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Emerging Trends in Restorative Dental Materials: Review Article

Nada Ahmad Alamoudi[1*], Asim Abdullah Aldhali[2], Abdulaziz Mohammed Alolyet[2], Esraa HamdanA ALjohani[3], Alaa Ghaleb Huraib[4], Faisal Fahad Alotaibi[5], Lulah Ali Alshabi[6], Yara Mohammed Ali Alshehri[7], Zainab Yaser Kheyami[8], Abduljabbar Ali Alzahrani[9]

[1]*Restorative Consultant, King Khalid University, Abha, Saudi Arabia.*
[2]*Dentist, Vision Colleges , Riyadh , Saudi Arabia.*
[3]*Dentist, Salem Basaffar Center , Jeddah , Saudi Arabia.*
[4]*Dentist , Prince Sultan Military Medical City , Riyadh , Saudi Arabia.*
[5]*Dentist , king Saud university , Riyadh , Saudi Arabia.*
[6]*Dentist, King Khalid University , khamis Mushait , Saudi Arabia.*
[7]*Dentist , King Khalid University , Abha , Saudi Arabia.*
[8]*Dentist, Private clinic, Bahrain,Bahrain.*
[9]*Dentist,Albaha university, Albaha, Saudi Arabia.*

ABSTRACT

Restorative dental materials have undergone a marked evolution over the past decade, driven by the need to improve restoration longevity, reduce secondary caries, and enhance biological integration within the complex oral environment. Contemporary research increasingly moves beyond passive structural replacement toward multifunctional materials capable of interacting dynamically with dental tissues, oral biofilms, and environmental stimuli. This narrative review synthesizes peer-reviewed literature published to examine emerging trends in restorative dental materials, with a focus on bioactive and ion-releasing systems, nanomaterial-enhanced composites, additive manufacturing and three-dimensional printing technologies, smart and stimuli-responsive materials, sustainability-oriented innovations, and advances in adhesive systems. Bioactive restorative materials, including glass ionomer–based systems and calcium-releasing composites, demonstrate the capacity to promote remineralization, enhance interfacial stability, and reduce secondary caries, with clinical performance comparable to conventional resin composites in appropriate indications. Nanotechnology has enabled significant improvements in mechanical strength, esthetics, and antimicrobial activity through nano-reinforced and biomimetic designs. Additive manufacturing supports digitally driven, patient-specific restorations with improved workflow efficiency and reduced material waste, although long-term durability data for definitive restorations remain limited. Smart materials introduce adaptive responses to environmental triggers such as pH fluctuations, offering targeted antimicrobial and remineralizing effects, while sustainability-focused approaches emphasize mercury-free formulations, biodegradable components, and environmentally responsible manufacturing. Advances in universal and bioactive adhesive systems further contribute to interfacial durability and simplified clinical protocols. Collectively, these developments reflect a paradigm shift toward biologically interactive, adaptive, and increasingly sustainable restorative dentistry. Despite promising laboratory and short-term clinical outcomes, challenges remain related to long-term performance, standardization of bioactivity and smart behavior, and clinical translation. This review provides a structured overview of current innovations, their clinical implications, and key research priorities, offering guidance for evidence-based material selection and future development in restorative dental practice.

Keywords: *Restorative dentistry, Bioactive materials, Nanomaterials, 3D printing, Smart materials, Dental adhesives*

Corresponding author: Nada Ahmad Alamoudi
e-mail ✉ nadaahmad@gmail.com
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INTRODUCTION

Restorative dentistry constitutes a central component of contemporary oral healthcare, aiming not only to restore the form and function of teeth compromised by caries, trauma, or wear, but also to preserve the long-term biological integrity of the dentition and surrounding tissues. Conventional restorative materials—including dental amalgam, resin-based composites, and glass ionomer cements—have enabled decades of clinical success; however, their limitations remain clinically significant. Issues such as material degradation, marginal leakage, secondary caries, and suboptimal biocompatibility continue to contribute to restoration failure and replacement, representing a substantial burden for patients and healthcare systems alike (Fernandes *et al.*, 2023; Liang *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023; Sequeira *et al.*, 2023; Chopra *et al.*, 2024; Li *et al.*, 2024).

Over the past decade, restorative dentistry has undergone a conceptual shift from passive replacement of lost tooth structure toward biologically informed and functionally active material systems. This transition reflects growing recognition that restorative materials exist within a complex oral environment characterized by dynamic mechanical loading, fluctuating pH, microbial challenge, and continuous interaction with dental hard tissues and saliva. Consequently, contemporary material development increasingly emphasizes bioactivity, multifunctionality, and environmental responsiveness, with the goal of enhancing tissue integration, supporting remineralization, and mitigating the etiological factors underlying restoration failure—particularly recurrent caries and interfacial degradation (Atia *et al.*, 2023; Fernandes *et al.*, 2023; Liang *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023; Xie *et al.*, 2023; Chopra *et al.*, 2024).

Historically, the introduction of resin composite materials in the mid-twentieth century marked a milestone in aesthetic and adhesive dentistry. Since then, incremental advances have improved mechanical performance and handling characteristics; however, recent research has expanded beyond incremental optimization toward fundamentally new material paradigms. Bioactive restorative materials capable of releasing therapeutic ions—such as fluoride, calcium, and phosphate—have been developed to promote dentin remineralization and modulate the cariogenic environment. These approaches align with contemporary preventive dentistry principles and have been increasingly recognized in professional guidelines and consensus statements (Christie *et al.*, 2023; Flores-Espinoza *et al.*, 2023; Liang *et al.*, 2023; Moharil *et al.*, 2023; Woźniak-Budych *et al.*, 2023).

