REVIEW ARTICLE

Orthodontics at the Nanoscale—Redefining Treatment through Nanotechnology: A Narrative Review

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Abstract

Traditional orthodontic materials, while integral to clinical practice, face inherent limitations such as frictional resistance, corrosion, and susceptibility to plaque accumulation. Nanotechnology has emerged as a promising field to address these challenges by manipulating materials at the nanoscale to enhance mechanical, chemical, and biological properties. This narrative review synthesizes predominantly preclinical evidence on nanomaterials in orthodontic therapy, spanning archwires, brackets, adhesives, and auxiliaries. Nanocoatings and nanofillers—including titanium dioxide (TiO_2), silver nanoparticles (AgNPs), and graphene—have shown promising results in preclinical studies for reducing friction, improving bond strength, and inhibiting biofilm formation to prevent white spot lesions. The review further explores nanotechnology in clear aligners and temporary anchorage devices (TADs), highlighting improvements in mechanical stability and osseointegration. Future applications, such as shape memory polymers (SMPs), smart brackets with nanosensors, and nanorobotics, theoretically offer precise force control and real-time monitoring. Despite these encouraging developments, concerns regarding nanoparticle toxicity and long-term biocompatibility necessitate further rigorous clinical evaluation. The current evidence base is predominantly *in vitro* and animal-derived; robust clinical trials are needed before nanotechnology can be widely translated into routine orthodontic practice.

Keywords: Adhesive restorations, Aligner therapy, Artificial intelligence, Health technology, Orthodontics.

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Introduction

Advances in material science have consistently played a pivotal role in the evolution of orthodontic therapy. While traditional orthodontic materials such as stainless steel, nickel–titanium alloys, ceramics, and polymer-based adhesives remain integral to clinical practice, their inherent limitations continue to influence treatment efficiency and outcomes. Challenges, including frictional resistance, corrosion, plaque accumulation, enamel demineralization, suboptimal esthetics, and variable biocompatibility, highlight the need for innovative material solutions.[1–3] In recent years, nanotechnology has emerged as a promising field with the potential to address many of these longstanding concerns in orthodontics.[4]

Nanotechnology refers to the manipulation and application of materials at the nanoscale, typically between 1 and 100 nanometers, where materials exhibit unique mechanical, chemical, and biological properties not observed at the macroscopic level.[5] At this scale, increased surface-to-volume ratios and altered surface characteristics allow for enhanced strength, improved wear resistance, superior surface reactivity, and favorable biological interactions.[6] These attributes have stimulated growing interest in the integration of nanomaterials into dental and orthodontic materials.[7]

The application of nanomaterials in orthodontics spans a wide spectrum of appliances and adjuncts. Nanoparticle-enhanced adhesives and composites have been developed to improve bond strength, reduce polymerization shrinkage, and enhance resistance to wear.[8–10] Surface modification of brackets and archwires using nanocoatings has been explored as a strategy to reduce friction at the bracket–archwire interface and improve corrosion resistance.[11–13] Additionally, antimicrobial nanomaterials such as silver, zinc oxide, and titanium dioxide nanoparticles have gained attention for their potential to inhibit bacterial colonization and biofilm formation, thereby reducing the risk of white spot lesions and gingival inflammation during orthodontic treatment.[14–16]

Beyond improvements in mechanical performance and antimicrobial activity, nanotechnology has contributed to advances in esthetic orthodontics. Nanofilled polymers and composites have facilitated the development of more translucent, color-stable, and durable esthetic brackets, aligners, and bonding materials.[17,18] Furthermore, emerging research has explored the use of nanomaterials in drug delivery systems, smart coatings, and biologically active surfaces that may influence bone remodeling and potentially accelerate orthodontic tooth movement.[19–21]

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Despite these encouraging developments, the clinical adoption of nanomaterials in orthodontics remains cautious. Concerns related to nanoparticle release, long-term biocompatibility, cytotoxicity, and environmental impact necessitate thorough evaluation before widespread clinical use.[22–24] Additionally, variability in experimental designs and outcome measures among available studies underscores the importance of critically appraising existing evidence.

