

Bioceramics in Dentistry: Applications, Advantages, and Clinical Challenges

Jimmy Cedillo Sr.¹, Ambreen Askar Bangash², Nikita Subhashbhai Agrawal³, Shifa Sakhi⁴, Naina Tasneem⁵, Yuktha Ameersheti⁶

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1. Department of Dentistry, University of Guayaquil, Guayaquil, ECU 2. Department of Dentistry, Sardar Begum Dental College, Gandhara University, Peshawar, PAK 3. Department of Bioengineering, Northeastern University, Boston, USA 4. Department of Healthcare Management, Concordia University Chicago, River Forest, USA 5. Department of Dentistry, Trine University, Angola, USA 6. Department of Health Informatics, Roosevelt University, Chicago, USA

Corresponding author: Jimmy Cedillo Sr., jjerry_cedillo@hotmail.com

Abstract

Bioceramic materials are increasingly used in dentistry because of their biocompatibility, sealing properties, and potential to support mineralized tissue formation. This narrative review summarizes their composition, properties, clinical applications, advantages, and limitations across vital pulp therapy, endodontic repair, periodontal and osseous regeneration, implant dentistry, restorative treatment, and tissue engineering. Calcium silicate cements, calcium phosphate ceramics, bioactive glass, zirconia, and alumina serve different clinical purposes, and their performance depends on formulation, handling, setting reactions, and treatment indication. Although laboratory and clinical findings support several biological and sealing advantages, these outcomes do not consistently establish superior long-term clinical effectiveness. Material selection should therefore be indication-specific and informed by comparative clinical evidence, mechanical and handling properties, esthetic requirements, retreatability, and cost. Well-designed trials with standardized outcomes and longer follow-up are needed to clarify the comparative effectiveness and cost-effectiveness of individual bioceramic formulations. Unlike previous reviews focusing on specific materials or dental applications, this review provides an integrated assessment of bioceramics across multiple dental disciplines, highlighting their clinical applications, advantages, and limitations. It distinguishes laboratory findings from clinical outcomes, identifies evidence gaps, and emphasizes the need for long-term comparative studies to guide evidence-based material selection.

Categories: Dentistry

Keywords: bioceramics, dental materials, dentistry, endodontics, pulp treatment

Introduction And Background

Biomaterials are designed to treat, repair, or replace damaged tissues while remaining in the body with minimal adverse tissue reactions and maintaining biocompatibility. The first biomaterials, made of ceramics, were developed primarily to be biocompatible, that is, to stay in the body without causing any appreciable adverse tissue reactions. Calcium phosphate ceramics became especially significant as their composition is very similar to the mineral phase of bone and dental tissue [1]. Of particular importance was hydroxyapatite, which is tissue-compatible and osteoconductive and is thus suitable for dental and bone applications. Further research led to the use of calcium phosphate ceramics as grafting materials being replaced by use in coatings, cements, scaffolds, and other more complex biocompatible materials [2].

The development of bioactive glass in 1969 was a major breakthrough. Larry Hench and his colleagues developed the synthetic material 45S5 Bioglass and showed that it could bond with live bone better than it did with nothing. Bioactive glass could react with body fluids and create a surface layer similar to that of the mineral part of bone. It was this discovery that helped develop a new paradigm in biomaterial research, shifting from a material which is tolerated by tissues to one that can actively interact with tissues [3].

Further developments brought a wider variety of calcium phosphate ceramics, bioactive glasses, glass-ceramics, and related materials for dental and biomedical applications. They were able to interact with hard structures and facilitate mineral deposition, thus stimulating research in bone regeneration, periodontal therapy, implant surfaces, and restorative dentistry. In addition, bioceramic materials were used in restorative materials and dental adhesives [4]. Researchers have reported the use of amorphous calcium phosphate, hydroxyapatite, bioactive glass, and tricalcium phosphate in the restorative systems, as they are capable of stimulating mineralization and enhancing interactions at the dental material-tooth interface [5].

Recently, bioceramics have evolved toward the development of new materials with specific biological functions. Existing formulations can be formulated to provide valuable ions, facilitate the formation of apatite, control cellular response, or have antimicrobial properties [6]. The biocompatibility of bioactive glass, its mineral-forming ability, and possible antimicrobial activity have been studied in many fields of dentistry. Processing techniques and surface modification have also been improved to allow the composition

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and structure of these materials to be optimized for the desired biological and clinical results [7].

