REVIEW ARTICLE

AI-Driven Nanomedicine in Modern Dentistry: Emerging Paradigms Across Prosthodontics, Endodontics, and Orthodontics

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ABSTRACT

The convergence of artificial intelligence (AI) and nanomedicine is redefining modern dentistry by enabling more precise, personalized, and minimally invasive care across prosthodontics, endodontics, and orthodontics. This review synthesizes recent advances in AI-driven design, characterization, and clinical translation of nano-engineered materials and devices for dental applications. It first outlines the fundamental concepts of dental nanomedicine and core AI methodologies including machine learning, deep learning, generative models, and inverse design used to optimize nanoparticle properties, nanocomposites, and functional coatings. The role of advanced imaging, spectroscopic, and biosensing techniques in generating high-quality datasets for AI models is then discussed. Subsequent sections examine specialty-specific applications, such as nanostructured and AI-optimized prosthodontic materials, antimicrobial and regenerative nanoplatforms in endodontics, and smart, low-friction, and sensor-augmented systems in orthodontics. Cross-cutting themes, including personalized and predictive dentistry, integration with digital workflows, regulatory and ethical considerations, and the impact of AI on scalability and quality control, are critically evaluated. Particular emphasis is placed on safety, nanotoxicology, long-term biocompatibility, and environmental implications of nanoparticle use in oral applications, highlighting the need for robust standards and "safe-by-design" and "eco-by-design" strategies. Overall, AI-driven nanomedicine holds substantial promise to transform diagnostic accuracy, therapeutic efficacy, and patient experience in dentistry, provided that technical innovation is matched by rigorous validation, interdisciplinary collaboration, and responsible governance.

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INTRODUCTION

The convergence of Artificial Intelligence (AI) and nanomedicine represents a significant advancement in modern healthcare, particularly in dentistry. AI, with its capabilities in data processing and machine learning, complements the precision and innovation of nanotechnology, which is pivotal in developing advanced dental materials and diagnostic tools. This synergy enhances the ability to diagnose, treat, and manage dental conditions with unprecedented accuracy and efficiency. The integration of AI and nanomedicine is transforming dental practices by enabling more personalized and effective patient care, thereby addressing the growing demand for innovative healthcare solutions [1, 2].

Dentistry stands to gain immensely from the convergence of AI and nanomedicine due to the complex nature of dental treatments and the need for precision in diagnosis and treatment planning. AI algorithms can analyze vast amounts of data to

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improve diagnostic accuracy, while nanotechnology provides tools for early detection of dental diseases [2, 3]. AI-driven nanomedicine facilitates the development of biocompatible materials and precise treatment modalities, leading to better patient outcomes in prosthodontics, endodontics, and orthodontics [4, 5]. The integration of AI allows for more efficient workflows and personalized treatment plans, which are crucial in managing complex dental cases [4].

This review paper focuses on the application of AI-driven nanomedicine in three key areas of dentistry: prosthodontics, endodontics, and orthodontics. AI enhances the design and fitting of dental prostheses, improving patient comfort and treatment success [4, 5]. AI aids in the precise detection and treatment of root canal issues, while nanotechnology offers advanced materials for endodontic procedures [6]. AI algorithms optimize treatment planning and monitoring, and nanotechnology contributes to the development of innovative orthodontic appliances [6].

Databases and Timeframe: The search was conducted across international databases, with a focus on the last decade to ensure the inclusion of the most recent advancements [6]. While the convergence of AI and nanomedicine in dentistry offers numerous benefits, it also presents challenges such as ethical considerations, data privacy issues, and the need for further validation of AI-driven technologies in clinical practice. These challenges must be addressed to fully realize the potential of these technologies in transforming dental care [4].

FUNDAMENTAL CONCEPTS

The integration of AI with nanomedicine is revolutionizing modern dentistry, particularly in prosthodontics, endodontics, and orthodontics. This synergy leverages the unique properties of nanomaterials and the computational power of AI to enhance diagnostic and therapeutic capabilities. The following sections delve into the fundamental concepts of nanomedicine, AI methods, and their interfacing in the context of dentistry.

