

# Recent Advances In Dental Science: A Comprehensive Review Of Emerging Trends And Technologies

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## Abstract

**Background:** Dental science has evolved into a technology-driven discipline that integrates digital systems, advanced biomaterials, and artificial intelligence. These innovations have transformed diagnostics, treatment planning, and patient care, shifting the field toward precision and personalized dentistry. This review highlights emerging trends and technologies shaping modern dental practice.

**Methods:** A comprehensive narrative review was conducted using data from PubMed, Scopus, and Web of Science (2015–2025). Peer-reviewed articles, clinical studies, and systematic reviews focusing on dental materials, digital technologies, imaging, regenerative approaches, and implantology were analyzed. Thematic synthesis emphasized innovation, translational potential, and clinical relevance.

**Results:** Recent advances include bioactive restorative materials, nanostructured ceramics, and regenerative scaffolds that promote tissue healing. Digital dentistry, CAD/CAM systems, and 3D printing have improved precision, efficiency, and customization. Artificial intelligence enhances diagnostic accuracy in caries detection, periodontal analysis, and treatment planning, while novel imaging modalities such as optical coherence tomography and hyperspectral imaging enable non-invasive visualization. In periodontics and implantology, regenerative and patient-centered approaches are improving outcomes and linking oral with systemic health.

**Conclusions:** Dental science is entering a new era defined by digital integration, biological regeneration, and personalized care. Continued interdisciplinary research and ethical implementation are essential to ensure that technological innovations translate into equitable, sustainable, and high-quality oral healthcare worldwide.

## Keywords

Dental innovation; digital dentistry; artificial intelligence; biomaterials; regenerative dentistry; tissue engineering; periodontics; dental implantology; imaging technologies; nanotechnology; precision dentistry.

## Introduction

Dental science has undergone a remarkable transformation over the centuries, evolving from rudimentary practices rooted in ancient civilizations to a highly sophisticated, technology-driven discipline that integrates advanced materials, digital workflows, and artificial intelligence to optimize patient care and outcomes. The earliest evidence of dental care dates back to 7000 BC, with archaeological findings indicating that early humans utilized crude tools for tooth extraction and cavity treatment. However, it was not until the 18th and 19th centuries that dentistry began to emerge as a formalized profession, marked by the establishment of the first dental school in 1840 and the introduction of foundational innovations such as amalgam fillings, anesthesia, and vulcanized rubber dentures. The 20th century witnessed an explosion of technological advancements, including the discovery of dental X-rays, the widespread adoption of water fluoridation, the development of dental implants, and the advent of orthodontic solutions like clear aligners. These milestones not only revolutionized the way dental diseases were diagnosed and treated but also laid the groundwork for the modern era of dental science, characterized by precision, patient-centered care, and continuous innovation (Güven, 2017).

The importance of continuous innovation in dental science cannot be overstated, as it directly impacts the quality, accessibility, and effectiveness of oral healthcare. Innovations such as digital imaging, computer-aided design and manufacturing (CAD/CAM), intraoral scanners, and laser dentistry have fundamentally transformed diagnostic accuracy, treatment planning, and procedural efficiency. These technologies enable clinicians to detect oral diseases at earlier stages, design customized restorations, and deliver minimally invasive treatments that enhance patient comfort and satisfaction. Furthermore, the integration of artificial intelligence and machine learning algorithms is beginning to revolutionize diagnostic workflows, allowing for automated image analysis, predictive modeling, and personalized treatment recommendations. Such advancements not only improve clinical outcomes but also empower patients to actively participate in their care, fostering greater trust and compliance. The relentless pursuit of innovation is essential for addressing emerging challenges in oral health, such as the rising prevalence of dental caries, periodontal disease, and oral cancer, as well as for expanding access to high-quality dental care in underserved populations (Gawali et al., 2024).

The objectives of this comprehensive review are to provide an in-depth analysis of the most recent advances in dental science, with a particular focus on emerging trends and technologies that are reshaping the field. The scope of the review encompasses a broad spectrum of topics, including digital dentistry, advanced biomaterials, regenerative approaches, artificial intelligence applications, and innovations in preventive and restorative care. By synthesizing the latest evidence from peer-reviewed literature, this review aims to highlight the transformative impact of these advancements on clinical practice, patient outcomes, and the future trajectory of dental science. Special attention will be given to the integration of interdisciplinary approaches, the translation of research findings into clinical applications, and the ethical and practical considerations associated with the adoption of new technologies. Ultimately, this review seeks to serve as a valuable resource for dental professionals, researchers, and policymakers, providing a comprehensive overview of the current state of dental science and offering insights into the opportunities and challenges that lie ahead (Gawali et al., 2024).