Literature Search Methodology

A comprehensive literature search was conducted using the electronic databases PubMed/MEDLINE, Scopus, and Web of Science. The search covered publications from January 2000 to December 2024. Keywords included: "nanotechnology AND orthodontics," "nanoparticles AND orthodontic brackets," "nanocoating AND archwire," "silver nanoparticles (AgNPs) AND orthodontic adhesive," "titanium dioxide (TiO_2) AND friction," "zinc oxide (ZnO) AND antimicrobial," "shape memory polymers (SMPs) AND clear aligners," and "nanorobotics AND dentistry." Inclusion criteria were: (1) English-language articles; (2) *in vitro*, *in vivo*/animal, or human clinical studies evaluating nanomaterial applications in orthodontics; (3) relevant narrative or systematic reviews; and (4) conceptual articles on future applications. Exclusion criteria included studies unrelated to orthodontics, non-peer-reviewed sources, duplicate publications, and articles unavailable in full text. Throughout this manuscript, the level of evidence for each cited finding is identified as *in vitro*, *in vivo*/animal, or clinical/human to aid interpretation of results (Table 1).[25]

Nanomaterials in Orthodontic Archwires and Brackets

Archwires are expected to deliver consistent, biologically acceptable forces while maintaining surface integrity in the harsh oral environment. Nanotechnology has primarily been applied to archwires in the form of nanocoatings rather than bulk material modification. Coatings incorporating titanium dioxide (TiO_2), diamond-like carbon (DLC), molybdenum disulfide, graphene, and nanoparticle-based composites have been investigated extensively.[11,13,26]

One of the principal objectives of nanocoating archwires is the reduction of friction at the bracket–archwire interface. Nanoscale surface smoothing decreases surface roughness and contact points, facilitating more efficient sliding mechanics during space closure and alignment. Studies have demonstrated that nanocoated NiTi and stainless-steel wires exhibit significantly lower frictional forces compared with uncoated counterparts, particularly under wet conditions simulating the oral environment (*Evidence level: predominantly in vitro tribological studies; limited in vivo or clinical data available*).[12,27,28]

In addition to friction reduction, nanocoatings enhance corrosion resistance and reduce metal ion release. This is clinically relevant for NiTi archwires, where nickel hypersensitivity and corrosion-related degradation remain concerns. Nanostructured oxide layers act as protective barriers, improving surface stability and biocompatibility.[2,23] Some nanocoatings also exhibit antimicrobial properties, contributing to reduced bacterial adhesion along the wire surface.[7]

Orthodontic brackets, whether metallic or ceramic, serve as critical interfaces for force transmission and are prone to plaque accumulation and friction-related inefficiencies. Nanotechnology has been applied to brackets through surface nanocoatings, nanoparticle impregnation, and nanoscale surface texturing.

Metal brackets coated with TiO_2 nanoparticles, silver nanoparticles, or DLC films have shown reduced surface roughness and improved wear resistance.[29,30] These modifications can significantly lower frictional resistance during sliding mechanics, potentially improving anchorage control and treatment efficiency. Ceramic brackets, which inherently exhibit higher friction, may particularly benefit from nanocoatings that smooth surface irregularities without compromising esthetics.[31,32]

Another important application of nanotechnology in brackets is biofilm control. Nanoparticle-coated bracket surfaces have demonstrated reduced bacterial adhesion and biofilm formation, which may help mitigate gingival inflammation and enamel demineralization commonly associated with fixed orthodontic appliances.[14,16] Unlike conventional antimicrobial agents, nanoscale coatings provide a more durable and surface-specific antibacterial effect.

Table 1: Various approaches for the synthesis of nanoparticles[25]

Method	*Process involved*	*Synthesis approach*
Physical	Ball milling Mechanochemical synthesis Plasma vapor deposition Laser pyrolysis Inert gas condensation Flame hydrolysis	Top-down approach
Chemical	Sol–gel or gel–sol conversion Plasma/laser/flame enhanced Chemical vapor deposition Sol thermal synthesis	Bottom-up approach
Biological	Fungi Bacteria Yeast Plant extracts	Intracellular and extracellular synthesis

Nanomaterials in Orthodontic Adhesives

Orthodontic adhesives play a critical role in ensuring effective bracket bonding while maintaining enamel integrity throughout treatment. Conventional resin-based adhesives, although widely used, are associated with limitations such as insufficient antibacterial activity, polymerization shrinkage, suboptimal mechanical properties, and increased risk of enamel demineralization around brackets. The incorporation of nanomaterials into orthodontic adhesives has emerged as a promising strategy to overcome these shortcomings by enhancing mechanical performance, bioactivity, and clinical longevity.

