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Research Article

A scientometric, bibliometric, and thematic map analysis of hydraulic calcium silicate root canal sealers

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No potential conflict of interest relevant to this article was reported.

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ABSTRACT

Objectives: This scientometric and bibliometric analysis explored scientific publications related to hydraulic calcium silicate-based (HCSB) sealers used in endodontology, aiming to describe basic bibliometric indicators and analyze current research trends.
Materials and Methods: A comprehensive search was conducted in Web of Science and Scopus using specific HCSB sealer and general endodontic-related terms. Basic research parameters were collected, including publication year, authorship, countries, institutions, journals, level of evidence, study design and topic of interest, title terms, author keywords, citation counts, and density.
Results: In total, 498 articles published in 136 journals were retrieved for the period 2008–2023. Brazil was the leading country, and the universities of Bologna in Italy and Sao Paolo in Brazil were represented equally as leading institutions. The most frequently occurring keywords were "calcium silicate," "root canal sealer MTA-Fillapex," and "biocompatibility," while title terms such as "calcium," "sealers," "root," "canal," "silicate based," and "endodontic" occurred most often. According to the thematic map analysis, "solubility" appeared as a basic theme of concentrated research interest, and "single-cone technique" was identified as an emerging, inadequately developed theme. The co-occurrence analysis revealed 4 major clusters centered on sealers' biological and physicochemical properties, obturation techniques, retreatability, and adhesion.
Conclusions: This analysis presents bibliographic features and outlines changing trends in HCSB sealer research. The research output is dominated by basic science articles scrutinizing the biological and specific physicochemical properties of commonly used HCSB sealers. Future research needs to be guided by studies with a high level of evidence that utilize innovative, sophisticated technologies.

Keywords: Calcium silicate sealers; Endodontics; Obturation; Retreatability; Scientometric analysis; Solubility

INTRODUCTION

Bioceramic materials are biocompatible metal oxides or ceramic materials such as alumina, zirconia, bioactive glass, glass ceramics, hydroxyapatite, calcium silicate, and resorbable

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calcium phosphate [1]. They were used initially in endodontology as retrograde filling materials for apical surgery [2]. Their advanced sealing ability and biocompatibility led to the expansion of their clinical implications for perforation repair, vital pulp therapy, apexification, revascularization, and root canal filling [3]. Although the term "bioceramic" refers to hydraulic cements that hydrate in the presence of water and interact with tissue fluids, it is an unclearly defined concept that fails to describe the composition and clinical action of these materials [2,4]. Many hydraulic cements used in clinical practice consist of tricalcium silicate mixtures [4]. Thus, the descriptor "hydraulic calcium silicate-based" (HCSB) is more representative of the category. A contemporary classification based on the materials' composition and clinical application has been proposed, which divides them into intra-coronal, intra-radicular, and extra-radicular hydraulic cements [5]. This provisional classification should be supported by further research, since it has the advantage of distinguishing HCSB materials with different composition, physical properties, and clinical uses.

Root canal sealers play a major role in root canal system obturation by filling voids, lateral, or accessory canals unable to be sealed by gutta-percha [6]. A great variety of endodontic sealers have been investigated and used in clinical practice, including zinc oxide-eugenol sealers, calcium hydroxide, glass ionomer and silicon sealers, epoxy resins, and the recently introduced bioceramic sealers [7]. Commercially, intra-radicular bioceramic or HCSB sealers have been released in 2 forms: a premixed single-component formula and a 2-component formula consisting of liquid and powder. The former requires moisture from the surrounding environment to set. Both formulas consist of di- and tricalcium silicates and have similar hydration, setting reactions, and resultant biological properties [8]. The first bioceramic or HCSB root canal sealer accompanied by the favorable properties of bioceramic cements was introduced in 2008, under the brand name ProRoot Endo Sealer (Dentsply Tulsa Dental Specialties, Charlotte, NC, USA) [9]. Since then, numerous HCSB sealers that exhibit advanced biological properties, such as biocompatibility and bioinductivity, have been launched commercially and used in clinical practice, including TotalFill BC Sealer (FKG, La Chaux de Fonds, Switzerland), Bio-C Sealer (Angelus, Londrína, PR, Brazil), EndoSequence Bioceramic Sealer (Brasseler USA, Savannah, GA, USA), and iRoot SP Sealer (Innovative BioCeramix Inc., Vancouver, BC, Canada) [10-12].

According to international guidelines, every new type of material should undergo rigorous examinations before clinical use [13]. HCSB sealers demonstrate novel biological and physicochemical properties in terms of biocompatibility, antimicrobial mechanism of action, and bioactivity [14]. However, inconsistent results have been reported regarding other physical properties, such as volumetric stability, flow, working–setting time, and solubility [15]. The solubility values for BioRoot RCS vary among experimental studies, from 11.05% to 37.6% [16,17]. The setting time of HCSB sealers has also shown different values in different studies. For instance, one study reported that MTA Fillapex had a final setting time of 4.55 hours [18], whereas the study of Prüllage *et al.* [19] showed that the same material failed to set completely even after 1 week. The recorded Totalfill BC sealer flow values varied from 30.8 ± 0.32 mm to 42.0 ± 1.3 mm, and the volumetric stability of Endoseal TCS ranged from a minimum of 0.43% at 7 days to a maximum of 2.5% at 7 days [20-23]. These data provide evidence that the above-mentioned physical properties of the tested HCSB sealers do not follow ISO 6876: 2012 recommendations.

Bibliometrics uses descriptive statistical methods to support the quantitative and qualitative analysis of a particular research field [24]. This type of analysis is used to evaluate research output, analyze research trends, and measure the research impact, attribution, and distribution of a scientific paper or a journal [25]. Alongside bibliometrics, scientometrics or science mapping analysis is a tool for the quantitative evaluation of scientific productivity and interactive relationships among publications and authors' collaborations, in general or specific research areas and with statistical, mathematical, and visualization techniques [25,26]. The results of these analyses offer important guidance to steer research strategies and focus researchers' scientific efforts on unexplored topics that are in demand. Bibliometric and scientometric studies have been performed in various dental fields, including endodontics [27,28]. To date, there is only 1 recent bibliometric study on the scientific production of silicate-based endodontic materials [29]. This study performed a bibliometric analysis of the different indications of silicate-based materials in endodontics, including vital pulp treatment, endodontic surgery, regenerative endodontics, and root canal obturation, with only 32 papers representing HCSB sealers. Considering the broad search indicated by the present study's protocol, an in-depth analysis of HCSB sealers may have been beyond the recent study's scope.