## Methods

This comprehensive review employed a narrative synthesis approach to analyze and integrate recent advancements in dental science, emphasizing technological innovations, materials development, and interdisciplinary applications. A systematic literature search was conducted across major scientific databases, including PubMed, Scopus, and Web of Science, covering publications from 2015 to 2025. Search terms included combinations of “dental materials,” “digital dentistry,” “artificial intelligence,” “regenerative dentistry,” “periodontics,” “imaging technologies,” and “implantology.” Only peer-reviewed articles, systematic reviews, and clinical trials published in English were included. Studies focusing on historical perspectives, novel materials, diagnostic technologies, and emerging clinical applications were

prioritized. Reference lists of key papers were also screened to identify additional relevant sources. Information was categorized thematically into seven domains: (1) innovations in dental materials, (2) advances in digital dentistry, (3) applications of artificial intelligence, (4) novel imaging technologies, (5) developments in periodontics, (6) regenerative and tissue engineering approaches, and (7) innovations in implantology. Each domain was critically evaluated for its scientific merit, clinical applicability, and potential future impact on dental practice. Data synthesis emphasized technological convergence, translational potential, and patient-centered outcomes.

### **Historical Perspective of Dental Science Advances**

The historical perspective of dental science advances is marked by a series of transformative milestones in dental materials, techniques, and technology, reflecting a profound shift from reactive to preventive and restorative dental care. The earliest dental interventions relied on rudimentary materials such as beeswax for impression making, which dates back to the mid-1800s, and the introduction of dental trays, gutta-percha, thermoplastic resins, and plaster of Paris represented significant early advances in the field of prosthodontics and restorative dentistry. These foundational innovations laid the groundwork for the development of more sophisticated impression techniques, including the double (corrective) impression and functional impression concepts, which greatly improved the accuracy and quality of dental restorations (Papadiochos et al., 2017).

Throughout the 20th century, the evolution of dental materials accelerated, with the introduction of dental amalgam, gold, and silver, which dominated restorative practices for decades. However, the latter half of the century witnessed a dramatic shift toward improved esthetics and biocompatibility, marked by the replacement of dental amalgam with dental composites and the adoption of reinforced dental ceramics for indirect restorations. The development of dental adhesive materials played a pivotal role in this transformation, enabling the reliable bonding of restorative materials to tooth structure and facilitating minimally invasive approaches to dental care. The advent of light-cured composites, advanced dental cements, and functional repair materials further expanded the possibilities for restorative dentistry, allowing for more durable, esthetic, and patient-friendly treatments (Bayne et al., 2019).

Parallel to these material advances, dental techniques and technologies have undergone a revolution. The development of digital imaging, CAD/CAM systems, and 3D printing has transformed diagnostic and treatment planning processes, enabling greater precision and customization in dental care. The integration of digital technologies into dental practice has also facilitated the implementation of universal aesthetic rules and guidelines, leading to more natural and individualized smile designs. Furthermore, the rise of minimally invasive techniques, such as fiber-post systems and advanced surgical approaches, has minimized tissue trauma and improved patient outcomes (Alshabib et al., 2023).

A critical shift in dental care philosophy has been the move from a reactive, disease-focused model to a preventive, whole-patient approach. Historically, dental care was primarily concerned with treating established diseases and restoring lost function. However, recent decades have seen a growing emphasis on preventive strategies aimed at preserving oral health and preventing the onset of disease. This paradigm shift is reflected in the development of individualized preventive care models, which consider the synthesis of risk- and need-oriented parameters, including systemic diseases, medications, lifestyle factors, and oral health status. The focus has expanded from viewing oral health in isolation to viewing the patient as a whole, with prevention strategies tailored to the unique needs and risks of each individual (Schmalz & Ziebolz, 2020).

The contemporary concept of individualized prevention in dentistry integrates risk-oriented and need-oriented approaches, recognizing that oral health is influenced by a complex interplay of systemic, behavioral, and environmental factors. This holistic model emphasizes primary prevention, aiming to preserve oral health rather than simply treating disease, and promotes a shift from a surgical to a medical

model of dental care. The implications of this approach are far-reaching, with the potential to increase the safety, effectiveness, and efficiency of preventive care in dental practice (Schmalz & Ziebolz, 2020).

### **Innovations in Dental Materials**

Bioactive and biomimetic restorative materials represent a cutting-edge frontier in dental science. Unlike traditional restorative substances that merely fill cavities or restore tooth structure, these materials actively promote the remineralization of dental tissues and support the biological processes of the pulp-dentine complex. Recent research has focused on developing advanced bioactive restorative adhesive materials (ABRAM) that combine antibacterial properties, enhanced sealing of the resin-dentine interface, and biofunctionality that supports pulp vitality. These materials often incorporate ion-releasing fillers such as bioactive glasses, calcium phosphates, and tailored silicates, which facilitate mineral deposition and dentine repair. Although currently few materials exhibit full bioactivity with sustained therapeutic effects, ongoing interdisciplinary research aims to develop formulations that extend the longevity of dental restorations by enabling natural tissue-like regeneration and protection from secondary caries. The integration of biomimetic analogues highlights a shift towards minimally invasive dentistry with biologically-driven therapeutic outcomes, underlining the importance of rigorous clinical validation for these innovative materials (Sauro et al., 2025).