Nanoparticles are incorporated into orthodontic adhesives either as fillers or as functional additives. Commonly investigated nanomaterials include silver nanoparticles (AgNPs), titanium dioxide (TiO_2), zinc oxide (ZnO), silica nanoparticles, hydroxyapatite (nHAp), and bioactive glass nanoparticles. Due to their high surface area and nanoscale dimensions, these

particles significantly influence the physicochemical properties of the adhesive even at low concentrations.[6]

One of the most clinically relevant applications of nanomaterials in orthodontic adhesives is the development of antimicrobial bonding agents. AgNPs, ZnO, and TiO_2 nanoparticles exhibit broad-spectrum antibacterial activity by disrupting bacterial cell membranes, generating reactive oxygen species, and inhibiting enzymatic activity. Adhesives containing these nanoparticles have demonstrated a significant reduction in *Streptococcus mutans* adhesion and biofilm formation without adversely affecting shear bond strength.[15,33–41] This antimicrobial effect is particularly beneficial in preventing white spot lesions, a common iatrogenic complication during fixed orthodontic treatment *(Evidence level: in vitro microbiological studies predominantly; clinical trials with patient-level white spot lesion outcomes are lacking.)*

Nanofillers also improve the mechanical properties of orthodontic adhesives. The addition of nanosilica and nanohybrid fillers enhances flexural strength, compressive strength, and wear resistance while maintaining adequate flow and handling characteristics. Compared with conventional microfilled adhesives, nanofilled systems demonstrate improved stress distribution at the adhesive–enamel and adhesive–bracket interfaces, reducing the risk of bond failure during orthodontic treatment.[18]

Bioactive nanomaterials such as nHAp and bioactive glass nanoparticles have been incorporated into orthodontic adhesives to promote enamel remineralization. These nanoparticles release calcium and phosphate ions, facilitating the formation of fluorapatite or hydroxyapatite at the enamel surface. Studies have shown that adhesives containing nHAp can reduce enamel demineralization adjacent to brackets and may even promote subsurface remineralization, offering a dual function of bonding and caries prevention.[34,35]

Another advantage of nanomaterial-modified adhesives is improved esthetics and optical properties. Nanoparticles with dimensions smaller than the wavelength of visible light enhance translucency and color stability, which is particularly important in esthetic orthodontic systems using ceramic brackets. Additionally, nanotechnology has enabled the development of self-adhesive and low-shrinkage orthodontic resins, improving chairside efficiency and marginal integrity.[36]

Despite these advantages, concerns remain regarding the potential cytotoxicity and long-term stability of nanoparticle-containing adhesives. Factors such as nanoparticle concentration, size, surface modification, and release kinetics influence biocompatibility. While most *in vitro* studies report acceptable cytotoxic profiles at clinically relevant concentrations, long-term *in vivo* studies are required to establish safety and durability under oral conditions.

Nanoparticle release from degrading adhesive matrices into the oral cavity, gingival tissues, and potentially the systemic circulation is a key area of concern. Silver nanoparticles (AgNPs) in particular have been shown in *in vitro* studies to induce oxidative stress and DNA damage in human gingival fibroblasts at concentrations above established thresholds, though the clinical relevance of these findings depends heavily on the actual release rate under intraoral conditions. Titanium dioxide (TiO_2) nanoparticles have been classified as possibly carcinogenic to humans (group 2B) by the International Agency for Research on Cancer (IARC) based on inhalation data, although oral exposure routes differ significantly. Long-term release kinetics of fixed orthodontic adhesives over 18–36 months of treatment remain largely uncharacterized. From a regulatory standpoint, nanoenhanced dental materials are subject to medical device regulations in most jurisdictions; however, specific nanoparticle safety testing requirements are not uniformly mandated, creating a gap between laboratory development and clinical authorization. Environmental impact is an additional consideration: disposal of nano-enhanced orthodontic materials and nanoparticle-containing wastewater from dental clinics may contribute to environmental nanoparticle accumulation, with ecotoxicological consequences that are only beginning to be studied. The field requires standardized international guidelines for nanoparticle safety assessment in dental applications, covering *in vitro* cytotoxicity, *in vivo* biocompatibility, release kinetics characterization, and environmental fate analysis, before broad clinical use can be responsibly endorsed.

