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Systematic Review

A Comparison of Niobium with Other Radiopacifying Agents in Endodontic Cements: A Systematic Review of Physicochemical Properties

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Abstract

This systematic review evaluated the use of niobium as a radiopacifying agent in endodontic cements compared with other radiopacifiers. This review was conducted in accordance with the PRISMA 2020 guidelines (OSF registration). The PICO strategy defined the population as endodontic cements, the intervention as niobium-based formulations, the comparison as other radiopacifying agents, and the outcome as physicochemical properties. Six databases and the gray literature were searched up to December 2025, and the risk of bias was assessed using the JBI Critical Appraisal Checklist for Experimental Studies. A total of 1273 studies were identified, of which 10 were included in the review. Seven of the included studies evaluated radiopacity, showing that Nb-containing cements exhibited values equal to or lower than those containing other radiopacifying agents but still meeting ISO/ADA standards. Seven studies analyzed pH, which remained alkaline and was not influenced by Nb. Five studies investigated setting time, with no differences compared with other radiopacifiers. Studies assessing solubility showed conflicting results, reporting increases, reductions, or no differences compared with zirconium. Overall, the included studies presented a low risk of bias. In conclusion, niobium demonstrated physicochemical properties comparable to those of other radiopacifiers used in endodontic cements. However, further studies are needed to evaluate its influence on the setting time and solubility of materials.

Keywords: Endodontics; niobium; physicochemical properties; radiopacifiers; root canal sealers

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1. Introduction

The radiopacity of materials is one of the key factors in dental practice, particularly in endodontic procedures where the proper interpretation of radiographs is essential for accurate diagnosis, treatment planning and monitoring of treatment progress [1,2]. It is one of several properties required for the clinical performance of endodontic materials, which must also exhibit adequate biological, chemical, and physicomechanical behavior [2–4]. According to International Organization for Standardization (ISO 6876) [5], endodontic materials should present a radiopacity equivalent to at least 3 mm of aluminum to allow for radiographic differentiation from surrounding dental structures [3].

Over the past few decades, several radiopacifying agents have been incorporated into endodontic cements. Among them, bismuth oxide (Bi_2O_3) was one of the most widely used compounds, well recognized for its excellent radiopacity [1,6]. However, its clinical use has declined in recent years due to its association with undesirable tooth discoloration, a limitation that has been consistently reported in both experimental and clinical settings and represents a relevant drawback, particularly in anterior teeth [7,8]. The frequency of tooth discoloration associated with materials containing bismuth oxide is high, as this compound is highly reactive when in contact with dentin collagen, sodium hypochlorite, blood, and other solutions commonly used in endodontic procedures. These interactions lead to the formation of black bismuth complexes, resulting in discoloration of the material and the surrounding dental tissues [7].

To overcome this limitation, different strategies have been proposed, including the addition of stabilizing substances such as aluminum fluoride (AlF_3) [8] or the replacement of bismuth oxide with alternative radiopacifying agents [9,10]. One example is calcium tungstate ($CaWO_4$), which does not contain heavy metals in its composition and therefore prevents tooth discoloration [11,12]. Recent studies have reported favorable outcomes regarding the color stability of materials containing these radiopacifiers [9,13].

More recently, other metallic oxides, such as zirconium (Zr) and niobium (Nb) oxides, have gained attention as promising radiopacifying agents. These compounds exhibited adequate biocompatibility, while eliminating the risk of tooth discoloration associated with bismuth-containing materials [2,4,14,15].

The use of niobium pentoxide (Nb_2O_5) has been extensively investigated as a radiopacifying agent in calcium silicate-based hydraulic cements, mainly due to its properties such as density, X-ray attenuation, and chemical stability, suggesting that Nb_2O_5 may offer additional advantages over traditional radiopacifiers [1,2]. However, the available literature presents conflicting results regarding specific physicochemical properties, including radiopacity, alkalinizing behavior, setting time, and solubility, with no clear consensus on whether niobium-based radiopacifiers offer advantages over conventional agents [2,3].