Parallel advances in nanotechnology have further transformed restorative material design. The incorporation of nanoscale fillers and functional nanoparticles has been shown to enhance mechanical strength, wear resistance, esthetics, and antimicrobial activity, while maintaining favorable handling properties. Such nanostructured systems also enable more precise control over material–tissue and material–biofilm interactions, offering new strategies to address bacterial colonization and biofilm-associated degradation at restoration margins (Aydın *et al.*, 2023; Gallicchio *et al.*, 2023; Unnadkat *et al.*, 2023; Atta *et al.*, 2024; Rues *et al.*, 2024; Uyumaz *et al.*, 2024). Digital technologies have likewise reshaped restorative workflows. Additive manufacturing techniques, particularly three-dimensional printing, now permit the fabrication of customized restorations with high geometric accuracy, reduced material waste, and improved reproducibility. These technologies support minimally invasive treatment planning and align with broader trends toward digital dentistry and personalized care (Alsaeed, 2022; Fronza *et al.*, 2022; Kodaira *et al.*, 2022). In parallel, the emergence of so-called "smart" restorative materials—designed to respond to environmental cues such as pH changes or mechanical stress—represents an effort to develop restorations that actively adapt to cariogenic challenges rather than merely withstand them (Aydın *et al.*, 2023; Unnadkat *et al.*, 2023; Ortega *et al.*, 2024).

Sustainability has also become an increasingly relevant consideration in dental material science. Environmental concerns related to material toxicity, waste generation, and lifecycle impact have prompted exploration of biodegradable components, mercury-free alternatives, and manufacturing processes with reduced ecological footprints. These developments reflect a growing intersection between clinical performance, public health priorities, and environmental responsibility within dentistry (Alsaeed, 2022).

Finally, progress in adhesive dentistry has resulted in the development of universal adhesive systems that aim to simplify clinical protocols while maintaining reliable bonding across diverse substrates. Such systems address technique sensitivity and may contribute to improved restoration longevity when appropriately applied (Colak & Katirci, 2023; Lekhwani *et al.*, 2023; Rues *et al.*, 2024). **Figure 1** summarizes the major emerging classes of restorative dental materials and their primary biological, functional, and clinical contributions.

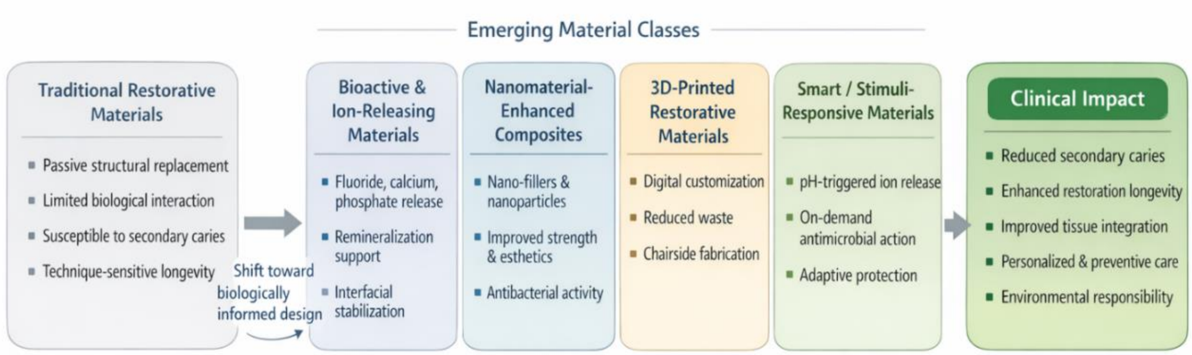

Figure 1. Emerging Trends in Restorative Dental Materials: From Passive Fillers to Bioactive and Adaptive Systems

Against this background, the present review synthesizes recent literature to provide a structured overview of evolving trends in restorative dental materials, with particular emphasis on bioactive, nanostructured, digitally manufactured, smart, and sustainable systems. By critically examining their clinical applications, advantages, and current limitations, this review seeks to inform evidence-based material selection and highlight future directions for research and clinical practice in restorative dentistry.

Bioactive and ion-releasing materials

Bioactive and ion-releasing restorative materials represent a significant conceptual departure from traditional inert filling materials, reflecting a broader shift in restorative dentistry toward biologically interactive treatment strategies. Rather than functioning solely as space-filling substitutes for lost tooth structure, these materials are designed to engage dynamically with the surrounding dental tissues and oral environment, with the aim of supporting remineralization, enhancing interfacial stability, and reducing susceptibility to recurrent disease (Li *et al.*, 2024). This paradigm is particularly relevant given that secondary caries and interfacial breakdown remain leading causes of restoration failure despite advances in adhesive techniques (Fernandes *et al.*, 2023; Liang *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023).

