REVIEW ARTICLE

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A Literature Review of the Effect of Heat on the Physical-Chemical Properties of Calcium Silicate–Based Sealers

SIGNIFICANCE

The present systematic review is the first to assess the effect of heat on the physical-chemical properties of calcium silicate-based sealers for their potential use in warm vertical compaction or continuous wave technique for root canal filling.

ABSTRACT

Introduction: Recently, calcium silicate–based sealers (CSSs) have gained popularity in endodontic practice due to their biocompatibility and antimicrobial properties. They are considered viable alternatives to epoxy resin-based sealers. With the increased use of CSSs and warm vertical compaction techniques in root canal treatment, evaluating the impact of heat on CSSs properties is essential, therefore this review aimed to present a qualitative synthesis of available *in vitro* studies assessing the impact of heat on the physical-chemical properties of CSSs. **Methods:** Following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis 2020 guidelines, a systematic advanced electronic search was performed in Scopus, Embase, Medline (via PubMed), Web of Science, and Cochrane databases in November 2023 and updated in April 2024. *In vitro* studies that evaluated the physical-chemical properties of CSSs were eligible. PRILE 2021 guidelines were used for the assessment of the risk of bias–included studies. **Results:** The search identified a total of 6421 preliminary results and 10 studies were included for qualitative assessment. Eleven different physiochemical properties were assessed by the included studies. Setting time and flow were the most evaluated property among the studies. A qualitative synthesis of the evidence on each property is presented. **Conclusions:** Based on the *in vitro* studies assessed in the present systematic review, results reveal that exposing CSSs to heat can accelerate their setting time, reduce their flow, and increase their film thickness. Concerns persist regarding solubility, viscosity, radiopacity, dimensional change, microhardness, porosity, and compressive strength, requiring further research. Certain CSSs, such as MTA Fillapex and Endosequence BC sealer HiFlow, show minimal changes under heat, making them potential candidates for warm filling techniques. *(J Endod 2024;50:1044–1058.)*

KEY WORDS

Bioceramic; calcium silicate; heat; physiochemical property; review; sealer

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The primary objective of root canal obturation is to effectively seal the root canal system in a 3-dimensional manner using biocompatible materials, after its chemical-mechanical disinfection. This process traps any remaining microorganisms within the root canal, preventing them from spreading to the surrounding periapical tissues and blocking the entry of microorganisms from the oral environment[1]. Generally, the sealing materials of choice are gutta-percha and sealers. The root canal sealer is used mainly to fill any irregularities present between the root canal wall and the core material, effectively ensuring a sturdy and secure seal[2].

Several methods have been used for root canal filling, including cold lateral compaction, single cone technique, Tagger's hybrid technique, carrier-based obturation, and warm vertical compaction. These approaches involve using gutta-percha along with different types of root canal sealers[3] such as glass ionomer, zinc oxide – eugenol, calcium hydroxide, silicone, epoxy resin, and calcium silicate–based sealers (CSSs).

The cold lateral and warm vertical techniques were initially designed to be used with zinc oxide – eugenol or epoxy resin sealers – while the single-cone technique gained popularity with CSSs[4-6].

Regardless of the technique employed, heated instruments are often used for the removal of excess filling and coronal compaction. Examples include the Calamus carrier system (Dentsply Sirona, Charlotte, NC, USA) and System B (Analytic Technology, Redmond, WA, USA)[7]. Warm vertical compaction technique may result in better adaptation of gutta-percha to the root canal wall and in better filling density compared to other techniques[8]. This is attributed to its ability to provide a uniform and tightly packed root canal filling that conforms to the irregularities of the root canals[9]. Nevertheless, as the temperature of the gutta-percha increases, it also affects the temperature of the sealer, which could potentially alter its physical properties[10].

In recent years, there has been a growing trend in the use of CSSs due to their desirable properties, namely biocompatibility[11], alkaline pH, antimicrobial properties, and bioactivity, that is, their ability to form hydroxyapatite on their surface and create a mineral attachment to the dentin substrate[12,13]. Altogether, these sealers exhibit physical-chemical and biological properties comparable to those of the established epoxy resin-based sealers[14], making them a viable alternative for root canal sealing. However, some manufacturers do not recommend their application with heat, while others have specifically designed CSSs, for example, TotalFill BC Sealer HiFlow (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) and EndoSequence BC Sealer HiFlow (Brasseler USA, Savannah, GA, USA) for this purpose.

Given the increased use of CSSs in endodontic practice, coupled with the prevalent adoption of warm vertical compaction technique for root canal filling, there is a need for the evaluation of the impact of the increased temperature from this technique on CSSs. Accordingly, the aim of the present systematic review is to perform a qualitative synthesis of *in vitro* studies on the effect of heat on the physicochemical properties of calcium silicate-based sealers.

MATERIALS AND METHODS

Protocol and Registration

The present work followed the guidelines recommended by Preferred Reporting Items for Systematic Reviews and Meta-Analysis 2020 Statement[15]. The systematic review protocol was previously registered and is available in the Open Science Framework repository (http://doi.org/10.17605/OSF.IO/ZX9BK).

Eligibility Criteria

In vitro studies that evaluated the physical-chemical properties of CSSs were eligible. The inclusion criteria were based on the PICOS framework[16], as follows: Population (P): CSSs; intervention (I): heat application/temperature increase; comparison/control (C): other CSSs or other type of sealer; outcome (O): physical-chemical properties of the tested sealers; and study design (S): *in vitro.*

Information Sources and Search Strategy

The search process, study selection, methodology and outcome data extraction, and quality assessment were carried out by 2 examiners (I.A. and JL.S.). A third examiner was consulted in the event of any doubt (L.F.). A systematic advanced electronic search was performed in Scopus, Embase, Medline (via PubMed), Web of Science, and Cochrane databases in November 2023 and was later updated in April 2024, without any date or language restrictions. The following terms were used "temperature", "heat", "warm", "silicate", "bioceramic", "seal*", and "fill*". Boolean operators "AND" and "OR" were used to annex the terms and develop a broad search strategy. The full search strategy is presented in Table 1. Additionally, the references of the included studies were screened for potentially eligible studies that did not appear in the preliminary database search.

Study Screening and Selection Process

The records resulting from the search strategy were exported from each database into Mendeley reference manager software (Elsevier, Amsterdam, The Netherlands) and duplicate records were discarded manually. Subsequently, an initial screening of the titles and abstracts of the resulting records was performed. Then, the full texts of the studies which met the inclusion criteria in the first screening were retrieved and an additional assessment was performed to confirm their eligibility. In addition, the references of the resulting articles were screened manually to check for potentially eligible studies which did not appear in the study search.

Data Collection Process and Data Items

Data extraction was subdivided into variables on study characteristics, methodology, and results. Regarding the study characteristics, the author and year of publication were extracted. Methodological variables included sealers used, physical-chemical properties, assessment tools, sample size, heated groups (indicating whether they were preheated or heated simultaneously), and temperature groups. Finally, regarding the study results, parameters regarding the different physical-chemical properties assessed and the significant results for the heated and nonheated groups were extracted.

TABLE 1 - Search Strategy

Database	Search strategy	Findings
PubMed	#1 All fields: temperature OR heat OR warm	1,295,340
	#2 All fields: silicate OR bioceramic	56,885
	#3 All fields: seal* or fill*	326,264
	#1 AND #2 AND #3	536
Scopus	#1 TITLE-ABS-KEY: temperature OR heat OR warm	7,246,892
	#3 TITLE-ABS-KEY: silicate OR bioceramic	205,748
	#4 TITLE-ABS-KEY: seal* or fill*	1,201,976
	#1 AND #2 AND #3	3332
Embase	#1 temperature OR heat OR warm	1,394,719
	#2 silicate OR bioceramic	30,309
	#3 seal* OR fill*	422,618
	#1 AND #2 AND #3	408
WOS	#1 Topic: temperature OR heat OR warm	4,930,908
	#2 Topic: silicate OR bioceramic	118,640
	#3 Topic: seal* OR fill*	625,013
	#1 AND #2 AND #3	2098
Cochrane	#1 TITLE-ABS-KEY: temperature OR heat OR warm	44,954
	#3 TITLE-ABS-KEY: silicate OR bioceramic	1450
	#4 TITLE-ABS-KEY: seal* OR fill*	35,284
	#1 AND #2 AND #3	47

