Research Article

Recent Advances in Calcium Silicate-Based Cements in Endodontic Therapy: A Systematic Review of Their Applications

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ABSTRACT

Background: Calcium silicate-based cements (CSCs) are widely used in endodontics because of their favourable physical and biological properties. Their formulations and clinical applications have expanded considerably in recent years. This study systematically reviews the evidence on the use of CSCs in contemporary endodontic applications and summarizes their clinical outcomes.

Methods: A systematic literature search was conducted in PubMed, Scopus, and Web of Science for studies published from 2016 to 2026. Studies were eligible if they were original primary research directly evaluating CSCs in vital pulp therapy, root-end filling/endodontic microsurgery, or root and furcation perforation repair. Reviews, case reports or series, studies focused exclusively on material characterization, and studies without a relevant endodontic application were excluded. Thirty-seven studies were included in the qualitative synthesis.

Results: The included studies predominantly evaluated CSCs in vital pulp therapy, followed by root-end filling and endodontic microsurgery and root or furcation perforation repair. MTA was the most extensively investigated material, while Biodentine, iRoot BP Plus, TheraCal, and other bioceramic materials were also evaluated. Overall, CSCs demonstrated favorable clinical and biological outcomes across the investigated applications. In comparative studies, several newer materials demonstrated clinical outcomes comparable to MTA, although consistent superiority of any single material was not established. Preclinical studies further demonstrated favorable biocompatibility, mineralized tissue formation, reduced inflammation, and tissue repair associated with several CSC formulations.

Conclusion: The results show that CSCs can be widely used in modern endodontics and give good results in several treatment modalities.More good clinical trials with standardized outcome measures and longer follow-up are needed to determine the comparative effectiveness and long-term performance of newer CSC formulations.

Keywords: Calcium silicate-based cements, Mineral trioxide aggregate, Biodentine, Endodontics, Vital pulp therapy.

INTRODUCTION

The tooth pulp is vulnerable tissue that can have serious health implications if exposed. It can be exposed by tooth trauma, dental caries, and tooth preparation accidents. Exposure can cause infection and inflammation, worsening patient pain and potentially harming the pulp [1]. Moreover, untreated dental caries will result in pulpitis, subsequently leading to periapical periodontitis [2]. Thus, requiring a vital pulp treatment to preserve the exposed dental pulp. In dental practice, the pulp capping materials are placed to protect the vital pulp and the exposure site from external environment [3]. Endodontic treatment is the most efficient approach to facilitate wound healing, depending upon the choice of therapeutic techniques and associated properties of materials [4]. Despite a range of materials, including adhesives, calcium hydroxide (CaOH), and calcium silicate-based cements (CSCs), have been proposed, CSCs are currently regarded as the gold standard in endodontic therapy due to their predominant biocompatibility, sealing ability and bioactivity.

Calcium silicate-based cements (CSCs) are self-settling blocks of bioactive cement produced from calcium and silicate. Mineral trioxide aggregate (MTA), a biocompatible compound with low cytoxicity and ability to stimulate dentin formation, is the first developed CSCs in 1900s [5]. CSCs has been extensively used across several endodontic procedures like pulp regeneration, root canal filling, apexification, perforation repair, root-end filling, and apexogenesis [6]. The suitability of biomaterials for endodontic applications is based upon their mechanical characteristics, shelf life, sustainability, and, especially, biocompatibility. The primary factors that influence the suitability of CSCs in endodontic therapy are their biocompatibility and sealing ability, as well as their physiochemical interactions with the external environment [7, 8]. Biodentine (Septodont, Saint-Maur-des-

Fosses, France), Bioaggregate (Innovative Bioceramics, Vancouver, Canada), Endosequence root repair material, iRoot BP plus, calcium-enriched mixture (BioniqueDent, Tehran, Iran), and TheraCal (Bisco, Schamburg, IL, USA) are among the effective alternatives that have been developed because of extensive research into the physical, chemical, and biological properties of CSCs. This review presents comprehensive insights into the types, properties, and application of various CSCs owing to their importance in endodontic therapy.

METHODS

Literature search

A literature search was conducted to identify studies evaluating calcium silicate-based materials for endodontic applications. Electronic searches were performed in PubMed, Scopus and Web of Science for studies published from January 2016 to the date of final search in 2026. The search strategy included commonly used calcium silicate-based materials such as mineral trioxide aggregate (MTA), Biodentine, BioAggregate, TheraCal, calcium-enriched mixture (CEM) and iRoot BP along with terms related to relevant endodontic applications. Table 1 shows the full search strategies and the number of records retrieved from each database.

Table 1: Database search strings and number of records retrieved.

Database	Search String	No. of Records
PubMed	("mineral trioxide aggregate"[Title/Abstract] OR "Biodentine"[Title/Abstract] OR "BioAggregate"[Title/Abstract] OR "TheraCal"[Title/Abstract] OR "calcium-enriched mixture"[Title/Abstract] OR "iRoot BP"[Title/Abstract]) AND ("vital pulp therapy"[Title/Abstract] OR "perforation repair"[Title/Abstract] OR "root perforation"[Title/Abstract] OR "regenerative endodontics"[Title/Abstract] OR "root-end filling"[Title/Abstract])	697
Scopus	TITLE-ABS-KEY (("mineral trioxide aggregate" OR Biodentine OR BioAggregate OR TheraCal OR "calcium-enriched mixture" OR "iRoot BP") AND ("vital pulp therapy" OR "perforation repair" OR "root perforation" OR "regenerative endodontics" OR "root-end filling")) AND PUBYEAR > 2015 AND PUBYEAR < 2027	974
Web of Science	TS=(("mineral trioxide aggregate" OR "Biodentine" OR "BioAggregate" OR "TheraCal" OR "calcium-enriched mixture" OR "iRoot BP") AND ("vital pulp therapy" OR "perforation repair" OR "root perforation" OR "regenerative endodontics" OR "root-end filling")) AND PY=(2016-2026)	875
Total	-	2546