The advent of dental bioceramics is therefore a new step toward more bioactive and regenerative systems from relatively inert materials. No longer simply filling gaps of missing tooth or bone structure, current research is working to develop materials that will interact positively with the body's healing processes [8]. This has led bioceramics to become a significant field of study within the dental materials field and provides a stimulus for restorative, regenerative, and tissue-preserving ideas in dentistry [9].

Unlike previous reviews focusing on specific bioceramic materials or dental applications, this review provides an integrated evaluation of their roles across multiple dental disciplines. It addresses the knowledge gap between laboratory findings and clinical effectiveness, highlighting material-specific limitations and the need for long-term comparative evidence. The present review addresses limitations of previous literature by integrating evidence across multiple dental applications, critically distinguishing laboratory findings from clinical outcomes, and identifying gaps in long-term comparative effectiveness and cost-effectiveness.

Review

A narrative literature search was conducted using PubMed/MEDLINE, Google Scholar, Web of Science, and Scopus to identify relevant publications on bioceramic materials in dentistry. The search focused on material composition, physicochemical properties, biocompatibility, bioactivity, clinical applications, advantages, limitations, and emerging developments. Relevant search concepts included "bioceramics," "calcium silicate cement," "mineral trioxide aggregate," "Biodentine," "calcium phosphate ceramics," "bioactive glass," "zirconia," and "alumina," combined with dental application terms such as "endodontics," "vital pulp therapy," "periodontal regeneration," "dental implants," "remineralization," "restorative dentistry," and "tissue engineering." The literature was considered for its relevance to the review objectives, reported material properties, clinical applications, and limitations. As this was a narrative review, the literature was synthesized descriptively rather than through a formal systematic review protocol. The exact search dates, database-specific search strings, and selection counts were not retained in the available records and are therefore not reported.

Bioceramics in endodontics and pulp protection

Endodontics involves the diagnosis, prevention, and treatment of diseases of the dental pulp, root canal system, and periradicular tissues [10]. Bioceramic materials have developed new treatment possibilities due to their favorable biological responses, sealing, and mineralized tissue-inducing properties. They are used in vital pulp therapy, root-end filling, apexification, perforation repair, and root canal obturation. The performance characteristics of the materials used for the clinical application depend upon the composition, physical properties, placement, and interaction with the surrounding tissues [11].

Mineral trioxide aggregate (MTA) has been extensively studied as a sealant material and for procedures involving direct pulp and periradicular contact. It can be used for direct pulp capping, pulpotomy, apexogenesis, barrier formation in apically open teeth, and repair of root and furcation perforations. MTA has been used in clinical studies with success in vital pulp therapy; in some studies, MTA was superior to calcium hydroxide in terms of success rate for direct pulp capping [12]. However, long setting time, handling problems, and tooth staining have made alternative formulations desirable.

Another calcium silicate cement employed for dentin replacement and vital pulp therapy is Biodentine. It has a relatively quick set time and incremental development of mechanical properties. The formulation is different from other products containing bismuth oxide as a radiopacifier, which may cause discoloration, and is made with zirconium oxide, which may decrease discoloration. In laboratory studies, Biodentine has also shown good push-out bond strength, and there is some indication that blood contamination would be less detrimental to Biodentine push-out bond than to MTA Plus. However, its comparative long-term clinical effectiveness needs to be explored [13].

Additionally, pre-mixed calcium silicate-based repair materials have also been developed, such as EndoSequence Root Repair Material and iRoot's range of products, to make clinical delivery easier. Under moist conditions, these materials can set and have been shown to be biocompatible in experimental studies. A few studies, however, have found that there is more leakage of bacteria through MTA than through other materials, which means that the sealing ability is not necessarily as good as that of other materials with good biological properties [14].

Other materials such as calcium-enriched mixture cement and BioAggregate have been shown to be potential pulpal protection and mineralized tissue formation materials. As calcium-enriched mixture cement is reported to possess antibacterial properties, good sealing ability, and to facilitate dentin bridge formation [15], it has been investigated as a direct and indirect pulp capping material. BioAggregate has been shown to release calcium ions and supports the migration of pulp cells, odontoblastic differentiation, and mineralization [16]. While these results warrant further investigation, evidence should be considered within the context of the study design and clinical relevance.

Besides MTA and Biodentine, other notable endodontic bioceramics include EndoSequence Root Repair Material, iRoot BP Plus, BioAggregate, and calcium-enriched mixture cement, which differ in composition, handling, setting characteristics, sealing ability, and biological response. Although these materials demonstrate promising properties for pulp protection, perforation repair, and apical barrier formation, their comparative clinical effectiveness, retreatability, cost, and long-term outcomes require further evaluation [17].

