseline risk, fluoride background exposure, adherence, and lesion activity. Also, outcomes range from surface change to real caries endpoints.
White spot lesions	Plaque stagnation around appliances creates fast lesion development. Early lesions are often inactive on the surface but active beneath.	Strategies that combine risk control with mineral support are most defensible clinically. Patient behaviour still dominates outcomes.	Nano approaches may improve lesion appearance or early mineral recovery in selected contexts. The effect is inconsistent across products.	Short follow-up, inconsistent lesion measurement, and large differences in oral hygiene compliance during orthodontics.
Dentin hypersensitivity and tubule occlusion	Pain is driven by exposed dentin and open tubules. Short contact time limits many agents.	Nano-mineral approaches fit hypersensitivity because tubule occlusion is a direct target. Symptom relief is achievable.	Durability of relief varies. Performance depends on consistency of use and erosive challenge.	Different stimuli protocols, different pain scales, variable baseline severity, and strong placebo response in sensitivity studies.

Continued.

Preventive-paediatric dentistry				
Restorative dentistry				
Nanofillers in resin composites	Improve wear resistance, polish retention, and optical properties without sacrificing handling.	Nano-filled and nano-hybrid composites are most convincing when the goal is surface quality and aesthetics. They often perform well in everyday restorative workflows.	Some formulations may show incremental gains in fracture resistance and long-term gloss retention, but improvements are not universal.	Particle size distribution, filler loading, coupling chemistry, and agglomeration control. Aging conditions also change results.
Adhesive systems	Bond durability remains the weak link. Water sorption and collagen degradation drive long-term failure.	Adhesives benefit most from strategies that stabilize the hybrid layer and reduce permeability. Controlled interface design matters more than adding nanoparticles alone.	Nano-reinforcement and bioactive interface concepts are attractive, especially when they aim to protect collagen and maintain sealing.	Differences in dentin substrate, solvent systems, curing protocols, and aging models. Many studies test early bond strength only.
Antimicrobial nano-additives and secondary caries prevention	Secondary caries is a leading cause of restoration replacement. The goal is biofilm control at the margin.	The most defensible strategies are those that preserve mechanical strength and keep surfaces smooth. Material stability comes first.	Contact-active systems and mineral-releasing designs may reduce biofilm activity while supporting mineral balance. Multifunctional approaches are conceptually strong.	Biofilms in the mouth are saliva-conditioned and polymicrobial. Many tests use simplified models, high concentrations, or short durations.
Bioactive restoratives and mineral-releasing strategies	Support margin integrity and reduce demineralization risk around restorations.	Ion-releasing systems are most credible when presented as supportive, not curative. They fit high-risk patients when coupled with standard prevention.	“smart” bioactive composites that combine ion release with acceptable mechanics are a realistic future direction.	Ion release depends on matrix chemistry and water uptake. More release can mean more degradation.
Aging, wear, and durability under oral conditions	Many restorations fail from fatigue, hydrolysis, and surface breakdown rather than early strength limits.	Materials that maintain smoothness and resist hydrolytic degradation age better clinically.	Nano-additives that reduce water sorption or stabilize the polymer network are promising, but not consistent across products.	Thermocycling protocols vary. Water storage times vary. Some studies avoid realistic fatigue loading.
Implant dentistry				
Nano-topography and early biological integration	Improve early healing and stability by optimizing the bone–implant interface.	Surface micro- and nano-roughness strategies can support early cellular attachment and clot organization. The concept aligns with early osseointegration biology.	Whether nano-features add a meaningful advantage beyond established roughened surfaces remains uncertain in many settings.	Surface fabrication methods differ widely, even when marketed under similar labels. Host factors often dominate outcomes.
8.2 nano-coatings for osteogenic signalling	Enhance osteoblast behaviour and bone formation through bioactive surface chemistry.	Coatings that remain stable and do not delaminate are the only clinically realistic options. Stability is the gatekeeper.	Controlled ion-releasing and biomimetic coatings may improve early integration in compromised bone conditions.	Coating chemistry, thickness, adhesion strength, and corrosion behaviour vary. Testing endpoints are often surrogate.

Continued.