Eligibility Criteria

The review included original studies published between 2016 and 2026, that directly evaluated a calcium silicate-based material as part of an endodontic treatment or repair procedure, and that investigated at least one of the following applications: vital pulp therapy including pulp capping or pulpotomy; root or furcation perforation repair; regenerative endodontics or apexification; or root-end filling/endodontic microsurgery. Human clinical studies, animal/in-vivo studies, and clinically relevant experimental studies were considered eligible. Studies were excluded if they were systematic reviews, scoping reviews, narrative reviews, meta-analyses, or other forms of secondary research; case reports or case series; studies focused exclusively on physicochemical, mechanical, or material-characterization properties without evaluating an endodontic application; cell-culture studies without an endodontic treatment or repair application; studies in which calcium silicate-based materials were not the primary intervention or material under investigation; or studies published outside the predefined period. This approach was adopted to maintain a focused evidence base comprising primary studies directly relevant to the clinical or biological application of calcium silicate-based materials in endodontics.

Results

Study Screening

The literature search identified a total of 2,546 records, comprising 697 records from PubMed, 974 from Scopus, and 875 from Web of Science (Table 1). The retrieved records were screened according to the predefined eligibility criteria, with particular emphasis on original primary studies directly evaluating calcium silicate-based

materials in endodontic applications. From the PubMed search results, 40 potentially relevant primary studies were shortlisted for detailed full-text based assessment. Following application of the eligibility criteria, three studies were excluded because they did not sufficiently meet the predefined scope: one study did not clearly evaluate a calcium silicate-based material as the primary intervention, one primarily evaluated mechanical/material-performance outcomes rather than an endodontic treatment application, and one focused on an alternative experimental material with MTA serving as a comparator. Consequently, 37 studies were considered eligible and included in the qualitative synthesis. The overall study-selection process is summarized in Figure 1.

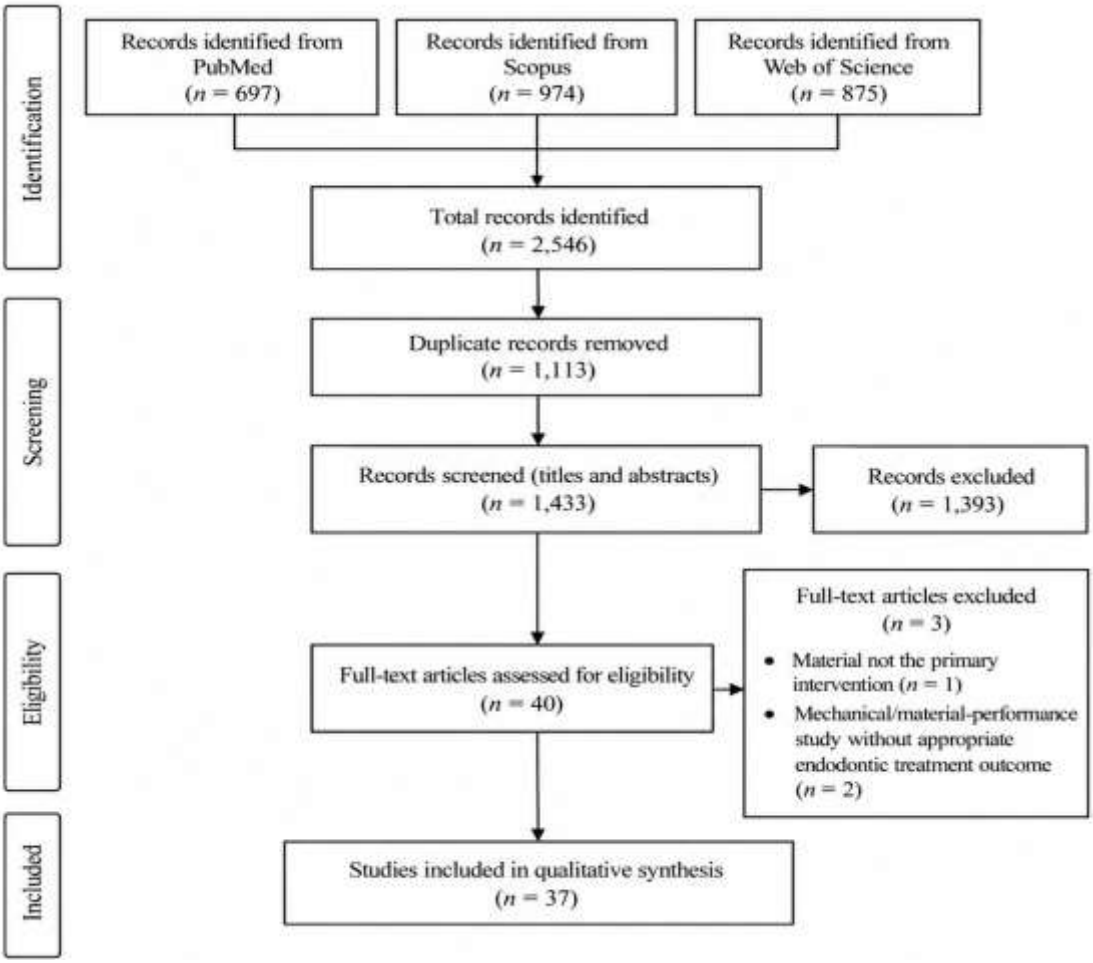


Figure 1: PRISMA flowchart of the study.