A defining characteristic of bioactive restorative systems is their capacity to release therapeutically relevant ions, most commonly fluoride, calcium, and phosphate. These ions contribute to the remineralization of demineralized enamel and dentin, buffer local acidity, and may alter the ecological balance of dental biofilms in a manner that is less conducive to cariogenic activity (Fernandes *et al.*, 2023; Liang *et al.*, 2023). Increasing experimental and clinical evidence suggests that such ion-mediated effects are especially beneficial in patients with elevated caries risk, where conventional restorative approaches may be insufficient to counteract ongoing pathological challenges (Paradowska-Stolarz *et al.*, 2023; Chopra *et al.*, 2024).

Glass ionomer cements (GICs) and resin-modified glass ionomer cements remain foundational examples of clinically established bioactive materials. Their ability to chemically bond to tooth structure, coupled with sustained fluoride release, has supported their widespread use in minimally invasive and preventive restorative strategies (Moharil *et al.*, 2023; Xie *et al.*, 2023). More recently, research has focused on enhancing the bioactivity of resin-based systems through the incorporation of bioactive glass fillers produced via sol–gel or melt-derived processes. These fillers have demonstrated the capacity to release calcium and phosphate ions and to promote apatite formation at the tooth–material interface, suggesting potential benefits for dentin repair and interfacial stability (Xie *et al.*, 2023).

Clinical evidence indicates that restorations incorporating bioactive components can achieve retention and survival rates comparable to conventional resin composites when used in appropriate indications. Moreover, comparative analyses and controlled clinical studies suggest a reduced incidence of secondary caries associated with certain bioactive materials, particularly in populations with high caries activity or compromised oral conditions (Paradowska-Stolarz *et al.*, 2023; Sequeira *et al.*, 2023). While such findings are encouraging, authors consistently emphasize the importance of patient selection, lesion location, and material-specific properties when interpreting clinical outcomes.

Beyond restorative fillings, bioactive and ion-releasing materials have gained particular prominence in vital pulp therapy. Calcium-releasing composites, hydraulic calcium silicate cements, and bioactive liners have been increasingly investigated for applications such as direct and indirect pulp capping. Evidence from systematic reviews indicates favorable outcomes in terms of dentin bridge formation and pulp vitality preservation, with reported success rates that compare favorably to traditional materials when strict clinical protocols are followed (Carneiro *et al.*, 2023; Li *et al.*, 2023; Urkande *et al.*, 2023; Ziaei *et al.*, 2024). The biological activity of these materials is often attributed to their alkaline pH, ion release, and capacity to stimulate odontoblastic differentiation and reparative dentinogenesis. Materials incorporating hydroxyapatite, calcium silicates, and related bioceramics further support tissue integration through chemical and structural similarity to natural hard tissues (Frąckiewicz *et al.*, 2023).

Despite their advantages, bioactive restorative materials are not without limitations. Concerns persist regarding mechanical strength, wear resistance, and long-term durability, particularly in high-load posterior applications. As a result, hybrid material systems that combine bioactive fillers with reinforced resin matrices have been developed to balance biological functionality with mechanical performance (Fernandes *et al.*, 2023; Flores-Espinoza *et al.*, 2023). Ongoing research also highlights the need for clearer and more standardized definitions of "bioactivity" in dentistry, as variability in testing methods and outcome measures complicates comparisons across studies and may obscure clinically meaningful distinctions between materials (Liang *et al.*, 2023). **Table 1** compares major classes of emerging restorative dental materials, highlighting their functional mechanisms, clinical advantages, and current limitations.

Table 1. Emerging Restorative Dental Materials: Mechanisms, Benefits, and Limitations

Material Class	Key Components	Primary Mechanism	Clinical Advantages	Current Limitations
Bioactive glass-based restoratives	Fluoride, calcium, phosphate ions	Ion release & apatite formation	Remineralization, caries inhibition	Lower wear resistance in stress-bearing areas
Calcium-releasing composites	Calcium silicates, bioceramics	Alkaline pH & dentin stimulation	Pulp protection, dentin bridge formation	Limited long-term mechanical data
Nanofilled / nano-hybrid composites	Silica, zirconia, silver nanoparticles	Nano-reinforcement & antibacterial action	Improved strength, esthetics, biofilm control	Concerns regarding nanoparticle biocompatibility
3D-printed resins	Photopolymers, ceramic-filled resins	Layer-by-layer digital fabrication	Customization, reduced waste	Limited durability for permanent posterior use
Smart restorative materials	pH-responsive polymers	Stimuli-triggered ion/agent release	Targeted caries prevention	Long-term stability not fully established

Sustainable composites	Bio-based fillers, mercury-free systems	Reduced environmental impact	Eco-friendly dentistry	Performance parity still under evaluation

Future developments in this field are increasingly focused on multifunctional designs that integrate bioactivity with additional protective mechanisms, such as antimicrobial or antibiofilm properties. By addressing both biological repair and microbial challenge, next-generation restorative materials aim to provide more comprehensive protection against restoration failure while aligning with minimally invasive and preventive care principles (Agrawal *et al.*, 2023; Li *et al.*, 2024).

Nanomaterials in restorative dentistry

Nanotechnology has had a substantial impact on restorative dentistry by enabling the design of materials with enhanced mechanical performance, improved esthetic outcomes, and added biological functionality. The incorporation of nanoscale fillers and functional nanoparticles into restorative systems represents a strategic evolution from conventional microfilled and hybrid composites, allowing finer control over material structure and behavior at the tooth–restoration interface (Gallicchio *et al.*, 2023; NWNA *et al.*, 2024).