Notably, most of the currently available evidence regarding radiopacifying agents and endodontic materials is derived from in vitro studies. Although laboratory-based investigations do not fully replicate the clinical environment, they play a fundamental role in elucidating the physicochemical mechanisms that govern material behavior. Parameters such as radiopacity, pH behavior, setting time, and solubility assessed under controlled conditions provide essential information for predicting clinical performance. Therefore, in vitro findings represent a critical first step in the pathway toward clinically relevant applications. Therefore, this systematic review investigated the use of Nb as a radiopacifying agent in endodontic sealers and repair cements.

2. Materials and Methods

2.1. Protocol and Registration

The present systematic review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist [16]. A research protocol was registered in the Open Science Framework (OSF) register (https://osf.io/dg6ps/, accessed on 4 January 2026).

2.2. Formulating the Review Question

The population, intervention, comparison, and outcome (PICO) approach was used to address the following question: "*Does niobium have superior properties compared to other radiopacifying agents in endodontic cements?*". In this process, the population (P) was endodontic cements (sealer or repair); the intervention (I) was niobium as a radiopacifier; the comparison (C) was other radiopacifying agents; and the primary outcome (O) was the physicochemical properties: radiopacity, pH, and setting time. The solubility analysis was considered a secondary outcome.

2.3. Eligibility Criteria

Inclusion criteria: in vitro studies that compared the use of Nb as a radiopacifier with other radiopacifying agents in endodontic sealer and/or repair cements. *Exclusion criteria*: studies that did not directly address the comparison between the properties of Nb and other radiopacifying agents, studies that did not include a comparison group of other radiopacifying agents, and duplicate studies.

2.4. Search Strategy

Electronic searches were conducted in PubMed/MEDLINE, Scopus, Web of Science, SciELO, Embase and Cochrane Library databases up to December 2025. The gray literature was consulted through *Google Scholar*, and manual searches were carried out in the reference lists of the eligible articles. The search strategy used a combination of keywords and Medical Subject Heading (Mesh) terms associated with the Boolean operators 'AND' and 'OR' as shown in Supplementary File S1. No restrictions to publication date or language were considered.

2.5. Study Selection

Study selection was carried out independently by two reviewers (HGSC and PCGT), in a two-step process. Duplicates were identified and removed using Mendeley Desktop software (version 1.19.8, Elsevier Inc. New York, NY, USA). In step 1, the reviewers appraised titles and abstracts of the records retrieved from the searches. Studies whose titles and abstracts met the eligibility criteria were immediately included.

If the titles and abstracts of studies provided insufficient information for a decision, their full texts were downloaded for further review. In step 2, a full-text assessment of the remaining studies was performed by the authors. Studies that complied with the eligibility criteria were included in this review. Discrepancies were resolved through discussion, and when necessary, a third reviewer (FB) was consulted.

Cohen's kappa coefficient was calculated to measure the inter-investigator agreement during the study selection process [17,18].

2.6. Data Extraction

Tables for data extraction were designed according to the following items: authors (year), type of materials, groups, radiopacifying agents, analyses of radiopacity, pH, setting time, solubility, and conclusion. Two reviewers (VCMD and ACSM) independently performed the data extraction. Study authors were contacted for clarification when uncertainties arose. Disagreements were resolved by discussion or with the help of a third reviewer (FB).

2.7. Risk of Bias Assessment

The risk of bias evaluation was independently assessed by two investigators (BF and PCGT). The Joanna Briggs Institute's (JBI) Critical Evaluation for Experimental Studies with modifications was employed [19].

The items of the checklist were: a clearly stated aim, justification of sample size, sample randomization, blinding of outcome assessors with respect to treatment allocation, equivalence of control and intervention groups at baseline, identical treatment of control and intervention groups other than for the interventions being compared, a clear description of the protocol of the treatment, standardization of the assessment of outcome, a reliable method for measurement of the outcome, and adequate statistical approach. Doubts and discrepancies were discussed until consensus was achieved. If not resolved, a third examiner (HGSC) was consulted.