Bioceramics beyond endodontics

Bioceramics are widely explored in the fields of periodontal regeneration, implant dentistry, restorative treatment, and tissue engineering. The clinical relevance of their use goes beyond structural replacement, as some formulations are able to react with surrounding tissues and promote mineral deposition [18]. However, the biological activity and clinical performance of these materials vary depending on the composition, surface properties, and application.

Periodontal and Osseous Regeneration

Alveolar bone, periodontal ligament, and cementum may be lost due to periodontal disease. Effective regeneration of these tissues is needed, not just the regeneration of the bone [19]. Scaffolds are being investigated using calcium phosphate-based materials that resemble the inorganic component of natural bone, such as hydroxyapatite and tricalcium phosphate. These materials can serve as a template for tissue ingrowth and allow cell and mineralized tissue interaction [19,20].

Bioactive glass has also been paid attention to due to its interaction with physiological fluids. It can form a hydroxycarbonate apatite surface, which can enhance the bonding with mineralized tissues. Systematic reviews have been published reporting positive clinical results since the application of bioactive glass for periodontal bone defects. However, the variability in the morphology of the defects, surgical procedures, and follow-up period, and in the methodology of the studies makes it difficult to develop a single predictable treatment protocol [20].

Therefore, bioceramics should be used as an integral part of a comprehensive periodontal treatment plan, and not as alternatives to proven regenerative treatments. The clinical effectiveness must be assessed based on appropriate outcome measures such as probing depth reduction, clinical attachment gain, radiographical bone changes, and long-term tooth retention. Another point of investigation should also include separating improvements in the radiographic bone fill from actual regeneration of the periodontal attachment apparatus [21].

Implant Dentistry

Because of its esthetic properties, biocompatibility, and corrosion resistance, zirconia has become an alternative ceramic material to be used in dental implants [1,20]. It is tooth-colored, which can be beneficial in certain clinical cases, especially in cases where soft-tissue appearance is critical.

Although there are indications for the benefit of zirconia implants, there is not yet sufficient evidence for indirect comparison of zirconia implants to conventional implants made from titanium. Clinical outcomes may be affected by variations in patient characteristics, loading protocols, surface treatment, and implant design. Further studies with longer-term follow-up periods and well-designed comparative studies are needed to address implant survival, changes in marginal bone, soft-tissue response, and mechanical complications [20].

The research on ceramic implant design has been extended by additive manufacturing. Three-dimensional printing can allow the creation of custom-made structures that have defined geometry and composition. The clinical application of these technologies, however, requires consistent manufacturing, sufficient mechanical properties and fatigue resistance, and proven osseointegration. Improvements in material properties, obtained from experiments, must not be used to demonstrate clinical superiority [21].

Restorative Dentistry and Remineralization

Studies have been conducted on the use of bioactive glass and calcium phosphate-containing materials with the view of releasing calcium and phosphate ions to promote remineralization of enamel and dentin [2,17]. These materials can be used in restorative materials, dentin hypersensitivity management, and prevention of mineral loss. They are not so much meant for mechanical restoration as for their potential biological activity [22].

However, laboratory mineral deposition does not mean long-term clinical remineralization. Factors such as oral fluids, dietary acids, bacterial activity, mechanical loading, and patient-related factors can all impact the longevity of mineral deposits and the performance of restorative materials. Further controlled clinical trials are required to establish if the laboratory effects seen have any clinical significance in terms of tooth

structure protection, sensitivity decrease, and restoration longevity [23].

Tissue Engineering and Regenerative Applications

The use of bioceramics in tissue engineering systems is also being investigated. Structural support and regulation of cellular interaction during tissue repair can be provided by calcium phosphate scaffolds and bioactive ceramic composites [17]. Their usefulness depends on the relationship between mechanical stability, porosity, degradation, and the release of biologically active ions [24].

New techniques focus on incorporating bioceramics with collagen or polymers or biologically active molecules to enhance cellular reactions and tissue integration. While these advances are encouraging, therapeutic use of these depends on evidence of consistent biological response, safety, and long-term therapeutic efficacy [25] (Table 1).

