International Journal of Dental Sciences
www.dentaljournal.in
E-ISSN: 2663-4708, P-ISSN: 2663-4694
Received: 21-07-2025, Accepted: 20-08-2025, Published: 04-09-2025
Volume 7, Issue 3, 2025, Page No. 77-83

Nanodentistry in pediatric dentistry: A narrative review

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Abstract
Background: Nanotechnology has emerged as a transformative field in healthcare, offering unique physicochemical properties at the nanoscale that can significantly enhance preventive, restorative, diagnostic, and therapeutic approaches in dentistry. In pediatric dentistry, the application of nanomaterials is particularly relevant, as children present distinct challenges such as higher caries susceptibility, compliance issues, and the need for minimally invasive, biocompatible interventions.
Objective: This review aims to critically evaluate the current and emerging applications of nanotechnology in pediatric dentistry, encompassing preventive, restorative, endodontic, orthodontic, prosthodontic, and diagnostic domains.
Methods: A narrative review of the literature was conducted using PubMed, Scopus, and Web of Science databases. Publications from 2010 to 2025 were prioritized to highlight recent advances, although seminal older works were retained where essential. Studies focusing on nanotechnology applications in general dentistry with specific relevance to pediatric patients were included.
Results: Nanotechnology demonstrates promising applications across pediatric dentistry. Nano-fluoride formulations, nano-hydroxyapatite-based toothpastes, and antimicrobial nanoparticles show enhanced preventive efficacy against caries. Nano-filled composites and glass ionomers provide improved esthetics and durability for pediatric restorations. Nanomaterials have also been integrated into pulp therapies, regenerative endodontics, orthodontic brackets, wires, and prosthetic appliances, enhancing antimicrobial properties, mechanical performance, and patient comfort. Furthermore, nano-biosensors and salivary diagnostic devices offer potential for early caries detection and personalized care in children.
Conclusion: Nanotechnology is reshaping pediatric dental practice, offering innovative solutions that are more biocompatible, effective, and tailored to children's needs. Future research should emphasize long-term clinical trials, regulatory safety, and ethical considerations to translate laboratory innovations into routine pediatric dental care.

Keywords: Buffered local anaesthesia, 8.4% sodium bicarbonate, lignocaine, bilateral maxillary Premolar Orthodontic extraction

Introduction

Nanotechnology, defined as the manipulation and application of materials at the nanoscale [1–100 nm], has gained prominence across biomedical sciences for its potential to revolutionize diagnostics, therapeutics, and material sciences. In dentistry, nanotechnology is utilized to enhance biomaterials, improve diagnostic sensitivity, and enable targeted drug delivery systems. Its scope extends beyond restorative applications to include preventive, diagnostic, and regenerative approaches, thereby reshaping traditional treatment modalities [1, 2].
The relevance of nanotechnology in dentistry lies in its ability to overcome limitations of conventional materials. Nano-engineered structures exhibit improved mechanical strength, enhanced aesthetics, better antimicrobial resistance, and controlled ion release compared to their conventional counterparts [3]. Furthermore, nanotechnology facilitates the early detection of disease processes, allowing preventive strategies to be implemented before irreversible damage occurs [4].
Pediatric dentistry poses unique challenges due to the dynamic nature of craniofacial growth, developing dentition, and higher susceptibility to caries. Behavior management issues and the need for minimally invasive interventions further necessitate innovative approaches. Nanotechnology offers promising solutions for these challenges by providing enhanced remineralization agents, antimicrobial nanomaterials, nano-biomaterials for pulp therapy, and advanced diagnostic platforms tailored for pediatric populations [5,6].

