

Review Article

Smart Restorative Materials in Dentistry: From Passive Restorations to Self-Healing, Ion-Releasing, and Stimuli-Responsive Systems

Dr. Ebtsam Ben Zeglam¹, Dr. Alasifa Arshad^{2*}, Dr. Dellal Hadjadj³, Dr. Sowmya Yelagandula⁴, Dr. Arun Kumar Boppa⁵, Dr. Unseba⁶, Dr. Ridhi Bhola⁷, Dr. Sandeep Singh⁷

¹Bachelor of Dental Surgery (BDS), Faculty of Dentistry, University of Tripoli, Tripoli, Libya; Master of Science (MS), New York University College of Dentistry (NYUCD), New York, USA; PhD, Rutgers University Faculty of Dental Medicine, Newark, NJ, USA

²BDS, RDH, Baqai Medical & Dental College, 51 Deh Tor Gadap Road, Karachi, Pakistan

³DDS, Oran University, Oran, Algeria, 2009

⁴BDS, NTR University of Health Sciences, Vijayawada, Andhra Pradesh, India

⁵Master's in Health Informatics, Marshall University, Huntington, WV, USA; BDS, Government Dental College, Vijayawada, India

⁶BDS, Altamash Institute of Dental Medicine, 2-R Sunset Boulevard, Defence Housing Authority (DHA), Karachi, Sindh, Pakistan

⁷MDS, Post Graduate Institute of Dental Sciences, Rohtak, Haryana, India

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Abstract: Conventional restorative materials primarily aim to replace lost tooth structure but remain susceptible to polymerization shrinkage, microcracking, wear, marginal degradation, and secondary caries. The development of smart restorative materials represents a shift toward materials capable of actively interacting with and responding to the oral environment. These materials include self-healing systems, ion-releasing and bioactive materials, and stimuli-responsive systems that respond to changes in pH, mechanical stress, temperature, or other environmental conditions. Emerging evidence suggests potential applications in resin composites, dental adhesives, remineralization, pulp protection, and prevention of secondary caries. However, limitations related to mechanical performance, long-term durability, biocompatibility, manufacturing complexity, and limited clinical evidence continue to restrict their widespread clinical use. This review discusses the current principles, applications, evidence, challenges, and future perspectives of smart restorative materials and their potential to transform conventional restorations into more adaptive and biologically interactive restorative systems.

Keywords: Smart Restorative Materials, Self-Healing, Ion-Releasing, Stimuli-Responsive, Bioactive Materials, Restorative Dentistry, Remineralization.

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1. INTRODUCTION

Restorative dentistry has evolved from conventional materials designed primarily to replace lost tooth structure toward adhesive and bioactive approaches that aim to preserve dental tissues and interact with the oral environment. Recent advances have introduced smart restorative materials, representing a further shift toward materials capable of responding to environmental changes, repairing damage, or providing biological benefits. This progression reflects the increasing demand for restorative systems with improved longevity, biological activity, and adaptability [1]. (Figure 1)

Despite advances in restorative materials, conventional restorations remain susceptible to polymerization shrinkage, microcracking, marginal degradation, wear, fracture, and secondary caries. These

processes can compromise the material, adhesive interface, and restoration-tooth margin over time. Most conventional materials also have limited capacity to actively respond to biological or environmental changes within the oral cavity [2].

Smart restorative materials are designed to overcome some of these limitations through functional and responsive properties. They can broadly be classified into three groups: self-healing materials, ion-releasing or bioactive materials, and stimuli-responsive materials. Self-healing systems aim to repair material damage such as microcracks; ion-releasing materials can provide fluoride, calcium, phosphate, and other ions that may support remineralization and protection; and stimuli-responsive materials respond to environmental factors such as pH, mechanical stress, temperature, or moisture.

*Corresponding Author: Dr. Ebtsam Ben Zeglam

BDS, RDH, Baqai Medical & Dental College, 51 Deh Tor Gadap Road, Karachi, Pakistan

Emerging applications include resin composites, dental adhesives, pulp and dentin protection, remineralization, and secondary caries prevention [3, 4]. However, many smart materials remain under laboratory or early clinical investigation, with concerns regarding mechanical

performance, long-term durability, biocompatibility, manufacturing complexity, and clinical validation. This narrative review summarizes their mechanisms, restorative applications, current evidence, limitations, and future clinical potential.