Study Characteristics

The 37 included studies comprised a range of clinical, retrospective, and preclinical experimental designs evaluating calcium silicate-based materials across different endodontic applications (Table 2). The evidence was predominantly focused on vital pulp therapy, including direct and indirect pulp capping and pulpotomy, while other studies evaluated calcium silicate-based materials for root-end filling and endodontic microsurgery and for root or furcation perforation repair. Mineral trioxide aggregate (MTA), Biodentine, iRoot BP Plus, TheraCal, and other bioceramic materials were the principal materials evaluated. Most clinical studies compared calcium silicate-based materials with established materials or alternative treatment approaches and generally reported favorable clinical and radiographic outcomes. Several studies also provided preclinical evidence of tissue compatibility, mineralized tissue formation, reduced inflammation, and periradicular healing. Overall, the included evidence encompassed both human clinical outcomes and experimental findings, with follow-up periods ranging from short-term assessments to long-term clinical observations. Detailed characteristics, interventions, applications, and principal findings of the included studies are presented in Table 2. The characteristics of the included studies provide an overview of the clinical and experimental applications of CSCs. To contextualize these applications, the composition and key physical and biological properties of commonly used CSCs are briefly summarized below.

Table 2: Characteristics and main findings of studies evaluating calcium silicate-based materials in endodontic applications

Study type / setting	Material(s)	Endodontic application	Main outcomes / findings	Clinical relevance	References
Prospective comparative clinical study; permanent teeth with reversible/irreversible pulpitis	TheraCal LC; iRoot BP Plus	VPT, DPC, partial/full pulpotomy	Both materials achieved 90.4% 1-year clinical success. TheraCal LC required less operating time and was associated with lower postoperative pain and shorter pain duration.	Both materials showed favorable short-term outcomes for VPT; TheraCal LC may offer handling/time advantages.	[9]
Prospective randomized controlled clinical study; immature traumatized permanent teeth	iRoot BP Plus vs calcium hydroxide	Partial pulpotomy	No significant difference in survival, survival time, root length, or dentin wall thickness. Calcific bridge was thinner with iRoot BP Plus.	iRoot BP Plus may be an effective capping material for partial pulpotomy of traumatized immature teeth.	[10]
Randomized controlled clinical trial; primary molars	Biodentine vs MTA	Indirect pulp capping	At 18 months, success was 96% for Biodentine and 94% for MTA, with no significant difference.	Both materials demonstrated comparable clinical and radiographic effectiveness for IPT in primary molars.	[11]
Randomized controlled clinical trial; mature permanent molars with symptomatic irreversible pulpitis	Biodentine	Full vs partial radicular pulpotomy	Twelve-month success was 78.3% for full pulpotomy and 86.4% for partial radicular pulpotomy; difference was not significant.	Biodentine-supported pulpotomy may be a treatment option for mature molars with symptomatic irreversible pulpitis.	[12]
Retrospective cohort; symptomatic irreversible pulpitis	iRoot BP Plus vs MTA	Direct pulp capping	At 36 months, pulp survival was 88.0% with iRoot BP Plus vs 86.9% with MTA, with no significant difference. Higher preoperative pain was associated with failure.	iRoot BP Plus demonstrated long-term performance comparable to MTA for DPC.	[13]
Prospective randomized clinical study; vital permanent teeth with deep caries	Biodentine vs MTA	DPC / pulpotomy	No significant difference between materials. Overall success was approximately 93% at 6 months, 96% at 1 year, 100% at 2 years, and 93.8% at 3 years.	Both materials provided favorable long-term VPT outcomes.	[14]
Randomized parallel-group clinical trial; deep carious lesions	TheraCal LC vs light-cured calcium hydroxide	Indirect pulp capping	Six-month success was 100% with TheraCal LC and 92.85% with calcium hydroxide; difference was not significant.	TheraCal LC may be used as an alternative IPC material.	[15]
Non-randomized clinical trial; 216 primary molars	TheraCal PT	IPT, DPC, partial pulpotomy, pulpotomy	Twelve-month combined success: 93.87% IPT, 80.4% DPC, 42.6% partial pulpotomy, 96.15% pulpotomy.	Outcomes suggest that treatment selection and case characteristics influence success when TheraCal PT is used.	[16]