Since their release in 2008, HCSB sealers have been the focus of ongoing research to establish their position and role in daily endodontic practice, as indicated by the increasing number of publications [8]. The data published to date present heterogeneous results, especially regarding their physical properties. An effective way of exploring and analyzing the ever-expanding field of HCSB sealers in literature is via scientometric and bibliometric analysis [25]. The objective of this study was to carry out a scientometric evaluation of published research on HCSB sealers. More specifically, the study assessed scientific publications related to HCSB materials used exclusively as root canal filling materials in endodontology in order to evaluate: 1) the annual scientific production; 2) the most active sources, authors, and affiliations; 3) each country's scientific production; 4) the most influential topics of interest and their development over time; 5) the level of evidence, study design, and fields of study; 6) the most commonly used title terms and author keywords; and 7) the most cited papers.

MATERIALS AND METHODS

Search strategy

The Clarivate Web of Science (WoS) platform and Elsevier's Scopus abstract and citation database were used to ensure the systematic nature of the present study. On August 10, 2023, 2 researchers conducted a combined search for HCSB sealer and general endodontic-related terms in Scopus and in 2 WoS Core databases, Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) (**Figure 1**). Search fields including article title and author keywords were combined with Boolean operators (AND, OR, and asterisk [*]) to find relevant studies. After the Boolean search strategy was run, the search scope was narrowed by using NOT to exclude the exact title or author keyword "surgery." Documents designated as articles and reviews were included, without restrictions upon language or publication date; non-article documents such as errata, letters, editorial materials, meeting abstracts, and notes were excluded. The data including the full records and cited references were exported in plain text format from WoS and comma-separated values (CSV) format from Scopus.

Data analysis

Bibliographic metadata were imported to RStudio version 0.98.1091 with Bibliometrix version 1.7. RTools version 3.6.1 was used for the comprehensive science mapping analysis,

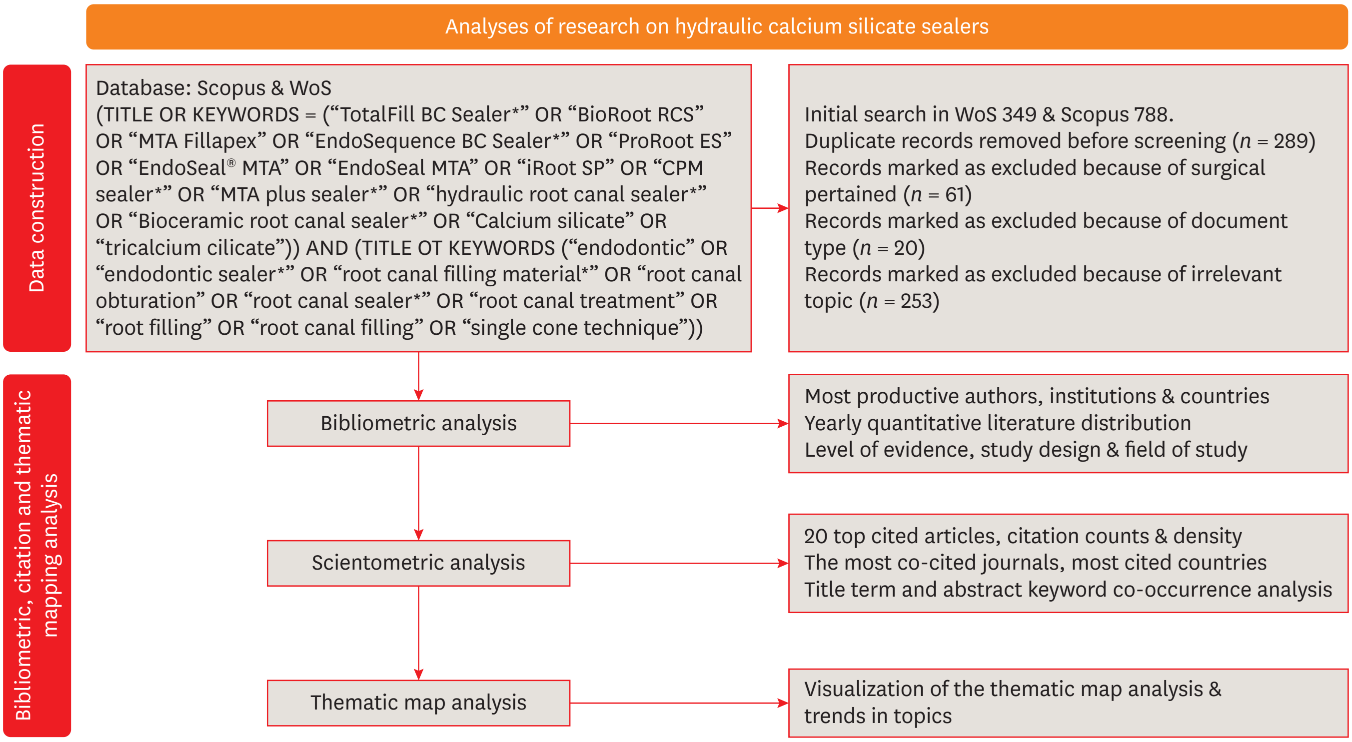

Figure 1. Search strategy.

and Biblioshiny was used as a web interface for Bibliometrix [30]. A bibliographic data frame was created, including all selected documents with the following details: authors' names, authors' affiliations, title, keywords, journal's metrics, and citation counts. The bibliometric analysis was performed, and bibliometric indicators were evaluated, including the yearly quantitative distribution of literature, productive and influential authors, institutions, countries, journals, citation counts, and density (the most cited publications). Further analysis included level of evidence, study design, and topic of interest. Visualization maps of the most frequent author keywords and title terms were constructed, delineating the most common subjects, research status, and annual trends over the study period. In addition, a thematic map visualization of the co-occurrence network clusters was created to indicate where documents expressed common concepts [27].

VOSviewer version 1.6.13, a network analysis tool, was utilized to construct a keyword co-occurrence network visualized as a distance-based map [24]. The co-occurrence of 2 keywords reflects the number of publications in which the keywords occurred together, while the distance between 2 items indicates the strength of the relationship between the items [24]. The size of the circles in the VOSviewer diagram indicates the number of publications with the corresponding keywords.

RESULTS

The initial search using HCSB sealer and general endodontic search terms identified 1,137 papers from the 2 electronic databases published since 2008, when official brands of HCSB sealers were launched in the market along with the first published reports evaluating them.

After duplicates were removed, a total of 848 articles were checked by title and abstract, and 334 were excluded for not matching the study's criteria for inclusion, *i.e.*, focused upon surgery or not relevant to HCSB sealers. The remaining 498 full-text articles were further assessed for a more detailed evaluation. **Figure 1** shows the steps followed for article selection.

Scientific production and sources

A literature search during the period 2008–2023 resulted in 498 documents from 136 sources. The scientific production rate has gradually risen since 2012 and reached its peak in 2022 (**Figure 2**). The annual growth rate describing the progression ratio of scientific production over time was estimated at 19.42%. The *Journal of Endodontics* published the most articles (*n* = 70), followed by the *International Endodontic Journal* (*n* = 37), *Materials* (*n* = 33), *Clinical Oral Investigations* (*n* = 26), *Australian Endodontic Journal* (*n* = 18), and *Brazilian Dental Journal* (*n* = 12). A similar trend was found in the total journal citation score for the first 2 leading journals (5,458 and 2,802 citations, respectively), while *Dental Materials* took third place with 546 citations and *Oral Surgery Oral Medicine and Pathology* came in fourth place with 394 citations.