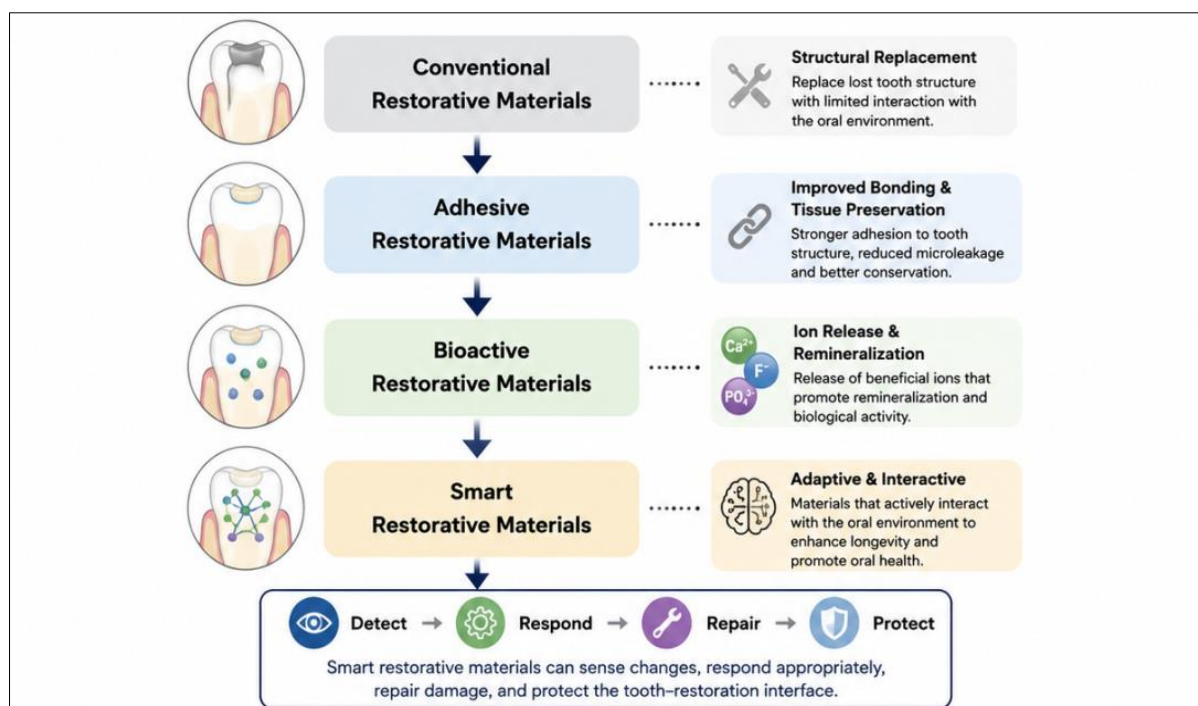


Figure 1: Evolution of Restorative Materials in dentistry

2. Smart Restorative Materials: Classification and Mechanisms

Smart restorative materials are an emerging class of dental materials designed to provide functions beyond the passive replacement of lost tooth structure. Their defining characteristic is the ability to respond to damage, environmental changes, or biological conditions through controlled chemical, physical, or biological mechanisms. Based on their primary mode of action, smart restorative materials can be broadly classified into self-healing materials, ion-releasing and bioactive materials, stimuli-responsive materials, and multifunctional systems.

2.1 Self-Healing Materials

Self-healing materials are designed to restore or partially recover their structural integrity following the formation of microcracks or other forms of damage. This property is particularly relevant to resin-based restorative materials, which are exposed to polymerization stresses, thermal fluctuations, and repeated occlusal loading. Self-healing mechanisms can be broadly classified as intrinsic or extrinsic. Extrinsic systems incorporate separate healing components, such as microcapsules containing healing agents, within the restorative matrix. When a crack propagates through the material, the capsules may rupture and release the healing agent into the damaged region, where subsequent chemical reactions can help seal or repair the defect. Other experimental approaches

use vascular or interconnected networks to deliver healing agents to damaged areas [5].

Intrinsic self-healing systems do not require separate healing agents and instead rely on reversible interactions within the material itself. These may include reversible covalent bonds, hydrogen bonding, ionic interactions, or other dynamic chemical interactions that allow polymer chains to reorganize following damage. Although self-healing restorative materials remain largely experimental, they offer the potential to reduce microcrack propagation and improve the long-term durability of restorations [6].