Nanomedicine applies nanoscale technologies to diagnose, treat, and prevent disease by operating at the molecular level. Central to dental nanomedicine are several classes of engineered materials: nanoparticles (1–100 nm) that enable targeted drug delivery and enhanced imaging thereby improving therapeutic efficacy while reducing off-target effects; nanotubes, cylindrical nanostructures valued for their high surface area and mechanical strength that serve as drug carriers and tissue-engineering scaffolds; nanocomposites, where nanoparticles are dispersed within a matrix to yield superior mechanical and functional properties for restorative materials; and nanocoatings, ultra-thin surface layers that confer antimicrobial activity and improved wear resistance, features especially important for implants and prostheses. [7-9].

AI comprises a range of computational techniques that accelerate the design, optimization, and clinical application of nanomedicine. Machine learning (ML) enables predictive modeling and optimization of nanomaterial properties, speeding discovery of effective nanocarriers and nanosensors. Deep learning (DL), using multilayer neural networks, supports complex data analysis and image processing to improve diagnostic imaging and material characterization. Reinforcement learning (RL) trains models by trial and error to identify optimal actions, with potential uses in adaptive treatment strategies and real-time decision-making. Explainable AI aims to make model outputs transparent and interpretable, a key requirement for regulatory compliance and clinical acceptance in healthcare [10-12].

AI-driven nanomedicine in dentistry relies on diverse data types and high-resolution characterization techniques. AI systems ingest multi-omics, imaging, and clinical datasets to refine material selection and personalize therapies. Imaging and surface-analysis modalities Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Optical Coherence Tomography (OCT) provide the nanoscale resolution needed to characterize nanomaterials and monitor their interactions with oral tissues. In parallel, biosignals captured by intraoral sensors and monitoring devices supply dynamic information on treatment response and patient status, enabling adaptive, patient-specific interventions [11, 13].

Despite substantial promise, integration faces practical and ethical barriers. Key challenges include data standardization, label quality, and model generalizability across populations and device platforms; ensuring data privacy and navigating regulatory frameworks; and establishing interdisciplinary workflows that combine materials science, AI, and clinical dentistry. Addressing these issues will require coordinated efforts in benchmarking, open datasets, explainable models, and governance policies to translate AI–nanomedicine advances into safe, equitable dental care [10, 14].

DATA ACQUISITION AND CHARACTERIZATION TECHNIQUES

The integration of advanced data acquisition and characterization techniques is pivotal in the field of AI-driven nanomedicine in modern dentistry. These techniques enable precise analysis and understanding of dental materials and biological tissues, facilitating innovations across prosthodontics, endodontics, and orthodontics. The following sections detail the various methods employed in this domain, highlighting their applications and significance.

Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and confocal microscopy are widely used to characterize dental tissues and materials at micro- and nanoscales. AFM provides high-resolution surface topography and biomechanical measurements of dental structures, facilitating quantitative assessment of pathological changes such as dental caries and oral cancer based on morphological properties [15]. SEM and TEM offer detailed morphological and particle-size distribution data for nanoparticles incorporated into dental materials, which is essential for understanding their physicochemical behavior and biological interactions. Confocal microscopy enables high-resolution, depth-resolved imaging of dental tissues, allowing visualization of structural alterations and material–tissue interfaces relevant to orthodontics and prosthodontics [16].

Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), and surface-sensitive techniques such as X-ray photoelectron spectroscopy (XPS) and energy-dispersive X-ray spectroscopy (EDX) together enable comprehensive chemical characterization of dental tissues and materials. Raman spectroscopy offers noninvasive analysis by detecting changes in mineral content and collagen structure, supporting diagnostics and treatment monitoring [17, 18]. FTIR complements Raman by probing molecular vibrations to reveal the chemical composition of dental materials and their interactions with biological tissues. XPS and EDX provide elemental and chemical-state information at material surfaces, which is essential for understanding surface chemistry, interfaces, and factors that influence material performance and biocompatibility [18].

Proteomics and Metabolomics are crucial for identifying biomarkers in oral tissues, facilitating the development of personalized dental treatments and diagnostics. They provide comprehensive data on protein and metabolite profiles, aiding in the understanding of disease mechanisms and treatment responses [19].