In parallel, advanced ceramics and composites have undergone significant improvements, driven by demands for strength, durability, and superior aesthetics. Modern resin-based composites now incorporate organic nanocomposites that enhance mechanical properties and wear resistance, while maintaining favorable handling characteristics. These composites are engineered to balance strength with translucency and color stability, ensuring they closely mimic the optical properties of natural teeth. Similarly, advances in ceramic technology, particularly with zirconia and lithium disilicate, have made these materials preferred choices for crowns, bridges, and implant-supported restorations. Their inherent high fracture toughness and wear resistance ensure that restorations can withstand occlusal forces, while multilayered shading and translucency effects provide unparalleled aesthetic integration. Moreover, dental zirconia has been refined by modifying its composition, such as reducing alumina content and increasing yttria concentration, to improve translucency without sacrificing durability. Lithium disilicate, recognized for its excellent optical properties, complements zirconia by offering high esthetic quality combined with solid mechanical performance (Woźniak-Budych et al., 2023).

These material advancements have a transformational impact on restoration outcomes. Durability is enhanced through superior mechanical strength and resistance to fracture and wear, directly influencing long-term clinical success and reducing the need for repairs or replacements. This durability is complemented by improved biocompatibility; modern materials are designed to minimize adverse tissue reactions, promote integration with surrounding oral tissues, and resist bacterial colonization, thus enhancing periodontal health and reducing the risk of inflammation-related failures. Aesthetically, the materials achieve natural tooth-like appearances through sophisticated control of translucency, color gradients, and surface texture, contributing to patient satisfaction and acceptance. Overall, the synergistic improvements in bioactivity, material composition, and aesthetic customization position these innovations at the forefront of dental restorative care, promising restorations that are not only functional but also biologically harmonious and visually indistinguishable from natural dentition (Gunasekaran et al., 2024).

### **Advances in Digital Dentistry**

Advances in digital dentistry have revolutionized the way dental care is delivered, offering unparalleled precision, efficiency, and customization in both diagnostics and treatment. One of the major technological breakthroughs has been the evolution and wide adoption of computer-aided design and manufacturing (CAD/CAM) systems in routine dental practice. These systems enable the digital capture of a patient's dentition through intraoral scanning or traditional impression digitization, followed by precise computer-assisted design of restorations that are then fabricated using milling machines or 3D printers. CAD/CAM

technology offers clinicians and dental technicians significant advantages over traditional methods including enhanced accuracy in marginal fit, reduced chairside time, and the ability to explore complex restorative designs employing advanced biocompatible materials. Milling machines used in CAD/CAM can be wet or dry, with various parameters optimized for different dental materials like zirconia and lithium disilicate, ensuring optimal surface quality and durability of prostheses. There is also flexibility between chairside systems, enabling same-day restorations, and laboratory-based systems, which support intricate designs with a broader material range (Eid, 2025).

Intraoral scanning (IOS) has emerged as a cornerstone in digital dentistry. Recent advances in IOS technology include continuous image capture, advanced software for seamless image stitching, and improved interoperability through open data interfaces. These improvements have made digital impressions more efficient and patient-friendly, mitigating the discomfort associated with traditional molding. Importantly, IOS now extends beyond impression taking to support diagnostics and treatment planning, with some scanners equipped with fluorescence or near-infrared imaging to detect caries and monitor soft tissue and tooth wear quantitatively. Deep learning and neural network-based image segmentation enhance the precision of orthodontic applications and treatment simulations, ensuring that restorations and aligners produced digitally are comparable or superior to those made from conventional molds. Integration challenges remain in adapting these scanners fully into large dental institutions, such as health record compatibility and data storage, but the direction is towards enhancing the overall patient care experience and clinical outcomes (Eggmann & Blatz, 2024).

The advent of 3D printing and additive manufacturing is another transformative trend impacting dental prosthetics. This technology allows for highly precise, customizable, and efficient fabrication of crowns, bridges, surgical guides, orthodontic devices, and both fixed and removable prosthodontics. 3D printing methods such as stereolithography, selective laser sintering, and digital light processing have enabled production that mimics the natural aesthetic and functional properties of dental tissues. Multimaterial printing, including lithography-based ceramic manufacturing, expands the potential to integrate various materials in single prints, enhancing prosthetic durability and biocompatibility. Clinical evaluations show patients fitted with 3D-printed prostheses experience improved comfort, stability, and satisfaction compared to traditional methods, alongside reduced production times and material waste, thus making it cost-effective. Despite these benefits, limitations such as material properties, costs, and technical expertise are ongoing challenges driving further research (Beefathimathul, 2025).