3.2 Ion-Releasing and Bioactive Materials

Ion-releasing materials are designed to release biologically relevant ions into the surrounding oral environment. Unlike conventional restorative materials, these systems can actively interact with adjacent tooth structure and may contribute to remineralization and protection against demineralization.

Fluoride-releasing materials can promote remineralization and increase the resistance of mineralized tissues to acid-mediated dissolution. Calcium and phosphate-releasing materials can increase the availability of ions required for the formation of calcium phosphate and apatite phases, supporting mineral deposition at the tooth restoration interface.

Strontium-containing materials may provide additional biological effects, including potential contributions to mineral formation. Other therapeutic ions, including zinc and selected antimicrobial ions, have also been incorporated into experimental restorative systems to provide antibacterial or protective effects [7].

The fundamental mechanism of ion-mediated remineralization involves the release of ions into the surrounding environment, followed by their diffusion toward demineralized tooth surfaces and participation in mineral precipitation or apatite formation. The magnitude and duration of these effects depend on the composition, solubility, ion-release kinetics, and surrounding oral conditions [8].

3.3 Stimuli-Responsive Materials

Stimuli-responsive restorative materials are designed to alter their properties or trigger a specific response when exposed to changes in the surrounding environment. This approach allows the material to respond selectively to conditions associated with restoration degradation or disease. pH-responsive materials can alter ion release, swelling, permeability, or other properties in response to acidic conditions associated with cariogenic activity. Mechanically responsive materials are designed to respond to deformation or stress and may activate healing or other protective mechanisms following mechanical damage. Temperature-responsive systems undergo reversible changes in their structure or properties following temperature variations, while moisture-responsive materials can respond to changes in water content or exposure to oral fluids [9].

Light-responsive systems can use specific wavelengths of light to initiate chemical or structural changes, whereas enzyme-responsive materials are designed to respond to enzymes associated with bacterial activity or tissue degradation. Although many of these systems are still being investigated experimentally, stimuli responsiveness represents an important approach toward developing restorative materials capable of adapting to dynamic oral conditions [3].

3.4 Multifunctional Smart Systems

The next generation of smart restorative materials is increasingly focused on combining multiple functional properties within a single material. Such systems may integrate self-healing with ion release, allowing a restoration to respond to structural damage while simultaneously providing a local source of remineralizing ions. Other combinations may include antibacterial activity with remineralization, or pH responsiveness with controlled ion release, enabling the material to respond preferentially to conditions associated with cariogenic activity [10].

Multifunctional systems could therefore provide simultaneous mechanical, chemical, and

biological benefits. Rather than relying on a single protective mechanism, these materials aim to create restorative systems capable of detecting environmental changes, responding appropriately, and supporting restoration longevity and preservation of the surrounding tooth structure [10].

4. Major Applications in Restorative Dentistry

The development of smart restorative materials has expanded their potential applications beyond conventional structural replacement. Their ability to respond to damage, release therapeutic ions, interact with dental tissues, and modify their behavior according to environmental conditions has generated interest in direct restorations, adhesive systems, pulp protection, remineralization, and prevention of restoration-associated disease. Although many applications remain under investigation, these materials may contribute to improved restoration durability and more biologically oriented restorative approaches.

4.1 Smart Resin Composites

Resin composites are among the most actively investigated applications of smart restorative technologies. Conventional composites may undergo polymerization shrinkage, microcrack formation, wear, and degradation during long-term service. Self-healing composites have therefore been developed to repair or limit the progression of microcracks through intrinsic or extrinsic healing mechanisms. By restoring structural continuity after early-stage damage, these systems may improve resistance to fatigue and potentially extend restoration longevity [11].

Ion-releasing composites represent another important development. The incorporation of fluoride, calcium, phosphate, strontium, or other ion-containing components can provide a localized source of biologically relevant ions. These materials may promote remineralization of adjacent tooth structure and reduce susceptibility to demineralization. Antibacterial and remineralizing composites have additionally been investigated to control cariogenic activity while supporting mineral recovery. However, achieving these biological functions without compromising strength, wear resistance, esthetics, and long-term stability remains an important challenge [12].

4.2 Smart Dental Adhesives

The adhesive interface is a critical determinant of the longevity of bonded restorations and is particularly vulnerable to hydrolytic degradation and enzymatic breakdown. Smart adhesive systems are being developed to improve the durability and biological performance of this interface.