Authors and publications

The total number of authors involved in the scientific production was 1,827 individuals with 2,556 appearances. Among the most productive authors were Tanomaru-Filho M with 17 papers, Gandolfi MG and Prati C with 15 papers each, and Camilleri J and Guerreiro-Tanomaru JM with 14 papers each. The frequency distribution of the scientific productivity revealed 1476 "occasional" authors who published just 1 paper and 145 "core" authors who have written at least 3 papers, while 206 authors contributed 2 papers. **Figure 3** depicts the top collaborating authors with their respective institutions and countries.

The top-cited publication, authored by Prati C and Gandolfi MG [31] in 2015, was published in *Dental Materials* and received 318 citations. The 20 most cited papers are listed in **Table 1**.

Institute and country-level scientific production

Overall, 521 institutions were involved in scientific production, with the most relevant ones being the University of Bologna (*n* = 28), the University of Sao Paulo (*n* = 28), and Yonsei University in South Korea (*n* = 23).

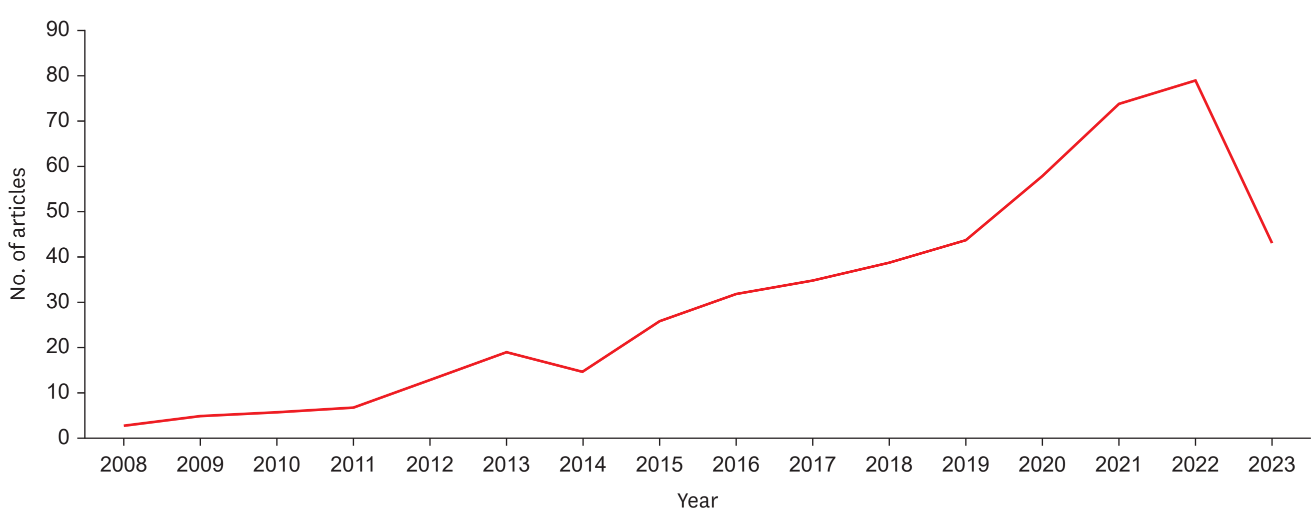

Figure 2. Annual scientific production of hydraulic calcium silicate-based sealer literature.

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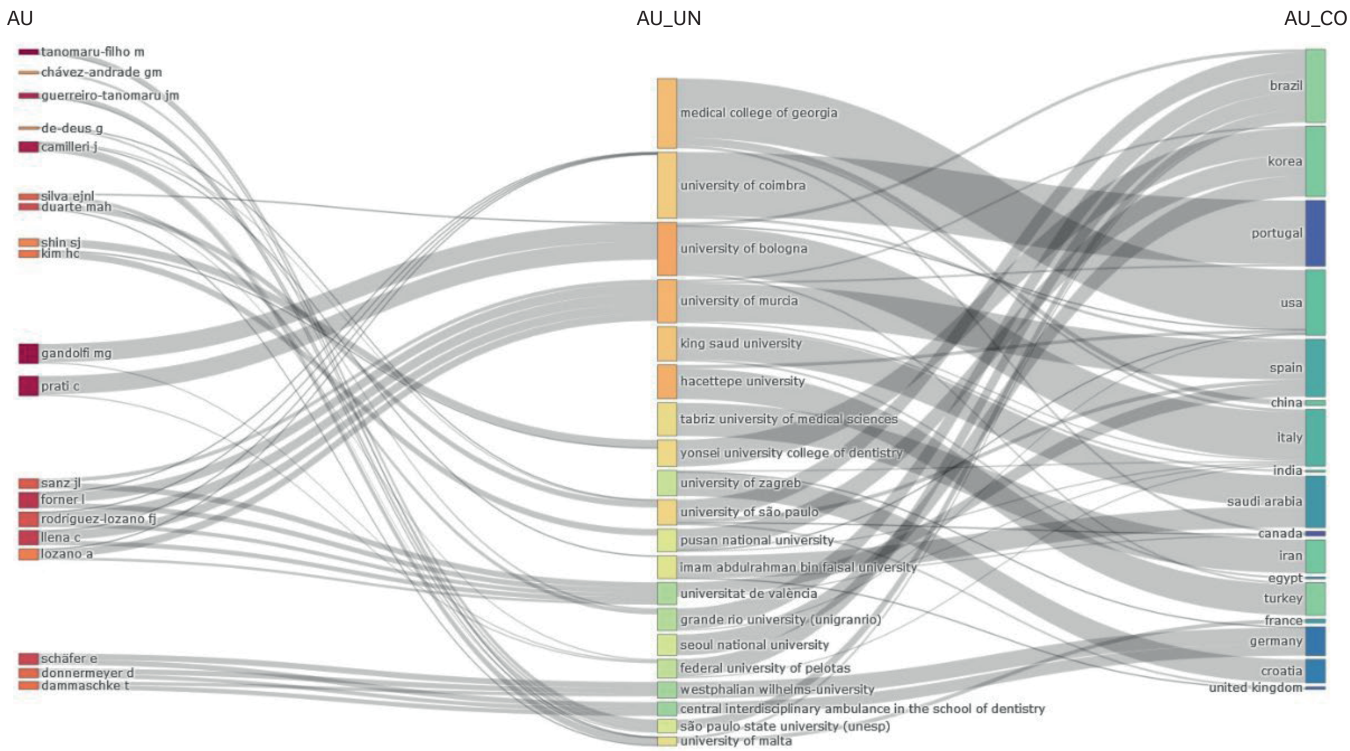

Figure 3. Visualization of collaborating authors' institutions and countries.