Commonly employed nanoparticles—including silica, zirconia, silver, and zinc oxide—are integrated into resin-based composites to improve flexural strength, wear resistance, and polish retention while reducing polymerization shrinkage and surface roughness (Christie *et al.*, 2023; Uyumaz *et al.*, 2024). Owing to their high surface area and uniform dispersion, nanofillers facilitate stronger filler–matrix interactions, which translate into improved mechanical stability under functional loading. In addition, nanoscale fillers allow higher filler loading without compromising handling characteristics, contributing to improved longevity of restorations.

Beyond mechanical enhancement, nanomaterials have enabled the development of biomimetic restorative designs that more closely replicate the hierarchical structure of natural enamel and dentin. By mimicking enamel-like prism organization and nanoscale mineralization patterns, nano-engineered composites demonstrate improved optical properties and interfacial adaptation, supporting both esthetic integration and functional performance (Chacón Gahona *et al.*, 2023; Woźniak-Budych *et al.*, 2023). Such biomimetic strategies align with minimally invasive dentistry principles by promoting more harmonious interactions between restorative materials and dental hard tissues.

Nanotechnology has also facilitated the incorporation of antibacterial functionality into restorative materials. Nanoparticles such as silver and zinc oxide exhibit broad-spectrum antimicrobial activity, primarily through disruption of bacterial cell membranes and interference with metabolic pathways. When embedded within restorative matrices, these particles have been shown to inhibit biofilm formation and reduce bacterial colonization at restoration margins—an effect that may contribute to lower rates of secondary caries when appropriately balanced with biocompatibility considerations (Flores-Espinoza *et al.*, 2023; Uyumaz *et al.*, 2024).

Clinically, nano-hybrid and nanofilled composites are now widely used for both anterior and posterior restorations. Long-term observational studies report favorable outcomes with respect to polishability, surface gloss retention, and color stability compared with earlier composite generations (Atia *et al.*, 2023; Chopra *et al.*, 2024). Nevertheless, concerns regarding potential cytotoxicity, nanoparticle release, and long-term biological effects have prompted careful material refinement. Contemporary formulations increasingly employ surface-treated or immobilized nanoparticles to minimize biological risk while preserving functional benefits (Frąckiewicz *et al.*, 2023; Moharil *et al.*, 2023).

Looking forward, nanotechnology is expected to play a key role in emerging fabrication techniques, particularly through the development of nano-enabled materials for additive manufacturing. Such approaches offer opportunities to combine nanoscale reinforcement with digital precision, potentially expanding the clinical applicability of printed restorations (Fronza *et al.*, 2022; Kodaira *et al.*, 2022).

Additive manufacturing and three-dimensional printed restorations

Additive manufacturing, commonly referred to as three-dimensional (3D) printing, has emerged as a transformative technology in restorative dentistry by enabling the rapid fabrication of patient-specific restorations with high geometric accuracy. Unlike subtractive milling techniques, 3D printing builds restorations layer by layer, allowing efficient material use, reduced waste, and greater design flexibility for complex clinical scenarios (Fronza *et al.*, 2022; Loya *et al.*, 2023; Atta, *et al.*, 2024).

Current dental 3D printing applications primarily involve photopolymer-based resins and, to a lesser extent, ceramic-filled or hybrid materials. These materials are widely used for temporary crowns, inlays, onlays, surgical guides, and provisional prostheses. Advances in printing resolution and post-processing protocols have resulted in restorations with dimensional accuracy comparable to conventionally milled counterparts, with reported marginal discrepancies generally within clinically acceptable ranges (Kodaira *et al.*, 2022; Atta *et al.*, 2024).

Recent overviews highlight that 3D-printed restorations demonstrate favorable fit and reproducibility, particularly for interim applications, while offering significant reductions in fabrication time and chairside adjustments (Fronza *et al.*, 2022). The ability to digitally design and fabricate restorations also supports streamlined workflows and enhances consistency across treatment stages, making additive manufacturing an attractive option within digital dentistry ecosystems.

Despite these advantages, limitations remain regarding the mechanical strength, wear resistance, and long-term stability of currently available printed materials, particularly for definitive posterior restorations subjected to high occlusal loads. As a result, most permanent applications continue to rely on milled ceramics or conventional composites, while research efforts focus on improving printed material formulations (Loya *et al.*, 2023).

An emerging area of interest involves the integration of bioactive components into printable resins, aiming to combine digital fabrication with ion release and remineralization potential. Preliminary studies suggest that incorporating bioactive fillers into printable matrices may enhance biological performance without compromising printability, although further validation is required before widespread clinical adoption (Xie *et al.*, 2023; Li *et al.*, 2024). Future developments may also include chairside or in-office printing systems capable of delivering immediate restorations, further reducing treatment time and improving patient experience (Loya *et al.*, 2023).

Smart and stimuli-responsive materials

Smart or stimuli-responsive materials represent an advanced class of restorative systems designed to adapt dynamically to changes in the oral environment. Unlike conventional materials with static properties, smart materials respond to specific triggers—such as pH fluctuations, temperature changes, or mechanical stress—to provide targeted protective or therapeutic effects (Atia *et al.*, 2023; Aydın *et al.*, 2023; Unnadkat *et al.*, 2023).