3. Results

3.1. Selected Studies

The flowchart of the search process is displayed in Figure 1. In total, 1273 records were screened. After the initial screening (step 1), 15 studies were selected for full-text assessment (step 2). Subsequently, five studies were excluded, and the reasons for their exclusion are presented in Figure 1 [20–24]. Ten studies that met the inclusion criteria were selected for data extraction [2,25–33].

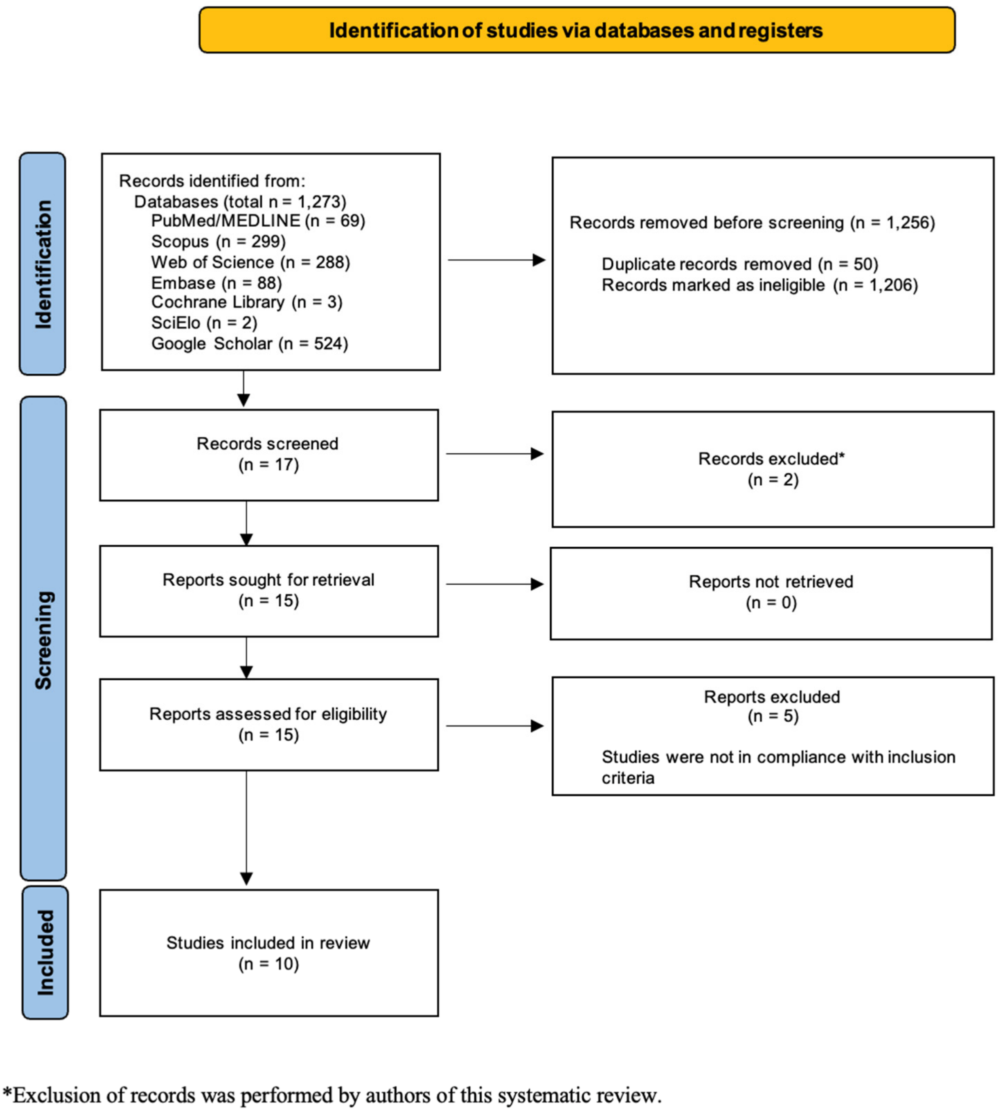

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart.