Study type / setting	Material(s)	Endodontic application	Main outcomes / findings	Clinical relevance	References
Randomized controlled clinical trial; deep carious lesions	Biodentine vs light-cured MTA	Indirect pulp capping	Both groups showed 93.33% 1-year success, with no significant difference.	Biodentine and light-cured MTA showed comparable short-term IPC outcomes.	[17]
Animal experimental study; rat molars	Biodentine vs TheraCal PT	Pulpotomy	Biodentine produced lower inflammatory scores and more complete hard-tissue formation than TheraCal PT. Inflamed pulps showed poorer outcomes than healthy pulps.	Provides preclinical evidence that material and pre-existing pulp inflammation may influence pulpal healing.	[18]
Histological animal study; dogs' teeth	MTA vs exogenous nitric oxide (NOC-18)	Direct pulp capping	NOC-18 showed greater odontoblast activity at 1 month; no significant difference in dentin bridge formation at 3 months.	Provides preclinical comparative evidence regarding MTA-associated pulp healing, although the primary experimental material was nitric oxide.	[19]
Randomized controlled clinical trial; primary molars	MTA with/without diode or Er,Cr:YSGG laser	Pulpotomy	All groups demonstrated high success. No significant intergroup differences were observed at 9 months.	MTA pulpotomy showed favorable outcomes; laser adjuncts did not demonstrate a significant advantage.	[20]
Randomized clinical trial; primary molars	Bioceramic putty vs MTA	Pulpotomy	Both materials were evaluated over 12 months as pulpotomy medicaments.	Supports the clinical evaluation of bioceramic putty as an alternative to MTA for pulpotomy.	[21]
Randomized clinical trial; mature permanent teeth with irreversible pulpitis	Bioceramic material	VPT	Study evaluated the influence of two contemporary chelating agents on VPT using a bioceramic material.	Provides clinical evidence concerning procedural factors associated with bioceramic-based VPT.	[22]
Randomized controlled clinical trial; immature mandibular first permanent molars	Potassium nitrate/polycarboxylate cement vs MTA	Pulpotomy	Twelve-month overall success was 92% in both groups; successful teeth showed continued root development and apical closure.	Provides evidence for pulpotomy and continued root development in immature permanent molars.	[23]
Randomized split-mouth controlled clinical trial; primary molars	MTA vs formocresol	Partial pulpotomy	At 24 months, overall success was 81.8% for MTA and 95.2% for formocresol; differences were not significant.	MTA demonstrated clinically acceptable outcomes for partial pulpotomy in primary molars.	[24]
Randomized clinical trial; primary molars	MTA vs platelet-rich fibrin	Pulpotomy	Six-month overall success was 92% with MTA and 90% with PRF.	MTA demonstrated favorable short-term pulpotomy outcomes and served as a clinical comparator for biologic alternatives.	[25]

Study type / setting	Material(s)	Endodontic application	Main outcomes / findings	Clinical relevance	References
Randomized controlled split-mouth animal study; dogs	Well-Root PT vs MTA	Direct pulp capping	Both materials significantly increased DSP expression compared with controls. No significant difference between Well-Root PT and MTA; laser had no significant effect.	Well-Root PT demonstrated comparable mineralization-related response to MTA in this animal model.	[26]
Randomized clinical trial; adult permanent molars	MTA vs PRF	Direct pulp capping	Both groups maintained pulp vitality at 6 months. PRF produced significantly greater dentin bridge volume; one MTA-treated tooth developed irreversible pulpitis.	MTA provided favorable pulp preservation, although PRF showed greater dentin bridge formation in this small study.	[27]
Randomized clinical trial; primary teeth	MTA vs laser-assisted MTA	Pulpotomy	At 9 months, laser-assisted MTA showed numerically higher clinical and radiographic success, although this was an adjunctive comparison.	MTA remained the common pulpotomy material; laser application may influence outcomes but requires further evidence.	[28]
Randomized controlled trial; primary molars	MTA vs propolis	Pulpotomy	At 24 months, success was 93.1% with MTA and 80% with propolis; differences were statistically nonsignificant.	MTA demonstrated sustained clinical success over 24 months.	[29]
Randomized clinical study; mature permanent molars with irreversible pulpitis	NeoPUTTY vs MTA	Full pulpotomy	Twelve-month success was 95.5% in both groups, with no significant difference in postoperative pain or clinical/radiographic outcomes.	NeoPUTTY showed short-term outcomes comparable to MTA for full pulpotomy.	[30]
Randomized single-blind clinical trial; primary molars	MTA with low-/high-power diode laser vs MTA alone	Partial pulpotomy	MTA alone and low-level laser/MTA showed high success; no significant differences among groups through 18 months.	MTA partial pulpotomy demonstrated favorable outcomes; laser addition did not significantly improve success.	[31]
Randomized controlled clinical trial; primary molars	Bacterial cellulose-reinforced MTA vs conventional MTA	Indirect pulp capping	Nine-month success was 88.23% for BC-MTA and 100% for conventional MTA. Both demonstrated favorable outcomes.	Conventional and modified MTA showed favorable IPT outcomes; longer-term validation is needed for BC-MTA.	[32]
Prospective randomized controlled study; teeth with persistent/recurrent apical disease	MTA vs iRoot BP Plus/RRM	Endodontic microsurgery / root-end filling	Twelve-month success was 93.1% for MTA and 94.4% for iRoot BP Plus, with no significant difference.	iRoot BP Plus demonstrated clinical performance comparable to MTA as a root-end filling material.	[33]

Study type / setting	Material(s)	Endodontic application	Main outcomes / findings	Clinical relevance	References
Randomized controlled clinical trial; persistent/recurrent apical periodontitis	MTA vs EndoSequence RRM	Endodontic microsurgery / root-end filling	PA success was 94.7% MTA vs 92% RRM; CBCT success was 86% vs 84%, respectively; differences were not significant.	Both materials provided predictable microsurgical outcomes.	[34]
Long-term clinical follow-up study	MTA	Apical surgery / root-end filling	Of 119 teeth available at 10 years, 81.5% were classified as healed.	Provides long-term evidence supporting MTA root-end filling after apical surgery.	[35]
Retrospective clinical study; postgraduate endodontic clinic	ProRoot MTA vs EndoSequence RRM	Root-end microsurgery	Success was 92.1% with MTA and 92.4% with ERRM, with no significant difference.	Both calcium silicate-based materials produced high clinical/radiographic healing rates.	[36]
Randomized controlled clinical trial; refractory periapical disease	iRoot BP Plus RRM alone vs iRoot BP Plus RRM + iRoot SP sealer	Endodontic microsurgery / root-end filling	One-year success was 92.8% with BP-RRM and 94.5% with combined BP-RRM/SP-RCS, with no significant difference.	Combined use produced a satisfactory clinical outcome but no demonstrated advantage over BP-RRM alone.	[37]
Retrospective cohort; endodontic microsurgery	MTA, RRM putty, injectable bioceramic + RRM putty	Root-end filling	PA success ranged from 85.4–94.1% and CBCT success from 67.9–88.2%; differences among materials were not significant.	Multiple calcium silicate-based retrograde materials showed high microsurgical success.	[38]
In-vivo animal study; dogs	MTA vs Biodentine	Root-end filling	Biodentine showed lower initial inflammation than MTA and comparable mineralization; differences in mineralization were not significant at later assessment.	Biodentine demonstrated favorable initial biocompatibility and may be an alternative to MTA in periradicular surgery.	[39]
Animal study; dogs	Biodentine vs MTA	Furcation perforation repair	Both showed comparable radiographic and hard-tissue responses. Biodentine demonstrated less inflammation, lower extruded-material volume, and greater cementum repair.	Biodentine showed favorable preclinical performance for furcation perforation repair.	[40]
Animal histopathological/immunofluorescence study; dogs	Biodentine vs MTA vs gutta-percha	Furcation perforation repair	Both Biodentine and MTA promoted mineralized tissue formation and avoided bone resorption. MTA showed greater frequency and thickness/area of mineralized tissue formation.	Both CSCs demonstrated superior tissue response compared with gutta-percha; MTA showed stronger mineralized tissue formation in this model.	[41]