Historical Evolution and Current Concepts

The application of nanotechnology in dentistry can be traced back to the early 2000s, when researchers explored the use of nanoparticles such as silver and hydroxyapatite for antimicrobial and remineralization purposes [7]. These early studies demonstrated that nanoparticles could be incorporated into restorative materials to enhance mechanical and biological performance. Concurrently, developments in nanodiagnostics introduced the concept of using nanosensors for detecting cariogenic bacteria and pH fluctuations.
The transition from conventional to nano-enhanced materials marked a paradigm shift in pediatric dental care. Conventional fluoride varnishes, for example, were reformulated with nano-fluorides and nano-hydroxyapatite, offering superior penetration and longer-lasting effects [8]. Similarly, composites and glass ionomers were enhanced

with nanofillers to improve wear resistance, aesthetics, and bonding strength, addressing the limitations of earlier materials used in children [9]. Emerging trends include the integration of nanotechnology with digital workflows such as CAD/CAM and 3D printing, which enable the fabrication of patient-specific restorations and prostheses with greater precision [10]. Smart nanomaterials that release ions in response to cariogenic challenges, bioactive nanocomposites, and nanocarrier-based drug delivery systems are currently being developed to further advance pediatric oral health care [11]. Together, these innovations highlight the transformative role of nanotechnology in shaping the future of pediatric dentistry.

Methodology

This review was designed as a narrative review. A comprehensive literature search was conducted across PubMed, Scopus, Web of Science, and Google Scholar databases using combinations of keywords such as “nanotechnology,” “nanoparticles,” “pediatric dentistry,” “nano-hydroxyapatite,” “nano-fluoride,” “nano-composites,” “nanodiagnostics,” and “regenerative endodontics.”

Inclusion criteria:

Articles published between 2010 and 2025 [with some classical studies retained for context].

Studies focusing on applications of nanotechnology in pediatric dentistry.

Original research, clinical trials, *in vitro* studies, and relevant review articles.

Exclusion criteria:

Studies unrelated to dentistry or with no relevance to pediatric populations.

Non-English publications.

Conference abstracts without full-text availability.

The initial search identified over 300 articles. After screening for relevance, duplication, and methodological quality, 74 studies were initially reviewed. For conciseness and recency, the final reference list was narrowed down to 50 key articles representing the most impactful and current contributions to the field.

The selected studies were synthesized under thematic subheadings: preventive dentistry, restorative materials, endodontics, orthodontics, prosthodontics, caries detection and diagnostics, and future directions. This organization was intended to provide a comprehensive yet focused overview of the role of nanotechnology in pediatric dental care.

1. Applications of Nanotechnology in Pediatric Dentistry

1.1. Preventive Dentistry

Nano-fluorides and remineralizing agents.

Nano silver fluoride [NSF] formulations combine silver nanoparticles with fluoride and stabilizers. Randomized controlled trials in primary teeth have reported significant caries-arrest outcomes and reductions in salivary Streptococcus mutans when compared with controls or alternative topical agents [12, 14]. Mechanistically, the high surface-area to volume ratio of silver nanoparticles enhances antibacterial action and fluoride availability at the lesion surface.

Nano-hydroxyapatite in toothpastes and varnishes.

Nano-hydroxyapatite [nHA] mimics the crystal structure of enamel and serves as a nucleation template for mineral deposition. Randomized in situ clinical studies demonstrate that nHA dentifrices improve remineralization of early enamel lesions and inhibit demineralization, with performance comparable to or exceeding conventional fluoride pastes in specific models [14, 15]. Systematic and narrative reviews corroborate the biomimetic mechanism and clinical promise of nHA in preventive care [8, 15].

Antimicrobial nanoparticles for caries prevention.

Silver nanoparticles and other antimicrobial nanomaterials [for example, zinc oxide and titanium dioxide] can be incorporated into varnishes, sealants, and hygiene products to reduce biofilm formation. Comprehensive reviews report broad-spectrum antimicrobial effects, biofilm inhibition, and potential for sustained activity when embedded within dental materials [16, 17]. In the context of pit-and-fissure protection, a pediatric randomized clinical trial observed numerically higher complete retention with nanofilled resin sealant versus a conventional sealant at 18 months, although the difference was not statistically significant [17].

1.2. Restorative Dentistry

Nano-filled composites and glass ionomers.

