BIODENTINE AS A BIOACTIVE TRICALCIUM SILICATE-BASED DENTINE SUBSTITUTE: PHYSICOCHEMICAL PROPERTIES, BIOLOGICAL INTERACTIONS, AND CLINICAL APPLICATIONS

Magdalena Rusu-Negraia [1,2], Dorin Ioan Cocoş [1,2,*], Antoanela Magdalena Covaci [1,2,*], Kamel Earar [1,2]

1. "Dunărea de Jos" University of Galati, Faculty of Medicine and Pharmacy, Medical and Pharmaceutical Research Center, 800008 Galati, Romania.
2. Dental-Medicine Department, Faculty of Medicine and Pharmacy, "Dunărea de Jos" University of Galati, 800201 Galati, Romania.
* Corresponding authors: Dorin Ioan Cocoş: cdorin1123@gmail.com
Antoanela Magdalena Covaci: anto_lucaci@yahoo.com

† All authors contributed equally to this work.

Abstract

Biodentine is a bioactive hydraulic calcium silicate–based material developed as a dentine substitute to overcome limitations associated with calcium hydroxide liners and mineral trioxide aggregate–based cements. This narrative review summarizes current evidence regarding its physicochemical properties, biological activity, interfacial behavior, adhesive performance, and clinical applications in restorative dentistry and endodontics. Biodentine is characterized by accelerated hydration, zirconium oxide–based radiopacity, progressive maturation, favorable dimensional stability, and mechanical properties approaching those of natural dentine. Its bioactivity is mediated by calcium and hydroxyl ion release, alkaline pH, mineral precipitation, and stimulation of pathways involved in pulp repair, odontogenic differentiation, and biomineralization. At the dentine–material interface, Biodentine demonstrates direct adaptation and ionic interaction, although interfacial morphology is influenced by maturation, placement technique, and analytical methodology. Clinically, it has shown favorable outcomes in vital pulp therapy, deep caries management, temporary coronal restoration, dentine replacement, perforation repair, apexification, and root-end filling. Its performance nevertheless depends on isolation, irrigation protocols, sufficient maturation, restorative timing, and case selection. Current evidence supports Biodentine as a clinically relevant bioactive dentine substitute, although further standardized long-term studies are required.

Keywords: Biodentine; hydraulic calcium silicate cement; dentine substitute; bioactivity; dentine–material interface; vital pulp therapy; restorative dentistry; endodontic repair.

1. Physicochemical characteristics of Biodentine

Biodentine is a tricalcium silicate–based dental material developed as a bioactive dentine substitute, designed to overcome several physicochemical and clinical limitations associated with earlier calcium hydroxide- and mineral trioxide aggregate (MTA)-based materials. Its formulation and behavior have been extensively investigated, with particular emphasis on composition, hydration mechanisms, mechanical performance, and stability in the oral environment [1–4].

From a compositional perspective, Biodentine consists primarily of tricalcium silicate (Ca_3SiO_5) as the main reactive phase, complemented by calcium carbonate as a filler and zirconium oxide as a radiopacifier [1,2]. Unlike MTA, which typically incorporates bismuth oxide, the use of zirconium oxide confers adequate radiopacity while minimizing undesirable effects on setting reactions and color stability [2–4].

The liquid component contains calcium chloride as a setting accelerator and a water-reducing hydrosoluble polymer, which together play a crucial role in

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controlling the kinetics of hydration and improving handling characteristics [1,2].

The setting reaction of Biodentine is governed by the hydration of tricalcium silicate, leading to the formation of a calcium silicate hydrate (C–S–H) gel and calcium hydroxide as secondary products [2]. This process is analogous to that observed in Portland cement-based materials; however, the optimized particle size distribution and the presence of calcium chloride significantly accelerate the reaction. As a result, Biodentine exhibits a clinically favorable initial setting time of approximately 12 minutes, markedly shorter than that of conventional MTA [1,2]. This rapid setting reduces the risk of material dissolution or displacement during the early post-placement period and allows single-visit clinical protocols in restorative and endodontic procedures [1].

Detailed physicochemical analyses have demonstrated that the hydration of Biodentine continues beyond the initial setting phase, contributing to progressive maturation of the material and enhancement of its mechanical properties over time [2,4].

The formation of a dense C–S–H matrix, combined with controlled porosity, underpins its mechanical behavior. Studies evaluating compressive strength have shown that Biodentine reaches values comparable to those of natural dentine after full maturation, supporting its indication as a dentine substitute rather than merely a base or liner material [1,4].