The inter-examiner kappa coefficients, indicating agreement between reviewers, were 0.898 for PubMed/Medline, 0.940 for Embase, 0.912 for Web of Science, 0.911 for Google Scholar, and 1.000 for both Scopus and Cochrane Library, as well as SciElo. According to the Landis and Koch scale, these values indicate an almost perfect level of agreement among reviewers during the study selection process [17]. No additional records were identified through manual searches of the reference lists.

3.2. Characteristics of the Included Studies

The specific characteristics of the included studies are detailed in Tables 1 and 2. Of the 10 studies considered, the evaluated materials were equally split between repair cements (n = 5) and sealers (n = 5). Furthermore, in terms of radiopacifying agents, niobium oxide was the predominant constituent (n = 7), followed by niobium pentoxide (n = 3).

Table 1. Characteristics of the included studies.

Author (Year)	Type of Material	Groups	Radiopacifying Agents	Conclusion
Guerreiro-Tanomaru et al. 2014 [27]	Repair cement	MTA White (Angelus)® PC + ZrO_2 micro PC + ZrO_2 nano PC + Nb_2O_5 micro PC + Nb_2O_5 nano	Zirconium oxide Calcium tungstate Niobium oxide	It can be concluded that micro- and nanoparticulated ZrO_2 and Nb_2O_5 may potentially be used as radiopacifying agents.
Mestieri et al. 2014 [28]	Repair cement	MTA White (Angelus) PC + 30% Nbµ PC + 30% Nbη	Niobium oxide microparticles and nanoparticles	The results demonstrated higher radiopacity for MTA, followed by Nbµ and Nbη, which had similar values. Cell culture analysis showed that PC and PC + NbO associations promoted greater cell viability than MTA.
Viapiana et al. 2014 [2]	Endodontic sealer	ES-Zr-micro ES-Zr-nano ES-Nb-micro ES-Nb-nano	Nano and microparticles of niobium or zirconium oxide	Root canal sealers based on a mixture of PC, ES and radiopacifier exhibited a degree of bioactivity although no evidence of cement hydration was demonstrated. The radiopacifier particle size had a limited effect on the sealer microstructure and chemical properties.
Viapiana et al. 2014 [29]	Endodontic sealer	ESa-Zr-micro ESa-Zr-nano ESa-Nb-micro ESa-Nb-nano	Zirconium oxide and niobium oxide micro- and nanoparticles	The experimental endodontic sealers based on PC exhibited physicochemical properties in accordance with ANSI/ADA specifications no. 57 and ISO 6876 standards, except for radiopacity. The sealers demonstrated suitable setting times, flow ability for clinical use, satisfactory compressive strength, and low solubility.
Silva et al. 2015 [30]	Repair cement	CSC + Nb_2O_5-micro CSC + Nb_2O_5-nano MTA White (Angelus)	Microparticulated and nanoparticulated niobium pentoxide	The addition of Nb_2O_5 to the CSC resulted in adequate characteristics regarding radiopacity and final setting time and provided an alkaline pH to the environment.