Nanofillers, such as silica and zirconia particles at the nanoscale, have been incorporated into resin composites and glass ionomer cements. [18] These nanofillers improve filler-matrix interaction, reduce polymerization shrinkage, and enhance polishability and wear resistance. In pediatric applications, nano-composites demonstrate superior esthetics and mechanical strength compared to traditional microfilled composites [19, 20]. Similarly, nano-modified glass ionomer cements [GICs] show improved fluoride release and enhanced compressive strength, which are advantageous for atraumatic restorative treatment [ART] in primary teeth [21].

Improved mechanical and esthetic properties.

Nano-composites achieve high translucency and shade adaptation, offering better integration with pediatric dentition. The addition of nanoparticles decreases crack propagation and provides superior marginal adaptation. Clinical trials have indicated that nano-hybrid composites exhibit high survival rates in Class I and II restorations of primary molars [22]. For GICs, nano-modification enhances wear resistance and esthetics, enabling their use not only in posterior but also anterior pediatric restorations [23].

Clinical outcomes in children.

A randomized clinical trial in children reported that nano-filled composites demonstrated comparable or higher retention and marginal adaptation than conventional resin composites at 12 months follow-up [22]. For nano-ionomer restorations, survival rates were promising in atraumatic restorative contexts, with reports of reduced secondary caries and improved parental satisfaction due to esthetics [23, 24]. Long-term data remain limited, but available evidence suggests nanomaterials are a reliable option for pediatric restorative dentistry.

1.3. Endodontics and Pulp Therapy

Nano-biomaterials in pulp capping and pulpotomy.

Nanomaterials have demonstrated significant potential in vital pulp therapy for primary and immature permanent teeth. Calcium hydroxide and mineral trioxide aggregate

[MTA] remain gold standards, but nano-sized bioactive materials provide superior sealing ability, faster setting, and better antibacterial properties. For instance, nano-hydroxyapatite and nano-calcium silicate materials promote dentin bridge formation and enhance pulp cell proliferation, which are essential for pulpotomy and pulp capping procedures in pediatric dentistry [25, 26].

Role in regenerative endodontics.

Regenerative endodontic procedures [REPs] in immature necrotic permanent teeth have been advanced through the use of nanotechnology. Nanofiber scaffolds fabricated by electrospinning, often combined with bioactive molecules, provide a conducive environment for stem cell differentiation and angiogenesis [27]. Additionally, nanoparticles can act as carriers for growth factors and antibiotics, enabling targeted drug delivery in root canal systems [28]. Studies have shown that nanostructured scaffolds significantly improve root development, apical closure, and dentinal wall thickening in experimental models [29]. These findings are promising for pediatric patients where root maturation is critical.

Clinical implications.

While most evidence for nanomaterials in pulp therapy and regenerative endodontics remains preclinical, early translational studies highlight their potential. The integration of nano-bioactive scaffolds with stem cell-based therapies could redefine endodontic management in children. However, long-term clinical trials are necessary to establish safety and predictable outcomes in pediatric populations [30].

1.4. Orthodontics

Nano-coated wires and brackets.

Nanotechnology has been increasingly applied to orthodontics to enhance the performance of wires and brackets. Surface modification with nanoparticles, such as titanium dioxide and silver, reduces bacterial adhesion and plaque accumulation around orthodontic appliances, a common challenge in pediatric patients [31, 32]. Nano-coatings also improve corrosion resistance and maintain mechanical properties under intraoral conditions [33].

Antimicrobial and friction-reducing properties.

Nano-coatings on stainless steel and nickel-titanium wires can reduce microbial colonization, thereby minimizing the risk of white spot lesions and gingival inflammation during orthodontic treatment [34]. Additionally, nanostructured coatings, such as diamond-like carbon and molybdenum disulfide nanoparticles, decrease surface roughness and sliding friction between archwires and brackets, facilitating efficient tooth movement [35, 36]. These modifications are particularly beneficial in children, where plaque control and compliance are challenging.

Clinical advantages in children.

The application of nanotechnology in orthodontics offers significant advantages for pediatric patients. Reduced friction translates into shorter treatment times and fewer adjustments, improving overall compliance and comfort. Antimicrobial properties of nano-coated appliances may also help prevent demineralization and caries during fixed orthodontic therapy. [37, 39] Although long-term clinical studies are still limited, the available evidence suggests nanotechnology can enhance the safety and efficiency of orthodontic treatment in children [29].