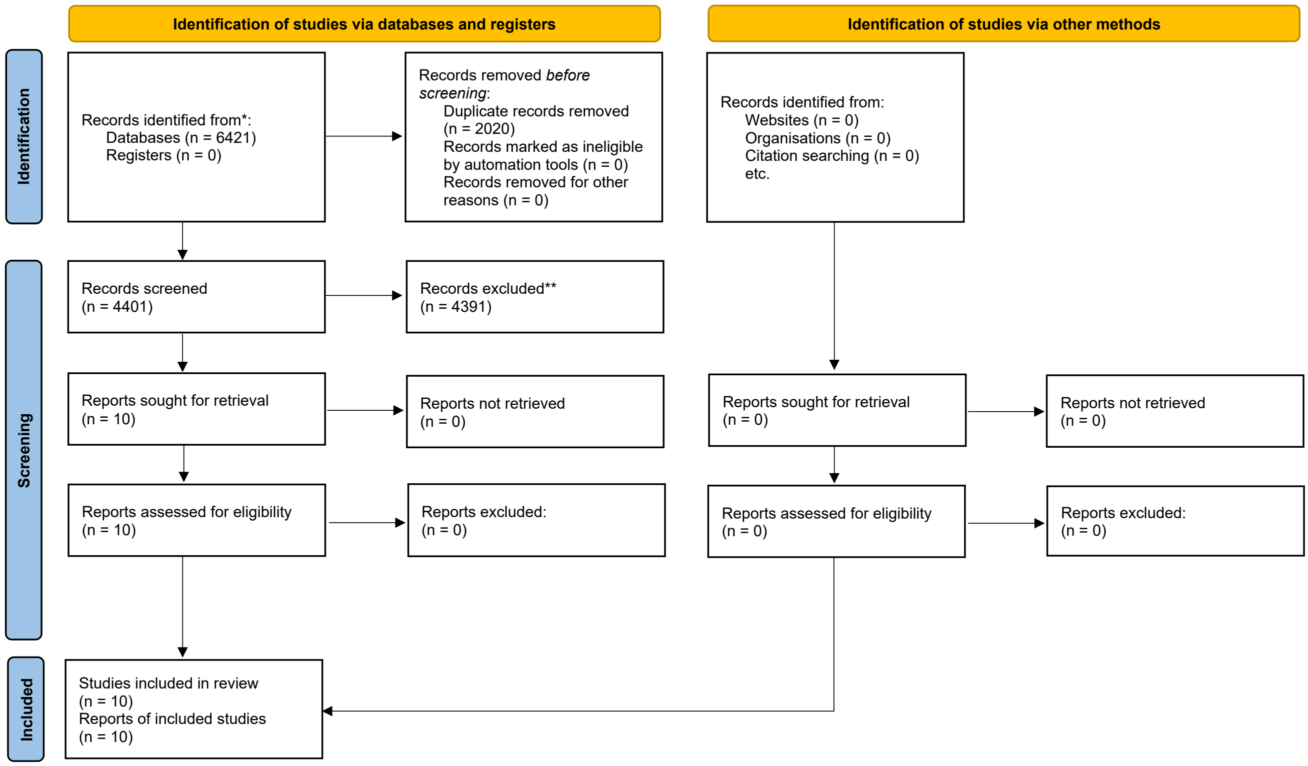

FIGURE 1 – Systematic flow chart representing the study search and selection process. Based on the PRISMA 2020 flow diagram[15]. * Records were retrieved from electronic databases. Repositories and registries were not used as a source. ** Records were excluded after title and abstract screening if one or more of the inclusion criteria were not met.

Study Risk of Bias Assessment

The evaluation of the inner methodological quality assessment (risk of bias) for the selected studies was conducted in accordance with the "PRILE 2021 guidelines for reporting laboratory studies in Endodontology"[17]. Each of the 40 items encompassed in the quality assessment tool underwent individual assessment to ascertain fulfilment or nonfulfilment. Additionally, the percentage of complied items was calculated as the ratio of complied items to the total number of items, multiplied by 100.

RESULTS

Study Selection

The search identified a total of 6421 preliminary results, where 536 articles were found in Medline (via PubMed), 3332 in Scopus, 408 in Embase, 2098 in Web of Science, and 47 in Cochrane. Duplicates were manually discarded using Mendeley reference management software (2020 duplicates), resulting in 4401 records. From the 4401 records, 4391 were excluded upon screening the title and abstract due to a lack of fulfilment of the eligibility criteria. The 10 resulting articles were evaluated and all 10 of them were considered as eligible for qualitative synthesis after full-text screening[18-27] (Fig. 1). No additional studies were found upon the manual reference searching for eligible studies.

Study Methodology

Studied Materials

The list of the commercially available CSSs assessed by the included studies, along with their manufacturers, form, and compositions are presented in Table 2.

Among the included studies, the most studied sealers were Endosequence BC sealer (BC) and Endosequence BC Sealer Hiflow (BCH), each evaluated in five different studies[18,19,21-24]; followed by BioRoot RCS (BR), which was utilized in 4 studies[18,20-22]. Conversely, the remaining sealers were assessed in either 1 or 2 studies.

Assays and Outcome Measures

Data on the physical-chemical properties assessed by the included studies, along with the respective methodologies used to evaluate them, are illustrated in Table 3. Studies included a minimum of 3 and a maximum of 10 sealer samples to assess each property. Sample characteristics in terms of group distribution, exposure to heat, and characteristics of such exposure (i.e., simultaneous heating or preheating) are also presented in the table.

The effect of heat on eleven different physical-chemical properties of CSSs was assessed among the included studies. These properties included: setting time, flow, film thickness, viscosity, solubility, radiopacity, pH, dimensional change, microhardness, porosity, and compressive strength (Table 3).

The specific details of the methods employed by the included studies to assess the aforementioned properties and their corresponding protocols are described below.

Setting Time

All 10 included studies investigated the setting time[18-27] in accordance with ISO (International Organization for Standardization) 6876 (2012) specifications, which recommends a minimum setting time of 30 minutes. Typically, for this property, sealers are prepared according to the manufacturer's instructions, placed into molds, and exposed to the desired temperature and conditions. The initial setting time is commonly determined using an indentation technique which employs a needle with a diameter of 2 mm and a total mass of approximately 100 g. The final setting time is determined using a Gillmore needle.

Sealers are deemed set when the needle, gently lowered onto the material's

TABLE 2 - List of the Commercially Available CSSs Assessed by the Included Studies

Sealer (abbreviation)	Manufacturer	Presentation	Composition	Assessing studies
Endosequence BC sealer (BC)	Brasseler USA, Savannah, GA, USA	Single pre-mixed paste	Zirconium oxide, calcium silicates, calcium phosphate monobasic, calcium hydroxide, filler, and thickening agents[28]	(Nomura et al., 2023)[18] (Mann et al., 2022)[19] (Aksel et al., 2021)[21] (Yamauchi et al., 2021)[23] (Chen et al., 2020)[24]
Endosequence BC Sealer Hiflow (BCH)	Brasseler USA, Savannah, GA, USA	Single pre-mixed paste	Zirconium oxide, calcium silicates, calcium phosphate monobasic, calcium hydroxide, filler, and thickening agents[28]	(Mann et al., 2022)[19] (Aksel et al., 2021)[21] (Antunes et al., 2021)[22] (Yamauchi et al., 2021)[23] (Chen et al., 2020)[24]
Bio-C sealer (Bio-C)	Angelus, Londrina, PR, Brazil	Single pre-mixed paste	Calcium silicates, calcium aluminate, calcium oxide, zirconium oxide, iron oxide, silicon dioxide, dispersing agent[29]	(Nomura et al., 2023)[18] (Antunes et al., 2021)[22]
BioRoot RCS (BR)	Septodont, Saint Maur-des-Fossés, France	Powder & liquid	Powder: tricalcium silicate, zirconium dioxide, and povidone. Liquid: water, calcium chloride, and polycarboxylate.[30]	(Nomura et al., 2023)[18] (Donnermeyer et al., 2021)[20] (Aksel et al., 2021)[21] (Antunes et al., 2021)[22]
EndoSeal MTA (ESMTA)	Maruchi, Wonju, Korea	Single pre-mixed paste	Calcium silicates, calcium aluminates, calcium aluminoferrite, calcium sulfates, radiopacifier, and thickening agents[28]	(Yamauchi et al., 2021)[23]
iRoot SP (iRSP)	Innovative BioCeramix, Vancouver, Canada	Single pre-mixed paste	Zirconium oxide, calcium silicates, calcium phosphate monobasic, calcium hydroxide, filler, thickening agents[31]	(Qu et al., 2016)[25]
MTA Fillapex (MTAF)	Angelus, Londrina, Brazil	Dual resin paste	Paste A: salicylate resin, bismuth trioxide, fumed silica, Paste B: fumed silica, titanium dioxide, mineral trioxide aggregate, and base resin.[31]	(Camilleri, 2015)[26] (Viapiana et al., 2014)[27]
Total fill BC Sealer (TFBC)	FKG Dentaire, La-Chaux-de-Fonds, Switzerland	Single pre-mixed paste	Zirconium oxide, dicalcium silicate, tricalcium silicate, calcium phosphate monobasic, calcium hydroxide, filler, thickening agents[20]	(Donnermeyer et al., 2021)[20]
Total fill BC Sealer HiFlow (TFHF)	FKG Dentaire, La-Chaux-de-Fonds, Switzerland	Single pre-mixed paste	Zirconium oxide, dicalcium silicate, tricalcium silicate, calcium hydroxide, filler[20]	(Donnermeyer et al., 2021)[20]
Well-Root (WRST)	Vericom, Gangwon-Do, Korea	Single pre-mixed paste	calcium silicate, zirconium oxide, filler, thickening agent[23]	(Yamauchi et al., 2021)[23]

surface within a timeframe ranging from 1 minute to 1 hour and does not leave a visible indentation. The elapsed time from the start of dispensation until the sealer is set is recorded as the setting time.

All 10 included studies used comparable methodologies for assessing setting time. Six utilized a Gilmore needle/cylindrical indenter for final setting time[18,20-23,25], while 2 studies[19,24] first used the Vicat identer for assessing initial setting and then used the Gilmore needle for final setting time assessment. Another 2[26,27] used a modified Vicat apparatus. Furthermore, heating of the sealers was done simultaneously in 3[18,25,27] of the studies, while the remaining 7[19-24,26] studies heated the sealers prior to the assessment.

Flow

Flow was assessed by 9 studies[18-26] in accordance with ISO 6876 (2012) specifications, which stipulate a minimum requirement for flow of at least 17 mm.