Among the most extensively investigated smart systems are pH-responsive restorative materials, which exploit the acidic conditions associated with cariogenic biofilms. These materials are engineered to release ions or antimicrobial agents selectively under low pH conditions, thereby counteracting demineralization and bacterial activity during periods of heightened caries risk (Unnadkat *et al.*, 2023). Such responsive behavior offers a promising strategy for addressing recurrent caries without continuous drug release, which may reduce unnecessary exposure and material fatigue.

Recent studies have described smart composites capable of modulating ion release or antimicrobial activity in response to environmental acidity, demonstrating significant reductions in bacterial viability in laboratory settings (Unnadkat *et al.*, 2023). Antimicrobial smart materials often incorporate polymerizable quaternary ammonium compounds or similar agents that provide contact-based antibacterial effects while maintaining long-term stability within the restorative matrix (Aydın *et al.*, 2023; Flores-Espinoza *et al.*, 2023).

The clinical potential of smart restorative materials is particularly relevant for patients with high caries susceptibility, compromised oral hygiene, or complex restorative histories. By providing on-demand protective responses, these materials may complement conventional preventive strategies and enhance restoration longevity in challenging clinical contexts (Atia *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023).

Nevertheless, challenges remain related to long-term durability, consistency of responsiveness over time, and potential material fatigue following repeated activation cycles. Ongoing advances in polymer chemistry and network design aim to improve stability and functional longevity while preserving responsiveness (Ortega *et al.*, 2024). Future directions increasingly focus on multifunctional smart materials that integrate stimuli responsiveness with bioactivity, antimicrobial effects, and even self-healing capabilities, representing a holistic approach to next-generation restorative material design (Agrawal *et al.*, 2023; Frąckiewicz *et al.*, 2023).

Sustainable and environmentally conscious dental materials

Sustainability has emerged as an increasingly important consideration in dental material science, driven by growing awareness of the environmental impact associated with healthcare delivery and material manufacturing. In restorative dentistry, this has prompted efforts to reduce ecological burden through the development of materials and clinical workflows that minimize waste generation, limit the use of hazardous substances, and incorporate environmentally responsible design principles without compromising clinical performance (Alsaeed, 2022; Tavas *et al.*, 2023).

One area of investigation has focused on life cycle assessment approaches to evaluate the environmental footprint of dental materials and associated consumables. Comparative analyses have demonstrated that reusable clinical kits and instruments can offer meaningful reductions in carbon emissions and material waste compared with single-use alternatives, particularly when sterilization processes are optimized and integrated into routine clinical workflows (Alsaeed, 2022). Such findings underscore the relevance of sustainability not only at the material level, but also across the broader restorative care pathway.

Material innovation has similarly explored the use of renewable or naturally derived components in restorative formulations. Experimental and early commercial composites incorporating bio-based fillers, such as cellulose-derived or plant-based particles, have shown promising mechanical performance while offering potential reductions in environmental impact. When appropriately engineered, these materials can maintain acceptable strength, wear resistance, and handling characteristics, suggesting feasibility for selected clinical applications (Ziaei *et al.*, 2024). In parallel, manufacturers have increasingly pursued mercury-free restorative alternatives and recyclable or reduced packaging systems, reflecting both regulatory pressures and evolving professional expectations (Agrawal *et al.*, 2023; Liang *et al.*, 2023).

Despite these advances, challenges remain in balancing environmental sustainability with the stringent mechanical, biological, and esthetic requirements of restorative materials. Durability, longevity, and clinical reliability remain paramount, and any compromise in performance risks increasing restoration replacement rates, which would ultimately negate environmental gains. Ongoing research therefore emphasizes the development of sustainable biomaterials that meet or exceed existing clinical benchmarks while reducing ecological impact across their life cycle (Moharil *et al.*, 2023; Ziaei *et al.*, 2024).

Future directions in this domain increasingly draw on principles of green chemistry, including the use of less toxic monomers, energy-efficient manufacturing processes, and materials designed for safer disposal or recycling. As sustainability considerations become more integrated into regulatory frameworks and professional guidelines, environmentally conscious material selection is likely to become an integral component of evidence-based restorative practice rather than a peripheral concern (Tavas *et al.*, 2023).

Advances in adhesive systems

Adhesive dentistry has undergone significant refinement over recent decades, with contemporary systems increasingly designed to simplify clinical protocols while maintaining reliable and durable bonding to enamel and dentin. The introduction of so-called universal or multi-mode adhesive systems represents a notable advance, as these materials can be applied using etch-and-rinse, self-etch, or selective-etch strategies, allowing clinicians to tailor their approach to specific clinical scenarios without changing products (Colak & Katirci, 2023; Lekhwani *et al.*, 2023; Rues *et al.*, 2024).

Recent analyses of the adhesive literature highlight sustained research interest in universal adhesives, particularly with respect to their chemical formulation and interaction with dentin. Functional monomers, such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), play a critical role in enhancing chemical bonding to hydroxyapatite, contributing to improved bond durability and resistance to hydrolytic degradation (Rues *et al.*, 2024). These advances address longstanding concerns regarding the stability of resin–dentin interfaces over time.

Beyond adhesion alone, emerging adhesive systems increasingly incorporate bioactive components aimed at enhancing interfacial integrity. Bioactive adhesives capable of releasing calcium, phosphate, or fluoride ions have been investigated for their potential to promote remineralization at the hybrid layer and reduce microleakage, particularly in challenging substrates such as caries-affected dentin (Carneiro *et al.*, 2024; Fernandes *et al.*, 2023). Such multifunctional designs reflect a broader trend toward adhesives that contribute actively to restoration longevity rather than serving solely as mechanical coupling agents.