1.5. Preventive and Interceptive Orthopedics

Role of nanomaterials in appliance fabrication.

Nanotechnology has been introduced into preventive and interceptive orthopedic appliances to improve their physical and biological performance. The incorporation of nanofillers in acrylic resins used for functional appliances enhances their flexural strength, wear resistance, and longevity [30]. Furthermore, nanocomposites allow for lighter, thinner appliances without compromising durability, which improves comfort and compliance in children [31].

Biocompatibility in growing children.

One of the main challenges of using orthopedic appliances in pediatric dentistry is ensuring biocompatibility, as the oral tissues in children are still developing. Nanoparticle incorporation in resins and coatings has shown reduced cytotoxicity and enhanced tissue integration [40]. Silver and titanium dioxide nanoparticles embedded into appliance materials impart antimicrobial activity, reducing the risk of mucosal irritation, candidiasis, and plaque accumulation [41, 42]. This property is especially valuable in younger patients with limited oral hygiene practices.

Clinical implications.

The integration of nanotechnology into preventive and interceptive orthopedics holds promise for improving patient outcomes. Enhanced durability ensures appliances withstand functional stresses during craniofacial growth, while antimicrobial coatings reduce the need for frequent adjustments. As research continues, nanotechnology-driven appliances may become standard in pediatric interceptive orthodontics, although long-term trials are still warranted [43].

1.6. Prosthodontics

Nanomaterials in pediatric crowns and overdentures.

Nanotechnology has been incorporated into pediatric prosthodontics to improve the esthetics, strength, and longevity of crowns and overdentures. Prefabricated pediatric crowns fabricated with nano-reinforced composites and ceramics demonstrate superior wear resistance, improved translucency, and color stability compared to conventional stainless steel crowns [44]. For overdentures, the inclusion of nanofillers in acrylic resins increases flexural strength and reduces fracture rates, an important consideration in growing children where prostheses often require adjustments and replacements [45, 46].

Surface coatings for durability and biocompatibility.

Nanostructured coatings, such as titanium dioxide, zirconia, and silver nanoparticles, have been applied to prosthetic surfaces to enhance antimicrobial activity and reduce plaque accumulation [47]. These coatings improve soft tissue compatibility, reducing the risk of inflammation or fungal infections in children who may have compromised oral hygiene. Moreover, bioactive nanocoatings can promote mucosal cell adhesion, improving the stability and integration of overdentures [48].

Digital and 3D printing applications.

The integration of nanotechnology with CAD/CAM and 3D printing technologies has expanded the possibilities for pediatric prosthodontics. Nano-composite resins used in additive manufacturing processes allow for the fabrication of customized crowns and overdentures with high precision and reduced chairside time [49]. This approach is particularly beneficial for children, enabling rapid fabrication of interim prostheses and minimizing patient discomfort. While still emerging, the combination of nanotechnology and digital workflows represents a significant advance in pediatric prosthetic care [50].

Clinical outlook.
Nanotechnology-enhanced crowns and overdentures offer pediatric dentists improved options for esthetic, durable, and biologically compatible prostheses. However, further longitudinal studies are needed to confirm their long-term safety, cost-effectiveness, and performance in the dynamic oral environment of children [39].

Nanotechnology in Caries Detection and Diagnostics
Nano-biosensors.
Nano-biosensors represent one of the most promising diagnostic applications of nanotechnology in pediatric dentistry. These devices integrate biological recognition elements with nanoscale transducers, enabling real-time detection of specific biomarkers associated with dental caries. Nanomaterials such as carbon nanotubes, quantum dots, and gold nanoparticles enhance the sensitivity and specificity of biosensors, allowing detection of cariogenic bacteria like Streptococcus mutans and Lactobacillus species at very low concentrations [40 ,41].