Clinical application	Bioceramic materials	Key properties and potential benefits	Limitations and evidence considerations
Vital pulp therapy	Mineral trioxide aggregate (MTA), Biodentine	Biocompatibility, dentin bridge formation, and support for pulp protection	MTA has a prolonged setting time and may cause discoloration; long-term comparative evidence for Biodentine requires further investigation [12,13]
Endodontic repair and apexification	MTA, EndoSequence Root Repair Material, iRoot products	Sealing ability, biocompatibility, and applicability in perforation repair and apical barrier formation	Sealing performance varies by formulation; some studies report differences in bacterial leakage [14]
Pulp protection and mineralization	Calcium-enriched mixture (CEM) cement, BioAggregate	Antibacterial potential, calcium-ion release, pulp-cell migration, and mineralized tissue formation	Further research is required to establish comparative clinical effectiveness [15,16]
Periodontal and osseous regeneration	Hydroxyapatite, tricalcium phosphate, bioactive glass	Support for tissue ingrowth, mineralized tissue interaction, and potential improvement in periodontal bone defects	Outcomes vary with defect morphology, surgical technique, and follow-up; radiographic bone fill does not necessarily demonstrate periodontal attachment regeneration [20,21]
Implant dentistry	Zirconia, calcium phosphate coatings	Esthetic potential, corrosion resistance, biocompatibility, and possible enhancement of implant–bone interactions	Long-term comparative evidence regarding implant survival, marginal bone changes, and mechanical complications remains necessary [20,21]
Restorative dentistry and remineralization	Bioactive glass, calcium phosphate-containing materials	Calcium and phosphate ion release, potential remineralization, and management of dentin hypersensitivity	Laboratory mineral deposition does not establish long-term clinical effectiveness; controlled clinical trials are needed [23]
Tissue engineering	Calcium phosphate scaffolds, bioactive ceramic composites	Structural support, cellular interaction, and potential integration with collagen, polymers, or bioactive molecules	Performance depends on mechanical stability, porosity, degradation, safety, and long-term therapeutic efficacy [24,25]

TABLE 1: Applications of bioceramic materials in dentistry.

Table created by authors.

Biological properties and clinical advantages

Bioceramic materials have been shown to possess good biocompatibility, bioactivity, and sealing properties, which make them suitable for use in vital pulp therapy, endodontic repair, and periradicular procedures. Some of the calcium silicate-based products release calcium and hydroxyl ions, which leads to mineral deposition and makes the pH alkaline, potentially inhibiting certain microorganisms. Other materials also create an interfacial layer of hydroxyapatite, which could contribute to mineralized tissue formation [26].

Further well-designed clinical studies are needed to establish the long-term effectiveness, safety, and cost-effectiveness of bioceramic materials across different dental applications. These properties may, however, change depending on the chemical composition, setting reactions, and application methods. Other factors that affect the clinical outcome include the following: pulpal diagnosis, control of contamination, canal disinfection, coronal sealing, and case selection. Laboratory evidence of release of ions, mineralization, and/or reduced leakage does not confirm long-term clinical success [27]. Despite these benefits, however, bioceramic materials have some clinical limitations such as relatively high cost, setting time and handling inconsistencies, and retreatment problems. Some sealers set tightly within the dentinal surface, hindering removal if the seal is persistent or the treatment fails. Furthermore, some formulations with bismuth oxide can discolor teeth, but other radiopacifiers such as zirconium oxide have been developed to minimize this. Their mechanical properties, such as brittleness, fracture resistance, and degradation characteristics, also play a role in their suitability for certain restorative and implant applications. These restrictions emphasize the need to consider each formulation on a case-by-case basis, based on its specific clinical use. The selection of each material should be based on clinical evidence, procedure requirements, esthetic considerations, cost-effectiveness, and the expected long-term performance, and not on the premise that all bioceramic materials have the same benefits [28].

Bioceramic materials exhibit good biocompatibility, bioactivity, and sealing properties, and are used in vital pulp therapy, periradicular procedures, and endodontic repair. Some of the calcium silicate-based formulations release calcium ions and hydroxyl ions, which leads to mineral deposits and an alkaline environment that can inhibit some microorganisms. Some materials also develop a layer of hydroxyapatite at their surface, which may facilitate mineralized tissue formation. They also have the ability to adapt to dentinal surfaces, dimensional stability, and moisture tolerance, which can potentially improve clinical utility. The properties, however, are dependent on chemicals, setting reactions, and application methods. Other factors such as pulpal diagnosis, contamination control, canal disinfection, coronal sealing, and case selection also play a significant role in the clinical outcome. Leakage, mineralization, or release of ions in the laboratory does not necessarily mean that the long-term clinical results will be better [29]. The principal biological properties, clinical advantages, and limitations of bioceramic materials relevant to their clinical selection are summarized in Table 2.