The assessment of this property involves mixing the sealers, dispensing them into the center of a glass plate of specific dimensions, and subsequently placing a

TABLE 3 - Study Characteristics

Study	Sealers	Property	Assessment tool	n	Heated groups	Groups
(Nomura et al., 2023)[18]	AHP, Bio-C, BR BC.	Setting time	Gilmore needle	3	H.S	37 °C/95% humidity
		Flow	Glass plates & digital calipers	3	H.S	100°C/1 min in oven
		Solubility	Distilled water	6	Pre.H	37°C/95% humidity
		pH	pHmeter calibrated with buffer solution	6	Pre.H	100°C/1 min in oven, then 37°C/100% humidity.
		Dimensional change	Distilled water	6	Pre.H	
(Mann et al., 2022)[19]	AHP BC BCH.	Setting time	Initial & final setting: Gillmore apparatus	3	Pre.H	37°C/95% humidity 200°C/30s in oven, then 37°C/100% humidity.
		Flow	Glass plates	3	H.S	RT 100°C/1 min then 9 mins at RT. 150°C
(Donnermeyer, et al., 2021)[20]	BR TFBC TFHF.	Setting time	Cylindrical indenter	3	Pre.H	37°C/30s 47°C/30s 57°C/30s 67°C/30s 77°C/30s 87°C/30s 97°C/30s 97°C/60s 97°C/180s
		Flow	Glass plates & digital micrometer	3	Pre.H	
		Film thickness	Digital clipper	3	Pre.H	
(Aksel et al., 2021)[21]	AHP BR BC BCH.	Setting time	Indenter	3	Pre.H	37°C.
		Flow	Glass plates & ImageJ software	5	Pre.H	200°C/10s in oven, then 37°C/100% humidity.
		Viscosity	Rheometer	5	Pre.H	200°C/30s in oven, then 37°C/100% humidity.
(Antunes et al., 2021)[22]	AHP Bio-C BR BCH	Setting Time	Gilmore needle	6	Pre.H	37°C/95% humidity
		Flow	Digital caliper	6	Pre.H	100°C/1 min in oven.
		Solubility	Distilled water	6	Pre.H	
		Radiopacity	Aluminum scale & ImageJ tool software	6	Pre.H	
		pH	Digital pH metre	6	Pre.H	
(Yamauchi et al., 2021)[23]	AHP BC BCH ESMTA WRST.	Setting time	Gilmore-type metric indenter	8	Pre.H	37C°/95% humidity. 100 C°/1 min in oven, then 37°C/100% humidity.
		Flow	Glass plates & ImageJ software	8	Pre.H	RT (23 ± 2°C) 100 C°/1 min in oven, then 37°C/100% humidity.
		Film Thickness	Glass plates & Microcaliper	8	H.S	RT (23 ± 2°C).
		pH	Digital pH meter (F-12, Horiba, Kyoto, Japan)	5	Pre.H	100 C°/1 min in oven.
(Chen et al., 2020)[24]	BC BCH.	Setting time	Initial setting: Vicat indenter Final setting: Gilmore needle	3	Pre.H	37°C/95% humidity. 100 C°/1 min in oven, then 37°C/100% humidity.
		Flow	Glass plates & Digital caliper	3	H.S	RT (21C) 100 C°/1 min in oven.
		Film thickness	Glass plates & micrometer	3	H.S	

(*continued on next page*)

TABLE 3 - Continued

Study	Sealers	Property	Assessment tool	n	Heated groups	Groups
		Microhardness	Microhardness tester	3	Pre.H	37°C. 100 C°/1 min in oven.
		Viscosity	Rheometer with the plate & plate geometry & a Peltier plate temperature control.	3	H.S	21°C 37°C 100°C 150°C with a shear rate range from 0.01–10s^{-1}
(Qu et al., 2016)[25]	AHP, iRSP RS ZOE.	Setting time	Gilmore-type metric indenter	5	H.S	37°C/95% humidity. 140C in oven.
		Flow	Micrometer		H.S	25°C/10 mins 140°C/10 mins
		Porosity	Stereoscopic microscope & ImageJ software	10	Pre.H	37C. 140°C/95%/48 hrs.
(Camilleri, 2015)[26]	AHP APX, Experimental-TS MTAF.	Setting time	Modified Vicat apparatus	3	Pre.H	37°C. 100 C°/1 min in oven.
		Flow	Micrometer	3	Pre.H	
		Film thickness	Micrometer	3	Pre.H	
(Viapiana et al., 2014)[27]	AHP MTAF PCS, Prototype-PC.	Setting time	Modified Vicat needle	8	H.S	37°C. 100 C°/1 min.
		Compressive Strength	Compressive Strength Testing machine	8	Pre.H	37°C. 100 C°/1 hr then 37°C.

BC, Endosequence BC sealer; BCH, Endosequence BC Sealer Hiflow; Bio-C, Bio-C sealer; BR, BioRoot RCS; ESMTA, EndoSeal MTA; H.S, heated simultaneously; iRSP, iRoot SP; MTAF, MTA Fillapex; N, number of sealer samples experimented in each group; Pre.H, PreheatedM; TFBC, Total fill BC Sealer; TFHF, Total fill BC Sealer HiFlow; WRST, Well-Root.

second glass plate (typically weighted at 20 g) and a 100-120 g weight centrally on top of the sealer. This assembly is then left undisturbed for 10 minutes before removal. The minimum and maximum diameters of the resulting sample disks are measured using tools such as digital calipers or micrometers. If the disks exhibit nonuniform circularity (with the maximum and minimum diameters deviating by more than 1 mm), the test is typically repeated. The mean value is considered indicative of the material's flow.

Six of the included studies[18,20,22,24-26] used digital calipers/micrometers, 2 of them used ImageJ software[21,23], while 1 of them did not specify the tool used to measure the sealer flow. Moreover, 4 of the included studies[18,19,24,25] heated the sealer simultaneously and 5 of them preheated them.[20-23,26]

Film Thickness

Four included studies evaluated the flow thickness,[20,23,24,26] also in accordance with ISO 6876 (2012) specifications, which prescribe a requirement for film thickness of 50 μm or lower.

Following exposure to the desired temperature, the sealers are positioned between two glass plates of specific dimensions. After a specified duration (typically 180 ± 5 seconds) from the start of placement, a vertical load of 150 N is applied on top of the glass plate using a universal testing machine, ensuring a complete filling of the material between the top and bottom glass plates. After 10 minutes from the placement, the thickness of the combined glass plates and sealer is measured using a calibrated device. The initial thickness of the 2 glass plates in contact is also measured before dispensing the sealer. The film thickness of the sealer is determined as the difference in thickness with and without the sealer in place.

Among the included studies, 3 of them used micrometers/microcalipers[23,24,26] and 1 of them used a digital clipper[20] to measure the thickness of the two glass plates before and after. Additionally, 2 studies preheated the sealers[20,26] and 2 heated the sealers simultaneously[23,24].

pH Analysis

This property was assessed by 3 studies[18,22,23]. Sealers are typically introduced into plastic tubes and submerged in purified water. Subsequently, they are stored at 37 °C with a relative humidity of 95% for a specified duration. Following each time interval, the average pH level is assessed using a pH meter that undergoes calibration before each measurement.

All sealers in the included studies were heated prior to the pH assessment, 2 of the studies used digital pH meters[22,23] and one of them used a pH meter calibrated with buffer solution[18].

Solubility

Solubility testing, evaluated by 2 included studies[18,22], shared a common methodology. Sealers in both studies were heated prior to the solubility evaluation. In each study, plastic molds or Teflon rings were employed to contain the sealers, followed by incubation at 37°C for a duration related to the setting time. Antunes et al[22] introduced a threefold setting time delay before initiating the test, while Nomura et al[18] subjected the samples to a heating process. Subsequently, both studies measured solubility by calculating the percentage of weight lost over the original weight. For Antunes et al[22], this involved drying samples in a vacuum desiccator, weighing them, immersing them in distilled water for 30 days, and then redrying and reweighing. Nomura et al[18] stored heated and unheated samples at 37 °C and 95% relative humidity for 3-fold the setting time before calculating solubility.

Viscosity

Viscosity, which was evaluated by 2 included studies[21,24], is conducted using a rheometer featuring specialized plate geometry, such as a flat steel parallel plate, coupled with precise temperature control. Following exposure to the desired temperatures, the sealers are placed on the steel plate, and the viscosity analysis is executed. The viscosity assessment within the 2 included studies in the review involved subjecting the samples to a controlled shear rate within a range of 0.01–10 s^{-1} [24] or a range of 0.01 - 1 s^{-1} [21].

Radiopacity

One study[22] evaluated the effect of temperature on the radiopacity of the sealers. Samples were prepared, preheated, and radiographs were later taken using a digital sensor along with an aluminum scale. The grey levels of the images were later analyzed using Image Tool software in a constant area of 3000 pixels. The radiopacity values were expressed in millimeters.

Dimensional Change

One study[18] assessed the dimensional change of CSSs. Specification N° 57 of ANSI/ADA[32] established 0.1% maximum values for expansion and 1.0% for contraction.

Cylindrical samples of each sealer (heated and unheated) were fabricated using a Teflon mold containing drilled holes for the 24-hour and 30-day tests. Then, the samples were stored at 37 °C and 95% relative humidity for 24 hours. After measuring the initial sample length on the longest axis of the cylinder, each sample was placed in a container with distilled water and stored at 37 °C for 24 hours or 30 days. New measurements were performed after the removal of excess water from the retrieved aged samples. The dimensional change was calculated using the following formula: $[(C_1 - C)/C] \times 100$, where C_1 = sample length on the longest axis of the cylinder after 24 hours or 30 days and C = sample original dimension.