Figure 4 shows corresponding authors by country, categorized further by their single-country publication (SCP) or multiple-country publication (MCP). Examining scientific production from this angle indicated that Brazil was the leading country (n = 85), followed by Turkey (n = 58) and South Korea (n = 33). Regarding MCP, as estimated by the number of papers written by at least one co-author with a national affiliation different from the first author's country, Brazil headed the list again with 223 appearances, followed distantly by Turkey and South Korea with 146 and 111 appearances, respectively. Concerning the total country's citation score, Brazil remained the leading country, having gained the highest number of citations (n = 2433), while the next 3 most cited countries were Turkey (n = 1219), Italy (n = 880), and the United States of America (n = 788).

Document type, level of evidence, study design, and topic of interest

Regarding the document type of included publications, 456 original scientific articles and 42 reviews were identified. Specifically, 422 studies were recognized as basic research, comprising 395 *in vitro*/*ex vivo* and 27 *in vivo* studies. Expert opinions were assessed via questionnaire in 2 studies. Regarding clinical studies, 3 case reports, 8 randomized clinical trials, and 16 clinical trials were recorded. Study type categorization also revealed 42 review articles (**Table 2**). Most laboratory studies as well as clinical trials examined more than 1 characteristic of calcium silicate materials using a variety of methods. The most sought properties are categorized in **Table 3**, according to their occurrences through the included basic and clinical experimental studies.

Title and author keyword occurrences

The most prevalent of the 960 keywords included in the term map with at least 20 occurrences were "calcium silicate" (n = 67), "endodontics" (n = 59), "root canal sealer" (n

Table 1. Top 20 highly cited papers on HCSB sealers

Paper	Citations (density)
Prati C, Gandolfi MG. Calcium silicate bioactive cements: biological perspectives and clinical applications. Dent Mater 2015;31:351-370.	318 (39.75)
Han L, Okiji T. Uptake of calcium and silicon released from calcium silicate-based endodontic materials into root canal dentine. Int Endod J 2011;44:1081-1087.	226 (18.83)
Candeiro GT, Correia FC, Duarte MA, Ribeiro-Siqueira DC, Gavini G. Evaluation of radiopacity, pH, release of calcium ions, and flow of a bioceramic root canal sealer. J Endod 2012;38:842-845.	213 (19.36)
Loushine BA, Bryan TE, Looney SW, Gillen BM, Loushine RJ, Weller RN, *et al*. Setting properties and cytotoxicity evaluation of a premixed bioceramic root canal sealer. J Endod 2011;37:673-677.	185 (15.42)
Al-Haddad A, Che Ab Aziz ZA. Bioceramic-based root canal sealers: a review. Int J Biomater 2016;2016:9753210.	161 (23)
Han L, Okiji T. Bioactivity evaluation of three calcium silicate-based endodontic materials. Int Endod J 2013;46:808-814.	157 (15.7)
Nagas E, Uyanik MO, Eymirli A, Cehreli ZC, Vallittu PK, Lassila LV, *et al*. Dentin moisture conditions affect the adhesion of root canal sealers. J Endod 2012;38:240-244.	149 (13.54)
Borges RP, Sousa-Neto MD, Versiani MA, Rached-Júnior FA, De-Deus G, Miranda CE, *et al*. Changes in the surface of four calcium silicate-containing endodontic materials and an epoxy resin-based sealer after a solubility test. Int Endod J 2012;45:419-428.	141 (12.81)
Silva EJ, Rosa TP, Herrera DR, Jacinto RC, Gomes BP, Zaia AA. Evaluation of cytotoxicity and physicochemical properties of calcium silicate-based endodontic sealer MTA Fillapex. J Endod 2013;39:274-277.	138 (13.8)
Vallés M, Mercadé M, Duran-Sindreu F, Bourdelande JL, Roig M. Influence of light and oxygen on the color stability of five calcium silicate-based materials. J Endod 2013;39:525-528.	129 (12.9)
Huffman BP, Mai S, Pinna L, Weller RN, Primus CM, Gutmann JL, *et al*. Dislocation resistance of ProRoot Endo Sealer, a calcium silicate-based root canal sealer, from radicular dentine. Int Endod J 2009;42:34-46.	114 (8.14)
Silva Almeida LH, Moraes RR, Morgental RD, Pappen FG. Are premixed calcium silicate-based endodontic sealers comparable to conventional materials? A systematic review of *in vitro* studies. J Endod 2017;43:527-535.	109 (18.17)
Siboni F, Taddei P, Zamparini F, Prati C, Gandolfi MG. Properties of BioRoot RCS, a tricalcium silicate endodontic sealer modified with povidone and polycarboxylate. Int Endod J 2017;50(Supplement 2):e120-e136.	109 (18.17)
Zhou HM, Du TF, Shen Y, Wang ZJ, Zheng YF, Haapasalo M. *In vitro* cytotoxicity of calcium silicate-containing endodontic sealers. J Endod 2015;41:56-61.	104 (13)
Camilleri J. Sealers and warm gutta-percha obturation techniques. J Endod 2015;41:72-78.	101 (12.63)
Sagsen B, Ustün Y, Demirbuga S, Pala K. Push-out bond strength of two new calcium silicate-based endodontic sealers to root canal dentine. Int Endod J 2011;44:1088-1091.	101 (8.42)
Gomes-Filho JE, Watanabe S, Bernabé PF, de Moraes Costa MT. A mineral trioxide aggregate sealer stimulated mineralization. J Endod 2009;35:256-260.	101 (7.21)
Bin CV, Valera MC, Camargo SE, Rabelo SB, Silva GO, Balducci I, *et al*. Cytotoxicity and genotoxicity of root canal sealers based on mineral trioxide aggregate. J Endod 2012;38:495-500.	99 (9)
Zhang W, Li Z, Peng B. *Ex vivo* cytotoxicity of a new calcium silicate-based canal filling material. Int Endod J 2010;43:769-774.	99 (7.62)
Akcay M, Arslan H, Durmus N, Mese M, Capar ID. Dentinal tubule penetration of AH Plus, iRoot SP, MTA fillapex, and guttaflow bioseal root canal sealers after different final irrigation procedures: a confocal microscopic study. Lasers Surg Med 2016;48:70-76.	91 (13)

HCSB, hydraulic calcium silicate-based.

= 56), “MTA Fillapex” (*n* = 48), “biocompatibility” (*n* = 42), “mineral trioxide aggregate” (*n* = 42), “AH Plus” (*n* = 35), “BioRoot RCS” (*n* = 34), and “cytotoxicity” (*n* = 34). **Figure 5** represents the development over time of search trends, based on the keywords analyzed. By reviewing the frequency of title terms, 1028 terms may be observed, with “sealers” (*n* = 236), “root” (*n* = 231), “calcium” (*n* = 222), “canal” (*n* = 209), “sealer” (*n* = 166), “silicate based” (*n* = 154), and “endodontic” (*n* = 116) presenting the highest frequency.