Digital impressions obtained through intraoral scanning are increasingly replacing conventional impression molding. Digital impressions offer superior accuracy, lower distortion risks, and enable immediate data transfer for CAD/CAM workflows. This shift enhances patient comfort by eliminating bulky impression materials and providing faster turnaround in restorative procedures. Multiple studies have demonstrated comparable or improved clinical performance of restorations made from digital impressions, validating their reliability. Moreover, the digital format facilitates seamless integration with AI and cloud-based technologies, promoting a connected clinical and laboratory ecosystem that improves treatment planning, communication, and outcome predictability (Beefathimathul, 2025).

A profound emerging trend is the integration of artificial intelligence (AI) into digital dentistry workflows, marking a paradigm shift. AI is now deeply embedded in intraoral scanners, CAD software, and diagnostic imaging, enabling real-time analysis and automation. AI applications include automated caries detection, periodontal disease identification, surgical planning, and restoration design with minimal human intervention. AI-powered CAD systems can generate highly accurate prosthetic designs quickly, transforming technicians from manual designers into supervisors who focus on customization and quality control rather than repetitive tasks. Predictive algorithms assess patient-specific risks, enabling personalized preventive strategies. Meanwhile, AI-driven robotics is beginning to assist in implantology and routine dental procedures with enhanced precision and efficiency. The increasing regulatory acceptance of AI-powered diagnostic tools signals wider clinical adoption and a future where AI fundamentally

augments clinical decision-making and workflow optimization, ultimately improving patient outcomes (Rokaya et al., 2024).

### **Artificial Intelligence in Dental Diagnosis and Treatment Planning**

Artificial intelligence (AI) is revolutionizing dental diagnosis and treatment planning, driving substantial improvements in accuracy, efficiency, and patient-centered care. AI-powered diagnostic approaches utilizing machine learning (ML) and deep learning (DL) algorithms are reshaping the evaluation of dental radiographs, intraoral scans, and clinical data, enabling automated, objective, and precise disease detection across a spectrum of dental pathologies. In routine practice, AI tools have demonstrated superior or comparable sensitivity and specificity to experienced clinicians while considerably reducing the diagnostic time, as evidenced by advanced systems using convolutional neural networks (CNNs) to detect dental caries, impacted teeth, residual roots, and full crowns from panoramic radiographs and intraoral images. For example, recent clinical trials report that AI-powered intraoral scan analysis achieves sensitivity and specificity values consistently exceeding 85%, streamlining caries detection and allowing earlier intervention with reduced diagnostic subjectivity. In caries detection, integrated neural network-based software supports clinicians by increasing their sensitivity, particularly for incipient enamel lesions, with studies reporting that AI use raises the area under the ROC curve (AUC) above clinician baseline performance, often promoting more timely and sometimes more aggressive restorative decisions (Hung et al., 2025).

Expanding beyond caries, AI platforms now address tooth wear measurement, plaque visualization, and the diagnosis of periodontal diseases, demonstrating F1 scores and diagnostic accuracy on par with dental experts. In periodontology, hybrid deep learning systems and automated segmentation technologies enable rapid, reliable bone loss quantification, accurate staging, and morphological defect visualization, providing robust data for individualized treatment design. In orthodontics, AI algorithms automate anatomical landmark detection, arch measurement, and predictive analytics for orthodontic outcomes, with validated models supporting faster, standardized, and less subjective diagnosis and planning. Plaque imaging and quantification by AI-assisted image analysis offers objective visualization and monitoring, helping personalize hygiene recommendations and disease prevention strategies. In endodontics, AI is increasingly used to predict therapy success and procedural complications through integrated analysis of clinical, imaging, and biometric data, supporting improved patient prognostication and guided therapy (Liu et al., 2025).

The personalization of dental treatment is one of AI's most transformative advances, leveraging patient-specific variables medical history, genetic factors, lifestyle, and imaging data, to optimize care pathways and tailor interventions. Predictive models for caries risk, periodontal progression, orthodontic outcomes, and restorative needs are now being incorporated into decision-support platforms, enabling dentists to design truly individualized preventive and therapeutic plans. Federated learning models have enabled cross-clinic model training with privacy-preserving architectures, supporting large-scale data consistency and clinical applicability. Explainable AI (XAI) further enhances clinical trust and interpretability, allowing practitioners clarity on decision rationale and enhancing patient communication (Mallineni et al., 2024).

Despite these advances, regulatory, ethical, and clinical adoption challenges remain critical. The deployment of AI in dentistry is shaped by concerns over data privacy, robustness of model validation, and regulatory harmonization across global jurisdictions. Uniform protocols for AI system evaluation, adoption, and integration into electronic health records are essential to safeguard clinical accuracy and interoperability. Ethical questions regarding algorithmic bias, decision transparency, and the risk of over-treatment due to high-sensitivity models require ongoing research, clinician training, and robust oversight. Clinical implementation must balance technical innovation with practical barriers, including system integration, workflow redesign, ongoing clinician education, and developing legal frameworks for liability in AI-supported care. Addressing these requirements will be essential for safe, responsible, and optimal integration of AI into routine dental practice (Lal et al., 2025).