Porosity and microstructural characteristics are critical determinants of both mechanical resistance and sealing ability. Investigations comparing Biodentine with other calcium silicate-based materials, including MTA and Bioaggregate, have reported a relatively homogeneous microstructure with reduced interconnected porosity once the material has fully set [3,4]. This microstructural compactness contributes to improved resistance to disintegration and reduced solubility when exposed to physiological fluids, features that are essential for long-term clinical stability [3,4]. Moreover, the dimensional stability of Biodentine during and after setting minimizes gap formation at the tooth, material interface, a factor closely linked to marginal integrity and prevention of microleakage [1,3].

Radiopacity is another essential physicochemical requirement for materials used in restorative dentistry and endodontics. The incorporation of zirconium oxide ensures that Biodentine meets established standards for radiographic detectability while maintaining chemical inertness within the cement matrix [2-4]. Unlike bismuth oxide-containing materials, zirconium oxide does not adversely affect hydration or contribute to discoloration, which is particularly relevant in aesthetically demanding clinical situations [4].

Thermal and chemical stability in the moist oral environment further distinguishes Biodentine from traditional materials. Experimental data indicate that Biodentine maintains its structural integrity and mechanical performance in the presence of tissue fluids, owing to the controlled release of calcium ions and the gradual densification of the C–S–H network [1,2]. This behavior contrasts with calcium hydroxide-based materials, which are prone to dissolution and loss of mechanical support over time.

Beyond bulk properties, the physicochemical interaction of Biodentine with surrounding dentine has been a subject of focused investigation. Studies examining the dentine–Biodentine interface have demonstrated the development of an interfacial region characterized by ionic exchange, elemental redistribution, mineral-rich deposits, and variable material adaptation [13–15]. Its morphology and extent depend on material maturation, storage conditions, specimen preparation, and analytical methodology [13,14]. These interfacial phenomena may contribute to sealing and material retention, although

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their long-term clinical significance remains incompletely established.

2. Bioactivity and biological interactions

The concept of bioactivity in calcium silicate–based materials extends beyond direct cellular responses and encompasses a complex set of physicochemical and interfacial phenomena that influence tissue compatibility, sealing ability, and clinical performance. In the case of Biodentine, biological interactions are primarily mediated through its ionic exchange with dentine and its behavior at the material–tooth and material–restoration interfaces, which indirectly modulate the local biological environment [15-20].

One of the most relevant biological interactions of Biodentine occurs at the interface with dentine when used as part of a layered or laminate restorative approach. The study by Hashem et al. demonstrated that the resin composite–calcium silicate interface exhibits distinct physical characteristics, influenced by the ongoing hydration and maturation of the calcium silicate substrate [15]. The gradual development of the hydrated matrix and the sustained alkaline environment facilitate ionic diffusion at the interface, contributing to interfacial stability. This interaction is biologically relevant, as interfacial integrity plays a critical role in preventing bacterial ingress and subsequent pulpal or periapical inflammation [15].

Adhesive interactions between Biodentine and restorative systems further influence its biological behavior in vivo. Odabaş et al. reported that the shear bond strength of adhesive systems to Biodentine is material- and protocol-dependent, reflecting the dynamic nature of the Biodentine surface during maturation [16]. The initial hydration phase is characterized by ongoing ionic release and surface reactivity, which may affect adhesive infiltration and polymerization. From a biological standpoint, appropriate bonding reduces marginal gaps and microleakage, thereby limiting microbial penetration and protecting underlying pulp tissues [16].

In endodontic applications, the interaction between Biodentine and root dentine is particularly relevant in perforation repair and root-end filling procedures. Aggarwal et al. demonstrated that Biodentine exhibits favorable push-out bond strength compared to other calcium silicate-based materials, indicating effective mechanical and micromechanical interaction with dentinal walls [17]. This enhanced retention is associated with reduced interfacial disruption under functional stresses, indirectly supporting periradicular tissue healing by maintaining a stable seal [17]. The biological and interfacial performance of Biodentine may also be influenced by chemical agents used during endodontic treatment. Dąbrowska et al. demonstrated that EDTA irrigation can affect the surface morphology, volume stability, and structural integrity of Biodentine, particularly when the material has not achieved sufficient maturation [18]. These findings indicate that irrigation protocols, exposure time, and activation methods may influence the final biofunctional interface.