Title term and abstract keyword co-occurrence analysis

A network analysis of title term and abstract field co-occurrence was generated using VOSviewer, which tends to exclude general terms, ignore structural label terms, and allocate a relevance score to each included term. Accordingly, a term co-occurrence map was created with the limit of involving title and abstract fields set at 10 occurrences under binary counting [24]. At least 339 terms met the threshold and were included in the term map based on text data. When the software took into account 60% of the terms with the highest relevance scores, 203 terms were selected. **Figure 6** depicts the term map extracted from the titles and abstracts of the papers. Four clusters were identified. The first, largest cluster with 83 items colored red included “canal” (*n* = 202), “teeth” (*n* = 151), “root” (*n* = 118), “gutta-percha” (*n* = 98), “obturation” (*n* = 95), “bond strength” (*n* = 79), “push” (*n* = 70), “section” (*n* = 45), “dentin” (*n* = 42), “single cone technique” (*n* = 41), “obturation technique”

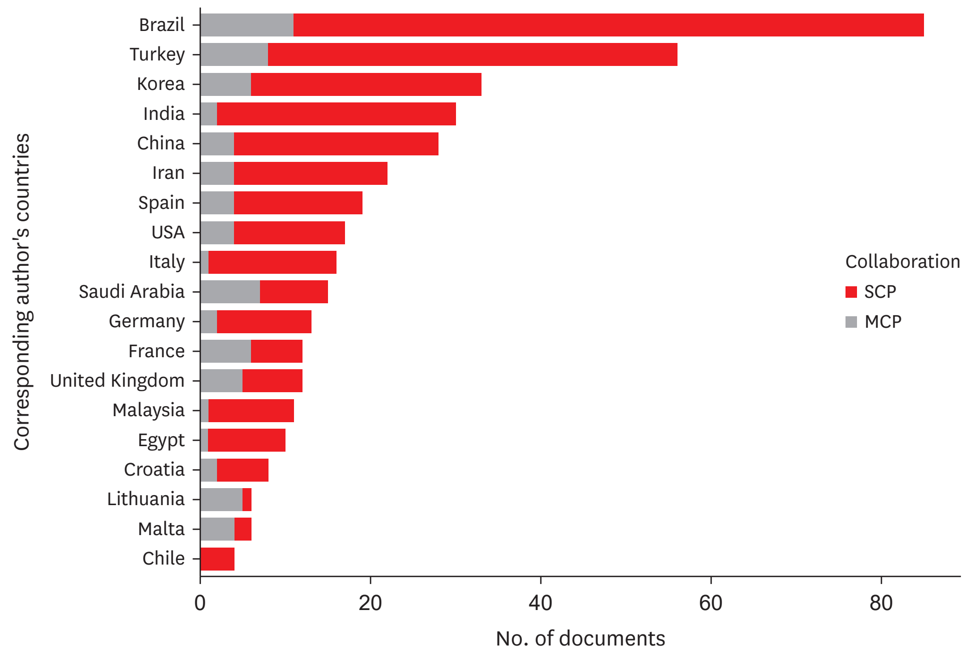

Figure 4. Countries of the corresponding authors in hydraulic calcium silicate-based sealer research, showing the number of papers from single-country publication (SCP) or multiple-country publications (MCP).

Table 2. Study design of HCSB sealer literature

Study type (level of evidence)	Articles
Review	
Systematic review (level of evidence 1)	9
Systematic review & meta-analysis (level of evidence 1)	8
Literature - narrative review (level of evidence 4)	22
Scoping review (level of evidence 4)	3
Clinical trial	
Non-randomized clinical trial (level of evidence 3)	16
Randomized clinical trial (level of evidence 1)	8
Observational study	
Retrospective cohort study (level of evidence 3)	3
Prospective cohort study (level of evidence 3)	2
Case report (level of evidence 4)	3
Basic research	
In vitro/*ex vivo* (level of evidence 5)	395
In vivo (level of evidence 5)	27
Expert opinion (level of evidence 5)	2

HCSB, hydraulic calcium silicate-based.

($n = 41$), "irrigation" ($n = 39$), and "retreatment" ($n = 36$), followed by the green cluster containing 61 items with the most prevalent being "cell" ($n = 69$), "cytotoxicity" ($n = 47$), "biocompatibility" ($n = 44$), "activity" ($n = 40$), and "bioactivity" ($n = 34$). A blue cluster with 40 items concentrated on "sealers' property" ($n = 75$), "electron microscopy" ($n = 61$), "water" ($n = 52$), "setting time" ($n = 46$), "solubility" ($n = 45$), "flow" ($n = 38$), and "iso" ($n = 34$), and the small yellow cluster presented the review ($n = 26$) research aspects, included "endodontic treatment" ($n = 34$), "biodentine" ($n = 25$), "systematic review" ($n = 17$), "PubMed" ($n = 13$), and "meta-analysis" ($n = 12$). Despite the distinct colored clustering, several relationships and connections exist among the above-mentioned terms.

Table 3. Topics of interest in clinical and laboratory studies

Properties tested	Total
Sealing ability	106
Biocompatibility - cytotoxicity	103
Adhesion	80
Bioactivity	63
Setting time	52
pH	47
Radiopacity	42
Flow	40
Retreatability	38
Antimicrobial activity	38
Solubility	36
Tubular penetration ability	33
Ion release	30
Elemental analysis	25
Dimensional stability	16
Outcome	15
Fracture resistance	15
Film thickness	12
Post-obturation pain	10
Compressive strength	10
Discoloration	6
Wettability	4