## Novel Imaging Technologies

Optical Coherence Tomography (OCT) has gained widespread attention in dentistry due to its ability to produce high-resolution, cross-sectional images of dental tissues without the need for ionizing radiation. OCT works by using coherent light waves to capture micrometer-scale images from within biological tissues, which has profound implications for non-invasive dental diagnostics. Recent advancements have improved OCT scanning speeds, image resolution, and three-dimensional (3D) imaging capabilities through Fourier domain and spectral domain methods. These enhancements allow clinicians to detect early lesions such as incipient caries and to visualize subtle structural changes within enamel and dentin that are not apparent with conventional radiography. Notably, 3D OCT imaging has demonstrated superior sensitivity in detecting enamel and dentin caries in posterior teeth, surpassing traditional two-dimensional radiographic techniques. Moreover, OCT has expanded to applications including assessment of marginal fit for subgingival crown preparations, evaluation of dental restorations, and monitoring of lesion progression or remineralization. This technology provides a safer alternative to X-rays, especially for frequent monitoring and pediatric patients, enabling timely, conservative interventions. The integration of OCT into clinical practice represents a crucial step toward minimally invasive dentistry by facilitating early diagnosis and precise treatment planning (Janjua et al., 2023).

Hyperspectral imaging (HSI) in dentistry is another cutting-edge modality that offers a non-invasive and highly sensitive approach to tissue evaluation. Unlike traditional imaging which captures images in three broad color bands (red, green, blue), HSI acquires detailed spectral information across hundreds of narrow wavelengths extending beyond visible light. This capability enables the identification of unique spectral signatures associated with different dental tissues and pathological states, thus allowing accurate differentiation of healthy tissue from disease. Recent studies have employed HSI combined with machine learning and deep learning algorithms to enhance the classification and diagnosis of oral conditions, including caries, lesions, and color characterization for restorative dentistry. HSI can rapidly capture data, minimizing artifacts related to tooth dehydration and color changes, and holds promise for real-time chairside applications with ongoing technological development. The rich spectral datasets acquired permit detailed mapping of tissue properties, potentially enabling the detection of early pathological changes and the objective evaluation of dental restorations. Future improvements are anticipated through artificial intelligence integration for automated analysis and improved diagnostic accuracy (Tejada-Casado et al., 2022).

Multi-modal scanning integrates multiple imaging technologies to provide comprehensive diagnostic information from a single scanning session. Recent advances focus on the combined use of cone-beam computed tomography (CBCT) with intraoral scanning (IOS), merging 3D volumetric data of hard tissues with high-resolution surface details of dental structures. This multimodal registration enhances the precision of dental modeling, orthodontic treatment planning, implant placement, and surgical interventions by accurately correlating anatomical details across different imaging modalities. Technologies utilizing artificial intelligence and advanced algorithms have considerably improved registration accuracy and automation efficiency, making the process more practical and reliable in clinical workflows. Furthermore, multi-modal imaging systems increasingly incorporate optical coherence tomography, digital intraoral scanning, and hyperspectral imaging into integrated platforms, facilitating a holistic visualization of both hard and soft tissues, including subgingival areas. This amalgamation allows dental professionals to detect early lesions, assess periodontal health, and evaluate restorative margins with greater confidence and less invasiveness (Zheng et al., 2025).

Enhanced visualization of subgingival areas has been challenging due to the anatomical complexity and limited accessibility beneath the gingival margin. However, novel imaging tools such as dental endoscopes combined with advanced optics provide magnified real-time visualization of subgingival calculus and periodontal tissues, markedly improving the detection and removal of deposits linked to periodontal disease. The use of two-photon autofluorescence microscopy further allows imaging through gingival tissues with

reduced light scattering and superior depth penetration, enabling focused visualization of subgingival calculus without interference from surrounding tissues. These technological improvements contribute to more thorough periodontal therapy and better clinical outcomes by allowing precise detection and targeted treatment of subgingival pathology. Enhanced imaging methods also aid in early detection of incipient lesions in subgingival and interproximal areas, promoting preventive care strategies (Chang et al., 2023).

Early lesion detection remains a critical objective in dental imaging, as timely identification and intervention can reverse or halt disease progression, reducing the need for invasive procedures. Emerging optical technologies such as OCT, hyperspectral imaging, and other novel fluorescence-based methods (e.g., quantitative light-induced fluorescence) are improving clinicians' ability to detect non-cavitated carious lesions at their earliest stages with higher accuracy than visual-tactile inspection or traditional radiography. These techniques provide detailed structural and compositional information, enabling a shift from the conventional "drill and fill" paradigm to a risk-based, preventive approach in caries management. Automated image analysis algorithms and artificial intelligence are playing an increasing role in assisting clinicians to accurately interpret complex imaging data, further enhancing early detection and personalized treatment planning (Gomez, 2015).