Clinical and laboratory evaluations suggest that filled adhesive systems may offer advantages over unfilled formulations in certain applications, including non-carious cervical lesions, where stress distribution and marginal adaptation are critical (Colak & Katirci, 2023). High-resolution morphological studies further demonstrate that self-etch and universal adhesives can achieve more uniform infiltration of dentin substrates under appropriate moisture conditions, resulting in more consistent hybrid layer formation (Lekhwani *et al.*, 2023).

Nevertheless, adhesive performance remains sensitive to technique-related factors, particularly moisture control and substrate variability. Excessive dentin wetness or desiccation can adversely affect bond strength, highlighting the continued importance of operator skill and protocol adherence. Innovations such as more hydrophobic resin matrices and improved solvent systems have been developed to mitigate technique sensitivity and enhance long-term bond stability (Flores-Espinoza *et al.*, 2023; Rues *et al.*, 2024).

Future developments in adhesive dentistry are expected to increasingly leverage nanotechnology to improve filler dispersion, mechanical reinforcement, and interfacial interaction at the nanoscale. Nano-enhanced adhesives hold promise for further improving durability and resistance to degradation, supporting the ongoing evolution of minimally invasive and long-lasting restorative strategies (Gallicchio *et al.*, 2023; Uyumaz *et al.*, 2024).

RESULTS AND DISCUSSION

The recent evolution of restorative dental materials, as documented in peer-reviewed literature published, reflects a fundamental shift in restorative dentistry from passive structural replacement toward biologically active, functionally adaptive, and patient-centered material systems. Collectively, advances in bioactive materials, nanotechnology, additive manufacturing, smart functionalities, sustainability-oriented design, and adhesive chemistry aim to address persistent clinical challenges such as secondary caries, interfacial degradation, material fatigue, and variability in patient-specific restorative needs.

Bioactive and ion-releasing materials: from restoration to therapeutic interface

Bioactive and ion-releasing materials represent one of the most transformative developments in contemporary restorative dentistry. Rather than acting solely as inert fillers, these materials extend the restorative concept toward therapeutic intervention by actively interacting with surrounding dental tissues (Atia *et al.*, 2023; Christie *et al.*, 2023; Fernandes *et al.*, 2023; Sequeira *et al.*, 2023; Li *et al.*, 2024). Systematic reviews and meta-analyses indicate that materials incorporating calcium phosphate fillers, zinc-based components, or fluoride-releasing phases can enhance remineralization processes and support dentin regeneration, particularly in caries-prone environments (Atia *et al.*, 2023; Fernandes *et al.*, 2023; Xie *et al.*, 2023; Li *et al.*, 2024). Fernandes *et al.*'s network meta-analysis of randomized controlled trials demonstrated a reduced risk of secondary caries associated with bioactive restoratives, attributing this benefit to sustained ion release and improved interfacial stability (Fernandes *et al.*, 2023).

Beyond restorative applications, bioactive materials have shown particular promise in vital pulp therapy and dentin–pulp complex regeneration. Studies investigating silicate-based cements, chitosan-modified scaffolds, and calcium-releasing liners report favorable outcomes in terms of pulp vitality preservation and reparative dentin formation (Christie *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023; Sequeira *et al.*, 2023). These effects are largely attributed to alkaline pH, bioavailable ion release, and the stimulation of odontoblastic differentiation. However, despite these biological advantages, mechanical limitations remain a concern. In vitro and clinical studies consistently report reduced wear resistance and fracture strength in high-load occlusal areas when compared with conventional resin composites (Liang *et al.*, 2023; Chopra *et al.*, 2024). Hybrid systems incorporating reinforced resin matrices have been proposed to address this limitation, but long-term clinical data remain limited (Flores-Espinoza *et al.*, 2023; Xie *et al.*, 2023). Furthermore, the lack of standardized definitions and testing methodologies for bioactivity complicates reproducibility and clinical translation, underscoring the need for consensus-driven evaluation frameworks (Atia *et al.*, 2023; Moharil *et al.*, 2023).

Nanomaterials as enablers of mechanical, biological, and esthetic performance

Nanomaterials have emerged as a pivotal trend in restorative dentistry by enabling simultaneous enhancement of mechanical properties, antimicrobial performance, and esthetic stability (Carneiro *et al.*, 2023; Gallicchio *et al.*, 2023; Unnadkat *et al.*, 2023; Urkande *et al.*, 2023; Ziaei *et al.*, 2024). Reviews of nanoscience applications in dentistry highlight how nanoparticles such as β-tricalcium phosphate, zeolites, and halloysite nanotubes reduce dentin permeability, inhibit bacterial adhesion, and improve resin–dentin bonding integrity (Agrawal *et al.*, 2023; Unnadkat *et al.*, 2023; Urkande *et al.*, 2023; Woźniak-Budych *et al.*, 2023). Woźniak-Budych *et al.* emphasized that nanomaterials doped with antimicrobial agents, such as chlorhexidine, provide sustained antibacterial effects while maintaining physicomechanical stability (Agrawal *et al.*, 2023; Urkande *et al.*, 2023).