Property or consideration	Biological or clinical significance	Limitations and clinical implications
Biocompatibility	Supports use in procedures involving pulp, periodontal tissues, and periradicular structures [26]	Tissue response depends on the specific formulation and clinical application [27]
Bioactivity and mineralization	Calcium-ion release and hydroxyapatite formation may support mineralized tissue deposition [26,29]	Laboratory mineralization does not independently establish superior clinical outcomes [27,29]
Alkaline pH	Hydroxyl-ion release can create an alkaline environment that may inhibit certain microorganisms [26,29]	Antimicrobial effects alone do not guarantee successful treatment [27]
Sealing ability and dentinal adaptation	Adaptation to dentinal surfaces and sealing properties may contribute to treatment effectiveness [26,27]	Performance varies by material composition, setting reaction, and placement technique [27]
Moisture tolerance and dimensional stability	May facilitate use in selected endodontic repair procedures [27,29]	Clinical outcomes also depend on contamination control, canal disinfection, coronal sealing, and case selection [27]
Setting and handling properties	Influence placement, manipulation, and procedural efficiency [28,30]	Setting time and handling inconsistencies may complicate clinical use [28,30]
Esthetic performance	Zirconium oxide radiopacifiers may reduce the discoloration associated with certain bismuth oxide-containing formulations [13,28]	Discoloration risk remains formulation-dependent and should be considered in esthetically sensitive areas [28]
Retreatment and mechanical performance	Material strength, fracture resistance, and degradation behavior influence suitability for different applications [28,30]	Some sealers adhere strongly to dentinal surfaces and may be difficult to remove during retreatment [30]
Cost and long-term effectiveness	Evidence-based material selection can support appropriate clinical and economic decisions [28]	Higher costs and insufficient long-term comparative evidence may limit the choice of material [28,30]

TABLE 2: Biological properties, clinical advantages, and limitations of bioceramic materials.

Table created by authors.

Although these benefits are apparent, bioceramic materials also have certain clinical drawbacks such as high costs, inconsistent setting time and handling properties, and possible handling problems during retreatment. Some sealers set to the dentinal surfaces very tightly, and removal is difficult in the event of a persistent infection or treatment failure [30]. In addition, some preparations with bismuth oxide can make the teeth discolored, and some other radiopacifiers were developed to minimize this effect, such as zirconium oxide. Mechanical properties such as brittleness, fracture resistance, and degradation behavior also affect their suitability for certain applications in restorative and implant materials. These restrictions underscore the need to take individual formulations into consideration for the clinical indications for which they are intended. It is important to note that while material selection may be informed by evidence-based clinical data, procedural needs, esthetic goals, cost considerations, and potential long-term results, the benefits are not necessarily consistent for all bioceramic materials [29,30].

Further well-designed comparative clinical trials with standardized outcomes and longer follow-up are necessary to establish their long-term effectiveness, safety, and cost-effectiveness and to support evidence-based material selection in clinical dentistry.

Conclusions

Bioceramic materials offer promising benefits across diverse dental applications, particularly in endodontic repair, tissue regeneration, implant dentistry, and restorative treatment. However, their clinical effectiveness varies by formulation and indication, and favorable laboratory findings do not necessarily translate into superior long-term outcomes. Therefore, material selection should be guided by available clinical evidence, procedural requirements, mechanical and esthetic properties, retreatability, and cost. Further well-designed comparative clinical trials with standardized outcomes and extended follow-up are needed to establish the long-term effectiveness and cost-effectiveness of individual bioceramic materials and strengthen evidence-based clinical decision-making.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Jimmy Cedillo Sr., Ambreen Askar Bangash, Nikita Subhashbhai Agrawal, Shifa Sakhi, Naina Tasneem, Yuktha Ameersheti

Acquisition, analysis, or interpretation of data: Jimmy Cedillo Sr., Ambreen Askar Bangash, Nikita Subhashbhai Agrawal, Shifa Sakhi, Naina Tasneem, Yuktha Ameersheti

Drafting of the manuscript: Jimmy Cedillo Sr., Ambreen Askar Bangash, Nikita Subhashbhai Agrawal, Shifa Sakhi, Naina Tasneem, Yuktha Ameersheti

Critical review of the manuscript for important intellectual content: Jimmy Cedillo Sr., Ambreen Askar Bangash, Nikita Subhashbhai Agrawal, Shifa Sakhi, Naina Tasneem, Yuktha Ameersheti

Supervision: Jimmy Cedillo Sr.

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