Table 1. *Cont.*

Author (Year)	Type of Material	Groups	Radiopacifying Agents	Conclusion
Tanomaru et al. 2015 [25]	Endodontic sealer	PC + Zr + 10% CaO PC + Nb + 10% CaO PC + Zr + 20% CaO PC + Nb + 20% CaO MTA White (Angelus)	Zirconium oxide Niobium oxide Calcium oxide	The addition of CaO to PC favored the alkaline property and the association PC + ZrO_2 + CaO presented potential for clinical use.
Bosso-Martelo et al. 2016 [31]	Endodontic sealer	CSC CSC + ZrO_2 micro CSC + ZrO_2 nano CSC + Nb_2O_5 micro CSC + Nb_2O_5 nano CSC + Bi_2O_3 CSC + $CaWO_4$ MTA White (Angelus) CSCR CSCR + ZrO_2 micro CSCR + ZrO_2 nano CSCR + Nb_2O_5 micro CSCR + Nb_2O_5 nano CSCR + Bi_2O_3 CSCR + $CaWO_4$ MTA White (Angelus)	Microparticles or nanoparticles of ZrO_2, Nb_2O_5, Bi_2O_3, or $CaWO_4$.	ZrO_2 micro radiopacifier may be considered a potential substitute for Bi_2O_3 when associated with CSC or CSCR.
Gomes-Cornélio et al. 2017 [32]	Endodontic sealer	MTA Plus (Avalon Biomed) Biodentine (Septodont) CSCR + 30% ZrO_2 CSCR+ 30% Nb_2O_5	Zirconium oxide Niobium pentoxide	All materials had suitable biocompatibility and bioactivity. The MTA Plus, Biodentine and CSCR ZrO_2 groups had the highest viability rates and velocity of proliferation whilst the CSCR Nb_2O_5 group produced more mineralized nodules.
Fen et al. 2018 [33]	Repair cement	MAWPC + BS MAWPC + NO MAWPC + BO	Barium sulfate Niobium oxide Bismuth oxide	The addition of radiopacifying agents to MAWPC maintained its high pH and favored the viability of HPLFs.
Queiroz et al. 2021 [26]	Repair cement	MTA Repair HP (Angelus) TCS + ZrO_2 TCS + $CaWO_4$ TCS + Nb_2O_5	Zirconium oxide Calcium tungstate Niobium oxide	Pure tricalcium silicate, along with various radiopacifiers, as well as MTA HP, exhibited suitable properties in terms of setting time, radiopacity, solubility, and alkalization capacity.

Bi_2O_3: Bismuth oxide, BO: Bismuth oxide, BS: Barium sulfate, Cao: Calcium oxide, $CaWO_4$: Calcium tungstate, CSC: Calcium silicate cement, CSCR: Calcium silicate experimental cement with resin, ES: Experimental sealer, HPLF: Human periodontal ligament fibroblast, MAWPC: Malaysian white Portland cement, MTA: Mineral trioxide aggregate, Nb: Niobium, Nbμ: Microparticles of niobium, Nb_2O_5: Niobium pentoxide, Nbη: Nanoparticles of niobium, NO: Niobium oxide, PC: Portland cement, pH: Potential of hydrogen, TCS: Tricalcium silicate-based, Wt: Weight, Zr: Zirconium, ZrO_2: Zirconium oxide.

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Table 2. Summary of results found for each selected study.