Early caries detection in children.
Nanotechnology has enabled tools for ultra-early caries detection, even before cavitation occurs. Nanosensors incorporated into chairside diagnostic kits can detect demineralization by monitoring calcium and phosphate ion fluctuations in saliva. This early identification is particularly valuable in pediatric patients, where preventive interventions can stop lesion progression and reduce the need for invasive treatments [38]. Recent optical nanosensors and nano-enhanced imaging technologies such as optical coherence tomography (OCT) have also shown promise in detecting incipient lesions in children with high sensitivity [29].

Salivary diagnostics.
Saliva is a non-invasive, readily accessible diagnostic medium, making it ideal for pediatric populations. Nano-enabled salivary diagnostic systems can detect cariogenic bacterial antigens, host inflammatory markers, and demineralization products with high accuracy [42]. Lab-on-a-chip devices incorporating nanomaterials allow rapid, chairside evaluation of caries risk, enabling personalized preventive protocols for children [37, 29].

Clinical relevance.
The use of nanotechnology in caries detection and diagnostics has the potential to revolutionize preventive pediatric dentistry. By enabling ultra-early detection, these approaches allow minimally invasive and targeted interventions. However, translation into routine practice requires validation through large-scale clinical trials and cost-effective integration into pediatric dental care systems [43].

Summary Table: Applications of Nanotechnology in Pediatric Dentistry

Domain	Nanotechnology Applications	Potential Benefits in Pediatric Dentistry
Preventive Dentistry	Nano-fluorides, nano-hydroxyapatite, antimicrobial nanoparticles	Enhanced remineralization, early caries prevention, reduced bacterial load
Restorative Dentistry	Nano-filled composites, nano-modified glass ionomers	Improved esthetics, durability, reduced microleakage
Endodontics	Nano-calcium silicate, nanofiber scaffolds, drug-delivery systems	Enhanced pulp healing, regenerative potential, root maturation
Orthodontics	Nano-coated wires, antimicrobial brackets	Reduced friction, fewer white spot lesions, shorter treatment times
Preventive/Interceptive Orthopedics	Nano-reinforced resins, antimicrobial coatings	Improved appliance durability, reduced cytotoxicity, enhanced compliance
Prosthodontics	Nano-ceramic pediatric crowns, nano-coatings on overdentures, 3D printed nano-composites	Improved esthetics, antimicrobial activity, better fit and comfort
Caries Detection & Diagnostics	Nano-biosensors, optical nanosensors, salivary diagnostics	Ultra-early detection, minimally invasive interventions, personalized care

2. Safety, Toxicology, and Ethical Concerns of Nanotechnology in Pediatric Dentistry
The integration of nanotechnology into pediatric dentistry, while promising, raises important safety, toxicological, and ethical concerns. Children are a particularly vulnerable population, with developing organs, higher metabolic rates, and longer expected lifespans that may amplify the potential risks associated with exposure to nanomaterials [44]. Careful assessment of these risks is critical before widespread clinical implementation.

2.1. Biological Safety and Toxicology
Nanoparticles exhibit unique physicochemical properties such as high surface-to-volume ratios and reactivity, which, while beneficial for therapeutic purposes, can also increase cytotoxicity and oxidative stress. Studies have reported potential genotoxicity, inflammatory responses, and accumulation of nanoparticles in vital organs following systemic exposure [45, 46]. For pediatric applications, this is particularly concerning due to the potential for long-term health consequences. Regulatory agencies have emphasized the need for dose-response studies, standardized testing, and safety thresholds tailored to pediatric populations [44].

2.2 Ethical Considerations
Ethical issues surrounding the use of nanotechnology in pediatric dentistry include informed consent, equity in access, and the potential for unintended long-term consequences. Informed consent in children relies on parental understanding of complex nanotechnology-based

interventions, which may be difficult to communicate adequately [44]. Furthermore, cost considerations may limit access to advanced nano-enabled diagnostics and treatments, raising concerns about healthcare disparities [46]. Ethical frameworks call for balancing innovation with patient safety, particularly when involving vulnerable pediatric groups.