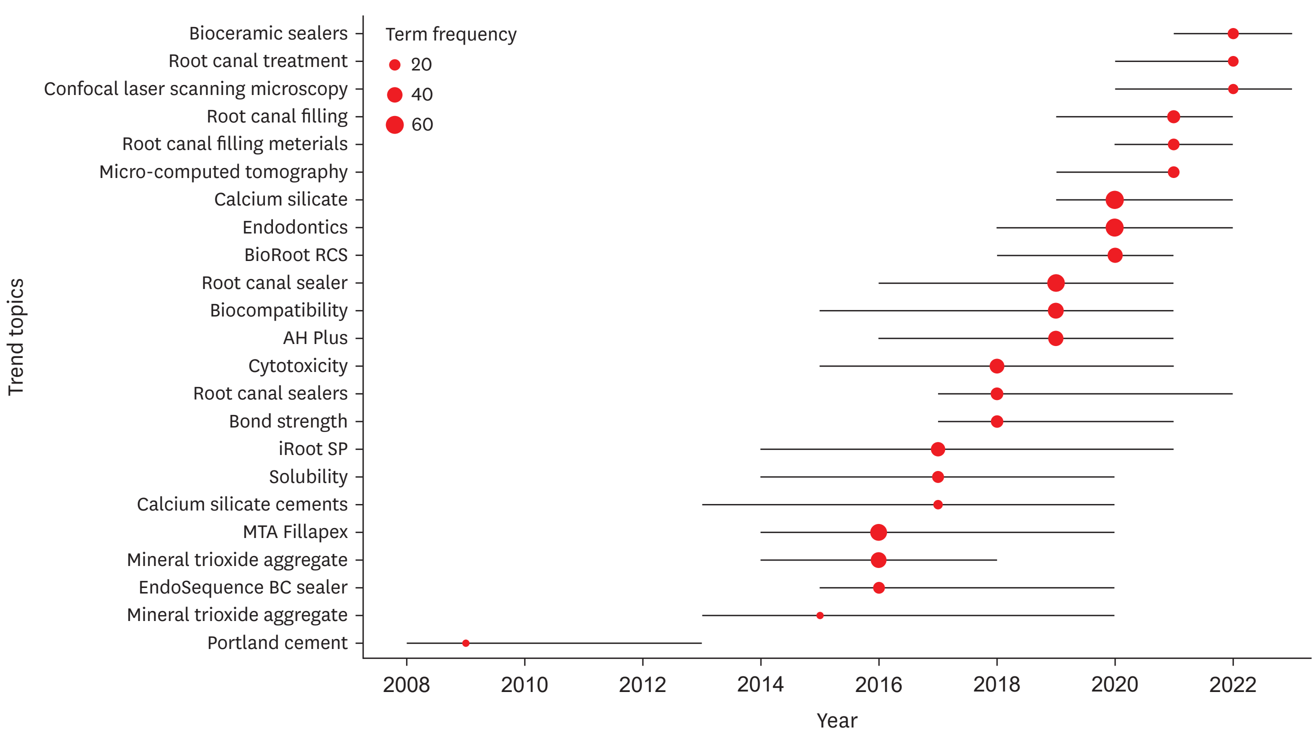

Figure 5. Overview of trends in topics over time, according to the frequency of author keywords.

Thematic map analysis

Figure 7 displays the results of the thematic map analysis. The top left quadrant includes clusters of "endodontic retreatment," "passive ultrasonic irrigation," "calcium silicate," and "AH Plus sealer" as niche themes. "Biocompatibility," "cytotoxicity," "pH," "radiopacity," and "hydration" in the upper right quadrant are indicated as motor themes. "Single cone"

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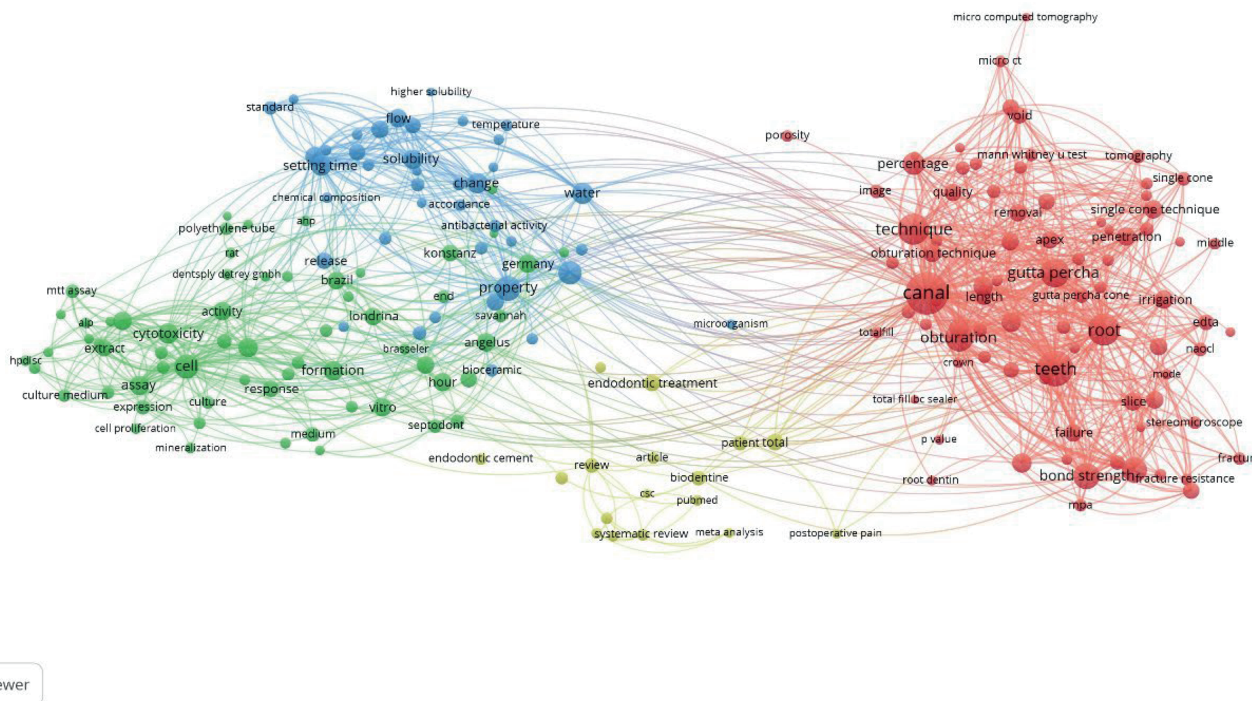

Figure 6. Co-occurrence network by VOSviewer, showing the most relevant terms occurring in the title or abstract of the included articles. The size of the node indicates the number of publications with the depicted term.

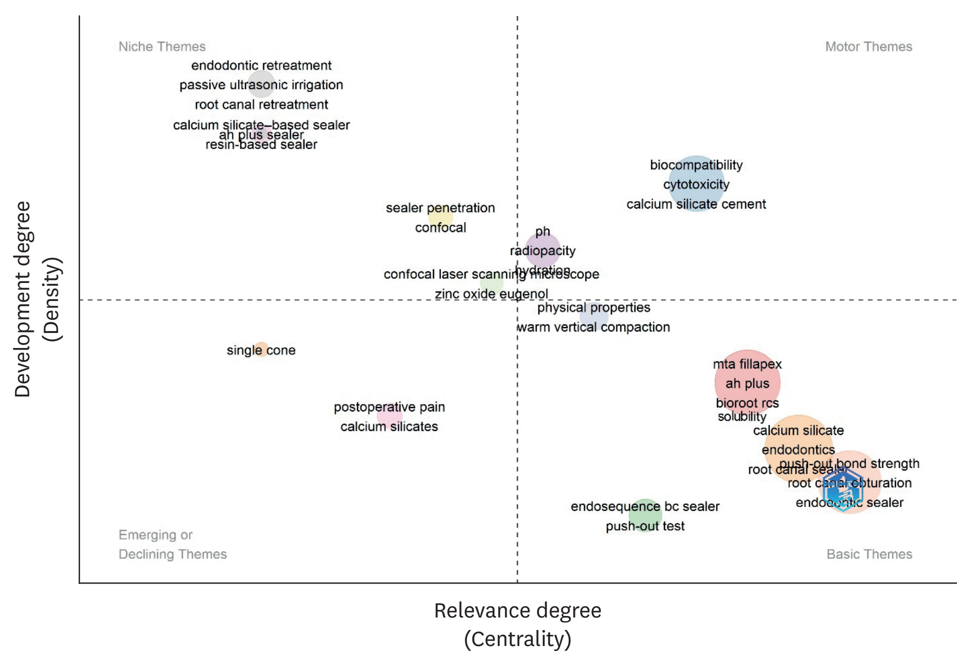

Figure 7. Thematic map analysis.

and "postoperative pain" were identified as emerging themes in the lower left quadrant. The lower right quadrant showed basic central themes with clusters of "physical properties" and "warm vertical compaction," "MTA Fillapex," "AH Plus," "BioRoot RCS and solubility," "root canal obturation" and "endodontic sealer," "EndoSequence BC sealer," and "push-out test."