Study type / setting	Material(s)	Endodontic application	Main outcomes / findings	Clinical relevance	References
In-vitro + randomized clinical trial; primary molars	Premixed bioceramic vs MTA	Furcal perforation repair	Premixed bioceramic showed better sealing experimentally and better clinical/radiographic performance at 6 and 12 months.	Premixed bioceramic material demonstrated potential as an alternative to MTA for furcal perforation repair.	[42]
Animal study; rats	Biodentine vs MTA	Furcation perforation repair	Both materials produced mild inflammatory responses, less bone resorption than positive controls, and cementum repair in 30% of samples.	Biodentine and MTA showed comparable favorable tissue responses in furcation repair.	[43]
In-vivo animal study; dogs	MTA ± PRF/CGF	Root/furcation perforation repair	MTA + PRF and MTA + CGF showed more bone formation, greater OPN expression, and fewer inflammatory cells than MTA alone. Healing was better in non-contaminated perforations.	Adjunctive biologic matrices may enhance tissue healing associated with MTA repair.	[44]
Prospective long-term cohort study	MTA	Root canal perforation repair	89% healed at first annual follow-up, with 4% additional healing at the second. Long-term reversal risk increased substantially over time; larger perforations and positive probing were associated with higher reversal risk.	Provides important long-term evidence that initial MTA healing may not necessarily represent permanent treatment success.	[45]

Composition of Calcium Silicate-Based Cements

Portland cement is the precursor to the development of MTA and other CSCs. Mineral trioxide aggregate (e.g., ProRoot MTA, Dentsply Sirona, York, USA) and Biodentine (Septodont, St. Maur-des-Fossés, France) are some examples of silicate-based cements whose structure is based on Portland cement (calcium, iron, and aluminum silicates) [46]. Additives like modifiers, radiopaque agents and drugs were added to improve the clinical properties of CSCs [47,48]. A range of calcium silicate products have been developed, relying either on the original composition or with slight modifications in relation to contemporary clinical practice (Table 3).

The powder of MTA is a mixture of a purified Portland cement and bismuth oxide. Calcium silicate cements undergo spontaneous setting when exposed to water due to their hydraulic properties [49]. CSCs are unique among dental materials in that they continue to release calcium ions for extended periods after setting, particularly in water. The primary components of the system, tricalcium silicate (Ca_3SiO_5) and dicalcium silicate (Ca_2SiO_4), undergo hydration reactions to produce calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate gel, which release calcium ions in a continuously [50]. The hydration of Ca_3SiO_5 significantly influences the setting process and the development of early strength, while Ca_2SiO_4 hydrates more slowly, contributing to added strength [51]. Over time, the nanoporous calcium silicate gel, incorporating $Ca(OH)_2$, will polymerize into a strong network, improving its mechanical properties and strength. The maximum total setting time for calcium silicate cements is approximately 170 minutes, which is a setback in clinical procedures such as apical surgery that necessitate shorter setting times due to the risk of wash-out with blood flow. Biodentine and TheraCal are examples of novel products that provide a faster setting time [52].

Table 3: Composition of various CSCs and their uses in endodontics.

Cement		Composition	Uses
MTA	Powder	tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite, with calcium sulfate and bismuth oxide.	root-end filling, perforation repair, pulp capping, and apexification
	Liquid	silicon dioxide, calcium oxide, magnesium oxide, potassium sulfate, sodium sulfate, and distilled water.	
Biodentine	Powder	tricalcium silicate, dicalcium silicate, calcium carbonate, and zirconium oxide	root perforations, internal/external resorptions, apexification, filling material, pulp capping, and pulpotomy
	Liquid	calcium chloride, water, and Hydrosoluble polymer	
MTA Plus	Powder	calcium oxide, silicon oxide, and bismuth oxide	root canal sealing, pulp capping, pulpotomies, apexification, root resorption, perforation repair, and root-end filling
	Gel	hydrated polymer gel	
TheraCal	–	calcium silicate particles (type III Portland cement), fumed silica, strontium glass, and a resin matrix with Bis-GMA and polydimethacrylate	pulp capping agent and protective liner
BioAggregate	Powder	aluminum-free calcium silicate, monocalcium phosphate, and tantalum oxide	root-end filling, apexification, pulp capping, root perforation repair, and in regenerative endodontics
	Liquid	deionized water	
EndoSequence Bioceramic	Powder	calcium silicate, calcium phosphate monobasic, calcium hydroxide, zirconium oxide, tantalum oxide, filler, and thickening agents	root canal sealing, perforation repair, pulp capping, and retrograde fillings
	Liquid	Distilled water	
Tech Biosealer Endo	Powder	mixture of white CEM, calcium sulfate, calcium chloride, bismuth oxide, and montmorillonite	promote hard tissue formation, root-end filling, and perforation repair
	Liquid	DPBS (Dulbecco's phosphate buffered saline)	