Microhardness

Microhardness testing was performed by one study[24], by injecting sealers into molds, placing wet cloth pieces between the molds and glass plates, and fixing the assembly with a clamp. After 24 hours in a 37°C water bath, the clamp was removed, and the assembly was submerged in water for an additional 48 hours. Specimens were then taken out, polished with 1200-grit sandpaper, and evaluated using a microhardness tester. Each specimen was tested at 3 points with 3-mm intervals and a 100 g load for 10 seconds.

Porosity

One study[25] assessed the porosity of CSSs. After filling the sealers into molds and exposing them to the desired temperatures and conditions, they were transversely sectioned at 3, 5, and 7 mm from the bottom of the mold. The porosity of sealers was analyzed under a stereoscopic microscope. The slides were scanned as bitmap images. The area of the molds (A_M) and the area of the voids (A_V) were recorded using ImageJ software (National Institutes of Health, Bethesda, MD), and the percentage of the area of voids (void % = 100 X A_V/A_M) was calculated.

Compressive Strength

Finally, one study[27] assessed the compressive strength of CSSs. The sealers were manipulated previously and inserted in the molds then exposed to the desired temperature & condition. After this, they were removed from the molds and tested in compression at a loading rate of 50 N/min.

Study Results

Significant differences observed by the included studies regarding the effect of heat on the physical-chemical properties of CSSs are illustrated in Table 4. Outcomes are subdivided by each physical-chemical property where results are shown as either significantly reduced due to heat (−), significantly increased due to heat (+), Exceeds ISO recommendations (**+***), Below ISO recommendations (**-***) or left as an empty cell if the sealers were not affected by heat. Complementarily, quantitative results are also extracted and listed in supplementary tables (1-4).

BC and BCH, which are premixed CSSs, showed minimal changes in their setting time from heat. Although it was shortened[18,19,22,23], it remained within the ISO recommendations. While BCH demonstrated slightly superior flow compared to BC under heat conditions[19,21,23], it did surpass ISO recommendations for flow in one study[22]. In another study[23], both BC and BCH exhibited reduced flow below ISO recommendations. Additionally, BCH showed increased solubility exceeding ISO recommendations in a study by Antunes et al[22]. The remaining properties remained within ISO guidelines.

BR, a liquid and powder sealer, demonstrated a significant reduction in its setting time[21,22] and flow[18,21] when subjected to heat. Furthermore, when subjecting BR to temperatures exceeding 77°C, it led to the immediate setting of the sealer, impeding the measurement of its setting time, flow, and film thickness in a study by Donnermeyer et al[20]. A significant increase in its solubility was also reported in another study[22], where it exceeded the ISO recommendations.

MTAF did not seem to be influenced by heat, except in a single study[27] where it exhibited lower compressive strength compared to resin-based AHP, regardless of whether it was exposed to heat or not. The remaining sealers were assessed in either one or two studies. Their results are outlined in Table 4.

Quality Assessment

The results from the quality assessment using the PRILE 2021 guidelines for reporting laboratory studies in Endodontology[17] are presented in supplementary table 5. The mean compliance of the included studies was 78.7% with a maximum score of 89% and a minimum score of 70%. None of the studies included in this review provided the area/field of interest or study type in the title, which is *in vitro* (item 1b), while all 10 studies mentioned at least two keywords related to the subject of the investigation (item 2a). Within the abstract, all studies presented clear objectives of the investigation (item 3b), the most significant results (item3d) and the main conclusions of the study (item 3e). All the included studies complied with both items related to the introduction (item 4a and 4b), providing a background summary of the scientific investigation (4a) and clearly stating the aim(s), purpose(s), or hypothesis(es) of the investigation (4b). In the Materials and Methods section, all studies successfully provided sufficient information about the methods and tools used in the study (item 5d). Additionally, they clearly specified the use of categories (item 5e) and detailed the numbers of replicated identical samples within each group (item 5f). Moreover, in the Results section, all studies provided comprehensive statistical results, including group comparisons (item 6c). In the discussion section, all studies fulfilled the initial two criteria by addressing the relevant literature and status of the hypothesis (item 7a), as well as providing the significance of the investigation (item 7b). Both items related to the conclusion section were also all fulfilled by all the studies (8a, 8b). Finally, the studies also fulfilled items 9a concerning study funding and 10a regarding conflicts of interest. The remaining items exhibited variations across individual studies, while Items (5b, 5g, 5h, 5i), 6b and (11a-h) were deemed as nonapplicable to the included studies.

TABLE 4 - Significant Results

Property	Study	Sealers used in study	Results	
			Nonheated	Heated
Setting time	(Nomura et al., 2023)[18]	AHP, Bio-C, BR, BC.	BR < AHP & BC	(−): AHP, BC. BR < AHP, BC.
	(Mann et al., 2022)[19]	BC, BCH, AHP.	BC, BCH > AHP	(−): BC, BCH, AHP. BC, BCH > AHP.
	(Donnermeyer et al., 2021)[20]	BR, TFBC, TFHF.		(**-***): BR (heating beyond 77 °C led to immediate setting).
	(Aksel et al., 2021)[21]	AHP, BR, BC, BCH.		(+): BC, BCH. (−): AHP, BR.
	(Antunes et al., 2021)[22]	AHP, Bio-C, BR, BCH	Bio-C: fastest in Dry conditions; slowest in Moist conditions.	Dry Conditions: (−): AHP, BR, BCH. (+): Bio-C. Moist Conditions: (+): BCH. BR: similar Setting time at both 37C & 100C.
	(Yamauchi et al., 2021)[23]	AHP, BC, BCH, ESMTA, WRST.		(−): AHP, BC, BCH. (**-***): ESMTA, WRST.
	(Chen et al., 2020)[24]	BC, BCH.		
	(Qu et al., 2016)[25]	AHP, iRSP, RS, ZOE.	AHP > iRSP > ZOE > RS	(−): AHP, iRSP, RS
	(Camilleri, 2015)[26]	AHP, APX, Experimental-TS, MTAF.	AHP > Experimental-TS	(−): AHP, APX
	(Viapiana et al., 2014)[27]	AHP, MTAF, PCS, Prototype-PC.	PCS: tendency to flow out from underneath the mold	(−): AHP, Prototype-PC.
Flow	(Nomura et al., 2023)[18]	AHP, Bio-C, BR, BC.	BR < AHP, Bio-C, BC	(−): AHP BR < AHP, Bio-C, BC.
	(Mann et al., 2022)[19]	AHP, BC, BCH.	BCH & BC < AHP	100°C: BCH > AHP & BC. 150°C: AHP > BCH & BC.
	(Donnermeyer et al., 2021)[20]	BR, TFBC, TFHF.		(**-***): BR (heating beyond 77°C led to immediate setting).
	(Aksel et al., 2021)[21]	AHP, BR, BC, BCH.	BC, BCH > AHP, BR.	BCH > BC & AHP > BR.
	(Antunes et al., 2021)[22]	AHP, Bio-C, BR, BCH		(+): BCH (−): Bio-C
	(Yamauchi et al., 2021)[23]	AHP, BC, BCH, ESMTA, WRST.		(**-***): All WRST, BCH > BC, AHP.
	(Chen et al., 2020)[24]	BC, BCH.	BCH > BC.	(−): BCH > BC
	(Qu et al., 2016)[25]	AHP, iRSP, RS, ZOE.	RS > AHP, iRSP, ZOE	AHP > iRSP, RS > ZOE
	(Camilleri, 2015)[26]	AHP, APX, Experimental-TS, MTAF.	(**-***): AHP, Experimental-TS	(+): AHP
Film thickness	(Donnermeyer et al., 2021)[20]	BR, TFBC, TFHF.		(**-***): BR (heat beyond 77°C led to immediate setting).
	(Yamauchi et al., 2021)[23]	AHP, BC, BCH, ESMTA, WRST.		ENMTA **(+*)**, WRST **(+*)** > BC, BCH, AHP
	(Chen et al., 2020)[24]	BC, BCH.		(+): BC BC > BCH
	(Camilleri, 2015)[26]	AHP, APX, Experimental-TS, MTAF.		(+): AHP & Experimental-TS.
pH	(Nomura et al., 2023)[18]	AHP, Bio-C, BR, BC.	Regardless of temperature; CSBS > AHP	
	(Antunes et al., 2021)[22]	AHP, Bio-C, BR, BCH	Regardless of temperature; after 21 days, all sealers had an alkaline pH above 7, & CSBS > AHP on day 21.	
	(Yamauchi et al., 2021)[23]	AHP, BC, BCH, ESMTA, WRST.	Regardless of temperature; CSBS > AHP	
Solubility	(Nomura et al., 2023)[18]	AHP, Bio-C, BR, BC.	(**+***): Bio-C "non-hydrated". Bio-C: hydrated & heated < hydrated & unheated. AHP < Bio-C, BR, BC.	(**+***): Bio-C "non-hydrated". (+): BC "dehydrated after 30 days". AHP < Bio-C, BR, BC.
	(Antunes et al., 2021)[22]	AHP, Bio-C, BR, BCH	(**+***): Bio-C, BR, BCH.	(**+***): Bio-C, BR, BCH. (−): BCH, Bio-C.

