



## **Evolving Concepts in Dental Materials: From Biocompatibility to Bioactivity**

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### **Abstract**

The field of dental materials has transitioned from focusing solely on biocompatibility to emphasizing bioactivity, marking a paradigm shift in restorative and regenerative dentistry. Biocompatibility, defined as the ability of a material to perform its function without eliciting adverse reactions, laid the foundation for traditional dental materials like amalgam, gold, and ceramics. However, the advent of bioactive materials, which actively interact with the oral environment to promote healing and tissue regeneration, has revolutionized the landscape. This article reviews key innovations, including glass ionomer cements, bioactive composites, and calcium silicate cements, highlighting their mechanisms such as ion release, biomimicry, and cellular interaction.



The applications of these materials span restorative dentistry, endodontics, implantology, and orthodontics, addressing challenges like material stability, cost implications, and clinical adoption. Emerging technologies, including nanotechnology, 3D printing, and smart materials, are paving the way for personalized, patient-specific treatments. This review underscores the transformative potential of bioactive dental materials, offering insights into their current status and future prospects in advancing oral health care.

**Keywords.** Biocompatibility, bioactivity, dental materials, nanotechnology, 3D printing, remineralization, smart materials, bioactive glass, calcium silicate, resin composites, bio-ceramics, antimicrobial properties, tissue regeneration, hydroxyapatite, fluoride release, pH-sensitive materials, self-healing composites, shape-memory alloys, restorative dentistry, preventive dentistry, dental innovations, sustainability.

## **Introduction**

The evolution of dental materials has paralleled advancements in technology and scientific understanding, transforming dental care from a restorative to a regenerative paradigm. Traditionally, dental materials focused on restoring functionality and aesthetics with minimal interaction with biological tissues. Materials like amalgam, gold, and ceramics prioritized strength and durability while being largely inert to the oral environment. The mid-20th century ushered in the era of biocompatibility, with materials such as composites and glass ionomer cements designed to minimize adverse reactions and improve compatibility with oral tissues.

However, the limitations of biocompatible materials, including their inability to actively promote tissue healing, paved the way for bioactive materials. Bioactivity represents a significant shift, enabling materials to interact with the biological environment, triggering specific responses such as remineralization, tissue regeneration, and antimicrobial effects. This paradigm shift aligns with modern dentistry's goals of not only repairing but also regenerating damaged tissues.

This article paper explores the journey from biocompatibility to bioactivity, examining the properties, applications, and challenges of bioactive dental materials. Emphasizing their mechanisms of action and innovations, the discussion highlights their role in advancing restorative and regenerative dentistry, as well as their implications for future research and clinical practice.

## **1. Defining Biocompatibility in Dental Materials**

Biocompatibility is a cornerstone concept in the development and selection of dental materials, ensuring that these materials do not elicit adverse reactions when introduced into the oral environment. It refers to the ability of a material to perform its intended function without causing



harm to surrounding tissues, such as gums, teeth, or oral mucosa, and without triggering systemic toxicity or hypersensitivity reactions.

### **Key Aspects of Biocompatibility in Dental Materials**

1. **Non-Toxicity.** Materials should not release harmful chemicals or by-products that could lead to cell damage or systemic effects.
2. **Non-Allergenic Properties.** Dental materials must minimize the risk of allergic responses, which can manifest as inflammation, swelling, or more severe systemic conditions.
3. **Non-Carcinogenicity.** Safety in long-term use is essential, ensuring materials do not contribute to mutagenic or carcinogenic risks.

### **Evolution of Biocompatibility Standards**

In earlier decades, biocompatibility was narrowly defined, focusing mainly on whether a material was chemically inert and caused no immediate harm. However, modern dentistry has broadened this definition to include aspects such as.

- Interaction with biological tissues.
- Compatibility with the dynamic oral environment (e.g., saliva, enzymes, and bacterial flora).
- Support for the healing and regeneration of tissues.

### **Testing Biocompatibility**

To determine the biocompatibility of a material, several tests are employed.