Properties of Calcium Silicate-Based Cements

The clinical performance of CSCs is influenced by their physical and biological properties. Key characteristics include setting time, mechanical strength, radiopacity, alkalinity, porosity, water interaction, biocompatibility, bioactivity, and antimicrobial activity. These properties vary according to cement composition and formulation and may influence the suitability of individual materials for specific endodontic procedures. Figure 2 illustrates different properties of CSCs.

Physical properties

The physical properties of CSCs influence their handling, stability, sealing ability, and clinical performance. Setting time is particularly relevant during procedures in which early material stability is required. Conventional MTA has a relatively long final setting time of approximately 150–170 minutes, whereas modified materials such as Biodentine and TheraCal have substantially shorter setting times, improving their clinical handling [53-56]. Mechanical strength also varies considerably among CSCs; Biodentine and TheraCal generally demonstrate higher strength than conventional MTA, while the strength of CSCs may increase with continued hydration [57–61]. Radiopacity is important for radiographic assessment, although differences exist among materials, with some formulations showing radiopacity close to or below recommended standards [62,63]. In addition, porosity, water absorption, and solubility influence strength, ion release, dimensional stability, and sealing performance. Overall, these physical characteristics contribute to the selection of CSCs according to the requirements of individual endodontic procedures.

Biological properties

The biological properties of CSCs are largely associated with their hydration products, calcium-ion release, and alkaline environment. Most CSCs demonstrate favorable biocompatibility and can support cellular proliferation, differentiation, and mineralized tissue formation, although responses vary among formulations [64–66]. Their bioactivity is characterized by calcium-ion release and formation of a hydroxyapatite-like layer in contact with biological fluids, which may contribute to tissue integration, remineralization, and repair [67]. The high alkalinity of hydrated CSCs also contributes to antimicrobial activity against several oral microorganisms [68]. However, differences in formulation can affect these responses; for example, resin-containing materials such as TheraCal may exhibit comparatively reduced ion release and bioreactivity. Thus, biological performance should be considered alongside the physical characteristics of individual CSCs when selecting materials for endodontic applications.

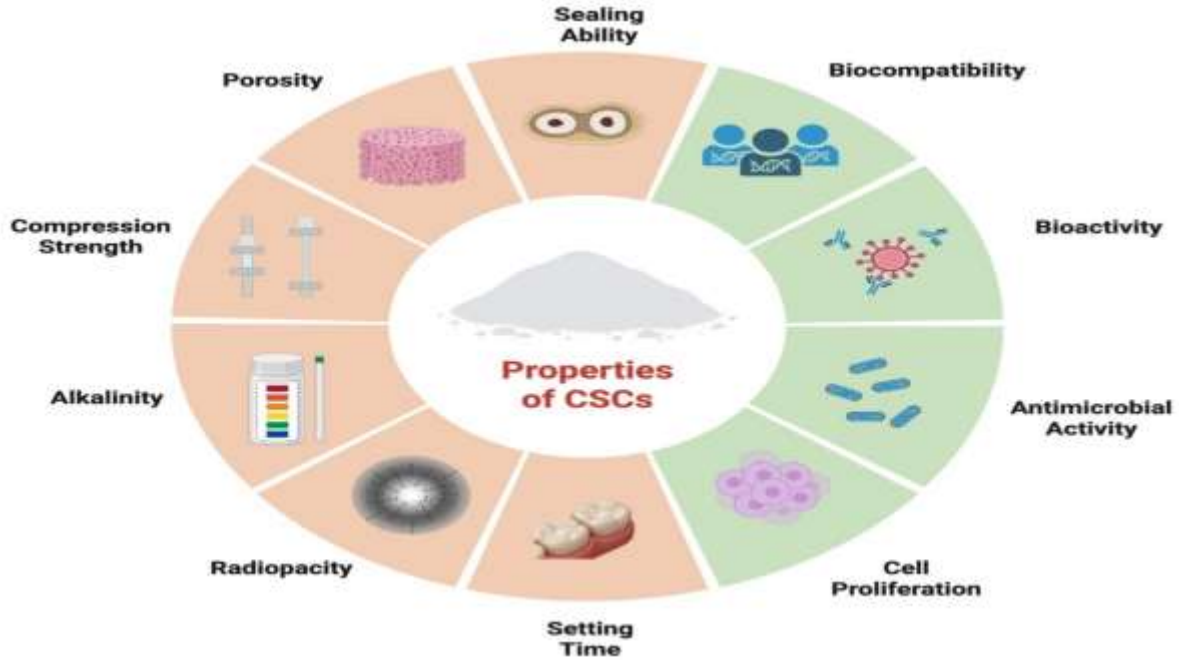


Figure 2: Illustration of physical and biological properties of CSCs. Created using BioRender.com

APPLICATIONS OF CSCS IN ENDODONTICS

The included studies demonstrate the use of CSCs across several endodontic applications, predominantly vital pulp therapy (VPT), root-end filling and endodontic microsurgery, and root or furcation perforation repair (Figure 3). The available evidence includes randomized clinical trials, prospective and retrospective clinical studies, and

animal experiments, with MTA remaining the most frequently evaluated material and newer formulations such as Biodentine, iRoot BP Plus, TheraCal, and other bioceramic materials increasingly investigated as alternatives.