(*continued on next page*)

TABLE 4 - Continued

Property	Study	Sealers used in study	Results Nonheated	Results Heated
Viscosity	(Aksel et al., 2021)[21]	AHP, BR, BC, BCH.	BR > AHP > BC, BCH	BR > BC > AHP > BCH. 200C: (−): AHP, BCH. (+): BC.
	(Chen et al., 2020)[24]	BC, BCH.		(−): BC, BCH. At all temperatures & at a shear rate of 0.01 and $0.1s^{-1}$: BC > BCH
Radiopacity	(Antunes et al., 2021)[22]	AHP, Bio-C, BR, BCH.		(−): BR
Dimensional change	(Nomura et al., 2023)[18]	AHP, Bio-C, BR, BC.		
Microhardness	(Chen et al., 2020)[24]	BC, BCH.		
Porosity	(Qu et al., 2016)[25]	AHP, iRSP, RS, ZOE.		(−): ZOE, iRSP.
Compressive strength	(Viapiana et al., 2014)[27]	AHP, MTAF, PCS, Prototype-PC.	AHP, Prototype-PC > PCS, MTAF.	(−): AHP. (+): Prototype-PC AHP, Prototype-PC > PCS, MTAF.

(−), Significantly reduced compared to non-heated due to heat; (+), Significantly increased compared to non-heated due to heat; >, Significantly greater than; <, Significantly lower than; (+*), Exceeds ISO recommendations; (-*), Below ISO recommendations;. BC, Endosequence BC sealer; BCH, Endosequence BC Sealer Hiflow; Bio-C, Bio-C sealer; BR, BioRoot RCS; ESMTA, EndoSeal MTA; iRSP, iRoot SP; MTAF, MTA Fillapex; TFBC, Total fill BC Sealer; TFHF, Total fill BC Sealer HiFlow; WRST, Well-Root.

DISCUSSION

Understanding the characteristics of the materials used in root canal treatment is crucial for effective treatment planning. Among them, CSSs hold significance in contemporary endodontics. Accordingly, this review evaluates heat's impact on the physical-chemical properties of recently developed CSS, aiming to address concerns raised by clinicians on combining the advantages of CSSs with warm gutta-percha filling techniques. To the authors` knowledge, this systematic review is the first to integrate and evaluate *in vitro* evidence on the effect of heat on the physiochemical properties of CSSs.

The ideal root canal sealer should have optimal physical-chemical properties, such as adequate sealing capability, dimensional stability, thin film thickness, proper setting and working times, insolubility in tissue fluid, and an appropriate adherence to canal walls[33]. Epoxy resin sealers are considered as the gold standard due to their excellent physical properties and sealing ability[14,34]. However, concerns regarding their cytotoxicity remain relevant[35]. In contrast, CSSs have gained recognition for their biocompatibility or lack of cytotoxicity, providing an alternative with favorable biological properties[36].

On the Methodology of the Included Studies

All studies mixed the tested sealers according to the manufacturer's instructions and then subdivided the groups to nonheated (room temperature or 37°C) or heated groups that were either exposed to the heat simultaneously while being tested or preheated. The recommended application time for the heat source is 10 s, which is sufficient to aid cutting and warming the gutta-percha for compaction. Nonetheless, the duration could be extended to 30 seconds or higher, depending on the clinician's expertise and the complexity of the case[37]. Among the included studies, it was observed that sealers were heated for different times, ranging from 10 seconds to 48 hours depending on the property assessed, which could potentially account for the different results observed across the studies. Similarly, variations in the temperatures to which the sealer was exposed can lead to different outcomes across the studies. While the temperature range among the included studies varied from 47°C to 200°C, the prevailing choice among them was 100°C, which was recommended by recent research[26] to replicate the clinical conditions observed in clinical conditions. This temperature choice aligns with the context of warm vertical compaction procedures, where heat is applied in continuous waves, and the entire process typically lasts around a minute. Although most thermoplasticized systems operate with device settings at a temperature of 200°C, the pluggers of warm obturation devices do not reach such temperature, as indicated by previous investigations[38]. Instead, the temperature is reached by the plugger is approximately 100°C[39].

An additional disparity in the methodologies of the studies lies in the heating of the sealers. While some studies subjected the sealers to preheating, followed by an incubation period at 37°C under relative humidity until the experimental procedure was initiated, other studies simultaneously heated the sealer and promptly conducted the experiment thereafter. This difference in the approach is likely to also affect the results since the timing and sequence of heat application can play a role in the outcomes *On the results of the included studies*.

Eleven different physical-chemical properties were evaluated throughout the included studies, as discussed below.

Setting Time

Setting time is directly related to the working time during root canal treatment. This characteristic depends on the constitution of the sealer, particle size, temperature, and humidity[40,41]. For this reason, all 10 included studies assessed the influence of heat on the physical-chemical properties of CSSS.

As previously mentioned, ISO recommends a setting time lower than 20 minutes for endodontic sealers. Different results were recorded among the studies. For example, it was observed that BC and BCH's setting time was shortened when exposed to heat in some studies[18,19,23], which is in accordance with the manufacturer's claims. This can be explained by the fact that BC Sealer and BCH, which share a similar composition, contain calcium dihydrogen phosphate and calcium hydroxide, in addition to calcium silicate. In this way, hydroxyapatite and water are produced after the reaction between calcium dihydrogen phosphate and calcium hydroxide during setting, and the water generated, in addition to the moisture in the environment, accelerates the hydration reaction of calcium silicate[20].

In contrast, in another study, their setting time was not affected by heat[24] Aksel et al[21] even found that both materials exhibited a longer setting time when exposed to heat (24 hours), which was longer than the manufacturer's claim (4–10 hours). Furthermore, it was reported that BR sealer was negatively affected by heat in all the studies that tested it. In fact, subjecting BR to heat beyond 77°C led to an immediate setting of the material in one of the studies[20] and the assessment of its physical properties was impossible. While another study[22] reported that in a dry and heated environment, BR had a significantly shorter setting time, possibly due to the enhancement of calcium chloride (which acts as a setting time accelerator) with the increase in temperature, as previously reported[42].

Bio-C sealer was not affected by heat in one of the studies[18], while its setting time was extended in another study[22] in both dry and moist conditions. On the other hand, the setting time of EndoSeal MTA (ESMTA) was reduced to approximately 2.5 minutes when exposed to heat. This was attributed to the hydration reaction of calcium silicate and pozzolanic reaction, which leads to the conversion of calcium hydroxide to insoluble phases such as calcium silicate hydrate[43]. This is believed to allow for rapid setting[44]. However, these results exceeded ISO recommendations, which suggests that the use of this sealer for warm vertical technique may be time-constrained for completing the procedure. Parallelly, Well-Root (WRST) exhibited a rapid setting, second only to the setting rate of ESMTA. This may be attributable to the fact that WRST contains calcium aluminosilicate, which is capable of setting more rapidly than calcium silicate[23].

The different results may be attributed to the differences in the methodologies carried out among these studies. One of the differences observed was the choice of molds used to contain the CSSs after mixing them. The majority of the studies used plaster/gypsum molds which were previously immersed in water for 24 hours, which seems like a convenient choice when using such sealers due to their necessity for moist to set. Another study utilized silicone rubber molds[21], due to their ability to withstand heat; however, it's worth noting that they are impermeable to moisture. To address this, wet filter papers were positioned beneath the silicone molds to ensure sufficient moisture for the setting process. According to the author, this approach appears appropriate since it provides a similar setting time to a dentin permeability pressure model that was used in a previous study[45]. Another included study opted for plastic molds[27], while the mold's material was unspecified in another study[26]. It should also be highlighted that all studies used molds that were approximately 10 mm in diameter and 1–2 mm in height. These dimensions are large and differ from instrumented root canals. Thus, the quantity and distribution of CSSs used during experimentation may differ from that of root canal treatment. This difference may reduce the representativeness the observed results.[21]

Flow

Flow rate is one of the primordial properties of CSSs, since it defines their viscosity and ability to fill irregularities in root canals[46]. Previous studies have described that it is dependent on particle size, shear rate, time, temperature, the inner diameter of the root canal, and the insertion speed[1]. Among the included studies, it was observed that heating significantly changed the flowability of all CSSs.

In 2 studies, a decline in the flow rate of BR was evident after subjecting it to elevated temperatures[18,21], while in another study it had fully set after exposure to temperatures of 87 °C and above[20]. Likewise, Bio-C sealer experienced a notable reduction in its flow, which was attributed to dehydration and polyethylene glycol degradation[22]. Heating also caused a significant decrease in flow in all sealers (AHP, BC, BCH, ESMTA, WRST) evaluated in the study by Yamauchi[23]. The flow of the tested sealers did not meet the aforementioned ISO 6876:2012 criterion after being subjected to heat, which was attributed to the accelerated setting reaction that occurred at elevated temperatures[26,47].

In various included studies[19,21,22,24], BCH exhibited an increased flow when exposed to a temperature of 100°C. This flow was significantly higher than that of BC Sealer. Likewise, TFHF exhibited a higher flow at all temperature levels when evaluated by Donnermeyer et al[20]. It is worth noting that, despite TFHF and BCH showing elevated flow rates compared to their respective original counterparts TF and BC, the latter still remained within clinically relevant thresholds recommended by the respective ISO guideline. Finally, the flow characteristics of MTAF in one of the studies[26] remained consistent, exhibiting similar flow properties at both 37 and 100°, unaffected by heat exposure.

In light of the previous observations, it is the flow of BCH, TFHF and MTAF exhibited the most favorable behavior with elevated temperatures, making them potentially well-suited for filling techniques that involve heat; in accordance with the recommendations provided by their manufacturers. In contrast, other CSSs' flow was negatively affected by heat, especially at higher temperatures and longer exposure time. Aksel et al[21]. reported that this can result in excessive weight loss due to the loss of moisture, as indicated in their thermogravimetric analysis, and can adversely impact the flowability, viscosity, and overall weight of the sealer.