Intraoral Sensors enable real-time monitoring of oral health parameters, such as pH and temperature, providing valuable data for preventive and therapeutic interventions in dentistry [20]. Biosensors are used for detecting specific biomarkers in saliva and other oral fluids, offering rapid and accurate diagnostics for conditions like dental caries and periodontal disease [21].

Standardization, labeling, and strategies to handle class imbalance are critical for reliable AI model development in dental applications. Standardization involves normalizing data formats and units to ensure consistency and accuracy across datasets, while careful labeling guarantees that data are correctly categorized for analysis. To address class imbalance, techniques such as data augmentation and synthetic data generation can improve model performance and robustness [22]. Despite these benefits, implementation challenges remain: high costs, technical complexity, and the need for specialized training, along with ethical and regulatory concerns related to patient safety and data privacy. Overcoming these barriers is essential for successful integration and widespread clinical adoption of AI and nanotechnology in dentistry.

AI METHODS FOR NANOMATERIALS DESIGN AND OPTIMIZATION

AI is increasingly pivotal in the design and optimization of nanomaterials, offering innovative solutions across various domains, including nanomedicine in dentistry. AI methods facilitate the prediction of nanoparticle properties, the discovery of new materials, and the optimization of synthesis processes, thereby enhancing the efficacy and precision of nanomaterials used in prosthodontics, endodontics, and orthodontics. This integration of AI into nanomaterials design is transforming traditional approaches, enabling more efficient and targeted development of dental materials. The following sections delve into specific AI methodologies applied in this context.

AI-driven predictive modeling utilizes machine learning (ML) to establish structureproperty relationships, crucial for understanding and predicting the behavior of nanoparticles in dental applications [23]. These models can predict mechanical, thermal, and chemical properties, aiding in the design of nanoparticles with desired characteristics for specific dental applications [24].

Generative models, including Generative Adversarial Networks (GANs) and Variational Autoencoders (VAEs), are employed to explore vast chemical spaces and generate novel nanomaterials with tailored properties [25, 26]. Inverse design capabilities allow researchers to specify desired properties and backtrack to identify potential material structures, streamlining the discovery process for dental nanomaterials [27].

AI techniques integrate multi-scale modeling approaches, bridging atomistic simulations with macroscopic behavior predictions, essential for understanding the comprehensive performance of dental nanomaterials [28, 29]. This integration helps in simulating the interaction of nanoparticles with biological tissues, crucial for developing biocompatible dental materials [29].

Active learning and Bayesian optimization are employed to optimize experimental workflows, reducing the need for extensive trial-and-error in nanoparticle synthesis [30]. These methods prioritize experiments that are most likely to yield informative data, accelerating the development of effective dental nanomaterials [28].

Explainability in AI models is crucial for gaining insights into the decision-making processes, ensuring that the predictions align with experimental observations [30]. Uncertainty quantification helps in assessing the reliability of AI predictions, which is vital for the clinical translation of AI-designed dental nanomaterials [29].

While AI offers significant advancements in nanomaterials design, challenges such as data quality, model interpretability, and computational costs persist. These issues can hinder the seamless integration of AI into experimental workflows, necessitating ongoing research to develop robust, interpretable models that can reliably predict and optimize nanomaterials for dental applications. Additionally, ethical considerations, particularly in terms of regulatory compliance and nanotoxicity, must be addressed to ensure the safe and effective use of AI-driven nanomaterials in dentistry [29].

PROSTHODONTICS APPLICATIONS

The integration of AI and nanotechnology in prosthodontics is revolutionizing dental care by enhancing the precision, durability, and functionality of dental restorations. These advancements are evident in the development of nanostructured biomaterials, surface engineering of implants, AI-guided design, and predictive maintenance strategies. However, the clinical translation of these technologies faces challenges such as regulatory hurdles and cost-effectiveness. The following sections delve into these aspects, highlighting the transformative potential and existing challenges in prosthodontics.