Nanomaterial in Mouthwash

The application of nanotechnology in oral hygiene products has shown promise in managing microbial load without the side effects associated with traditional agents. Abadi et al. investigated the efficacy of silver nanoparticles (AgNPs) as an active ingredient in alcohol-free mouthwashes, specifically targeting immunocompromised patients who cannot tolerate ethanol-based solutions. Their study demonstrated that AgNPs possessed potent antimicrobial properties against common oral pathogens, including *Streptococcus mutans* and *Candida albicans*, with minimum inhibitory concentrations (MIC) ranging from 0.78 to 3.12 µg/mL. The authors concluded that AgNP-based formulations offer a viable, biocompatible alternative to chlorhexidine or alcohol-based rinses, particularly for maintaining oral hygiene in patients with sensitive or inflamed mucosa.[37]

Nanomaterial in an Elastomeric Ligature

Orthodontic elastomeric ligatures, primarily composed of synthetic polyurethane, are widely utilized in clinical practice due to their cost-effectiveness, ease of application, and patient comfort.[38] However, their significant disadvantage lies in their susceptibility to microbial colonization; the material's surface roughness and retentive design foster the accumulation of bacterial plaque, leading to increased levels of *Streptococcus mutans*, *Lactobacilli*, and *Staphylococcus aureus*.[39,40] This bacterial proliferation exacerbates the risk of enamel demineralization and gingival inflammation during prolonged fixed appliance therapy.[41]

To mitigate these adverse effects, nanotechnology has been employed to modify elastomeric ligatures into active scaffolds capable of delivering anticariogenic, anti-inflammatory, and antibacterial agents.[42] A prominent advancement is the incorporation of silver nanoparticles (AgNPs) into the elastomeric matrix. Studies demonstrate that AgNPs possess potent antibacterial properties that significantly reduce dental biofilm adhesion and prevent enamel demineralization without compromising the mechanical properties or chemical stability of the ligatures.[43,44] This is a critical advantage over traditional fluoride-releasing ligatures, which often exhibit an inconsistent release pattern characterized by an initial burst followed by a rapid logarithmic decline, limiting their long-term efficacy. Consequently, nanosilver-modified ligatures offer a more sustained and mechanically reliable solution for maintaining oral hygiene and preventing white spot lesions during orthodontic treatment.

Nanomaterial in Power Chain

Orthodontic power chains are widely used for space closure due to their affordability and flexibility, yet they suffer from

significant clinical limitations. Traditional chains, composed of polymeric materials like polyesters, are prone to force decay and degradation caused by the oral environment's temperature and pH. A major drawback is their hydrophilic nature, which leads to fluid absorption and subsequent discoloration, compromising esthetics and hygiene.

To address these issues, nanotechnology has introduced "nanoimprinting" to modify the surface properties of power chains. Research by Cheng et al. utilized this technique to engineer nanostructures known as "nanopillars" onto the chain's surface. This modification effectively alters the material's surface energy, converting it from hydrophilic to hydrophobic. By repelling rather than absorbing oral fluids, nanoimprinted chains resist staining and material degradation, thereby enhancing their biocompatibility and overcoming the inherent disadvantages of traditional orthodontic auxiliaries.[45]

Nanotechnology in Temporary Anchorage Devices

The integration of nanotechnology into orthodontic materials addresses critical clinical challenges regarding microbial colonization and mechanical efficiency.[46] Recent literature highlights the efficacy of surface modifications and nanocomposites in enhancing appliance performance. Ghasemi et al. evaluated stainless steel brackets coated with silver and titanium dioxide (TiO_2) nanofilms, reporting that these coatings successfully reduced surface roughness and frictional resistance while exhibiting significant antimicrobial activity.[47] Similarly, Toodehzaeim et al. demonstrated that incorporating copper oxide nanoparticles into orthodontic adhesives provided antimicrobial benefits without compromising shear bond strength, offering a preventive strategy against enamel demineralization.[48]