Author	Groups	Radiopacity mmAl	Analyses of pH	Setting Time (min)	Solubility (%)
Guerreiro-Tanomaru et al. 2014 [27]	White MTA (Angelus) PC + ZrO_2-micro PC + ZrO_2-nano PC + Nb_2O_5-micro PC + Nb_2O_5-nano	White MTA: 4.902 ± 0.60 [a] PC + ZrO_2-micro: 3.505 ± 0.26 [c] PC + ZrO_2-nano: 4.19 ± 0.3 [b] PC + Nb_2O_5-micro: 4.19 ± 0.31 [b] PC + Nb_2O_5-nano: 3.752 ± 0.17 [bc]	1 d: White MTA: 10.74 ± 0.23 [a] PC + ZrO_2-micro: 10.15 ± 0.40 [ab] PC + ZrO_2-nano: 9.89 ± 0.72 [b] PC + Nb_2O_5-micro: 9.83 ± 0.53 [b] PC + Nb_2O_5-nano: 9.66 ± 0.80 [b] 3 d: White MTA: 10.20 ± 0.87 [a] PC + ZrO_2-micro: 9.46 ± 0.60 [ab] PC + ZrO_2-nano: 9.04 ± 0.86 [b] PC + Nb_2O_5-micro: 9.12 ± 0.86 [b] PC + Nb_2O_5-nano: 8.70 ± 0.78 [b] 7 d: White MTA: 9.82 ± 1.17 [a] PC + ZrO_2-micro: 8.67 ± 0.68 [b] PC + ZrO_2-nano: 8.60 ± 0.53 [b] PC + Nb_2O_5-micro: 8.47 ± 0.74 [b] PC + Nb_2O_5-nano: 8.10 ± 0.30 [b] 14 d: White MTA: 9.57 ± 1.12 [a] PC + ZrO_2-micro: 8.27 ± 0.22 [b] PC + ZrO_2-nano: 8.02 ± 0.12 [b] PC + Nb_2O_5-micro: 8.02 ± 0.11 [b] PC + Nb_2O_5-nano: 7.92 ± 0.08 [b] 21 d: White MTA: 9.34 ± 1.03 [a] PC + ZrO_2-micro: 8.08 ± 0.12 [b] PC + ZrO_2-nano: 7.89 ± 0.13 [b] PC + Nb_2O_5-micro: 7.78 ± 0.06 [b] PC + Nb_2O_5-nano: 7.74 ± 0.06 [b] 28 d: White MTA: 9.21 ± 1.10 [a] PC + ZrO_2-micro: 7.80 ± 0.15 [b] PC + ZrO_2-nano: 7.73 ± 0.11 [b] PC + Nb_2O_5-micro: 7.68 ± 0.08 [b] PC + Nb_2O_5-nano: 7.68 ± 0.09 [b]	n.a.	n.a.
Mestieri et al. 2014 [28]	White MTA (Angelus) PC + 30% Nbμ PC + 30% Nbη	White MTA: 5.018 [a] PC + 30% Nbμ: 3.371 [b] PC + 30% Nbη: 3.701 [b]	n.a.	n.a.	n.a.

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Table 2. *Cont.*

Author	Groups	Radiopacity mmAl	Analyses of pH	Setting Time (min)	Solubility (%)
Viapiana et al. 2014 [2]	ES-Zr-micro ES-Zr-nano ES-Nb-micro ES-Nb-nano	ES-Zr-micro: 2.8 ES-Zr-nano: 2.7 ES-Nb-micro: 3.0 ES-Nb-nano: 2.3 The experimental sealers exhibited a similar average radiopacity.	1 d: ES-Zr-micro: ≅ 9.8 ES-Zr-nano: ≅ 9.6 ES-Nb-micro: ≅ 9.7 ES-Nb-nano: ≅ 9.8 7 d: ES-Zr-micro: ≅ 9.7 ES-Zr-nano: ≅ 9.9 ES-Nb-micro: ≅ 9.7 ES-Nb-nano: ≅ 9.8 14 d: ES-Zr-micro: ≅ 9.6 ES-Zr-nano: ≅ 9.7 ES-Nb-micro: ≅ 9.0 ES-Nb-nano: ≅ 9.0 21 d: ES-Zr-micro: ≅ 8.8 ES-Zr-nano: ≅ 7.8 ES-Nb-micro: ≅ 7.9 ES-Nb-nano: ≅ 7.9 28 d: ES-Zr-micro: ≅ 9.0 ES-Zr-nano: ≅ 8.3 ES-Nb-micro: ≅ 8.4 ES-Nb-nano: ≅ 8.3 The radiopacifier did not have an effect on the pH.	n.a.	n.a.
Viapiana et al. 2014 [29]	ESa-Zr-micro ESa-Zr-nano ESa-Nb-micro ESa-Nb-nano	ESa-Zr-micro: 2.64 ± 0.15 [a] ESa-Zr-nano: 2.42 ± 0.26 [a] ESa-Nb-micro: 2.46 ± 0.40 [a] ESa-Nb-nano: 2.31 ± 0.41 [a]	n.a.	ESa-Zr-micro: 288 ± 38 [a] ESa-Zr-nano: 564 ± 162 [b] ESa-Nb-micro: 248 ± 25 [a] ESa-Nb-nano: 632 ± 107 [b]	ESa-Zr-micro: 3.42 ± 0.80 [a] ESa-Zr-nano: 2.24 ± 0.46 [ab] ESa-Nb-micro: 1.89 ± 0.6 [b] ESa-Nb-nano: 1.92 ± 0.53 [b]
Silva et al. 2015 [30]	CSC + Nb_2O_5 micro CSC + Nb_2O_5 nano White MTA (Angelus)	CS+ Nb_2O_5-micro: 3.52 ± 0.12 [a] CS + Nb_2O_5-nano: 3.75 ± 0.17 [a] White MTA: 4.73 ± 0.44 [a]	1 d: CSC + Nb_2O_5 micro: 10.42 (0.10) [a] CSC + Nb_2O_5 nano: 10.42 (0.10) [a] White MTA: 10.34 (0.23) [a] 7 d: CSC + Nb_2O_5 micro: 10.09 (0.29) [a] CSC + Nb_2O_5 nano: 9.87 (0.19) [a] White MTA: 10.22 (0.10) [a] 14 d: CSC + Nb_2O_5-micro: 9.90 (0.17) [a] CSC + Nb_2O_5-nano: 10.50 (0.23) [b] White MTA: 9.96 (0.13) [a] 28 d: CSC + Nb_2O_5-micro: 9.59 (0.45) [a] CSC + Nb_2O_5-nano: 9.57 (0.23) [a] White MTA: 9.69 (0.18) [a]	CS + Nb_2O_5-micro IV: 45.8 (3.8) [a] FV: 158.8 (10.4) [a] CS + Nb_2O_5-nano IV: 47.4 (4.8) [a] FV: 152.3 (7.3) [a] White MTA IV: 24.7 (4.3) [b] FV: 161.9 (6.4) [a]	n.a.