Clinical implications of nanotechnology include improved polishability, color stability, and marginal adaptation of nano-hybrid composites, particularly in caries-affected dentin (Christie *et al.*, 2023; Frąckiewicz *et al.*, 2023; Chopra *et al.*, 2024). Nevertheless, concerns persist regarding long-term biocompatibility, nanoparticle release, and potential cytotoxicity. Several reviews emphasize the necessity of rigorous in vivo studies and standardized safety assessments to mitigate these risks (Urkande *et al.*, 2023; Ziaei *et al.*, 2024). Importantly, recent research increasingly positions nanomaterials not as standalone solutions, but as enabling platforms that synergize with bioactive components, resulting in hybrid systems that enhance remineralization while maintaining mechanical durability (Carneiro *et al.*, 2023; Gallicchio *et al.*, 2023).

Additive manufacturing and digital customization of restorations

Additive manufacturing technologies, particularly three-dimensional (3D) printing, have fundamentally altered the fabrication landscape of restorative dentistry by enabling precise, patient-specific designs and efficient material utilization (Chacón Gahona *et al.*, 2023; Colak & Katirci, 2023; Lekhwani *et al.*, 2023; Loya *et al.*, 2023; Tavas *et al.*, 2023; Atta *et al.*, 2024; NWNA *et al.*, 2024; Uyumaz *et al.*, 2024). Reviews of dental 3D printing technologies describe applications ranging from crowns and copings to periodontal scaffolds and hard tissue engineering constructs, often demonstrating superior marginal fit and internal adaptation compared with traditional techniques (Loya *et al.*, 2023; Tavas *et al.*, 2023; Uyumaz *et al.*, 2024). Comparative studies evaluating additively manufactured zirconium oxide ceramics and reinforced acrylic resins report mechanical properties comparable to subtractively milled counterparts, supporting their use in selected prosthodontic applications (Colak & Katirci, 2023; Lekhwani *et al.*, 2023; Loya *et al.*, 2023; Tavas *et al.*, 2023).

Despite these advantages, challenges remain related to post-curing effects, color stability, wear resistance, and cytotoxic potential of printable resins (NWNA *et al.*, 2024; Rues *et al.*, 2024). In vitro studies indicate that sintering protocols, layer thickness, and printing orientation significantly influence mechanical performance and long-term stability (Chacón Gahona *et al.*, 2023; Colak & Katirci, 2023; Lekhwani *et al.*, 2023). While additive manufacturing offers clear benefits in reducing chair time and material waste, further longitudinal clinical studies are required to validate the durability of printed restorations in the oral environment (Aydın *et al.*, 2023; Atta *et al.*, 2024).

Smart and stimuli-responsive materials: toward adaptive restorations

Smart and stimuli-responsive materials introduce a dynamic dimension to restorative dentistry by enabling restorations to respond to environmental changes such as pH fluctuations, temperature variation, or mechanical stress (Alsaeed, 2022; Fronza *et al.*, 2022; Kodaira *et al.*, 2022; Alshabib *et al.*, 2023; Luo *et al.*, 2024; Maravić *et al.*, 2023; Ortega *et al.*, 2024). pH-responsive composites and glass hybrids are particularly relevant in cariogenic environments, where acidic conditions trigger ion release or antimicrobial activity, thereby counteracting demineralization and biofilm progression (Alshabib *et al.*, 2023; Luo *et al.*, 2023; Ortega *et al.*, 2024). Clinical trials evaluating smart bulk-fill materials and monochromatic composites report acceptable mechanical performance and resistance to discoloration, even following exposure to whitening agents (Alsaeed, 2022; Alshabib *et al.*, 2023; Luo *et al.*, 2023).

Emerging applications also include shape-memory polymers in orthodontics and adaptive polymer networks in implant dentistry (Kodaira *et al.*, 2022; Ortega *et al.*, 2024). However, variability in activation thresholds, long-term functional stability, and concerns regarding genotoxicity in certain metallic smart materials highlight the need for cautious clinical translation (Kodaira *et al.*, 2022). Future research increasingly focuses on integrating smart behavior with nanotechnology and bioactivity to develop multifunctional systems capable of self-healing, antimicrobial response, and tissue interaction (Fronza *et al.*, 2022; Maravić *et al.*, 2023).

Sustainability and environmental considerations in restorative materials

Although sustainability-focused dental materials remain an emerging research area, indirect evidence from multiple domains indicates growing attention to environmentally conscious design (Moharil *et al.*, 2023; Tavas *et al.*, 2023; Urkande *et al.*, 2023). Studies investigating polyetheretherketone (PEEK) biomaterials, natural-derived hydrogels, and biodegradable scaffolds suggest that environmentally friendly alternatives can achieve acceptable biocompatibility and mechanical performance (Carneiro *et al.*, 2023; Moharil *et al.*, 2023). Additionally, additive manufacturing inherently supports waste reduction through precise material deposition, aligning restorative dentistry with broader sustainability goals (Lekhwani *et al.*, 2023; Tavas *et al.*, 2023).

Life-cycle considerations, including reduced reliance on mercury-containing materials and increased use of recyclable packaging, further support this trend (Atia *et al.*, 2023; Liang *et al.*, 2023). However, sustainability must be balanced against clinical durability, as premature restoration failure would negate environmental benefits. Consequently, future research should prioritize materials that achieve both long-term clinical reliability and reduced ecological impact.