Nano-filled composites and ceramic nanocomposites enhance restorative and prosthetic dental materials by leveraging nanoscale fillers to improve mechanical performance and aesthetics. Nano-filled composites incorporate nanoparticles to increase elastic modulus and surface hardness, reduce polymerization shrinkage, and allow higher filler loading, producing restorations that are more durable and visually appealing [31, 32]. Ceramic nanocomposites, which integrate nanoceramics, deliver superior strength and wear resistance while closely mimicking the natural appearance of teeth, thereby improving both functionality and esthetics of dental prostheses [32].

Surface modifications at the nanoscale, such as sandblasting and plasma spraying, enhance osseointegration and mechanical stability of implants. These coatings can also be bioactive, promoting bone regeneration [33]. Nanostructured surfaces can reduce bacterial adhesion and promote osteogenesis, thereby improving the longevity and success rate of dental implants [33, 34].

AI facilitates the design of customized prostheses by analyzing patient-specific data, leading to better fitting and more comfortable dental solutions [5]. AI-driven generative design allows for the optimization of prosthetic structures, enhancing their functionality and aesthetic appeal while reducing material waste [5].

AI models can predict the wear and potential failure of dental restorations, allowing for timely interventions and maintenance, thus extending the lifespan of prosthetic devices. Advanced modeling techniques help in understanding the wear patterns and fatigue behavior of dental materials, contributing to the development of more durable prosthodontic solutions [5].

The integration of nanotechnology and AI in prosthodontics faces regulatory challenges, as existing frameworks may not fully address the unique properties and risks associated with these technologies [35]. Manufacturability and Cost-effectiveness: While nanomaterials offer superior properties, their production can be costly and complex, posing challenges for widespread clinical adoption. Ensuring cost-effectiveness without compromising quality is crucial for the successful translation of these technologies into clinical practice [35, 36].

While the advancements in AI and nanotechnology hold great promise for prosthodontics, it is essential to address the challenges related to biocompatibility, cytotoxicity, and environmental impact [37]. Additionally, the development of standardized regulatory guidelines and cost-effective manufacturing processes will be critical for the broader adoption of these technologies in clinical settings. Balancing innovation with safety and accessibility will ensure that the benefits of these emerging paradigms are realized in modern dentistry.

ENDODONTICS APPLICATIONS

The integration of AI-driven nanomedicine in endodontics is revolutionizing dental care by enhancing antimicrobial efficacy, promoting pulp regeneration, and improving diagnostic capabilities. This approach leverages the unique properties of nanoparticles to address challenges in root canal treatments and tissue regeneration. The following sections explore the various applications of nanotechnology in endodontics, highlighting its transformative potential.

Nanoparticles enhance antimicrobial action by deeply penetrating dentinal tubules, offering superior disinfection compared to conventional methods [38]. They facilitate targeted drug delivery and sustained-release systems, improving the efficacy of intracanal therapies [39].

Nanomaterials serve as scaffolds and carriers for growth factors, supporting stem cell differentiation and pulp tissue regeneration [38, 40].These materials can be used in cell-free approaches to attract endogenous stem cells, promoting true pulp regeneration [40].

AI-enhanced nanoscale imaging improves the visualization of canal anatomy and detection of microleakage, aiding in precise diagnosis and treatment planning [38]. Smart sensors utilizing nanotechnology can monitor pH and microbial load, providing real-time feedback for treatment adjustments [38].

Despite the benefits, concerns about the safety, cytotoxicity, and long-term biocompatibility of nanoparticles persist, necessitating further research to ensure their safe application in clinical settings [38, 39].

While the potential of AI-driven nanomedicine in endodontics is vast, it is crucial to address the challenges related to the safety and regulatory approval of these technologies. Continued research and development are essential to fully realize the benefits of nanotechnology in dental care, ensuring that these innovations are both effective and safe for widespread clinical use.

ORTHODONTICS APPLICATIONS

The integration of nanotechnology and AI in orthodontics is revolutionizing treatment methodologies, enhancing precision, and improving patient outcomes[41, 42]. These advancements are evident in various applications, from material innovations to AI-driven treatment planning. The following sections explore these emerging paradigms in orthodontics[43].