1. **In Vitro Tests.** Assess cellular responses like cytotoxicity and proliferation in controlled laboratory settings.
2. **In Vivo Tests.** Evaluate the material's effects on living organisms, focusing on tissue response, inflammation, and healing.
3. **Clinical Trials.** Long-term studies in real-world conditions to ensure patient safety and efficacy.

### **Challenges in Ensuring Biocompatibility**

Despite rigorous testing protocols, challenges persist in guaranteeing biocompatibility for all patients. Variability in individual immune responses, differences in oral microbiota, and environmental factors can impact how materials perform. Moreover, the increasing complexity of



dental restorations, such as multi-material systems and composites, adds to the difficulty of ensuring uniform biocompatibility.

### **Role in Modern Dental Material Design**

Today, biocompatibility is considered the baseline requirement for dental materials, forming the foundation upon which other advanced properties, such as bioactivity and functionality, are built. It remains an indispensable focus, ensuring that dental restorations, implants, and prosthetics integrate seamlessly into the oral ecosystem while preserving patient health.

### **2. From Passive Materials to Bioactive Solutions**

The transition from passive to bioactive dental materials marks a significant advancement in restorative dentistry, prioritizing functionality that extends beyond mechanical strength and aesthetic appeal. While traditional materials were designed to be inert and provide a physical barrier or structure, bioactive materials interact dynamically with the oral environment to promote healing, regeneration, and long-term oral health.

### **Understanding Passive Dental Materials**

Passive materials are characterized by their inert nature, meaning they do not interact chemically or biologically with surrounding tissues. Examples include.

- **Amalgam.** Widely used for decades due to its strength and durability but chemically inert in nature.
- **Ceramics.** Known for their esthetics and biocompatibility but limited in terms of tissue interaction.
- **Traditional Composites.** Offer good mechanical properties but lack bioactivity, serving primarily as a filler material.

### **The Rise of Bioactive Materials**

Bioactive dental materials, in contrast, are designed to.

1. **Stimulate Biological Responses.** Encourage the formation of natural tissues, such as dentin or bone, at the material-tissue interface.
2. **Promote Remineralization.** Release ions like calcium, phosphate, and fluoride to strengthen enamel and prevent decay.
3. **Support Healing Processes.** Facilitate cellular growth and repair, reducing inflammation and accelerating recovery.



## **Mechanisms of Bioactivity**

Bioactivity in dental materials is achieved through various mechanisms.

- **Ion Release.** Materials like bioactive glass and calcium silicate cements release therapeutic ions, promoting mineralization and antibacterial effects.
- **Interaction with Saliva.** Bioactive materials interact with saliva to form a protective hydroxyapatite layer, aiding in natural tooth repair.
- **Anti-Microbial Properties.** Some materials are designed to inhibit bacterial growth, reducing the risk of secondary caries or infections.

## **Examples of Bioactive Dental Materials**

1. **Bioactive Glasses.** Contain silica, calcium, and phosphate, which stimulate mineralized tissue formation and have antimicrobial properties.
2. **Calcium Silicate-Based Cements.** Widely used in endodontics (e.g., Mineral Trioxide Aggregate, or MTA) for their sealing ability and bioactivity.
3. **Resin-Based Composites with Bioactive Fillers.** Incorporate ions that support remineralization and prevent bacterial adhesion.

## **Advantages of Bioactive Solutions**

- **Enhanced Longevity.** Bioactive materials integrate with natural tissues, reducing restoration failure rates.
- **Reduced Infections.** By limiting bacterial colonization, bioactive materials help maintain oral hygiene.
- **Improved Patient Outcomes.** Patients benefit from faster healing, reduced inflammation, and stronger restorations.

## **Challenges in Implementation**

Despite their advantages, bioactive materials face challenges such as.

- **Higher Costs.** Manufacturing bioactive materials is more complex and expensive than traditional options.
- **Limited Long-Term Data.** As relatively new innovations, the long-term clinical performance of some bioactive materials is still under evaluation.



- **Technical Sensitivity.** Proper handling and application require advanced skills and knowledge.