Advances in adhesive systems and interfacial stability

Advances in adhesive dentistry underpin many of the material innovations discussed above. Universal and bioactive adhesive systems have simplified bonding protocols while improving interfacial stability across diverse substrates (Atia *et al.*, 2023; Christie *et al.*, 2023; Fernandes *et al.*, 2023; Liang *et al.*, 2023; Moharil *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023; Sequeira *et al.*, 2023; Xie *et al.*, 2023; Chopra *et al.*, 2024; Li *et al.*, 2024). Reviews of contemporary adhesive generations report enhanced performance in direct restorations, particularly through the use of functional monomers such as 10-MDP and improved solvent systems (Sequeira *et al.*, 2023; Li *et al.*, 2024). Bioactive adhesives capable of releasing calcium and phosphate ions further contribute to remineralization at the hybrid layer, reducing microleakage and interfacial degradation (Fernandes *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023).

Table 2 summarizes the clinical relevance, evidence maturity, and future research priorities associated with emerging restorative dental material technologies.

Table 2. Clinical Translation and Research Gaps in Emerging Restorative Dental Materials

Material Trend	Current Clinical Use	Strength of Evidence	Key Challenges	Priority Research Needs
Bioactive restoratives	Moderate	Moderate–High	Standardization of bioactivity testing	Long-term randomized clinical trials
Nanomaterial-based systems	Widespread (nano-hybrids)	Moderate	Biocompatibility & release safety	In vivo safety & degradation studies
3D-printed restorations	Limited (temporary use)	Low–Moderate	Wear resistance, aging behavior	Long-term clinical performance
Smart materials	Experimental	Low	Durability of responsiveness	Clinical validation & fatigue resistance
Sustainable materials	Emerging	Low	Performance equivalence	Life-cycle and clinical outcome studies
Advanced adhesive systems	Widespread	High	Technique sensitivity	Interfacial aging & bioactivity integration

Surface modification strategies, including PEEK treatment and resin cement classification systems, enhance adhesion across restorative materials (Liang *et al.*, 2023; Paradowska-Stolarz *et al.*, 2023). Systematic overviews consistently emphasize the importance of moisture control and substrate management, with innovations in hydrophobic resin chemistry mitigating technique sensitivity (Xie *et al.*, 2023; Chopra *et al.*, 2024). These advances position adhesive systems as active contributors to restoration longevity rather than passive coupling agents.

CONCLUSION

The studies represent a pivotal phase in the evolution of restorative dental materials, characterized by a clear transition from passive restorative solutions toward biologically interactive, functionally adaptive, and increasingly sustainable material systems. Advances in bioactive ion-releasing materials, nanotechnology-enabled composites, additive manufacturing, smart and stimuli-responsive systems, environmentally conscious formulations, and modern adhesive technologies collectively reflect a redefinition of restorative dentistry's objectives—from simple structural replacement to long-term biological integration and disease modulation.

Bioactive materials have emerged as a cornerstone of this transition, demonstrating meaningful potential to support remineralization, enhance interfacial stability, and contribute to tissue regeneration, particularly in caries-susceptible clinical scenarios. In parallel, nanomaterials have enabled significant improvements in mechanical performance, antimicrobial behavior, and esthetic durability, while also serving as foundational platforms for biomimetic and multifunctional material design. Additive manufacturing has further expanded restorative possibilities by enabling precise customization, streamlined workflows, and reduced material waste, aligning restorative care with principles of personalization and efficiency. Smart materials introduce an additional layer of sophistication by offering adaptive responses to environmental challenges, suggesting a future in which restorations actively participate in maintaining oral health rather than merely resisting degradation.

Sustainability, although still an emerging theme within restorative material research, has gained increasing relevance as environmental considerations intersect with clinical decision-making. The gradual incorporation of biodegradable components, mercury-free alternatives, waste-reduction strategies, and greener manufacturing processes signals an important shift toward environmentally responsible dentistry. Concurrently, advances in adhesive systems have played a critical enabling role across all material classes by improving interfacial durability, simplifying clinical protocols, and supporting the longevity of increasingly complex restorative systems.

Despite these advances, several challenges remain. Long-term clinical evidence beyond short- and medium-term follow-up periods is still limited for many emerging materials, and variability in testing methodologies complicates direct comparison and translation into routine practice. The absence of standardized evaluation frameworks for bioactivity, smart responsiveness, and sustainability further underscores the need for coordinated methodological development.

Future research should prioritize extended clinical trials to establish long-term performance and failure modes, alongside the development of standardized protocols that capture both biological and functional outcomes. Particular promise lies in hybrid materials that integrate multiple emerging trends—such as nano-reinforced bioactive systems or smart materials with regenerative capacity—while maintaining clinical practicality. Advances in computational modeling and artificial intelligence may further accelerate material design and optimization, enabling more targeted and efficient innovation. Finally, continued emphasis on green chemistry, biodegradable constituents, and harmonized regulatory pathways will be essential to ensure that technological progress aligns with environmental responsibility and patient safety.

In summary, emerging restorative dental materials are reshaping the discipline by bridging biological science, engineering innovation, and clinical practice. As evidence matures and interdisciplinary collaboration expands, these materials hold substantial potential to improve restoration longevity, reduce treatment failure, and advance patient-centered, sustainable restorative care.

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