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Table 2. *Cont.*

Author	Groups	Radiopacity mmAI	Analyses of pH	Setting Time (min)	Solubility (%)
Tanomaru-Filho et al. 2015 [25]	PC + Zr + 10% CaO PC + Nb + 10% CaO PC + Zr + 20% CaO PC + Nb + 20% CaO White MTA (Angelus)	n.a.	3 h: PC + Zr + 10% CaO: 10.66 (±0.13) [a] PC + Nb + 10% CaO: 10.35 (±0.25) [a] PC + Zr + 20% CaO: 10.92 (±0.23) [ab] PC + Nb + 20% CaO: 10.97 (±0.17) [b] White MTA: 9.57 (±0.33) [c] 12 h: PC + Zr + 10% CaO: 10.12 (±0.24) [b] PC + Nb + 10% CaO: 10.21 (±0.21) [b] PC + Zr + 20% CaO: 10.43 (±0.29) [b] PC + Nb + 20% CaO: 10.53 (±0.21) [b] White MTA: 8.77 (±0.77) [a] 24 h: PC + Zr + 10% CaO: 9.00 (±0.40) [b] PC + Nb + 10% CaO: 8.94 (±0.44) [b] PC + Zr + 20% CaO: 9.33 (±0.45) [b] PC + Nb + 20% CaO: 9.38 (±0.56) [b] White MTA: 9.12 (±0.35) [a] 7 d: PC + Zr + 10% CaO: 10.26 (±0.21) [b] PC + Nb + 10% CaO: 10.15 (±0.23) [b] PC + Zr + 20% CaO: 10.43 (±0.17) [b] PC + Nb + 20% CaO: 10.19 (±0.30) [b] White MTA: 10.33 (±0.20) [b] 14 d: PC + Zr + 10% CaO: 9.56 (±0.54) [b] PC + Nb + 10% CaO: 10.10 (±0.70) [b] PC + Zr + 20% CaO: 10.12 (±0.29) [b] PC + Nb + 20% CaO: 10.23 (±0.76) [b] White MTA: 9.71 (±0.31) [b] 21 d: PC + Zr + 10% CaO: 9.69 (±0.38) [ab] PC + Nb + 10% CaO: 10.10 (±0.04) [b] PC + Zr + 20% CaO: 9.92 (±0.35) [b] PC + Nb + 20% CaO: 10.10 (±0.49) [b] White MTA: 9.25 (±0.40) [a]	PC + Zr + 10% CaO IV: 42.60 (±13.35) [a] FV: 229.4 (±27.62) [a] PC + Nb + 10% CaO IV: 72.20 (±1.30) [b] FV: 237.6 (±49.75) [a] PC + Zr + 20% CaO IV: 24.60 (±6.06) [a] FV: 106.0 (±10.84) [a] PC + Nb + 20% CaO IV: 45.00 (±3.46) [a] FV: 303.4 (±1.67) [a] White MTA IV: 24.60 (±1.51) [a] FV: 137.8 (±1.78) [a]	PC + Zr + 10% CaO: 0.50% (±0.6) [a] PC + Nb + 10% CaO: 0.62% (±0.6) [a] PC + Zr + 20% CaO: 3.27% (±0.6) [a] PC + Nb + 20% CaO: 5.18% (±1.1) [b] White MTA: 0.30% (±0.00) [a]