Self-healing adhesives may use dynamic chemical interactions to repair microdamage within the adhesive layer and maintain bond integrity. Ion-releasing and remineralizing adhesives can provide calcium,

phosphate, fluoride, or other ions at the dentin adhesive interface, potentially supporting mineral deposition and improving the stability of the hybrid layer. Such approaches may also help counteract the degradation of exposed collagen within the hybrid layer. Although promising, the long-term clinical effectiveness of these systems depends on maintaining adequate bond strength while providing sustained biological activity [13].

4.3 Pulp Protection and Dentin Remineralization

Smart and bioactive materials have considerable potential in the management of deep carious lesions and procedures aimed at preserving pulp vitality. Calcium and phosphate releasing systems can create a mineral-rich environment that supports remineralization of partially demineralized dentin. Bioactive materials may also promote the formation of mineralized tissue and contribute to reparative dentin formation [14].

These properties may be particularly relevant to indirect and direct pulp protection, where maintaining a favorable biological environment is essential. Rather than functioning solely as physical barriers, bioactive restorative materials may interact with dentin and pulpal tissues through ion release and mineralization-related processes. Their potential role in minimally invasive management of deep caries is therefore an important area of ongoing research [15].

4.4 Secondary Caries Prevention

Secondary caries remains one of the major causes of restoration failure. Smart materials may address this problem by modifying the local environment surrounding restoration margins. Ion-releasing materials can provide fluoride, calcium, phosphate, or other ions that may promote remineralization and increase resistance to demineralization. Antibacterial components

may further reduce bacterial activity associated with biofilm formation [16].

pH-responsive systems represent a more targeted approach by responding to acidic conditions associated with cariogenic activity. Such materials may potentially increase ion release or activate protective functions when the local pH decreases. The combination of antibacterial activity, controlled ion release, and remineralization could therefore provide a more dynamic approach to protecting the tooth restoration interface. However, evidence for meaningful reductions in secondary caries under clinical conditions remains limited for many emerging systems [17].

4.5 Other Emerging Applications

Smart restorative concepts are also being explored in digitally fabricated restorations. The incorporation of functional materials into CAD/CAM blocks and 3D-printed restorative polymers may eventually allow the fabrication of restorations with controlled mechanical, biological, or responsive properties. Such approaches could be particularly relevant for restorations exposed to high mechanical stresses, where self-healing or damage-responsive behavior may improve resistance to fatigue and fracture [18].

Advances in digital manufacturing may also facilitate the development of patient-specific smart restorative systems in which material composition and functional properties are tailored to individual caries risk, occlusal loading, or biological requirements. These applications remain largely investigational, but the integration of smart materials with digital dentistry could represent an important direction for personalized restorative care [18]. (Figure 2)



Figure 2: Clinical Applications of Smart Restorative Materials

5. Advantages and Limitations of Smart Restorative Materials

Smart restorative materials offer important advantages by responding to changes in the oral environment, repairing microdamage, releasing therapeutic ions, and supporting remineralization and antibacterial protection. These properties may improve restoration durability and contribute to preservation of

tooth structure. However, challenges including compromised mechanical properties in some formulations, limited healing capacity, uncontrolled ion release, water sorption, degradation, biocompatibility, and manufacturing complexity remain. Most importantly, translating promising laboratory performance into predictable long-term clinical outcomes remains a major challenge [19-23]. (Table 1)

Table 1: Advantages and limitations of smart restorative materials

Advantages	Limitations
Adaptive response to changes in the oral environment	Compromised mechanical properties in some formulations
Self-repair and potential improvement in restoration durability	Limited durability and repeated healing capacity
Ion-mediated remineralization	Challenges in achieving controlled and sustained ion release
Antibacterial and protective effects	Water sorption and material degradation
Potential reduction of secondary caries	Biocompatibility concerns
Preservation of tooth structure	Manufacturing complexity and increased cost
	Difficulty translating laboratory findings into consistent clinical performance

6. Future Perspectives

The future development of smart restorative materials is likely to move beyond single-function systems toward multifunctional, biologically interactive, and clinically adaptable materials. Rather than simply replacing lost tooth structure, next-generation restorations may be designed to detect changes in the local environment, respond selectively to disease-related stimuli, promote tissue repair, and maintain their functional properties throughout service. Recent advances in biomaterials engineering, nanotechnology, digital manufacturing, and materials informatics are creating new opportunities to achieve this transition. However, successful clinical translation will require simultaneous optimization of biological activity, mechanical performance, durability, safety, manufacturability, and cost.