Aesthetic stability constitutes another clinically relevant consideration, particularly in anterior restorations. Mutlu and Akbulut showed that the color behavior of Biodentine may be influenced by the irrigating solution and observation period. Although Biodentine does not contain bismuth oxide, clinically perceptible discoloration may still occur under certain experimental conditions [19]. Such changes may require additional restorative intervention and should therefore be considered in aesthetically demanding regions.

Radiographic assessment represents an additional aspect of clinical performance. Çapan et al. demonstrated that the radiopacity of calcium silicate-based cements varies according to their elemental composition and radiopacifying

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components [20]. Adequate radiographic visibility is essential for evaluating material placement, adaptation, healing, and treatment outcomes.

3. Interfacial behavior and adhesive performance

The interfacial behavior of Biodentine is a critical determinant of its clinical success, as it directly influences sealing ability, mechanical stability, and long-term biological outcomes. Unlike inert restorative materials, Biodentine exhibits an evolving interface with dentine and restorative systems, driven by ongoing hydration reactions and ionic exchange processes [1-4]. This dynamic behavior differentiates it from conventional liners and underpins its classification as a bioactive dentine substitute.

At the dentine–cement interface, Biodentine demonstrates direct material contact and the development of a variable interfacial layer. Microscopic and elemental analyses have identified mineral-rich deposits and redistribution of calcium- and silicon-related components, although marginal gap formation and interfacial morphology vary according to experimental conditions and evaluation methods [13,14]. These interfacial characteristics may contribute to sealing, but their magnitude and clinical relevance should not be considered uniform across all applications.

Adhesive performance is influenced by the maturation stage of Biodentine at the time of bonding. Odabaş et al. demonstrated that shear bond strength to Biodentine varies depending on the adhesive system used and the interval between material placement and bonding [16]. In the early setting phase, ongoing hydration and surface alkalinity may interfere with adhesive polymerization, whereas delayed bonding allows surface stabilization and improved adhesion. These findings highlight the necessity of protocol standardization when Biodentine is used in layered restorative techniques [15,16].

The physical characteristics of the resin composite–Biodentine interface have been further elucidated by Hashem et al., who reported that the integrity of this interface depends on both material compatibility and mechanical properties of the hydrated cement [15]. The elastic modulus of Biodentine, which approximates that of dentine, contributes to favorable stress distribution at the interface, reducing the risk of debonding under functional loading [1,15]. This biomechanical compatibility is a distinct advantage over stiffer or more brittle materials.

In endodontic applications, push-out bond strength is commonly used as a surrogate marker for interfacial performance. Comparative studies have shown that Biodentine exhibits bond strength values comparable or superior to MTA when used for furcation perforation repair or root-end filling [17,18]. This property is clinically relevant because resistance to dislodgement contributes to the maintenance of the seal under condensation forces, functional stresses, and subsequent restorative procedures. The interaction between the material and root dentine is influenced by surface conditioning and irrigant exposure, emphasizing that interfacial behavior is modulated by clinical variables as well as intrinsic material properties [18].

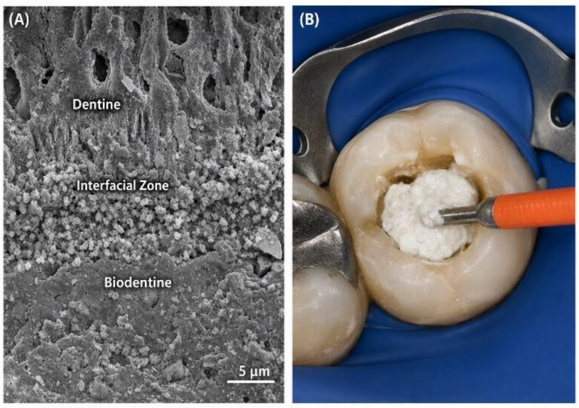

Figure 1. Interfacial morphology and clinical application of Biodentine (a,b).

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Figure 1. Interfacial morphology and clinical application of Biodentine. (A) Representative scanning electron microscopy image illustrating the dentine–Biodentine interface, including an interfacial region characterized by close material adaptation and mineral-rich deposits. The appearance and extent of this region may depend on specimen preparation and microscopic methodology. (B) Clinical placement of Biodentine in a deep coronal cavity under rubber dam isolation before definitive restorative treatment.