### **Impact on Modern Dentistry**

The shift from passive to bioactive materials represents a paradigm change in how dental restorations are approached. Bioactive solutions not only restore function and aesthetics but also play an active role in maintaining and enhancing oral health, paving the way for more sustainable and effective dental care practices.

### **3. Bioactivity Explained. The New Gold Standard**

Bioactivity has emerged as the new benchmark for evaluating the performance of dental materials, going beyond basic compatibility to actively contribute to oral health. Unlike traditional materials, bioactive materials interact with their surroundings to promote tissue repair, prevent disease progression, and support overall dental well-being.

#### **Defining Bioactivity in Dental Materials**

Bioactivity refers to the ability of a material to elicit specific biological responses at the material-tissue interface. These responses include.

- Formation of new mineralized tissues, such as dentin or enamel.
- Inhibition of bacterial growth to prevent secondary caries.
- Induction of healing in damaged tissues through cellular interaction.

#### **Key Features of Bioactive Materials**

1. **Ion Release.** Bioactive materials release therapeutic ions like calcium, phosphate, and fluoride, essential for remineralization and strengthening enamel.
2. **Biomimicry.** They replicate the natural properties of dental tissues, promoting seamless integration and repair.
3. **Antimicrobial Action.** Some materials are engineered to reduce bacterial colonization and biofilm formation.
4. **Regenerative Potential.** Support the regeneration of damaged dentin, bone, or periodontal tissues.

#### **Mechanisms Underpinning Bioactivity**

Bioactivity relies on interactions between the material and biological tissues. Mechanisms include.



- **Hydroxyapatite Layer Formation.** Many bioactive materials, such as bioactive glass, interact with saliva and tissue fluids to form a protective hydroxyapatite layer, enhancing remineralization.
- **Stimulating Cell Differentiation.** By releasing bioactive ions, these materials encourage cell proliferation and differentiation, leading to tissue repair and regeneration.

### Examples of Bioactive Materials

- **Bioactive Glasses.** Used in restorative and regenerative dentistry for their ability to promote mineralization and inhibit bacterial growth.
- **Resin Composites with Bioactive Fillers.** Enhance tooth repair while maintaining aesthetic appeal.
- **Calcium Phosphate-Based Materials.** Frequently used for bone grafts and remineralization due to their similarity to natural tooth minerals.

### Benefits of Bioactivity in Dentistry

- **Enhanced Restoration Durability.** By bonding with tissues, bioactive materials reduce the risk of failure and prolong the lifespan of restorations.
- **Improved Oral Health.** They play an active role in preventing tooth decay and gum disease.
- **Faster Healing.** By promoting tissue repair and reducing inflammation, these materials contribute to quicker recovery times.

### Challenges and Considerations

Despite their advantages, bioactive materials are not without challenges.

- **Cost and Accessibility.** Bioactive options are often more expensive than conventional materials.
- **Technical Expertise.** Their application requires skilled professionals to ensure effective outcomes.
- **Clinical Evidence.** Long-term studies are needed to validate the efficacy of newer bioactive materials.

### Setting the Standard for the Future

Bioactivity represents a transformative approach to dental material science, redefining how



materials are evaluated and used in clinical practice. As the field continues to evolve, bioactive materials are likely to become the gold standard in restorative and preventive dentistry, setting the stage for improved patient care and long-term oral health.

#### **4. Cutting-Edge Technologies in Dental Material Development**

Innovations in dental materials are transforming the field of dentistry, driven by cutting-edge technologies that improve functionality, biocompatibility, and bioactivity. These advancements are enabling the creation of smarter, more efficient materials tailored to the needs of patients and clinicians alike.

##### **Nanotechnology in Dental Materials**

Nanotechnology has revolutionized dental material science by manipulating materials at the molecular level to enhance their properties. Applications include.

- **Nanofillers in Composites.** Provide superior strength, wear resistance, and aesthetic properties.
- **Antibacterial Nanoparticles.** Incorporation of silver or zinc nanoparticles to reduce biofilm formation and secondary caries.
- **Nano-Hydroxyapatite.** Used in toothpastes and remineralizing agents to repair enamel and prevent sensitivity.