Film Thickness

Regarding film thickness, different results were observed across the included studies. BC's and BCH's thickness was in accordance with ISO 6876:2012 recommendations[24]. However, when heated to 100°C, there was a significant increase in film thickness of BC Sealer, whereas BCH thickness was not affected. Likewise, MTAF exhibited favorable characteristics, maintaining its film thickness below the recommended 50 μm whether or not heat was applied[26].

Parallelly, Donnermeyer et al[20] observed that the film thickness of TFBC and TFHF was not influenced by heat, complying with ISO standards across all tested temperatures (37 °C to 97 °C). However, in the same study, it was found that BR film thickness varied at around 8 μm when exposed to temperatures lower than 77 °C, while heating it above this temperature caused its immediate setting, making the measurement of film thickness unfeasible. Finally, when ESMTA and WRST were heated[23], their film thickness exceeded 50 μm. This increased film thickness after heating was explained by heat-induced acceleration of setting time. The efficacy of a sealer in relation to its thickness was previously reported to vary depending on the type of sealer[48]; CSSs tend to expand by approximately 0.2% to 6%[49]; however, they have also been reported to be more soluble than other sealers such as AHP and to release greater amounts of calcium ions[50]. The reaction between released calcium ions and surrounding phosphate ions generates apatites, which deposit as a precipitate on the surface layer of the sealer[51,52]. However, dissolution of a thick layer of sealer might be unfavorable for long-term maintenance of root canal sealing ability.

pH Analysis

pH is recognized as a significant chemical characteristic of sealers, given that the alkalinity of the sealer can elevate the pH of tissue fluids. This is particularly important in the presence of localized inflammation, where tissue fluid pH tends to be low[53].

Included studies[18,22,23] that evaluated the impact of heat on pH reported that heating did not alter the alkalinity of the tested CSSs (Bio-C, BR, BC, BCH, ESMTA, WRST). Also, regardless of temperature, CSSs showed elevated pH levels in comparison with the gold standard sealer AH plus.

The primary reaction responsible for the setting of calcium silicate-based sealers is the hydration of calcium silicates. Throughout this procedure, calcium hydroxide is generated, and upon encountering water or tissue fluid, it releases hydroxide ions and calcium ions, resulting in an alkaline pH[13,51,54,55]. Heating accelerates the hydration reaction in calcium silicate-based root canal sealers. This acceleration increases the production of calcium hydroxide at the initial setting stage, potentially impacting the release of ions[23]. Nevertheless, as observed, the pH of CSS was unaffected by heat, consistently maintaining an alkaline level (above 7). Clinically, this alkalinity is valuable for its antimicrobial benefits[56] and the promotion of calcification[54], rendering these sealers precisely what practitioners seek for various obturation techniques, whether involving heat or not, in the execution of endodontic treatments.

Solubility and Dimensional Stability

Solubility[57] and dimensional stability[58] represent crucial physical-chemical properties of a root canal filling material. Elevated solubility in a canal sealer could lead to structural loss in the oral environment, compromising the sealer's integrity[59]. Shrinkage is a dimensional alteration in endodontic sealers which has the potential to create gaps at the sealer/dentin or sealer/gutta-percha interface[60]. These gaps may serve as pathways for microorganisms and their harmful byproducts to infiltrate periapical tissues, compromising the integrity of the endodontic seal[59].

Dimensional change was assessed by Nomura et al[18] and reported that Bio-C sealer exceeded the recommended expansion limit after heat (0.1%). BR had slight shrinkage at 24 hours but expanded slightly at 30 days and BC Sealer showed slight shrinkage at both 24 hours and 30 days, aligning with previous findings[29,61].

Solubility's results varied among the included studies. It was observed in one of the included studies[22] that the solubility of Bio-C, BR, and BCH decreased when exposed to heat. However, at both temperatures, it remained above the recommended value by the ISO standards, which is less than 3%. This contrasts with AH Plus, which exhibited an average solubility of less than 1%, irrespective of the temperature. In another study[18], it was reported that Bio-C sealer was found to be less soluble after heating than without heating. However, the solubility in the dehydrated samples was higher than ISO standards. Nevertheless, the solubility values of BR and BC sealers, even after heating, were within the recommended solubility for sealers; irrespective of whether the samples were weighed wet or dry.

AHP met this solubility requirement in all the included studies, as reported in a previous study[29]. The low solubility of AHP was attributed to the strong cross-links in epoxy resin-based materials and to being a hydrophobic material and not adsorbing water[27,44]. In contrast, the elevated solubility of CSSs can be explained by the nanometric hydrophilic particles, which increase their surface area and allow more liquid molecules to contact the sealer when immersed[62]. However, considering the varied observations in the results related to the solubility of CSSs and the limited studies on dimensional changes, further investigations should be performed to expand on the evidence on these two properties.

Viscosity and Microhardness

As previously discussed, the importance of viscosity in endodontic sealers lies in its role in defining their flow rate and ability to fill irregularities in root canals[46]. Complementarily, the sealer's microhardness provides valuable information about the material's resistance to deformation, wear, and overall durability.

Two studies evaluated the impact of heat on the viscosity of sealers. Aksel et al[21] demonstrated that the viscosity of BC was significantly increased by temperature at shear rates of 0.01 and 0.1 s^{-1} regardless of the exposure time, while BCH showed a gradual decrease in its viscosity by heat. Chen et al[24] demonstrated that both BC and BCH showed a decreased viscosity with increasing shear rate. At a shear rate of 0.01 and 0.1 BCH exhibited lower viscosity than BC sealer at all temperatures measured. The author of the latter study suggested that increasing the shear rate during sealer insertion could enhance its flow by reducing viscosity within the clinically relevant range of shear rates (0.01–1 s^{-1}). In theory, elevating the insertion rate for sealers may improve flow into irregularities and around the core material. However, excessive flow rates may lead to apical extrusion, potentially causing periapical tissue damage[24]. Further research is needed to evaluate the impact of these insertion rates on sealer extrusion beyond the apical foramen during compaction.

Microhardness was only assessed in one study[24]. It was reported that the microhardness of BC and BCH were not influenced by heat and they both exhibited similar values at heated and nonheated conditions. Further evidence on different CSSs is required to confirm these results.

Radiopacity, Porosity, and Comprehensive Strength

Radiopacity is a physical property that enables the observation of root canal materials by means of radiographic and tomographic images to verify the quality of the filling and its long-term performance[63]. ISO 6786-2012 recommends a radiopacity value that is greater than 6- mm Al. An included study[22] observed that the application of heat had no significant change on the radiopacity of BCH and Bio-C sealers. BR, on the other hand, exhibited a significant reduction in its radiopacity. However, all the tested sealers maintained values that were within the ISO recommendations.

In contrast, AHP had the highest value of radiopacity. This high value was attributed to its composition, which contains 2 radiopacifiers: zirconium oxide and calcium tungstate; in contrast with other tested sealers, which only contain zirconium oxide in their composition[13].

Porosity serves as an indicator that reflects the quality of root canal obturation and its ability to seal in a three-dimensional manner. With decreasing porosity, the seal of the root canal filling improves[39]. This property was examined in an included study by Qu et al[25] and reported a significant reduction of porosity in iRoot SP at high temperatures.

A study evaluated the compressive strength of AH Plus, MTAF, and a prototype sealer based on Portland cement. The study revealed that the compressive strength of AH Plus significantly decreased after exposure to heat; likely due to degradation of its amine components observed in FTIR analysis. In contrast, the prototype sealer, which also contains epoxy resin, exhibited increased cross-link polymerization and higher compressive strength values after heating, despite the higher porosity levels observed in the latter sealer.

Altogether, assays on the effect of heat on CSS radiopacity, porosity, and comprehensive strength are based on individual studies. Thus, further investigations are necessary to ascertain their results.

Potential Clinical Outcomes and Recommendations

Overall, the aforementioned changes in the physio-chemical properties of CSSs can hinder the clinician's ability to manipulate the sealers effectively during root canal filling approaches involving heat such as warm vertical compaction or continuous wave techniques. Insufficient manipulation, accelerated setting time, and/or reduced flow may cause inadequate spread of the sealer can compromise the quality of the root canal filling, potentially leaving voids or gaps that house bacteria and facilitate microbial ingress, leading to treatment failure or postoperative complications. Therefore, ensuring optimal setting time and flow characteristics of heat-applied sealers is crucial for their successful application and long-term efficacy in endodontic treatment.

Resin-based sealers are susceptible to shrinkage and both resin-based and calcium silicate-based sealers are susceptible to dissolution over time[55,64]. However, CSSs are known to expand in volume by 0.2–6%[49], which is considered beneficial for achieving a tight seal[65]. An increase in their film thickness was observed across the included studies, which may offset the negative effects of dissolution to some degree. However, further investigation is needed to determine whether the thicker sealer layer formed by CSSs, especially after heat application, maintains an acceptable level of long-term sealing quality. Altogether, the scarce evidence for each individual CSS hinders the proposal of specific clinical recommendations for their use in heat-based root canal filling techniques. Nevertheless, clinicians should be aware of the potential reduction of the setting time and flow and increase in solubility and film thickness of CSSs subjected to the temperature increase in heat-based root canal filling techniques.