Vital Pulp Therapy

VPT represented the largest application category, comprising 24 of the 37 included studies. CSCs were evaluated for direct and indirect pulp capping, partial pulpotomy, and full pulpotomy in both primary and permanent teeth. Overall, the clinical studies demonstrated favorable outcomes for MTA and newer CSC formulations. Biodentine showed outcomes comparable to MTA for indirect pulp capping, with reported 18-month success rates of 96% and 94%, respectively, while another randomized trial reported comparable 1-year success of 93.33% for Biodentine and light-cured MTA [11,17]. Similarly, Biodentine-based VPT produced favorable longer-term outcomes when compared with MTA, with no significant differences between materials over follow-up periods extending to three years [14].

iRoot BP Plus also demonstrated clinical performance comparable to established materials. In traumatized immature permanent teeth, partial pulpotomy using iRoot BP Plus produced outcomes comparable to calcium hydroxide with respect to survival, root development, and dentin wall thickness [10]. In symptomatic irreversible pulpitis, direct pulp capping with iRoot BP Plus showed a 36-month pulp survival rate of 88.0%, comparable to 86.9% for MTA [13]. TheraCal formulations have similarly been investigated in VPT. TheraCal LC achieved 90.4% clinical success at one year and was associated with shorter treatment time and reduced postoperative pain compared with iRoot BP Plus [9]. TheraCal LC also demonstrated a high 6-month success rate when used for indirect pulp capping [15], while TheraCal PT showed variable outcomes across different VPT procedures, with higher success for indirect pulp treatment and pulpotomy than for partial pulpotomy [16].

Several studies investigated MTA against alternative materials or adjunctive approaches. MTA demonstrated favorable outcomes when compared with formocresol, platelet-rich fibrin, propolis, and other biological or procedural alternatives in pulpotomy studies [24,25,29]. Laser-assisted MTA pulpotomy generally produced outcomes comparable to MTA alone, with no consistent significant improvement associated with laser application [20,28,31]. Newer materials have also shown promising short-term results. NeoPUTTY achieved a 12-month success rate comparable to MTA in full pulpotomy of mature permanent molars [30], while bioceramic putty demonstrated favorable outcomes in primary molars [21]. Modified MTA formulations, including bacterial cellulose-reinforced MTA, also demonstrated clinically acceptable outcomes, although conventional MTA showed a higher numerical success rate in the reported follow-up period [32].

Preclinical studies further support the biological potential of CSCs in VPT. Biodentine produced lower inflammatory responses and more complete hard-tissue formation than TheraCal PT in an inflamed rat pulp model [18]. Similarly, Well-Root PT produced mineralization-related responses comparable to MTA in an animal direct pulp-capping model [26]. Collectively, the clinical and experimental evidence indicates that CSCs can support pulp preservation and hard-tissue formation across different VPT procedures, although outcomes vary according to material formulation, treatment modality, pulp status, and clinical context.

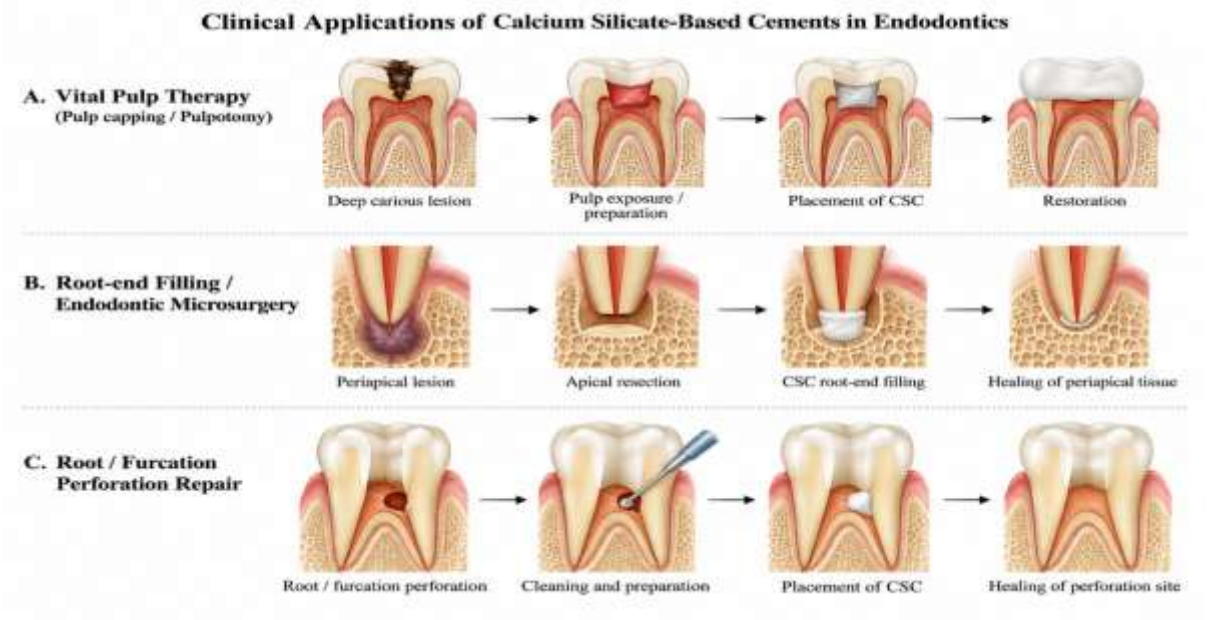


Figure 3: Clinical applications of CSCs in endodontics. Created using BioRender.com

Root-end filling and endodontic microsurgery

Seven included studies evaluated CSCs as root-end filling materials during endodontic microsurgery or apical surgery. MTA was most frequently used as the reference material, while iRoot BP Plus, EndoSequence Root Repair Material (RRM), and other bioceramic materials were evaluated as alternatives. Randomized clinical studies generally reported high healing rates with no significant differences between MTA and newer calcium silicate-based materials. MTA and iRoot BP Plus produced 12-month success rates of 93.1% and 94.4%, respectively, in patients undergoing endodontic microsurgery [33]. Similarly, MTA and EndoSequence RRM demonstrated comparable outcomes when assessed using both periapical radiographs and CBCT, with no significant differences between materials [34].