### **Advances in Periodontics**

Recent advances in periodontics have increasingly underscored the intricate relationship between periodontal health and systemic diseases, revolutionizing both research paradigms and clinical management strategies within dental science. Scientific evidence now robustly supports the notion that periodontal diseases, especially chronic periodontitis, extend far beyond local oral pathology, exerting significant influence on a spectrum of systemic conditions including cardiovascular diseases, diabetes mellitus, adverse pregnancy outcomes, respiratory illnesses, rheumatoid arthritis, and osteoporosis. Mechanistically, this connection is mediated by persistent inflammation, microbial translocation, and immunological cross-talk, as oral microbiota and pro-inflammatory mediators disseminate throughout the body, catalyzing or exacerbating pathological processes. Cutting-edge research synthesizes epidemiological, molecular, and translational data, revealing bidirectional associations and interdependent pathogenetic pathways; e.g., diabetes not only increases susceptibility to periodontitis but periodontal inflammation also impairs glycemic control, forming a vicious cycle that mandates integrated disease management. Other systemic conditions, such as rheumatoid arthritis and pregnancy-related complications, have now been shown to be significantly impacted by periodontal status, motivating calls for interdisciplinary care addressing both oral and general health (Susin et al., 2025).

Emerging evidence from recent systematic reviews and pathogenesis-focused studies categorizes systemic disease-associated periodontal manifestations along distinct lines: those resulting from generalized systemic inflammation (e.g., diabetes, arthritis), those secondary to immune dysfunction (e.g., various immunodeficiencies, genetic syndromes), and conditions where metabolic defects or tissue-level abnormalities directly compromise periodontal integrity (e.g., Down syndrome, neutropenia, hypophosphatasia). This nuanced perspective enables more targeted diagnosis and therapeutic intervention, ushering in an era where oral and systemic health are addressed in concert rather than isolation. Multidisciplinary care plans integrating regular periodontal surveillance, treatment, and medical management are now advocated for at-risk patient populations, substantiating the clinical imperative to bridge dental and medical specializations (Hasan et al., 2025).

Technological breakthroughs are rapidly transforming periodontal diagnostics and therapeutics. Artificial intelligence (AI)-powered diagnostic platforms utilizing deep learning and advanced imaging modalities significantly improve the sensitivity and specificity of periodontal disease detection, risk stratification, and monitoring of treatment responses. Algorithms based on CNNs, U-Net, and hybrid architectures offer precise assessment of bone loss, plaque burden, and other clinical parameters, facilitating early intervention and customized therapy. Meanwhile, tissue engineering advances incorporate bioactive scaffolds, stem cell cultures, spheroid architectures, and 3D printing to restore lost periodontal tissues, moving closer to true

regenerative outcomes. The application of enamel matrix derivatives (EMD) and gene therapy support robust cementum formation and tissue regeneration; novel biomaterials incorporating controlled drug delivery, anti-inflammatory, and antibacterial functions promise synergistic control over complex periodontal disease processes (Wu et al., 2025).

Therapeutic modalities increasingly emphasize multifactorial intervention strategies that integrate systemic disease management with contemporary dental treatments: these include modular biomaterial systems designed for anti-biofilm efficacy, controlled release of anti-inflammatory agents, and precision tissue regeneration, complemented by systemic disease surveillance and metabolic control. The future of periodontics is thus defined by the convergence of new materials, biotechnology, digital diagnostics, and interdisciplinary care protocols. The ongoing translation of research insights into clinical practice, underpinned by robust evidence from large-scale meta-analyses and interventional trials, is anticipated to further elucidate the bidirectional pathways linking periodontal and systemic health outcomes. As such, periodontics stands at the forefront of a broader movement within dental science toward integrated, efficient, and personalized healthcare, with profound implications for disease prevention, management, and overall patient well-being (Natarajan et al., 2025).

### **Regenerative Dentistry and Tissue Engineering**

Stem cell therapies in dental pulp regeneration have garnered significant attention, largely due to the discovery of dental pulp stem cells (DPSCs) capable of self-renewal and multilineage differentiation. These stem cells, found within dental pulp tissue, demonstrate the ability to differentiate into odontoblasts, adipocytes, chondrocytes, osteoblasts, nerve cells, and endothelial cells, facilitating the regeneration of dentin-pulp complexes. Recent studies have shown promising outcomes where DPSCs can form functional dental pulp tissue with restored vasculature and innervation, crucial for maintaining tooth vitality. Mesenchymal stem cells derived from various sources such as bone marrow and umbilical cord also contribute to regenerative endodontic procedures with encouraging evidence from animal studies and emerging clinical trials. Despite methodological variations, many studies report enhanced pulpal regeneration, resolution of periapical lesions, and restoration of tooth vitality following stem cell therapies, indicating their future clinical potential in endodontics (Shah et al., 2024).