Nevertheless, clinical studies have demonstrated positive and similar rates of success for both CSSs and epoxy resin-based sealers, as reported in a study using warm vertical compaction at 150°C[66] or a carrier-based technique in another study[67]. In a different study, a 1-year success rate of 99% was reported when utilizing four different of premixed CSSs in conjunction with either the continuous wave technique or the carrier-based technique[68]. Additionally, in another study, 82% of cases treated with AH Bioceramic sealer using a carrier-based technique (Thermafil; Dentsply, Konstanz, Germany) showed complete healing after 1 year[69]. Again, further long-term clinical studies are necessary to confirm these results.

Strengths, Limitations, and Future Perspectives

The present review reports a systematic advanced search that aimed to qualitatively assess all physical-chemical properties studied in laboratory studies on the effect of heat on CSS properties. The inclusion criteria were intentionally kept broad, not focusing on a specific property but instead, the term "silicate" was used to ensure the inclusion of all potentially eligible studies on calcium silicate-based materials. Furthermore, standardized guidelines were followed to perform this review (Preferred Reporting Items for Systematic Reviews and Meta-Analysis 2020 Statement)[15] and the quality assessment of the included studies (PRILE 2021 guidelines)[17].

The strengths and weaknesses of the included studies, assessed using PRILE 2021 guidelines[17], ranged from a minimum of 70%[23] to a maximum of 89%[24] of percentage of item fulfilment, indicating an adequate level of transparency and reliability for potential replication in future research. Notably, none of the included studies met the requirement of item 1A, which refers to clearly identifying the study as laboratory/*in vitro* based. However, this omission does not significantly impact the investigation process. Other items, such as item 5C, which addresses the use of a justified sample size and the inclusion of negative and positive control samples, hold importance for the validity and reliability of the study. These aspects should be carefully considered in future investigations. Furthermore, items 7c, 7d, and 7e are related to the identification of the strengths, limitations, and implications for future research, respectively. Compliance with these items varied among the included studies, with some neglecting to address these critical aspects. Future studies must ensure meeting these items to provide transparent and credible guidance for future replication and to prevent misinterpretation.

The main limitation of this review arises from the heterogeneity among the methodologies employed in the included studies, which hinders the quantitative synthesis of the data or meta-analysis. Furthermore, only 10 different CSSs underwent assessment of their physicochemical properties under heat, and some of these sealers were only evaluated in a single study. Currently, recent reviews in the field of CSSs identify more than thirty commercially available formulations, although many of them lack supporting evidence for many of their properties, applications, and clinical performance[70,71]. Further studies on the properties of emerging CSS formulations used in daily endodontic practice should also be performed. In addition, the *in vitro* nature of the included studies acts as an inherent limitation in terms of the representativeness of the data into the clinical setting. These studies are conducted in controlled laboratory settings, lacking the potential factors and dynamic conditions from the oral medium. Thus, results should be interpreted as a collection of preliminary evidence that may act as the baseline for future studies. However, given the importance of *in vitro* studies and their necessity before the clinical application of sealers, future similar studies should evaluate physical-chemical properties at clinically relevant temperatures, with a maximum of 100°C. The use of standardized methodologies, following ISO recommendations, is crucial to increase the replicability of studies and to facilitate their comparison. In terms of the effect of heat on the physical-chemical properties of CSSs, the following properties should be further investigated: solubility, viscosity, radiopacity, dimensional change, microhardness, porosity, and compressive strength.

CONCLUSION

Based on the *in vitro* studies assessed in the present systematic review, results reveal that exposing CSSs to heat may accelerate their setting time, reduce their flow, and increase their film thickness. Changes in their solubility, viscosity, radiopacity, dimensional change, microhardness, porosity, and compressive strength remain a relevant concern and should be further investigated. Different temperatures may have different effects on the physiochemical properties of CSSs. Studies report that MTAF, BCH, and TFHF sealer exhibit minimal changes in their physical-chemical properties when exposed to heat, maintaining them within the range of values stated in ISO recommendations. Thus, these sealers may be potentially eligible for heat-based filling techniques for root canal treatment.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Israa Ashkar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **José Luis Sanz:** Conceptualization, Formal analysis, Software, Supervision, Writing – review & editing. **Leopoldo Forner:** Project administration, Software, Supervision, Validation, Visualization. **James Ghilotti:** Writing – review & editing. **María Melo:** Project administration, Software, Supervision, Validation, Visualization.

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SUPPLEMENTARY TABLE 1 - Mean Values ± Standard Deviation (SD) for Setting Time (min), Flow (mm) Film Thickness (µm), Viscosity (Pa.S), and Radiopacity (mm Al)

		Property														
		Initial setting time (min)		Final Setting time (min)				Flow (mm)			Film thickness (um)		Viscosity		Radiopacity	
Study	Sealers used	unheated	Heated	Unheated		Heated		Unheated	Heated		Unheated	Heated	Unheated	Heated	Unheated	Heated
(Nomura et al., 2023)[18]	AHP			1127 ± 38		910 ± 16		24.1 ± 0.6	21.0 ± 1.8							
	Bio-C			140 ± 23		124 ± 14		19.4 ± 0.2	18.5 ± 1.0							
	BR			85		67 ± 4		16.5 ± 0.5	17.3 ± 0.6							
	BC			604 ± 48		489 ± 49		19.4 ± 0.3	19.9 ± 1.2							
(Mann A, 2022)[19]	AHP			*		*		*	*							
	BC			*		*		*	*							
	BCH			*		*		*	*							
(Aksel et al., 2021)[21]									10 seconds	30 seconds						
	AHP			*		*		24.31 ± 0.28	25.31 ± 1.03	25.92 ± 1.06			*	*		
	BR			*		*		19.46 ± 0.03	16.77 ± 1.74	12.79 ± 1.21			*	*		
	BC			*		*		27.86 ± 0.33	27.07 ± 0.59	27.17 ± 0.24			*	*		
	BCH			*		*		27.87 ± 0.33	32.75 ± 0.66	32.49 ± 0.71			*	*		
(Antunes et al., 2021)[22]				Moist method		Dry method										
				unheated	heated	unheated	heated									
	AHP			420.00 ± 26.83	461.00 ±4.33	467.50 ± 14.74	418.00 ± 4.47	21.08 ± 1.76	22.93 ± 1.11						9.29 ± 0.37	8.55 ± 0.13
	Bio-C			41.66 ± 9.30	254.00 ± 4.33	502.50 ± 22.07	983.00 ± 4.33	33.87 ± 2.75	18.74 ± 4.04						7.11 ± 0.51	6.41 ± 1.06
	BR			172.50 ± 8.21	182.00 ± 4.09	550.00 ± 12.24	152.16 ± 4.99	17.25 ± 2.35	21.89 ± 2.00						7.96 ± 0.39	6.94 ± 0.32
	BCH			407.50 ± 34.31	297.00 ± 4.33	3735.00 ± 13.41	2749.83 ± 4.11	23.74 ± 1.68	29.41 ± 2.42						7.84 ± 0.31	7.67 ± 0.39
(Yamauchi et al., 2021)[23]	AHP			730 ± 9.2		355 ± 36.8		23.2 ± 2.8	8.1 ± 0.4		17.8 ± 4.1	22.1 ± 7.2				
	BC			279 ± 15.2		55 ± 5.5		23.8 ± 1.2	9.0 ± 0.6		25.3 ± 5.0	25.6 ± 4.3				
	BCH			253 ± 13.4		68 ± 15		25.8 ± 2.0	12.3 ± 1.4		24.6 ± 7.4	27.9 ± 4.6				
	ESMTA			53 ± 2.3		2.5 ± 0.3		25.2 ± 2.4	‡		25.8 ± 6.9	308.9 ± 107.1				
	WRST			98 ± 4.8		14 ± 2.9		25.9 ± 1.8	16.7 ± 1.1		33.5 ± 12.1	63.0 ± 18.7				
(Chen et al., 2020)[24]	BC	†4.760.3	†4.360.3	†72.760.6		†71.361.1		†22.960.2	19.260.1		18.761.9	27.761.5	*	*		
	BCH	†4.760.3	†4.360.3	†72.760.6		†71.361.1		25.060.1	23.660.2		16.762.0	20.360.3	*	*		
(Qu et al., 2016)[25]	AHP			542.8 ± 16.4		12.9 ± 0.7		23.0 ± 1.1	23.7 ± 0.4							
	iRSP			245.8 ± 15.9		14.2 ± 0.6		22.1 ± 0.4	25.6 ± 0.7							
	RS			49.3 ± 1.5		2.7 ± 0.4		24.8 ± 0.9	12.4 ± 1.3							
	ZOE			144.0 ± 4.1		274.2 ± 7.4		22.9 ± 0.9	13.3 ± 1.5							
(Camilleri, 2015)[26]	AHP			†20 ± 1.3		†2.5 ± 0.1		15 ± 0.3	18 ± 0.8		60 ± 9.1	175 ± 9.9				
	APX			†37 ± 3.5		†7 ± 0.2		18 ± 0.4	19 ± 0.3		27 ± 11.3	27 ± 5.6				
	Experimental-TS			†1.5 ± 0.1		†0.5 ± 0.0		15 ± 0.3	6 ± 0.1		72 ± 11.3	349 ± 13.4				
	MTAF			†9 ± 0.0		†9 ± 0.1		25 ± 0.4	25 ± 1.1		33 ± 4.2	32 ± 0.7				
(Viapiana et al., 2014)[27]	AHP			*		*										
	MTAF			*		*										
	PCS			*		*										
	Prototype-PC			*		*										

Mean ± standard deviation for setting time and flow.
*Results shown in a graph only.
†Immeasurable.
‡Results recorded in hour.