Long-term clinical evidence also supports the use of MTA for root-end filling. A 10-year follow-up study of teeth treated with apical surgery and MTA root-end filling reported healing in 81.5% of teeth available for assessment [35]. Retrospective clinical data similarly demonstrated comparable success for ProRoot MTA and EndoSequence RRM, with success rates of 92.1% and 92.4%, respectively [36]. Other approaches, including the combined use of iRoot BP Plus root repair material and iRoot SP sealer, produced high one-year success rates but did not demonstrate a significant advantage over iRoot BP Plus alone [37]. A retrospective CBCT-based analysis also found high healing rates across different calcium silicate-based retrograde materials, without significant differences between material groups [38].

Preclinical evidence supports the favorable tissue response of newer materials. In an animal study, Biodentine produced lower initial inflammation than MTA and demonstrated comparable mineralization at later assessment [39]. Overall, the available evidence suggests that CSCs provide predictable outcomes as root-end filling materials, with several newer formulations demonstrating clinical performance comparable to MTA.

Root and furcation perforation repair

Six studies evaluated CSCs for the repair of root or furcation perforations, including animal studies and clinical investigations. Biodentine and MTA were the most frequently investigated materials. In animal models, both materials generally produced favorable periradicular tissue responses, including reduced inflammation, limited bone resorption, and mineralized tissue formation [40,41,43]. Biodentine demonstrated lower inflammatory responses and greater cementum repair than MTA in one animal study, although other investigations reported broadly comparable tissue responses between the two materials [40,43]. In another histopathological study, both Biodentine and MTA promoted mineralized tissue formation and prevented bone resorption, while MTA showed greater mineralized tissue formation than Biodentine [41].

Clinical evidence also supports the use of calcium silicate-based materials for perforation repair. A clinical study comparing premixed bioceramic material with MTA reported favorable clinical and radiographic outcomes for both materials, with the premixed bioceramic demonstrating better experimental sealing and favorable clinical performance over 12 months [42]. Long-term clinical evidence for MTA showed 89% healing at the first annual assessment, with additional healing observed subsequently; however, larger perforations and positive probing findings were associated with an increased risk of reversal of healing over time [45]. Adjunctive biological materials have also been investigated. The addition of platelet-rich fibrin or concentrated growth factors to MTA was associated with greater bone formation, increased osteopontin expression, and fewer inflammatory cells compared with MTA alone in an animal model [44].

Overall, the included studies indicate that CSCs, particularly MTA and Biodentine, provide favorable biological and clinical responses in perforation repair. However, treatment outcome may also depend on factors such as perforation size, contamination, tissue condition, and the use of adjunctive regenerative materials.

CONCLUSION AND FUTURE PERSPECTIVES

CSCs have become important materials in contemporary endodontics because of their favourable physical and biological characteristics, including bioactivity, biocompatibility, alkalinity, calcium-ion release, sealing ability, and adequate mechanical properties. Based on the 37 studies included in this review, CSCs were predominantly investigated for vital pulp therapy, root-end filling and endodontic microsurgery, and root or furcation perforation repair. Overall, MTA remains the most extensively investigated material, while Biodentine, iRoot BP Plus, TheraCal, and other newer bioceramic materials have demonstrated generally favourable clinical or preclinical outcomes. In many comparative studies, newer CSCs produced outcomes comparable to MTA, although clear and consistent superiority of one material over another was not demonstrated. Treatment outcomes were also influenced by factors such as pulp status, treatment modality, lesion characteristics, follow-up duration, and clinical conditions.

Continued development of CSCs has focused on improving handling characteristics, setting time, mechanical performance, radiopacity, bioactivity, and biological responses while addressing limitations associated with conventional MTA. The findings of the present review indicate that newer materials show considerable potential, but the available evidence remains heterogeneous, particularly with respect to sample size, study design, follow-up duration, and outcome assessment. Further well-designed, adequately powered randomized clinical trials with standardized outcome measures and longer follow-up are therefore needed to establish the comparative clinical effectiveness and long-term prognosis of newer CSC formulations. Future research should also investigate the molecular mechanisms underlying CSC-mediated tissue repair and regeneration, as well as the potential benefits of combining CSCs with biologically active materials or regenerative approaches. Such evidence may facilitate more predictable and application-specific selection of CSCs in endodontic treatment.

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Author Contributions
Asma Abdullah Nurul and Nazmul Huda Syed: Conceptualization and study design.
Shazia Fathima J.H. and Nazmul Huda Syed: Literature search, data acquisition, and investigation.
Rahimi L. Muhamud, Vidyadevi Chandavarkar, and Sushma Bommanavar: Methodological supervision and supervision of the literature search and data acquisition.
Shazia Fathima J.H. and Nazmul Huda Syed: Writing – original draft.
All authors: Reviewed and approved the final version of the manuscript.

Conflict of Interest
The authors declare that they have no conflict of interest

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