Advances in temporary anchorage devices (TADs) have also been achieved through nanostructuring to promote stability. Jang et al. found that modifying miniscrew surfaces with TiO_2 nanotube arrays significantly enhanced osseointegration compared to untreated surfaces.[49] In a subsequent *in vivo* study, Jang et al. utilized these nanotube arrays for drug delivery, observing further improvements in bone-implant contact.[50] Collectively, these findings suggest that nanomaterials can optimize the biological and mechanical longevity of orthodontic components.

Nanomaterials in Clear Aligners

Clear aligner therapy relies on thermoplastic polymers such as polyurethane and PETG, which offer excellent esthetics and comfort but exhibit limitations including force decay, surface wear, biofilm accumulation, and discoloration. The incorporation of nanoparticles into clear aligner materials has emerged as a promising strategy to enhance their mechanical, biological, and esthetic performance.

Nanoparticles such as silica (SiO_2), titanium dioxide (TiO_2), silver nanoparticles (AgNPs), zinc oxide (ZnO), and graphene-based materials are incorporated as nanofillers or functional additives. Even at low concentrations, these nanoparticles significantly improve material properties due to their high surface area and nanoscale dimensions.[6] Nanofillers like nanosilica enhance elastic modulus, tensile strength, and wear resistance, resulting in more stable force delivery and reduced stress relaxation—critical factors for predictable tooth movement in aligner therapy.[51,52]

Antimicrobial activity is a major advantage of nanoparticle-modified aligners. AgNPs, ZnO, and TiO_2 nanoparticles inhibit the adhesion and growth of cariogenic bacteria such as *Streptococcus mutans*, reducing biofilm formation, halitosis, and the risk of enamel demineralization during prolonged aligner wear.[15,53,54] Additionally, nanomodification improves surface smoothness and wettability, which further limits plaque accumulation and enhances patient comfort.

Nanoparticles also contribute to improved optical properties. Their small size minimizes light scattering, maintaining aligner transparency and resistance to staining from dietary chromogens. TiO_2 nanoparticles may additionally provide photocatalytic self-cleaning effects under light exposure, supporting better oral hygiene.[32,35]

Despite these benefits, concerns remain regarding long-term biocompatibility and potential nanoparticle release due to wear and degradation. While *in vitro* studies report acceptable cytotoxicity at clinically relevant concentrations, long-term clinical evidence is limited.[55] Overall, nanoparticle-enhanced clear aligners represent an important advancement with the potential to improve treatment efficiency and patient experience (Fig. 1).

Future Scope of Nanomaterials (Conceptual/Future Perspectives)

Shape memory polymers are smart, stimuli-responsive materials capable of recovering a predefined shape when exposed to external triggers such as heat, light, or electromagnetic fields. Incorporation of nanomaterials—including carbon nanotubes, graphene, silica nanoparticles, and metallic nanofillers—significantly enhances the functional performance of SMPs. These nanoparticles improve mechanical strength, thermal conductivity, and recovery stress by reinforcing the polymer network and increasing interfacial bonding at the nanoscale.[56,57] Nanofillers also enable precise tuning of the glass transition temperature and accelerate shape recovery kinetics, resulting in more predictable and efficient actuation.

In biomedical and orthodontic applications, nanoparticle-reinforced SMPs can be activated by body temperature or light-induced photoactive nanoparticles, allowing the delivery of light and continuous forces compatible with biological tissues.[58] Such force modulation is advantageous for controlled tooth movement with reduced patient discomfort. Additionally, nanomaterials help