SUPPLEMENTARY TABLE 2 - Results for Setting Time (min), Film Thickness (µm), and Flow (mm)

Study			Group number	Setting time Mean	Setting time SD	Setting time Different from group number	Film Thickness Mean	Film Thickness SD	Film Thickness Different from group number	Flow Mean	Flow SD	Flow Different from group number
(Donnermeyer et al., 2021) 20	First replicate	37° (30 s)	1	63.3	4.2	3	7.7	0.00	-	20.9	2.1	-
		47° (30 s)	2	67.3	2.1	3,4,5	7.8	0.04	-	20.7	3.1	-
		57° (30 s)	3	52.3	1.5	1,2,4,5	7.7	0.01	-	21.7	1.4	-
		67° (30 s)	4	60.0	1.7	2,3	7.7	0.01	-	21.8	1.9	-
		77° (30 s)	5	58.3	4.0	2,3	7.7	0.01	-	23.0	2.0	-
		87° (30 s)	6	*		*	*		*	*		*
		97° (30 s)	7	*		*	*		*	*		*
		97° (60 s)	8	*		*	*		*	*		*
		97° (180 s)	9	*		*	*		*	*		*
		P-value				*P* = .025057			*P* = .973880			*P* = .609215
	Second replicate	37° (30 s)	1	Mean	SD	2,4,5,9	7.7	0.00	4,6,4,9	24.9	0.7	-
		47° (30 s)	2	19.3	1.4	1,6,7	7.7	0.00	6,7,9	25.0	0.7	-
		57° (30 s)	3	17.5	0.5	4	7.7	0.00	7,9	24.6	0.3	-
		67° (30 s)	4	18.1	0.1	1,3,6,7,8	7.7	0.01	1,8	24.7	0.8	-
		77° (30 s)	5	17.1	0.4	1,6,7	7.7	0.00	6,7,9	25.4	1.1	-
		87° (30 s)	6	17.5	0.3	2,4,5,8,9	7.7	0.01	1,2,5,8	23.9	0.5	-
		97° (30 s)	7	19.2	0.4	2,4,5,9	7.7	0.01	1,2,3,5,8	28.0	2.0	-
		97° (60 s)	8	19.1	0.6	4,6	7.7	0.00	4,6,7,9	24.8	1.5	-
		97° (180 s)	9	18.1	0.4	1,6,7	7.7	0.00	1,2,3,5,8	26.2	2.8	-
		P-value				*P* = .020231			*P* = .0187664			*P* = .213943
	Third replicate	37° (30 s)	1	23.0	0.0	6,7,8,9	7.8	0.07	-	29.0	1.1	5,8
		47° (30 s)	2	23.2	0.2	4,5,6,7,8,9	7.7	0.01	-	30.7	1.7	4,5,6,8,9
		57° (30 s)	3	23.0	0.9	6,7,8,9	7.7	0.01	-	30.7	0.8	4,5,6,8,9
		67° (30 s)	4	22.5	0.7	2,8,9	7.7	0.00	-	28.4	1.0	2,3,8
		77° (30 s)	5	22.3	0.5	2,8	7.7	0.01	-	27.7	0.2	1,2,3,7
		87° (30 s)	6	22.2	0.1	1,2,3,8	7.7	0.00	-	28.5	0.3	2,3,8
		97° (30 s)	7	22.0	0.4	1,2,38	7.7	0.01	-	29.1	1.3	5,8
		97° (60 s)	8	20.0	0.6	1,2,3,4,5,6,7	7.7	0.01	-	26.7	0.2	1,2,3,4,6,7
		97° (180 s)	9	21.6	0.1	1,2,3,4	7.7	0.00	-	28.1	1.7	2,3
		P value				*P* = .0111865			*P* = .204195			*P* = .021105

*Material fully set after the heat treatment process: Setting time tending toward zero, film thickness, and flow test not applicable.

SUPPLEMENTARY TABLE 3 - Mean Values ± Standard Deviation (SD) for Ph (%), Solubility (%), and Dimensional Change (%)

		Property																	
		Ph (%)										Solubility (%)				Dimensional change (%)			
		3 hours		24 hours		72 hours		168 hours		30 days		Hydrated (30 days)		Nonhydrated (30 days)		24 hours		30 days	
Study	Sealer used	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated	Unheated	Heated
(Nomura	AHP			6.85 ± 0.27	7.26 ± 0.09					7.00 ± 0.22	7.06 ± 0.11	0.070 ± 0.083	0.070 ± 0.060	0.071 ± 0.064	0.070 ± 0.034	0.19 ± 0.15	0.32 ± 0.20	0.43 ± 0.40	0.55 ± 0.24
et al.,	Bio-C			12.20 ± 0.05	12.27 ± 0.08					12.51 ± 0.05	12.39 ± 0.16	-1.834 ± 0.575	-1.091 ± 0.353	-5.524 ± 0.216	5.215 ± 0.231	0.34 ± 0.12	0.36 ± 0.70	0.29 ± 0.19	0.31 ± 0.71
2023)[18]	BR			12.16 ± 0.02	12.17 ± 0.02					12.01 ± 0.14	12.19 ± 0.09	-1.269 ± 0.164	-0.980 ± 0.130	-2.528 ± 0.239	-2.289 ± 0.153	-0.10 ± 0.15	-0.10 ± 0.15	0.10 ± 0.15	0.15 ± 0.25
	BC			12.19 ± 0.06	12.21 ± 0.16					12.58 ± 0.03	12.32 ± 0.61	-0.529 ± 0.329	-0.533 ± 0.180	-1.101 ± 1.274	-2.083 ± 0.241	-0.25 ± 0.45	-0.24 ± 0.21	-0.20 ± 0.50	-0.14 ± 0.16
(Antunes	AHP													0.12 ± 0.14	0.08 ± 0.12				
et al.,	Bio-C													12.67 ± 1.09	9.35 ± 0.77				
2021)[22]	BR													13.01 ± 0.95	11.61 ± 1.53				
	BCH													11.79 ± 1.45	5.34 ± 1.11				
(Yamauchi	AHP	*9.21 (0.65)	*9.06 (1.09)	*6.12 (0.71)	*6.38 (1.62)	*6.24 (1.03)	*6.36 (2.05)	*6.23 (1.49)	*5.78 (2.01)										
et al.,	BC	*11.12 (0.16)	*10.74 (0.34)	*10.55 (0.23)	*11.17 (0.30)	*10.70 (0.12)	*10.96 (0.27)	*10.34 (0.21)	*10.43 (0.15)										
2021)[23]*	BCH	*10.94 (0.24)	*10.94 (0.19)	*10.73 (0.36)	*10.76 (0.14)	*10.72 (0.27)	*10.78 (0.21)	*10.56 (0.06)	*10.37 (0.16)										
	ESMTA	*10.41 (0.26)	*10.62 (0.69)	*10.61 (0.07)	*10.43 (0.32)	*10.78 (0.59)	*10.75 (0.35)	*10.96 (0.76)	*10.88 (0.45)										
	WRST	*10.81 (0.22)	*10.68 (0.38)	*10.52 (0.32)	*10.38 (0.46)	*10.50 (0.25)	*10.47 (0.41)	*10.49 (0.08)	*10.18 (0.35)										

*Data present the medians (interquartile range).

SUPPLEMENTARY TABLE 4 - Mean Values ± Standard Deviation (SD) for Microhardness, Porosity, and Compressive Strength

		Property					
		Microhardness (kg/mm2)		Porosity (void %)		Compressive strength	
Study	Sealer	Unheated	Heated	Unheated	Heated	Unheated	Heated
(Chen et al., 2020)[24]	BC	26.6 ± 0.2	27.0 ± 0.2				
	BCH	26.3 ± 0.3	27.1 ± 0.3				
(Qu et al., 2016)[25]	AHP			*0.00\0.00 (2.97)	*0.00\0.00 (1.61)		
	iRSP			*0.35\0.44 (1.20)	*0.12\0.39 (0.94)		
	RS			*0.54\1.25 (4.32)	*0.50\1.08 (4.53)		
	ZOE			*0.00\0.15 (2.60)	*0.00\0.00 (1.35)		
(Viapiana et al., 2014)[27]	AHP					†	†
	MTAF					†	†
	PCS					†	†
	Prototype-PC					†	†

*Porosity: 50th percentile\interquartile (range).
†: Results shown in a graph only.

SUPPLEMENTARY TABLE 5 - Quality Assessment of Included Studies

	1		2	3					4		5										6			7					8		9	10	11								
Author	a	b	a	a	b	c	d	e	a	b	a	b	c	d	e	f	g	h	i	j	a	b	c	a	b	c	d	e	a	b	a	a	a	b	c	d	e	f	g	h	%
Nomura et al., 2023[18]	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	85
Mann et al., 2022[19]	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	78
Donnermeyer et al., 2021[20]	N	Y	Y	N	Y	Y	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	81
Antunes et al., 2021[22]	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	NA	Y	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	81
Yamauchi et al., 2021[23]	N	Y	Y	N	Y	N	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	70
Chen et al., 2020[24]	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	89
Qu et al., 2016[25]	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	78
Camilleri, 2015[26]	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	Y	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	74
Viapiana et al.,2014[27]	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	NA	N	Y	Y	Y	NA	NA	NA	Y	N	NA	Y	Y	Y	N	N	N	Y	Y	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	70
																																									78

Quality assessment of included studies using the PRILE 2021 guidelines for reporting laboratory studies in endodontology.[17]
Y, item reported in the study; N, Y, item not reported in the study; NA, Nonapplicable.