Nanotechnology has enabled the development of nanocoatings that reduce friction in orthodontic appliances, improving sliding mechanics and enhancing patient comfort [44, 45]. Antibacterial surfaces created through nanotechnology inhibit bacterial growth and biofilm formation, reducing the risk of infections during orthodontic treatment [44].

Smart aligners incorporating force-modulating nanomaterials allow for controlled force delivery, optimizing tooth movement and reducing treatment time. These materials respond to environmental changes, providing adaptive orthodontic solutions that enhance treatment efficiency [46].

AI technologies facilitate predictive tooth movement models by analyzing large datasets, improving treatment precision and efficiency. AI-driven aligners and braces are designed to apply optimal forces, reducing discomfort and treatment duration [47, 48].

Intraoral sensors and AI-powered remote monitoring tools provide real-time feedback, enabling remote treatment adjustments and enhancing patient compliance.These technologies reduce the need for frequent in-person visits, making orthodontic care more accessible [47].

AI and nanotechnology contribute to modeling relapse risk and assessing material fatigue, ensuring long-term treatment success. These innovations support sustainable orthodontic practices by promoting biocompatibility and reducing environmental impact [47].

While these advancements offer significant benefits, challenges such as data privacy, algorithmic bias, and ethical considerations in AI applications remain. Addressing these issues is crucial for the widespread adoption of AI and nanotechnology in orthodontics, ensuring that these technologies continue to enhance patient care and treatment outcomes.

CROSS-CUTTING THEMES

AI-driven nanomedicine is transforming modern dentistry by integrating advanced technologies across various specialties, including prosthodontics, endodontics, and orthodontics. This integration is characterized by several cross-cutting themes that highlight the potential and challenges of these emerging paradigms. The following sections explore these themes in detail.

AI technologies are being utilized to develop targeted therapies that address antimicrobial resistance, a growing concern in dental care. By analyzing microbial profiles, AI can help design personalized antimicrobial treatments that are more effective and reduce the risk of resistance development [49].

Personalized dentistry leverages AI to analyze genetic, microbial, and systemic health data, enabling patient stratification and tailored treatment plans . This approach moves beyond traditional methods, optimizing therapeutic choices to suit individual patient biology. AI-driven predictive analytics and nanomarker profiles facilitate early disease detection and personalized treatment strategies, enhancing treatment efficacy and patient compliance [50, 51].

The integration of AI in dentistry raises ethical concerns, particularly regarding data privacy, consent, and ownership. Ensuring responsible AI implementation involves addressing these issues and mitigating biases in AI algorithms to maintain fairness and transparency [50].

Regulatory bodies like ISO, FDA, and EMA are developing guidelines for the use of AI and nanomaterials in dentistry, focusing on safety, efficacy, and standardization. These regulations aim to ensure that AI-driven innovations meet the required standards for clinical application [50].

Additive manufacturing technologies, supported by AI, are enhancing the scalability and reproducibility of dental prosthetics and materials. AI-driven quality control systems ensure the consistency and reliability of dental products, facilitating large-scale production [52].

While AI-driven nanomedicine offers significant advancements in dentistry, it also presents challenges such as high implementation costs and the need for continuous updates to AI models. Addressing these challenges requires a balanced approach that considers both technological innovation and ethical implications. A concise synthesis of these specialty-specific applications, shared benefits, and recurrent challenges is provided in Table 1, offering a structured overview to guide future research and clinical translation.

SAFETY, TOXICOLOGY, AND ENVIRONMENTAL IMPACT

The integration of AI-driven nanomedicine in modern dentistry, particularly in prosthodontics, endodontics, and orthodontics, necessitates a comprehensive understanding of safety, toxicology, and environmental impacts. This involves assessing the nanotoxicology of oral applications, long-term biocompatibility, and environmental considerations. These aspects are crucial for ensuring the safe and effective use of nanomaterials in dental applications.

Nanoparticles can enter the human body through various routes, including oral ingestion, inhalation, and dermal contact, potentially leading to systemic distribution and accumulation in organs [53, 54].