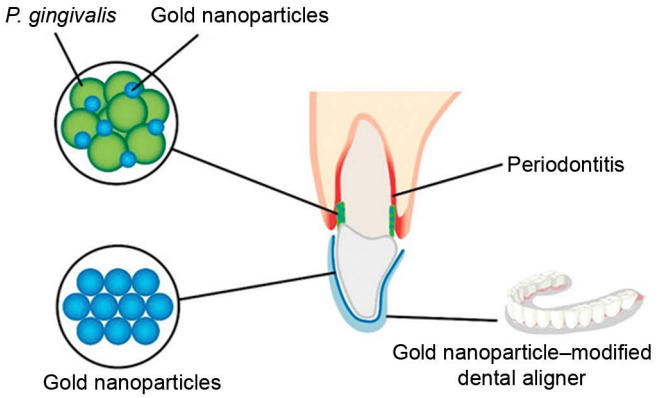

Fig. 1: Representative illustration of nanocoated clear aligner material showing surface nanostructure modifications intended to enhance mechanical performance, biocompatibility, and antimicrobial properties[55]

preserve optical clarity, stain resistance, and esthetics, which are critical for intraoral appliances. The high elongation capacity of SMP nanocomposites (up to 300%) permits sustained force application over a wide range of movement, potentially reducing treatment duration and clinical visits. Overall, nanomaterial-enhanced SMPs represent a promising class of next-generation smart polymers with expanding applications in dentistry and biomedicine.[56–58]

Smart orthodontic brackets incorporating nanosensors represent an advanced application of nanotechnology aimed at improving precision and biological control of tooth movement. These brackets integrate nanomechanical or nanoelectromechanical sensors within the bracket base to measure orthodontic forces and moments in real-time. Nanosensors fabricated using materials such as silicon nanowires, graphene, or carbon nanotubes provide high sensitivity and rapid signal transmission while maintaining minimal size and weight. Continuous monitoring of applied forces allows clinicians to adjust mechanics within a biologically optimal range, reducing undesirable effects such as root resorption and periodontal damage. Smart brackets also have the potential to shorten treatment duration by enabling controlled, efficient force delivery and reducing chairside adjustments. Despite their promising clinical advantages, challenges related to power supply, long-term biocompatibility, and cost must be addressed before widespread clinical adoption.[59]

Biological microelectromechanical systems (Bio-MEMS) and biological nanoelectromechanical systems (Bio-NEMS) represent advanced miniaturized technologies that integrate mechanical, electrical, and biological components at the micro- and nanoscale, respectively. These systems enable precise sensing, actuation, and controlled delivery within biological environments. Bio-MEMS typically operate at the micrometer scale and are widely used for diagnostics, drug delivery, biosensing, and tissue engineering. In contrast, Bio-NEMS function at the nanoscale, offering superior sensitivity, faster response times, and the ability to interact directly with molecular and cellular processes.

The incorporation of nanomaterials such as carbon nanotubes, nanowires, graphene, and metallic nanoparticles significantly enhances the performance of Bio-NEMS by improving electrical conductivity, mechanical strength, and signal transduction efficiency. In orthodontics and other biomedical fields, Bio-MEMS and Bio-NEMS have been explored for real-time monitoring of applied forces, detection of biochemical changes, and acceleration of tissue remodeling. Implantable nanosensors can provide continuous feedback on force magnitude and biological response, allowing more precise and biologically compatible treatment strategies. Despite their promising potential, challenges related to biocompatibility, long-term stability, and power supply remain. Continued advances in nanomaterials and fabrication techniques are expected to expand the clinical applicability of Bio-MEMS and Bio-NEMS in personalized and minimally invasive healthcare.[60–62]

Nanorobots represent a futuristic application of nanotechnology with significant potential in orthodontics.[63] These nanoscale devices are designed to perform precise mechanical and biological tasks within the oral environment. In orthodontic applications, nanorobots have been theoretically proposed to assist in rapid and painless tooth movement by directly manipulating periodontal tissues and alveolar bone remodeling processes.[64] Nanorobots may also enable targeted delivery of anesthetic, anti-inflammatory, or antimicrobial agents, thereby enhancing patient comfort and reducing treatment-related complications.[65,66] Dentifrobots, a proposed subtype, could continuously remove plaque and biofilm around orthodontic appliances, minimizing the risk of enamel demineralization and gingival inflammation.[61–64] Although current applications remain largely conceptual and experimental, advances in nanomaterials, artificial intelligence, and biomedical engineering may enable the future clinical realization of nanorobotic systems in orthodontic diagnosis and therapy.