Preventive-paediatric dentistry				
Antibacterial nano-surfaces and biofilm resistance	Reduce early bacterial adhesion and lower risk of peri-implant inflammation.	Strategies that preserve surface stability and do not increase roughness in a plaque-retentive way are most defensible.	Contact-active surfaces and ion-based antimicrobial coatings are interesting but require long-term validation.	Oral biofilms are saliva-conditioned and polymicrobial. In vivo proteins can mask antibacterial effects.
Drug-loaded nano-reservoir surfaces	Deliver antimicrobials or anti-inflammatory agents locally to avoid systemic exposure.	Local delivery is conceptually strong for early healing or high-risk infection situations, if release is controlled and safe.	Stimuli-responsive release and multi-drug approaches may become clinically useful in selected cases.	Release kinetics differ greatly between lab testing and peri-implant conditions. Refillability and stability are unresolved.
Orthodontics				
Nano-modified adhesives and enamel protection	Reduce white spot lesions without sacrificing bond reliability.	The most defensible goal is modest biofilm reduction while keeping bond strength within clinical limits. Adhesive stability matters more than novelty.	Mineral-releasing and hybrid bioactive adhesives may support enamel protection in high-risk cases.	Studies use different tooth substrates, curing protocols, biofilm models, and aging methods. Clinical outcomes are rarely measured.
Nano-coated wires and brackets for biofilm control	Reduce bacterial adhesion on hardware that retains plaque.	Coatings that do not alter mechanical performance, corrosion resistance, or friction are the only realistic candidates.	Antibacterial coatings can reduce early adhesion, but clinical durability is a major obstacle.	Coating thickness, bonding strength, and wear resistance vary. Saliva pellicle can blunt contact effects.
Friction, force delivery, and mechanical stability concerns	Maintain efficient tooth movement while adding antimicrobial function.	Mechanical performance must remain primary. Any benefit that compromises friction or force delivery is clinically costly.	Some nano-coatings may preserve friction in controlled conditions, but long-term behaviour under oral wear is uncertain.	Testing speeds, lubrication, and wear simulation differ widely. Many studies avoid realistic intraoral aging.
Prosthodontics				
Nano-reinforcement of PMMA and denture base materials	PMMA fractures, wears, and accumulates surface damage over time.	Reinforcement is most defensible when it improves strength without increasing roughness or water uptake. Handling and repairability must remain acceptable.	Carbon-based and ceramic nano-additives may improve mechanical performance at low loading, but outcomes are formulation-dependent.	Dispersion quality, concentration, polymerization method, and aging protocols vary widely. Some additives act as defects when agglomerated.
Antifungal nanotechnology for denture stomatitis	Candida-driven biofilms are common, and relapse is frequent with poor hygiene.	Strategies that reduce biofilm load without toxicity are the most realistic. The base material must remain stable and non-irritating.	Metal and metal-oxide additives can reduce fungal adherence in laboratory settings, but long-term clinical benefit is not consistently demonstrated.	Many studies measure fungal counts only. Few test long-term wear, colour, or mucosal response.
Optical outcomes, surface roughness, and long-term aging	Discoloration, roughness, and porosity worsen plaque retention and aesthetics.	Smooth, polishable surfaces are central to long-term comfort and hygiene. Any additive that increases roughness is a clinical liability.	Some nano-fillers may improve polish retention, but colour stability can be compromised depending on the additive.	Colour testing methods differ. Aging conditions differ. Many studies underrepresent cleaning habits and dietary staining.

A review of new-generation restorative composites framed this evolution clearly. Multifunctional systems are being designed to combine antibacterial effects, mineral ion release, and even self-healing. The review also stressed why clinical translation is slow. The same factors that enable function, such as reactive fillers and multiple agents, can destabilize polymer networks or weaken mechanical integrity over time. The result is a field rich in concepts but uneven in robust clinical evidence.[56] More recent studies are more disciplined. They define a clinical target first, then design functions around it. A study developed a resin coating for root caries that combined NACP with DMAHDM, a quaternary ammonium antibacterial monomer. The work tested mechanical properties, ion release, antibacterial effects against S. mutans, and cytotoxicity on relevant cells. This is the right direction methodologically. It treats safety and mechanics as co-primary outcomes, not afterthoughts.[57] Still, the translational question remains open. A coating may show strong antibacterial and mineral release signals in controlled assays, but the clinical endpoint is whether root caries progression slows over months and years in high-risk patients. Orthodontics has followed the same multifunctional logic. White spot lesions are not only a bacterial problem. They are a mineral balance problem under plaque stagnation. A study designed an orthodontic adhesive containing amorphous calcium phosphate–polydopamine–Ag hybrid fillers. It explicitly aimed to combine antibacterial activity with remineralization support while maintaining bond performance. This type of hybrid filler reflects the current trend: one component supports mineral repair, another supports antimicrobial function, and a third improves integration or stability.[58] Yet the same limitation persists. Orthodontic success is not only lab biofilm reduction. It is fewer new lesions during real treatment. Most multifunctional orthodontic adhesive studies still stop short of patient-level demineralization outcomes. Across dentistry, the main argument for multifunctional nano-systems is strong. Caries is multifactorial, so materials that address only bacteria or only minerals will have limited effect. A review in Nanoscale made this point directly for anti-caries strategies. It emphasized that unifunctional materials have limits, and that multi-mechanism designs are more realistic for managing biofilms and enamel damage together.[59] However, this does not justify inflated claims. Multifunctionality increases the chance of hidden failure modes. Aging, water sorption, optical stability, and particle release become more complex once multiple agents are combined. Hybrid nano-systems are not “the future” by definition. They are useful only when they meet three conditions. They keep mechanical performance within clinical thresholds. Their activity persists after saliva conditioning and aging. Their safety profile remains acceptable at realistic exposure levels. Studies are improving, especially those that test mechanics, ion release, antibacterial effects, and cytotoxicity in the same design.[57] What is still missing is long follow-up clinical validation. Without it, multifunctional dental nanotechnology remains more convincing as a materials strategy than as an established clinical intervention. Figure 3 provides an overview of the major nanomaterial classes, their principal mechanisms, representative dental applications, and their current translational status in dentistry. Table 1 summarizes the clinical roles of nanotechnology across dental specialties.

CONCLUSION

Nanomaterials have expanded the possibilities of modern dentistry, but their clinical maturity remains uneven. Calcium phosphate and nano-hydroxyapatite currently show the most clinically grounded evidence, particularly for caries prevention and dentin hypersensitivity, whereas many metallic, metal-oxide, polymeric, carbon-based, and hybrid systems remain supported mainly by laboratory or early translational data. Future research should therefore focus on whether these materials deliver durable benefit under realistic oral conditions without introducing safety concerns.

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