6.1 Development of Multifunctional and Multi-Stimuli-Responsive Materials

An important future direction is the development of multifunctional materials capable of performing several protective functions simultaneously. Current research has largely investigated individual properties such as self-healing, ion release, antibacterial activity, or pH responsiveness. Future systems may combine these functions within a single restorative platform. For example, a material could detect an acidic microenvironment associated with cariogenic activity, increase the release of calcium, phosphate, or fluoride ions, suppress bacterial activity, and simultaneously initiate a self-repair mechanism in response to mechanical damage. Such multi-responsive systems could provide more targeted protection than materials that continuously release therapeutic components regardless of environmental conditions [24, 25].

The development of stimulus-specific responses may also improve the efficiency and longevity of therapeutic activity. pH-responsive systems have already demonstrated the ability to increase ion or antibacterial release under acidic conditions, while emerging smart delivery platforms are being designed to respond to enzymatic activity, temperature, light, pressure, or other environmental signals. Future research should determine whether combining endogenous stimuli, such as acidic pH or bacterial enzymes, with externally controlled stimuli can provide predictable and clinically useful responses without compromising the structural integrity of the restoration [25].

6.2 More Controlled and Sustained Ion Delivery

Ion-releasing materials are expected to remain an important area of development, particularly for remineralization, dentin repair, and caries prevention. Future materials should aim not simply to release large quantities of ions, but to provide controlled, sustained, and condition-dependent delivery at clinically relevant concentrations. Current evidence indicates that ion release is strongly influenced by material composition, particle characteristics, solubility, diffusion pathways, and the surrounding environment. Excessive or rapid release may provide only short-term activity, whereas insufficient release may fail to produce meaningful biological effects [26].

Advanced carrier systems, porous particles, nanostructured fillers, mesoporous materials, and stimuli-responsive delivery platforms may help regulate the timing and location of ion release. Combining calcium and phosphate delivery with fluoride, strontium, zinc, or other therapeutic ions may further enhance remineralization and protective effects. However, future studies should establish standardized methods for measuring ion release and determining whether

laboratory measurements correlate with clinically relevant mineral recovery and restoration performance. Recent reviews continue to identify controlled release, biocompatibility, and long-term stability as important challenges for clinical translation [27].

6.3 Bioinspired and More Effective Self-Healing Systems

Self-healing materials represent one of the most distinctive opportunities for transforming restorative dentistry. Future research should focus on improving the efficiency, repeatability, and biological compatibility of healing mechanisms while minimizing their effect on mechanical and esthetic properties. Current extrinsic systems can provide healing through encapsulated agents, whereas intrinsic systems use reversible chemical interactions within the polymer network. The next generation of materials may combine these approaches or use bioinspired mechanisms that more closely mimic the continuous repair processes observed in biological tissues [3-28].

An important objective will be the development of materials capable of responding to repeated low-level damage rather than repairing a single experimentally induced crack. Clinical restorations are exposed to millions of loading cycles, thermal fluctuations, moisture, and chemical challenges. Therefore, future self-healing materials must demonstrate repeated healing capacity under realistic oral conditions and retain adequate strength, wear resistance, optical properties, and bonding performance after multiple healing cycles. At present, self-healing restorative materials remain largely experimental, making long-term fatigue testing and clinically relevant validation essential [28].

6.4 Integration with Digital Dentistry, 3D Printing, and 4D Manufacturing

Digital manufacturing may provide an important pathway for incorporating smart functionality into customized restorative systems. CAD/CAM and additive manufacturing technologies allow greater control over restoration geometry, material composition, and spatial distribution of functional components. In the future, smart materials could potentially be incorporated into digitally fabricated restorations in which mechanical, biological, and responsive properties are designed according to the clinical indication [29].

An emerging extension of this concept is 4D printing, in which printed structures are designed to undergo predictable changes over time or in response to stimuli such as temperature, moisture, or pH. Although applications in dentistry remain largely experimental, 4D-printed bio-smart materials could eventually enable restorations or therapeutic devices with programmable adaptive behavior. Such systems may be particularly relevant to situations in which changes in the oral environment or tissue conditions occur over time [29].