Biomaterials play an indispensable role in dental tissue engineering by acting as scaffolds that provide a three-dimensional microenvironment conducive to cell attachment, proliferation, and differentiation. These scaffolds, made from both natural and synthetic materials, support the architectural and functional regeneration of dental tissues. Natural biomaterials such as collagen and fibrin have shown superior biocompatibility and efficacy in promoting dental pulp-like tissue formation compared to synthetic alternatives. Advances in nanotechnology and piezoelectric biomaterials further enhance scaffold functions by enabling bioactive, stimuli-responsive environments that mimic the native extracellular matrix, fostering enhanced cell-scaffold interactions and tissue healing. The use of composite scaffolds combining polymers with bioactive ceramics has broadened the scope of tissue engineering, aiming for optimal mechanical properties and biological performance needed for successful pulp-dentin complex regeneration (Sharma et al., 2014).

Looking forward, prospects for whole-tooth regeneration represent the frontier of regenerative dentistry. Inspired by embryonic tooth development, pioneering work in bioengineering has developed the "organ germ method," which involves high-density epithelial and mesenchymal cell manipulation to recreate the precise cellular interactions necessary for tooth morphogenesis. Successful preclinical models have demonstrated the generation of structurally and functionally correct bioengineered teeth capable of eruption, integration with alveolar bone, and restoration of natural tooth functions such as mastication and periodontal ligament responsiveness. While whole-tooth regeneration remains investigational, ongoing research focuses on elucidating the cellular and molecular mechanisms steering odontogenesis, optimizing stem cell sources, signaling pathways, and scaffold designs to achieve reproducible, clinically applicable outcomes soon (Sui et al., 2019).

## **Innovations in Dental Implantology**

Recent advances in dental implantology have significantly transformed the landscape of oral rehabilitation, driven by innovations in implant materials, digital technologies, and patient-centered treatment approaches. The progression from traditional titanium implants to novel materials marks a crucial step in enhancing implant performance and clinical outcomes. New implant materials now include biocompatible alternatives such as zirconia, titanium-zirconium alloys, and scaffold-based designs, which offer improved osseointegration, mechanical strength, and aesthetic properties. Surface modifications have become a frontier in implantology, with nanostructured and bioactive coatings designed to mimic natural bone mineral structures, thereby promoting faster and stronger integration. These advanced surfaces facilitate specific cellular responses that enhance healing and reduce implant failure, while innovations such as antimicrobial coatings help prevent bacterial colonization, minimizing post-operative infections. Research is ongoing into composite materials that blend the strength of titanium with the tooth-colored aesthetics of zirconia, as well as into smart implant surfaces embedded with sensor technologies capable of real-time monitoring of implant status, although clinical standardization and widespread adoption remain challenges (James et al., 2025).

Digital workflows have revolutionized implant planning and placement, enhancing precision, efficiency, and patient outcomes. The integration of three-dimensional cone beam computed tomography (3D CBCT) imaging enables detailed visualization of jaw anatomy, nerve locations, and bone quality, allowing for highly personalized treatment planning. Intraoral digital scanners replace traditional impression methods, offering superior patient comfort and accuracy. Virtual implant placement is facilitated through specialized software that simulates the optimal position and angulation of implants, allowing for the creation of custom surgical guides produced by 3D printing. These guides ensure precise, minimally invasive implant placement and reduce surgical time. Furthermore, computer-aided design and computer-aided manufacturing (CAD/CAM) technologies optimize the fabrication of implant prosthetics, enhancing fit, function, and aesthetics. Dynamic navigation systems provide real-time surgical guidance, offering accuracy comparable to static guides and increased flexibility in complex cases. Developments in artificial intelligence and machine learning contribute to improved treatment planning accuracy and predictive analytics, although issues such as cost, required expertise, and need for further clinical validation persist. The digital approach streamlines the entire implant process from diagnosis through surgery to final restoration, resulting in better communication between clinicians and patients, higher success rates, and enhanced patient satisfaction (Kafedzhieva et al., 2025).

Patient-centered considerations are increasingly prioritized in dental implantology, reflecting a shift from purely clinician-focused metrics to those that incorporate the patient's perspective on satisfaction, functionality, and quality of life. Studies report high levels of patient satisfaction post-implant treatment, particularly regarding esthetics, comfort, and functional outcomes such as chewing efficiency. The use of validated patient-reported outcome measures (PROMs) like the Oral Health Impact Profile (OHIP-14) illustrates significant improvements in oral health-related quality of life after implant procedures. These findings validate the impact of dental implants beyond clinical success, emphasizing their role in enhancing patients' self-esteem, psychological well-being, and social interactions. Patient-centered care also involves respecting autonomy, shared decision-making, and tailoring treatment plans to individual needs, considering factors such as bone quality, medical history, esthetic demands, and personal expectations. This holistic approach fosters greater patient trust and adherence, ultimately improving long-term success and satisfaction (De Bruyn et al., 2015).