The unique physicochemical properties of nanoparticles, such as size, surface charge, and surface area, influence their interaction with biological systems, potentially causing toxic effects [53, 55]. AI and machine learning are pivotal in processing toxicological data, helping to predict and categorize the toxicological profiles of nanomaterials used in dentistry [55].

Long-term biocompatibility studies are essential to evaluate the safety of nanomaterials in dental applications, ensuring they do not elicit adverse biological responses over time. Regulatory standards and guidelines are necessary to harmonize the evaluation of nanomaterial safety, involving collaboration between academia, industry, and regulatory bodies [55, 56].

The release of nanoparticles into the environment poses risks to ecosystems, necessitating effective waste management strategies to mitigate potential

Table 1. Core applications and challenges of AIdriven nanomedicine in modern dentistry.

Area	Main AI–nanomedicine applications	Key benefits	Main challenges
Prosthodontics	AI-optimized nano-composites and implant coatings	Stronger, more aesthetic restorations; better osseointegration and less biofilm	Cost and manufacturing complexity; limited long-term clinical data
Endodontics	Antibacterial nanoparticles and regenerative nano-scaffolds with AI-enhanced imaging	Deeper disinfection; potential pulp regeneration; more accurate diagnosis	Cytotoxicity and biocompatibility concerns; few large clinical studies
Orthodontics	Low-friction, antibacterial nano-coatings; smart aligners; AI-guided planning and remote monitoring	Faster, more comfortable treatment; fewer visits; improved hygiene	Data privacy, bias in algorithms; device cost and validation needs
Data & design	Advanced imaging/spectroscopy and sensors feeding AI models for nano-material design	Better characterization; faster, targeted material optimization	Need for standardized, high-quality data; model interpretability
Safety & environment	AI-assisted nanotoxicology, biocompatibility and environmental risk assessment	More systematic risk evaluation; safer and more sustainable materials	Gaps in nano-specific standards; limited chronic exposure and ecological data

environmental impacts [53, 55].

Understanding the ecotoxicity of nanoparticles is crucial, as they can affect air, water, and soil quality, impacting various organisms [55].

While the potential of AI-driven nanomedicine in dentistry is promising, it is imperative to address the associated safety and environmental concerns. This involves not only understanding the toxicological impacts but also implementing robust regulatory frameworks to ensure the responsible use of nanomaterials.

CONCLUSION

The convergence of AI and nanomedicine is reshaping modern dentistry by enabling a transition from conventional, procedure-centered care toward data-driven, personalized, and minimally invasive interventions across prosthodontics, endodontics, and orthodontics. AI methods accelerate the design, optimization, and characterization of nano-engineered materials, while nanotechnology provides high-resolution diagnostics, smart therapeutics, and functionalized surfaces that enhance mechanical performance, antimicrobial efficacy, and tissue integration. Together, these technologies support more precise diagnosis, tailored treatment planning, and dynamic monitoring, with the potential to improve long-term outcomes and patient experience.

At the same time, the review highlights critical cross-cutting challenges that must be addressed to translate AI-driven nanomedicine into routine clinical practice. These include data standardization and quality, model transparency and generalizability, regulatory and ethical considerations, and persistent gaps in long-term safety, toxicology, and environmental impact assessments of nano-enabled dental products. Robust evaluation of nanotoxicology, long-term biocompatibility, and nanoparticle release across the full life cycle of materials is essential to ensure that clinical gains are not offset by delayed adverse effects on patients or ecosystems.

Looking forward, progress will depend on truly interdisciplinary collaboration between dental clinicians, materials scientists, AI researchers, toxicologists, and regulators. Priorities for future work include establishing open, well-annotated datasets; developing explainable and clinically validated AI models; implementing nano-specific standards and regulatory frameworks; and embedding “safe-by-design” and “eco-by-design” principles into AI-guided material discovery. For clinicians, cautious, evidence-based adoption of AI-driven nanotechnologies anchored in rigorous validation and transparent communication with patients will be key to harnessing their benefits while maintaining trust. For researchers and policymakers, aligning innovation with safety, affordability, and equity will determine whether AI-driven nanomedicine can fulfil its promise as a transformative paradigm for prosthodontic, endodontic, and orthodontic care in the coming decade.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

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