##### **3D Printing and Additive Manufacturing**

The advent of 3D printing has enabled unprecedented precision and customization in dental materials. Examples include.

- **Customized Restorations.** Fabrication of crowns, bridges, and dentures tailored to individual patient anatomy.
- **Surgical Guides.** Precise planning and execution of implant surgeries using 3D-printed guides.
- **Biofabrication.** Emerging potential to print materials that mimic natural dental tissues.

##### **Smart Materials with Adaptive Properties**

Smart dental materials are engineered to respond dynamically to changes in the oral environment. Key innovations include.

- **Self-Healing Composites.** Materials that repair microcracks autonomously, extending the



lifespan of restorations.

- **pH-Sensitive Materials.** Respond to acidic environments by releasing remineralizing ions, preventing demineralization.
- **Thermochromic Materials.** Change color in response to temperature, offering diagnostic potential.

### **Digital Dentistry and CAD/CAM Technology**

Computer-Aided Design and Manufacturing (CAD/CAM) systems have streamlined the production of dental restorations. Benefits include.

- **Precision and Speed.** Faster fabrication of high-accuracy restorations compared to traditional methods.
- **Reduced Material Waste.** Efficient use of dental materials, reducing environmental impact.

### **Bioengineering and Regenerative Materials**

Advances in bioengineering have enabled the development of regenerative materials for tissue repair and regeneration. Examples include.

- **Stem Cell-Infused Scaffolds.** Promote the regeneration of bone and periodontal tissues.
- **Peptide-Based Biomaterials.** Enhance cellular attachment and tissue growth in dental applications.

### **AI-Driven Material Design**

Artificial Intelligence (AI) is becoming a powerful tool in the discovery and development of dental materials. Contributions include.

- **Predictive Modeling.** AI algorithms predict material behavior under various conditions, optimizing formulations.
- **Customization.** Tailoring material properties to specific patient needs based on clinical data.

### **Sustainability in Dental Material Technologies**

The growing emphasis on sustainability has influenced material development, encouraging the use of eco-friendly technologies.



- **Biodegradable Materials.** Reduce environmental impact without compromising performance.
- **Recyclable Packaging and Processes.** Aim to minimize waste during production and application.

### Challenges and Future Directions

Despite these advancements, challenges persist.

- **High Costs.** Cutting-edge technologies are often expensive, limiting accessibility in certain regions.
- **Integration into Clinical Practice.** Training and education are needed to ensure widespread adoption by dental professionals.
- **Long-Term Validation.** Many new materials require long-term clinical trials to establish efficacy and safety.

Cutting-edge technologies in dental materials are shaping the future of dentistry, enabling more effective, personalized, and sustainable solutions for oral healthcare. These innovations continue to push the boundaries of what is possible, promising significant improvements in patient outcomes and clinical efficiency.

## 5. Key Characteristics of Modern Dental Materials

Modern dental materials are designed to meet the evolving demands of restorative, preventive, and aesthetic dentistry. These materials blend advanced functionality with patient-centered considerations, ensuring durability, safety, and biocompatibility while enhancing the overall oral health experience.

### 1. Biocompatibility

- Dental materials must not cause adverse reactions in the oral tissues or systemic toxicity.
- Ensures compatibility with the oral environment, minimizing inflammation, allergies, or hypersensitivity.

### 2. Bioactivity

- A hallmark of modern materials, bioactivity promotes interaction with surrounding tissues to stimulate healing, remineralization, or regeneration.
- Examples. Glass ionomer cements that release fluoride, and bioactive glasses that



encourage hydroxyapatite formation.

### **3. Aesthetic Excellence**

- Materials must mimic the natural appearance of teeth in terms of color, translucency, and texture.
- Composite resins, ceramics, and zirconia achieve life-like esthetics with superior color stability.

### **4. Strength and Durability**

- Resistance to mechanical forces like chewing, grinding, and biting is essential to avoid fractures or wear.
- Materials such as high-strength ceramics and nanofilled composites exhibit enhanced toughness and longevity.