DISCUSSION

In this study, a scientometric analysis emphasizing HCSB sealer research has been performed using the WoS SCIE, WoS SSCI, and Scopus databases. Novel scientometric tools, including the Bibliometrix R package, Biblioshiny, and VOSviewer, were used for comprehensive science mapping and research evaluation. In detail, the present study provides a descriptive quantitative analysis of 498 papers published in 136 sources, by 1,827 authors originating from 46 countries. HCSB sealer research has an annual scientific production growth rate of 19.42%, suggesting the ongoing growth potential of this field. A similarly increasing research trend was observed for the number of citations. The majority of HCSB research, according to corresponding authors' affiliations, originated from Brazil, Turkey, and South Korea. Nonetheless, the most prolific authors had affiliations in Brazil (Tanomaru and Guerreiro-Tanomaru), Italy (Gandolfi and Prati), and the United Kingdom (Camilleri). Consistently, the University of Bologna in Italy, the University of Sao Paolo in Brazil, and Yonsei University in South Korea contributed the largest numbers of articles. Analysis of publication sources revealed that most studies were published in the 2 leading endodontic journals, the *Journal of Endodontics* and the *International Endodontic Journal*. These endodontic-focused research journals were the most frequently cited, by which their contributions to HCSB sealer research have been verified. As expected, basic laboratory study design representing the lowest level of evidence was predominant in HCSB sealer research.

Regarding the thematic map analysis, "endodontic retreatment," "passive ultrasonic irrigation," "calcium silicate-based sealer," and "AH Plus" surfaced as niche terms of limited interest that no longer need to be investigated. "Biocompatibility, "cytotoxicity," "pH," "radiopacity," and "hydration" were observed as well-developed motor themes central to the field, which indicated the strong correlation of themes dedicated to biological and physical properties within HCSB sealer research. "Single cone" and "postoperative pain" were identified as emerging themes that are inadequately developed but have the potential to become more central as motor themes. The basic central themes necessary for transdisciplinary endodontic research issues included 3 main clusters with different centrality and density. The first one consisted of themes with moderate to high centrality and density, such as "physical properties," "warm vertical compaction," "MTA Fillapex," "AH Plus," "BioRoot RCS," and "solubility," which were similar and linked to each other. The second included "root canal obturation" and "endodontic sealer" with low density and centrality, indicating individual themes not linked to each other but still foundational to HCSB sealer research. Finally, the third cluster had "EndoSequence BC sealer" and "push-out test" with low centrality but high density, presenting essential themes for a good understanding of the field.

The list of top 20 cited papers included publications from 2009 to 2017, each of which was cited 91 to 318 times (**Table 1**). The most cited paper was published by Prati and Gandolfi [31] in *Dental Materials*. This narrative review was among the first to analyze research progress on hydraulic calcium silicate cements, including sealers. The composition of MTA-based materials, their beneficial properties, and their limitations were thoroughly discussed, and the regenerative potential of the innovative use of calcium silicate cements as endodontic sealers to the damaged periradicular tissues was analyzed. Next in the top cited list were 2 *in vitro* comparative studies. The second most cited paper (226 citations) was published in the *International Endodontic Journal* by Han and Okiji [32]. This study used X-ray spectroscopy to evaluate the uptake of calcium and silicon ions to the dentin-material interface when MTA or

Biodentine was used as root canal filling material in bovine teeth. Though this study did not evaluate a classic intra-radicular HCSB sealer, it was not excluded because it was among the first studies to provide evidence on the bioactive role and calcifying effect of HCSB cements in root canal dentin. The third paper (213 citations), published in the *Journal of Endodontics*, was a laboratory study favorably evaluating the physicochemical properties of EndoSequence BC sealer, including its radiopacity, pH, calcium release, and flow characteristics [33]. Only 3 papers among the top 20 were cited fewer than 100 times.

Research on hotspots and developmental trends is important for researchers as well as clinicians. Keywords represent important aspects of the literature and reveal research foci of the area investigated. When the frequencies and clustering of keywords are analyzed over time, the priorities and research interests in different periods become evident [34]. **Figure 5** shows the trends in topics from authors' keywords. Research commenced in 2008, and the earliest published studies aimed to investigate calcium silicate cements; during the next few years, basic research issues pertaining to biological properties (biocompatibility and cytotoxicity) remained a main investigative goal, while the center of research interest shifted towards the investigation of physical properties such as solubility, bond strength, and adhesion. Subsequently, MTA Fillapex was a focal point for research. Afterwards, until 2022, BioRoot RCS and iRoot SP joined the most frequently occurring authors' keywords, along with AH Plus, which is still considered the gold standard of *in vitro* comparative studies. In 2019, research interests shifted to the evaluation of calcium silicate sealers' adhesion by push-out bond strength. Most recently, with new research techniques and concepts, the topic of root canal obturation intersects new areas of investigation, including imaging. Consequently, many recent articles continue to investigate the physical and biological properties of calcium silicate sealers, while innovative, advanced technologies such as micro-computed tomography (CT) and confocal laser scanning microscopy have guided research trends.

During the past years, HCSB sealer research has been rapidly expanding. As evidenced by this study, more than 80% of the research efforts have been focused on the *in vitro* evaluation of various physicochemical properties, such as biocompatibility and antibacterial properties, sealing ability, adhesion, retreatability, and solubility evaluation. It seems logical that the majority of bench work is focused primarily on biocompatibility assays, especially when the material tested is introduced to clinical use mainly for its bioactive potential. The evaluation of sealing ability and adhesion by push-out bond strength has provided some promising results, since most studies found no differences between HCSB and epoxy resin sealers. However, serious concerns were raised subsequently over HCSB sealers' solubility and retreatability. The research focus shifted towards *in vitro* studies evaluating these properties, especially solubility, which presents a possible threat to seal quality. Only a few preclinical studies have evaluated and confirmed the bioactive potential of calcium silicate sealers using histomorphology in animals. Sixteen clinical studies evaluated the success rate or post-obturation pain of root-filled teeth with various obturation techniques including lateral condensation, warm vertical compaction, or the single cone technique using HCSB sealers or epoxy resin sealers in humans. Many studies found no differences between groups; however, most of them used follow-up periods that barely exceeded 12–15 months [11]. Only 1 clinical prospective study with a follow-up period of 30 months (the longest) also observed similar success rates [35]. Only 8 studies were characterized as randomized control trials; unfortunately, they did not use long follow-up periods [11,35,36]. Finally, there were 42 review papers, with 17 characterized as systematic reviews, 22 narrative reviews, and 3 scoping reviews discussing the use of HCSB sealers with an emphasis on the bioactive and regenerative potential of the materials, the variation of sealers' properties depending on their formulation, the disadvantage of solubility, and the need of long-term clinical studies in order to provide a high level of evidence regarding clinical outcomes [15,37]. Overall, only 17 systematic reviews and 8 randomized controlled trials, representing 5% of all included papers, provided the highest level of evidence.