Nevertheless, digital fabrication alone does not guarantee superior material performance. Recent systematic evidence indicates that currently available 3D-printed restorative resins may still demonstrate inferior mechanical or optical properties compared with established CAD/CAM materials. Future research should therefore focus on developing printable smart formulations with adequate conversion, mechanical strength, dimensional stability, wear resistance, biocompatibility, and long-term intraoral stability [29, 30].

6.5 Artificial Intelligence and Materials Informatics

Artificial intelligence and materials informatics may significantly accelerate the discovery and optimization of future smart restorative materials. Traditional material development often relies on sequential modification and testing of compositions, which can be time-consuming and resource-intensive. Materials informatics can integrate large datasets involving chemical composition, filler characteristics, polymer structure, mechanical properties, ion release, biological activity, and environmental responsiveness to identify potentially optimal formulations [30].

AI-assisted inverse design may eventually allow researchers to begin with a desired clinical property, for example, high fracture resistance combined with sustained calcium release and pH responsiveness and computationally identify candidate material compositions capable of achieving those targets. Machine learning may also help predict degradation behavior, polymerization characteristics, biocompatibility, and interactions among multiple components before experimental synthesis. Recent work has identified AI-driven inverse design and multiscale computational approaches as emerging strategies for accelerating dental material development [31].

However, the effectiveness of AI-based materials discovery will depend on the availability and quality of standardized datasets. Current dental materials research remains fragmented, with differences in experimental methods, testing conditions, reporting standards, and outcome measures. Establishing interoperable databases and standardized testing protocols will therefore be essential before AI can reliably predict clinical performance [32].

6.6 Personalized and Risk-Based Restorative Materials

Future smart restorative dentistry may increasingly move toward patient-specific material selection rather than the use of a single material for broad clinical indications. Individual differences in caries risk, salivary composition, oral microbiome, occlusal loading, dietary habits, and restoration location may influence the optimal properties required from a restorative material [33].

A high-carries-risk patient, for example, may benefit from a material emphasizing pH responsiveness, antibacterial activity, and sustained remineralizing ion release, whereas a patient with high occlusal loading may require greater fracture resistance and damage-responsive behavior. Integration of patient-specific clinical data with digital dentistry and AI-based materials selection could eventually allow restorative materials to be selected or manufactured according to individual biological and mechanical requirements. Such personalized approaches remain conceptual or experimental but represent a logical progression of smart restorative dentistry [34].

6.7 Establishing Standardized Testing and Clinical Validation

Perhaps the most important future requirement is the development of standardized methods for evaluating smart restorative materials. The term “smart” encompasses diverse mechanisms and should not be considered evidence of clinical benefit by itself. Future studies should distinguish between demonstration of a material response under laboratory conditions and evidence of improved clinical outcomes [35].

Standardized evaluation should include mechanical properties, fatigue behavior, wear, water sorption, degradation, ion-release kinetics, antibacterial activity, remineralization, cytotoxicity, and stability of the responsive mechanism. Importantly, these properties should be assessed under conditions that more closely reproduce the oral environment, including cyclic loading, thermal changes, fluctuating pH, saliva exposure, and multispecies biofilms. Recent reviews have emphasized that inconsistent assessment methods remain a major barrier to comparing bioactivity across materials [36].

Long-term randomized clinical trials are also required to determine whether smart functions translate into meaningful improvements in restoration survival, marginal integrity, secondary caries prevention, postoperative sensitivity, and preservation of tooth structure. Current clinical studies of ion-releasing and bioactive restorative materials generally demonstrate acceptable short- to medium-term performance, but consistent superiority over conventional restorative materials has not yet been established. Future research should therefore prioritize clinically relevant endpoints and sufficiently long follow-up periods rather than relying primarily on short-term laboratory measures.

7. CONCLUSION

Smart restorative materials represent an important transition from passive replacement of tooth structure toward adaptive, biologically interactive restorative systems. Self-healing, ion-releasing, antibacterial, remineralizing, and stimuli-responsive technologies offer promising opportunities to improve restoration durability, protect surrounding dental tissues,

and reduce disease-related degradation. Future progress will depend on multifunctional material design, controlled therapeutic delivery, bioinspired self-repair, digital and AI-assisted manufacturing, personalized applications, and rigorous clinical validation. Despite substantial experimental advances, these materials should currently be viewed as an emerging technology rather than a universal replacement for conventional restorations. Continued interdisciplinary research linking materials science with restorative dentistry and clinical research will be essential for translating smart restorative concepts into predictable, durable, and patient-centered clinical solutions.

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