### **5. Adhesive Properties**

- Strong bonding to tooth surfaces or restorations minimizes the risk of detachment and secondary decay.
- Advances in adhesive systems ensure durable bonds with minimal technique sensitivity.

### **6. Antimicrobial Effects**

- Many modern materials incorporate antibacterial agents, such as silver nanoparticles or fluoride, to inhibit bacterial growth and biofilm formation.
- Reduces the risk of secondary caries and postoperative infections.

### **7. Resistance to Degradation**

- Resistance to hydrolysis, discoloration, and degradation in the moist oral environment is critical.
- Modern materials, such as advanced composites and ceramics, maintain their structural integrity over time.

### **8. Ease of Handling and Application**

- Materials should be user-friendly for clinicians, offering consistency in application and predictable results.
- Light-curing composites and bulk-fill materials improve efficiency and reduce chair time.



## **9. Thermal Compatibility**

- The coefficient of thermal expansion should match that of natural tooth structures to prevent microleakage or cracking due to temperature changes.

## **10. Smart Functionality**

- Smart materials exhibit adaptive properties, such as self-healing, pH-sensitivity, or color change, enhancing their performance in dynamic oral conditions.
- Example. Materials that release remineralizing ions when exposed to acidic environments.

## **11. Sustainability and Eco-Friendliness**

- Growing demand for sustainable materials that minimize environmental impact during production and disposal.
- Use of biodegradable components and recyclable packaging aligns with green dentistry practices.

## **12. Cost-Effectiveness**

- Affordability remains a critical factor to ensure accessibility, particularly in regions with limited healthcare resources.
- Manufacturers strive to balance advanced features with economic feasibility.

## **Applications of These Characteristics**

- Restorative procedures. Fillings, crowns, and bridges rely on strength, aesthetics, and biocompatibility.
- Preventive dentistry. Sealants and fluoride-releasing materials combat early decay.
- Prosthodontics. Dentures and implants require durability, comfort, and precision.

By integrating these key characteristics, modern dental materials not only restore form and function but also actively contribute to long-term oral health and patient satisfaction. The continued evolution of these materials reflects the dynamic needs of contemporary dentistry.

## **6. Smart Materials in Dentistry**

Smart materials represent a transformative innovation in dentistry, offering adaptive properties that respond dynamically to the oral environment. Unlike traditional materials, which are static in nature, smart materials are designed to sense changes and react in ways that enhance their



functionality, durability, and therapeutic benefits.

### **Characteristics of Smart Materials**

Smart materials are characterized by their ability to respond to stimuli such as temperature, pH changes, mechanical stress, or moisture. These responses can include self-healing, remineralization, or changes in color, making them versatile and effective in various dental applications.

### **Examples of Smart Materials**

One prominent example is self-healing composites, which are engineered to repair microcracks autonomously by releasing monomers that polymerize upon damage. Another is pH-sensitive materials, which release remineralizing ions like calcium and phosphate in acidic conditions to counteract enamel demineralization. Additionally, shape-memory alloys, commonly used in orthodontics, can revert to their original form under specific conditions, ensuring precise tooth movement.

### **Applications in Dentistry**

Smart materials have broad applications across dental specialties. In restorative dentistry, self-healing composites prolong the life of restorations by addressing minor damages. In orthodontics, shape-memory alloys enhance treatment efficiency and comfort. Preventive applications include bioactive sealants that actively release fluoride in response to pH changes, preventing early-stage decay.

### **Advantages Over Conventional Materials**

These materials provide significant advantages over conventional ones. They offer enhanced longevity due to their self-repair mechanisms and adaptability. Their ability to actively interact with the oral environment also reduces the risk of secondary caries or restoration failure. Moreover, smart materials can improve patient outcomes by promoting tissue healing and regeneration.

### **Challenges and Future Directions**

Despite their benefits, smart materials face challenges, including higher costs, technical sensitivity, and the need for specialized handling. Research is ongoing to develop more affordable and user-friendly options. Future directions include integrating artificial intelligence and nanotechnology to create even more responsive and efficient materials tailored to individual patient needs.