With the data provided by this bibliometric study, it becomes evident that great attention has been drawn to the physical properties of HCSB sealers. As root canal sealers, to prevent re-infection, they should provide a stable seal by filling the voids unavoidably present between dentinal walls and the main obturation material. For this purpose, an ideal sealer should be characterized by specific properties, such as insolubility and dimensional stability [38]. Both properties have been introduced as requirements in the ANSI/ADA specification No. 57 and in the ISO 6876 standard for root canal sealing materials. Based on the recommendations, the mass loss of a sealer during a 24-hour immersion in water should not be greater than 3% of its total mass. To date, it has been documented that most HCSB sealers do not fulfill ANSI/ADA requirements. For instance, the solubility of iRoot SP and MTA Fillapex has been found to be more than 20% and 14%, respectively, with a tendency to increase over time [39]. In another study, although Endoseal presented solubility similar to that of AH Plus, higher dimensional changes were observed for the Endoseal group over time [23]. Overall, it is clear that AH Plus Bioceramic, Endoseal MTA, BioRoot RCS, EndoSequence BC, TotalFill, MTA Fillapex, and Sealer Plus BC do not meet the ANSI/ADA requirements, and it is unknown whether other HCSB sealers have solubility values in line with the recommendations [40]. Thus, it is evident that solubility represents an important aspect of HCSB sealer research. The results of the present scientometric study concur, as indicated in the thematic map analysis, where sealer solubility was depicted as a basic theme crucial for structuring the research topic (**Figure 7**).

Most importantly, as emphasized by the study of Vieira *et al.* [41], a basic requirement of root canal filling materials is its long-term stability and disintegration resistance. It has been shown that voids following sealer disintegration may create a nutrient pathway for residual bacteria, leading to the activation of previously deactivated biofilms in lateral canals or isthmuses, or the activation of bacteria within dentinal tubules. Under this perspective, the guidelines for reporting randomized trials in *Endodontics* clearly state that a longer follow-up period should be chosen to evaluate long-term success rates and provide reliable data in support [42]. Thus, the use of materials that have not been adequately evaluated by laboratory and clinical trials with suitably long follow-up periods should be avoided in clinical practice. So far, serious concerns have been raised regarding the solubility and volumetric stability of HCSB sealers [15,38,40]. The lack of well-designed, long-term clinical trials for laboratory studies' high solubility rates of sealers like Bio-C Sealer, BioRoot RCS, MTA Fillapex, Sealer Plus, and TotalFill BC Sealer should be considered seriously, especially when these materials are used with a single cone technique in clinical practice. As the thematic map analysis indicated, this technique represents an emerging theme gaining popularity among clinicians. It may be of the utmost importance to consider the strong evidence suggesting that the use of materials and obturation methods like Resilon, which have not been adequately evaluated in *in vitro* studies or long-term clinical trials, may lead to unnecessary failures [43].

Retreatability or retrievability is one of the characteristics required for an ideal root canal sealer, so that a conservative reintervention is feasible in case of endodontic treatment failure [7]. The current analysis revealed 38 studies for which retreatability pertained. Different experimental approaches proposed engine-driven or manual removal instruments, supplementary cleaning protocols, ultrasonic irrigation, XP-endo finisher, and laser-activated irrigation. The evaluated parameters included time to gain apical patency and amount of residual filling materials. Quantification of residual filling materials was evaluated via micro-CT, microscopy, cone-beam CT, and conventional radiography. Most *in vitro* studies reported smaller amounts of filling remnants for HCSB sealers such as BioRoot RCS and MTA Fillapex than for epoxy resin sealers such as AH Plus [44,45]. Some studies concluded that HCSB sealers required significantly longer retreatment times, whereas other studies found the opposite result [36,44-46]. The use of engine-driven versus manual instrumentation showed enhanced and more effective cleaning capacity combined with less operation time [45]. Finally, supplemental cleaning protocols seemed beneficial in reducing a high volume of filling remnants. For example, additional use of XP-endo Finisher R (XPR) improved the removal of filling materials regardless of sealer type [49,50]. Finally, the use of passive ultrasonic irrigation or laser-activated irrigation contributed to better debridement of root canal walls by presenting a lower volume of residual materials [46,48].

The discoloration induced by HCSB sealers has also been addressed [49]. Overall, 6 *in vitro* studies have been identified, with 2 of them examining the discoloration potential of MTA Fillapex compared either to iRoot SP or to Roth-811 [49,50]. In all studies, discoloration was assessed with the use of spectrophotometric devices; observation periods varied, 3 to 6 months. It was found that both MTA Fillapex and iRoot SP induced clinically perceptible discoloration that increased during the first 3 months and gradually became stable at 6 months, with no difference recorded between them [50]. Clearly, knowledge is scarce about the stability of tooth color after the use of HCSB sealers, and as new materials are released, the research gap expands.

Several study limitations should be addressed regarding this bibliometric investigation. Due to changing citation volumes over time, the temporary but dynamic nature of scientometric analysis narrows the results within the short time of the study's data extraction (August 2023). Another possible limitation is the inability of scientometric analysis to comparatively evaluate each included study's results and synthesize the available data into clear conclusions, as systematic reviews do. This type of study emphasizes papers' citation scores, authors, and affiliations and often ignores or fails to discover self-citation strategies or "the obliteration by incorporation" effect [51,52]. In this way, through scientometric analysis, research work of great quality and significance may not gain as much attention as it deserves. The methodological protocols, study design, results, quality, and impact of research articles are addressed more thoroughly via systematic reviews and meta-analyses.

CONCLUSIONS

This scientometric and bibliometric analysis used research mapping tools in scrutinizing the scientific literature about HCSB sealers to present bibliographic features, characterize the field, and depict the field's development. HCSB research is currently grounded on studies investigating the biological and specific physicochemical properties of commonly used HCSB materials that need to be investigated thoroughly with innovative, advanced technologies. The research output is dominated by basic science articles, which represent the lowest level of evidence. More HCSB sealer studies with a high level of evidence should be undertaken in the future. Research should be directed towards the investigation of possible interactions among HCSB sealers and various obturation techniques.

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