4. Clinical applications and performance

The clinical applicability of Biodentine is directly derived from its physicochemical stability, bioactive potential, and favorable interfacial behavior. Since its introduction, Biodentine has been employed across a wide spectrum of restorative and endodontic indications, with growing clinical evidence supporting its performance as a dentine substitute [1,5].

In restorative dentistry, Biodentine has been evaluated as a dentine substitute and temporary coronal restoration in deep carious lesions. A prospective observational study by Martens et al. demonstrated favorable medium-term performance when Biodentine was used as a temporary filling and dentine substitute in selected permanent teeth with deep caries [5]. These findings support its use as a temporary coronal restoration and permanent dentine substitute when appropriate isolation, case selection, and definitive restorative planning are ensured.

Vital pulp therapy represents one of the most clinically relevant indications for Biodentine. Clinical and experimental evidence supports favorable outcomes for calcium silicate-based materials in vital pulp therapy, while cellular studies indicate that Biodentine promotes odontogenic differentiation, mineralization-related activity, and regenerative signaling in human dental pulp stem cells [4,6–9]. These biological effects, together with sealing capacity and an alkaline environment, support its use in direct pulp capping and pulpotomy when case selection and operative protocols are appropriate.

In endodontics, Biodentine has been applied in perforation repair, apexification, and root-end filling. Comparative evaluations of push-out bond strength and sealing ability have demonstrated that Biodentine performs reliably in perforation repair scenarios, where resistance to dislodgement and long-term sealing are critical [17,18]. Its relatively short setting time offers a practical advantage over MTA in surgical and non-surgical endodontic procedures [2,17].

Aesthetic considerations also influence clinical performance, particularly in anterior teeth. Studies assessing color stability have shown that Biodentine exhibits limited discoloration compared to materials containing bismuth oxide, making it suitable for use in aesthetically sensitive areas [19]. Additionally, adequate radiopacity ensures reliable postoperative assessment and follow-up, facilitating clinical decision-making [20].

Despite these advantages, certain limitations must be acknowledged. Biodentine is primarily intended as a permanent dentine substitute. When used coronally, definitive enamel replacement with a resin composite or an indirect restoration is generally required, although the material may temporarily replace both dentine and enamel during staged restorative treatment [1,5,15]. Moreover, clinical success remains highly dependent on appropriate handling, effective moisture control, adequate maturation, careful case selection, and adherence to standardized bonding and restorative protocols.

Table 1. Physicochemical, biological, interfacial, and clinical characteristics of Biodentine based on published evidence

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Domain	Evaluated parameter	Key findings	Ref.
Physicochemical properties	Chemical composition and hydration	Tricalcium silicate–based cement with accelerated hydration, formation of C–S–H gel and calcium hydroxide, and stable radiopacity due to zirconium oxide	[1–3]
Physicochemical properties	Mechanical behavior	Progressive increase in compressive strength over time, reaching values comparable to natural dentine after maturation	[1–3]
Physicochemical properties	Porosity and dimensional stability	Reduced interconnected porosity and favorable dimensional stability after setting, contributing to sealing ability	[3,4]
Biological interactions	Ionic release and bioactivity	Sustained release of calcium ions promotes mineral deposition and favorable dentine–material interaction	[7,9,10]
Biological interactions	Cellular response	Induction of odontoblast-like cell differentiation and stimulation of mineralization processes	[7,9,10,11]
Interfacial behavior	Dentine–cement interface	Development of a variable interfacial layer characterized by elemental redistribution, mineral-rich deposits, and material–dentine adaptation	[13,14]
Interfacial behavior	Adhesive performance	Bond strength dependent on maturation time and adhesive system; delayed bonding improves interfacial stability	[15,16]
Interfacial behavior	Endodontic retention	Favorable push-out bond strength in perforation repair and root-end applications	[17,18]
Clinical applications	Restorative dentistry	Reliable dentine substitute in deep posterior restorations with satisfactory clinical performance	[5]
Clinical applications	Vital pulp therapy	Favorable pulp response comparable to MTA in direct pulp capping and pulpotomy procedures	[6,7,9]
Clinical applications	Endodontic repair	Effective material for perforation repair and root-end filling with adequate sealing and handling	[17,18]
Clinical performance	Aesthetic and radiographic behavior	Color stability influenced by exposure conditions and irrigating solutions; radiopacity dependent on cement composition and radiopacifying components	[19,20]

Table 1 summarizes the main physicochemical properties, biological interactions, interfacial behavior, and clinical applications of Biodentine as reported in experimental and clinical studies. Reference numbers correspond to the bibliography listed in the manuscript and are indicated in brackets.