Clinical Implications, Cost Considerations, and Current Availability

Despite the predominantly preclinical nature of the evidence base, certain nanotechnology-based orthodontic products have entered commercial availability. Nanofilled orthodontic adhesives and composite bonding agents (e.g., Transbond XT by 3M and various nanohybrid bonding systems) are now commercially available and widely used in clinical practice, offering improved translucency and wear resistance compared to earlier generations of microfilled composites. Nanoparticle-incorporated elastomeric ligatures with antimicrobial properties have been described in the literature, though widespread commercial availability remains limited. Nanocoated archwires (incorporating DLC or TiN coatings) are commercially produced by several manufacturers, though clinical superiority over conventional wires has not been definitively established in randomized trials.

From a cost perspective, nanoenhanced orthodontic materials generally carry a higher unit cost than conventional alternatives due to the complexity of nanoparticle synthesis and surface modification processes. This cost premium may limit accessibility in resource-limited clinical settings and low-income patient populations. Until robust clinical trial evidence demonstrates meaningful improvements in patient outcomes that justify the additional cost, widespread adoption is likely to remain selective. Clinicians considering nanoenhanced products should weigh available preclinical evidence, manufacturer data, and patient-specific risk factors (e.g., susceptibility to white spot lesions, nickel sensitivity) when making material selection decisions. Regulatory approval status should also be verified, as nanoenhanced dental materials are subject to medical device regulations that vary by jurisdiction (FDA in the United States, CE marking in Europe, BIS in India).

Conclusion

Nanotechnology represents a scientifically promising avenue for advancing orthodontic materials and appliances. Evidence from *in vitro* and animal studies indicates that nanocoated archwires and brackets can meaningfully reduce frictional resistance and bacterial adhesion; that nanoparticle-reinforced adhesives (incorporating AgNPs, TiO_2, ZnO, and nHAp) can improve mechanical performance and antimicrobial activity; and that nanoengineered elastomers and aligners may offer enhanced biocompatibility and esthetic durability. However, this review identifies several critical research gaps that must be addressed before clinical translation can be considered. First, the overwhelming majority of published evidence derives from *in vitro* experiments with limited sample sizes, heterogeneous methodologies, and short follow-up periods, making direct clinical extrapolation unreliable. Second, long-term nanoparticle release kinetics, cytotoxicity thresholds, and systemic biocompatibility under sustained intraoral conditions remain poorly characterized. Third, no standardized regulatory framework currently governs the clinical use of nanoenhanced orthodontic materials, and environmental disposal implications are underexplored. Fourth, emerging concepts such as nanorobotics, dentifrobots, and Bio-MEMS/NEMS remain entirely theoretical with

no human clinical data. To advance the field, future research should prioritize: (1) well-designed, adequately powered randomized clinical trials comparing nanoparticle-modified and conventional orthodontic materials for clinically meaningful outcomes such as white spot lesion incidence, bond failure rates, and treatment duration; (2) standardized *in vivo* toxicology studies assessing systemic nanoparticle exposure over orthodontic treatment timescales; (3) development of clear regulatory guidelines for nanoenhanced dental devices; and (4) cost-effectiveness analyses to evaluate clinical viability of commercially available nanotechnology-based products. Until such evidence is established, the application of nanotechnology in clinical orthodontics should be approached with appropriate scientific caution.

Data Availability Statement

The data supporting the findings of this narrative review are derived from previously published studies, all of which are cited within the manuscript. No new datasets were generated or analyzed for this review.

Ethical Approval

Ethical approval was not required for this study as it is a narrative review based exclusively on previously published literature and did not involve human participants, animals, or identifiable patient data.

Study Design

This study was designed as a narrative review of the literature, synthesizing available evidence on the applications of nanomaterials in orthodontics from *in vitro* studies, *in vivo* studies, and relevant clinical reports.

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Author Contributions

All authors contributed equally to the conception, literature review, drafting, and critical revision of the manuscript. All authors have read and approved the final version of the manuscript.

AI Disclosure

The authors confirm that no artificial intelligence (AI) tools were used in the preparation, writing, or revision of this manuscript.

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