Smart materials in dentistry are paving the way for a more adaptive and patient-centered approach to oral healthcare. Their ability to respond intelligently to the dynamic oral environment represents



a significant leap forward in material science and clinical dentistry.

## **7. Comparative Analysis. Biocompatible vs. Bioactive Materials**

The development of dental materials has transitioned from prioritizing biocompatibility to embracing bioactivity as a critical feature. While both types of materials have their merits, their distinct properties and applications shape how they contribute to dental treatments.

### **Definition and Core Principles**

**Biocompatible Materials** are designed to coexist with living tissues without causing adverse reactions. They are inert and chemically stable, ensuring they do not harm surrounding tissues or the systemic health of patients.

**Bioactive Materials**, on the other hand, interact dynamically with tissues to promote biological responses. They are engineered to stimulate healing, regeneration, and remineralization, going beyond mere compatibility to actively enhance oral health.

### **Functional Differences**

- Interaction with Tissues**  
Biocompatible materials maintain a passive relationship with tissues, ensuring they do not irritate or harm the oral environment. For example, gold alloys and ceramics are biocompatible but do not integrate with tissues. Bioactive materials, such as calcium silicate cements, release ions that stimulate tissue regeneration and create a chemical bond with dental structures.
- Therapeutic Benefits**  
Biocompatible materials primarily serve structural and restorative roles. They are reliable and durable but lack the capability to enhance tissue health actively. Bioactive materials offer therapeutic benefits by promoting the formation of new dentin, inhibiting bacterial growth, and facilitating the remineralization of enamel.
- Applications**  
Biocompatible materials are widely used for fillings, crowns, and prosthetics where stability and durability are critical. Bioactive materials find applications in restorative, preventive, and regenerative dentistry, such as endodontic treatments (e.g., mineral trioxide aggregate) and fluoride-releasing restorations.



## Comparative Advantages

- **Biocompatible Materials.** Known for their reliability, non-toxicity, and ability to function effectively without disrupting biological systems. They are often cost-effective and readily available.
- **Bioactive Materials.** Provide added value by enhancing tissue healing, reducing secondary caries, and improving the longevity of restorations through active biological interactions.

## Limitations

Biocompatible materials, while safe, do not contribute to the regeneration of tissues, potentially leading to the need for replacement over time. Conversely, bioactive materials, though highly effective, can be cost-prohibitive and require more advanced clinical expertise to apply correctly.

## Clinical Implications

The choice between biocompatible and bioactive materials depends on the specific needs of the patient and the clinical scenario. In cases requiring long-term structural stability, biocompatible materials may suffice. However, for situations where healing, regeneration, or prevention of recurrent issues is necessary, bioactive materials offer significant advantages.

## Conclusion

The evolution of dental materials from biocompatibility to bioactivity marks a significant shift in restorative and preventive dentistry. Biocompatible materials laid the foundation for safe, durable restorations, focusing on minimizing adverse tissue reactions. However, the advent of bioactive materials has introduced a paradigm shift, emphasizing not just compatibility but active contribution to oral health.

Bioactive materials go beyond passive functionality, promoting tissue regeneration, remineralization, and antimicrobial properties. This transformative approach has redefined dental care, providing solutions that are not only restorative but also preventive and regenerative. Innovations such as nanotechnology, 3D printing, and smart materials have further enhanced the capabilities of bioactive materials, enabling customized and efficient treatments.

Despite challenges like higher costs and technical complexity, bioactive materials represent the future of dentistry. Their ability to interact dynamically with oral tissues ensures better patient outcomes, reduced secondary caries, and prolonged restoration life. As research and technology advance, these materials will become more accessible, bridging the gap between advanced science and routine clinical practice.



The integration of biocompatible and bioactive materials in dentistry provides a comprehensive toolkit for addressing diverse clinical needs. This synergy offers clinicians the flexibility to tailor treatments, ensuring long-term success and patient satisfaction. By embracing bioactivity as the new gold standard, dental material science is poised to deliver a new era of sustainable, effective, and patient-centered care.

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