5. Clinical limitations, handling considerations, and future perspectives

Despite its favorable physicochemical and biological characteristics, the clinical performance of Biodentine remains dependent on several material-related and operator-dependent factors. The relatively rapid initial setting time represents an important practical advantage compared with conventional mineral trioxide aggregate; however, initial hardening should not be interpreted as complete physicochemical maturation. Hydration reactions continue after placement, with progressive development of the calcium silicate hydrate matrix and gradual improvement in mechanical properties [1–3]. Consequently, early exposure to excessive moisture, mechanical loading, adhesive procedures, or chemical agents may alter the surface structure and

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compromise the integrity of the material before full maturation.

The interaction between Biodentine and restorative materials is particularly relevant when the cement is used as part of a layered restorative technique. Bond strength depends on the adhesive system, surface condition, and interval between Biodentine placement and application of the definitive restoration [15,16]. During the early hydration phase, surface alkalinity, residual moisture, and continued ionic release may interfere with adhesive infiltration and polymerization. Delayed bonding may improve surface stability, although prolonged waiting periods are not always compatible with single-visit treatment protocols. Therefore, restorative timing should be selected according to the clinical indication, cavity configuration, remaining tooth structure, and expected functional loading.

Endodontic procedures introduce additional variables. Exposure to chelating solutions may affect the morphology, volume stability, and surface integrity of Biodentine, particularly when the material has not reached sufficient maturation [18]. Irrigation protocols should therefore be carefully controlled when Biodentine is placed in perforations, apical plugs, or resorptive defects. The type of irrigant, contact time, activation method, and sequence of application may influence the final material–dentine interface. Similarly, resistance to dislodgement remains relevant in perforation repair and root-end applications, where mechanical stability is required to maintain sealing under functional and procedural stresses [17,18].

Aesthetic behavior also requires consideration. Although Biodentine does not contain bismuth oxide and therefore avoids one of the discoloration mechanisms associated with some traditional calcium silicate cements, color changes may still occur depending on environmental exposure, irrigating solutions, blood contamination, and observation time [19]. This is particularly relevant in anterior teeth and cervical lesions, where even limited chromatic alteration may affect patient satisfaction. Radiographic assessment is likewise influenced by material composition and radiopacifier content. Adequate radiopacity is essential for evaluating material placement, marginal adaptation, and follow-up outcomes, although radiographic visibility varies among calcium silicate-based formulations [1–3,20].

The current evidence base also presents methodological limitations. Many studies evaluating Biodentine are in vitro, ex vivo, or based on short-term biological models, while clinical studies remain heterogeneous in terms of case selection, operative technique, restorative protocol, and follow-up duration [4–6]. Future investigations should prioritize standardized clinical protocols, longer observation periods, patient-centered outcomes, and direct comparisons with newer bioceramic materials. Additional research is also required to clarify the long-term significance of interfacial mineral deposition, elemental redistribution, and dentine adaptation observed under microscopic conditions [13,14]. Overall, Biodentine should be regarded as a biologically active dentine substitute whose success depends not only on intrinsic material properties, but also on correct handling, maturation, isolation, restorative timing, and case selection.

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Conclusions

Biodentine represents a significant advancement among tricalcium silicate-based materials, combining favorable physicochemical properties with stable interfacial behavior and predictable clinical handling. Its accelerated setting, mechanical compatibility with dentine, and sustained ionic activity justify its classification as a true dentine substitute, and the evidence reviewed supports its reliable use in restorative dentistry and endodontics when correct clinical protocols are respected across diverse clinical indications and treatment contexts, with consistent medium-term outcomes documented.

From a broader perspective, biodentine illustrates the shift toward biologically oriented dental materials that actively interact with hard tissues rather than acting as inert fillers, and its clinical performance is closely linked to its physicochemical maturation and interfacial dynamics, emphasizing the importance of timing, surface management, and material selection. Future research should focus on long-term clinical outcomes, standardized bonding protocols, and comparative effectiveness against newer bioceramics to further refine its indications and optimize patient-centered results in contemporary restorative and endodontic practice worldwide, supported by clinical trials, systematic evaluations, and translational research.

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