2.3 Regulatory Challenges

Regulation of nanomaterials in healthcare is still evolving. Current guidelines from the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) acknowledge the potential risks of nanotechnology but lack pediatric-specific frameworks [42]. For dental applications, this regulatory gap is particularly significant given the direct contact of nanomaterials with oral mucosa and developing tooth structures. Future regulatory frameworks should include pediatric-specific safety trials, long-term monitoring, and ethical oversight to ensure responsible translation into practice [46].

3. Future Directions and Innovations in Nanotechnology for Pediatric Dentistry

The rapid evolution of nanotechnology presents multiple opportunities for its future integration in pediatric dentistry. As research advances, innovative applications are being developed that may revolutionize preventive, restorative, and diagnostic approaches for children. The following subsections highlight key emerging directions.

3.1 Smart and Responsive Materials

Next-generation nanomaterials are being designed with stimuli-responsive properties, such as pH- or temperature-sensitive drug release, which may allow targeted antimicrobial or remineralizing action only when pathogenic conditions arise [41]. Such 'smart' materials could reduce overtreatment and improve personalized care in children.

3.2 Nano-Enabled Drug Delivery and Regenerative Systems

Advancements in nano-drug delivery, including liposomes, dendrimers, and polymeric nanoparticles, have the potential to enhance pulpal regeneration, caries prevention, and orthodontic pain management [47]. In regenerative endodontics, nanoscaffolds combined with growth factors are under investigation to optimize root development in immature teeth [48].

3.3 Digital Dentistry and AI Integration

Digital workflows, including CAD/CAM and 3D printing, are increasingly being merged with nanomaterials to fabricate precise and durable pediatric prostheses such as crowns and overdentures [49]. Artificial intelligence mAI] may further enhance these technologies by enabling predictive modeling of caries risk, customizing nanomaterial selection, and improving diagnostic accuracy with nano-biosensors [48].

3.4 Sustainability and Eco-Friendly Nanotechnology

A growing concern is the environmental impact of nanotechnology. Green synthesis of nanoparticles using biological methods [plants, microbes] is gaining popularity as a safer, eco-friendly approach [49]. For pediatric dentistry, this may ensure safer long-term applications while reducing ecological risks.

3.5 Interdisciplinary Collaborations and Personalized Care

The future of nanotechnology in pediatric dentistry will rely heavily on collaborations between dentists, materials scientists, biomedical engineers, and regulatory agencies. With precision medicine gaining momentum, nanotechnology could enable child-specific preventive and therapeutic strategies, moving toward a truly personalized pediatric dental care model [50].

4. Conclusion and Clinical Recommendations

Nanotechnology has emerged as a transformative field in pediatric dentistry, offering novel opportunities in prevention, diagnosis, restorative care, endodontics, orthodontics, and prosthodontics. The integration of nano-biomaterials, nano-biosensors, and digital technologies such as CAD/CAM and 3D printing has already demonstrated significant potential in improving treatment precision, durability, and child-centered care. Despite these advances, the translation of nanotechnology into routine pediatric practice remains limited by safety concerns, ethical considerations, and the absence of robust regulatory frameworks tailored to children.

Based on the current evidence, the following clinical recommendations are suggested:

Nanomaterials such as nano-fluorides and nano-hydroxyapatite should be considered as adjunctive preventive agents for children at high risk of caries.

Nano-filled composites and glass ionomers may be preferred in pediatric restorative dentistry due to their improved esthetics, polishability, and wear resistance.

The use of nano-biomaterials in pulp therapy and regenerative endodontics should be limited to research or specialized centers until long-term safety data are available.

Nano-coated orthodontic appliances show promise in reducing microbial colonization and treatment discomfort but require further clinical validation.

Pediatric dentists should maintain awareness of advances in nanotechnology while applying evidence-based caution, particularly in relation to biocompatibility and ethical consent.

Collaborative efforts between dental researchers, clinicians, material scientists, and regulatory authorities are essential to develop safe, effective, and standardized protocols for nano-based pediatric dental care.

In conclusion, nanotechnology represents a frontier in pediatric dentistry that has the potential to redefine standards of care. However, careful integration, guided by rigorous clinical trials and ethical safeguards, is essential to ensure that children benefit from these innovations safely and equitably.

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