## **Future Directions and Emerging Trends**

Recent advances in dental science have been significantly shaped by emerging technologies and interdisciplinary approaches that are poised to transform the field in unprecedented ways. One of the most promising areas is the application of nanotechnology in dental materials and drug delivery systems. Nanotechnology has revolutionized dentistry by enhancing the properties of dental materials such as

composites, adhesives, and implants. For instance, nanoparticles improve antibacterial characteristics, durability, and biocompatibility of materials, thereby reducing bacterial colonization and plaque formation. Nanostructured surfaces on dental implants enhance osseointegration and stability, improving implant success rates. Moreover, nano-sized particles in remineralization agents have been shown to substantially aid enamel repair and prevent decay. These innovations contribute to longer-lasting restorations, better treatment outcomes, and enhanced patient comfort. However, ongoing research is essential to address challenges related to toxicity, durability, and regulatory approvals to fully harness the advantages of nanotechnology in clinical practice (Sreenivasalu et al., 2022).

Precision dentistry, guided by genomics and personalized medicine, represents another frontier that is reshaping dental care. Recent advances in genomics, metabolomics, and related omics sciences enable the development of highly predictive models tailored to the individual's unique biological systems. This approach allows for rapid diagnosis, targeted therapies, and personalized treatment planning that considers genetic risk factors, microbial colonization patterns, and inflammatory responses. Precision dentistry holds promise in various domains, including cancer prevention, management of orofacial malformations, pain control through targeted pharmacogenomics, and even orthodontics and regenerative dentistry. The integration of global genomic databases and collaborative networks may further accelerate the predictive and preventive potential of this approach, potentially reducing healthcare costs and improving patient outcomes significantly. Despite these advantages, integrating precision medicine into routine dental practice faces challenges including data integration, ethical concerns, and the need for robust clinical validation (Malcangi et al., 2023).

Sustainability and eco-friendly innovations in dentistry are increasingly recognized as critical imperatives due to their implications for environmental health and resource conservation. Dentistry is traditionally energy and resource-intensive, generating considerable waste, including hazardous materials like mercury from dental amalgams. The field has responded by adopting the principles of green dentistry, which emphasize reducing, reusing, recycling, and rethinking dental practices to minimize ecological footprints. Innovations include using recyclable and biocompatible materials, reducing plastic waste, conserving water and energy, and promoting preventive oral care strategies that lower overall waste production. Legislative measures and institutional protocols also support sustainable dental waste management. Education and awareness about sustainability among dental students and practitioners are essential to fostering the adoption of these eco-friendly practices, which align with the United Nations Sustainable Development Goals. Continued interdisciplinary efforts are needed to develop novel materials and techniques that further advance environmental stewardship within dental care (Guerra et al., 2025).

Finally, the role of global collaboration and interdisciplinary research has become increasingly vital in advancing dental science. Collaborative research efforts across countries and disciplines enhance the quality, impact, and innovation potential of dental studies. Evidence shows that internationally collaborated dental research often results in publications with higher citation rates and greater scientific influence. Collaborations allow pooling diverse expertise, resources, and patient data, enabling the development of comprehensive approaches to complex dental problems. Interdisciplinary practices involving healthcare professionals beyond dentistry, such as medical, pharmaceutical, and bioengineering experts, facilitate holistic patient care and foster breakthrough technologies. Global networks and scientific consortiums also expedite knowledge exchange and standardization of care protocols, accelerating the translation of research findings into clinical practice. As the field of dental science grows more complex and technologically driven, fostering such collaborations is essential for sustainable progress and innovation (Alonaizan et al., 2023).

## Conclusions

Contemporary dental science is undergoing a paradigm shift toward precision, personalization, and sustainability, driven by unprecedented technological and material innovations. The integration of artificial intelligence, regenerative approaches, digital workflows, and advanced biomaterials has transformed

traditional diagnostic and therapeutic paradigms into minimally invasive, predictive, and patient-focused models of care.

These innovations have collectively enhanced diagnostic accuracy, treatment efficiency, and clinical outcomes while promoting interdisciplinary collaboration and evidence-based practice. However, challenges remain in clinical validation, ethical regulation, and equitable access to these technologies. Future directions emphasize the harmonization of technological innovation with bioethics, global collaboration, and environmental sustainability to ensure the responsible and inclusive advancement of dental healthcare. The convergence of biotechnology, data science, and material innovation heralds a new era of dentistry characterized by predictive prevention, personalized therapies, and improved quality of life.

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