Table 2. *Cont.*

Author	Groups	Radiopacity mmAl	Analyses of pH	Setting Time (min)	Solubility (%)
Bosso-Martelo et al. 2016 [31]	CSC CSC + ZrO_2-micro CSC + ZrO_2-nano CSC + Nb_2O_5-micro CSC + Nb_2O_5-nano CSC + Bi_2O_3 CSC + $CaWO_4$ White MTA (Angelus) CSCR CSC + ZrO_2-micro CSC + ZrO_2-nano CSC + Nb_2O_5-micro CSC + Nb_2O_5-nano CSCR + Bi_2O_3 CSCR + $CaWO_4$ White MTA (Angelus)	CSC: 1.51 ± 0.1 ^{c} CSC + ZrO_2-micro: 5.94 ± 0.9 ^{a} CSC + ZrO_2-nano: 4.34 ± 0.2 ^{b} CSC + Nb_2O_5-micro: 4.09 ± 0.4 ^{b} CSC + Nb_2O_5-nano: 4.02 ± 0.5 ^{b} CSC + Bi_2O_3: 5.78 ± 0.5 ^{a} CSC + $CaWO_4$: 5.67 ± 0.5 ^{a} White MTA: 5.96 ± 0.7 ^{a} CSCR: 1.05 (±0.2) ^{c} CSCR + ZrO_2-micro: 5.28 (±1.0) ^{a} CSCR + ZrO_2-nano: 3.91 (±0.1) ^{b} CSCR + Nb_2O_5-micro: 3.45 (±0.3) ^{b} CSCR + Nb_2O_5-nano: 3.61 (±0.4) ^{b} CSCR + Bi_2O_3: 5.32 (±0.4) ^{a} CSCR + $CaWO_4$: 5.18 (±0.6) ^{a} White MTA: 5.96 (±0.7) ^{a}	3 h: CSC: ≅ 9.0 CSC + ZrO_2-micro: ≅ 8.1 CSC + ZrO_2-nano: ≅ 9.0 CSC + Nb_2O_5-micro: ≅ 8.7 CSC + Nb_2O_5-nano: ≅ 9.0 CSC + Bi_2O_3: ≅ 8.5 CSC + $CaWO_4$: ≅ 8.2 CSCR: ≅ 8.5 CSCR + ZrO_2-micro: ≅ 7.4 CSCR + ZrO_2-nano: ≅ 7.3 CSCR + Nb_2O_5-micro: ≅ 6.7 CSCR + Nb_2O_5-nano: ≅ 6.8 CSCR + Bi_2O_3: ≅ 8.3 CSCR + $CaWO_4$: ≅ 8.3 White MTA: ≅ 9.3 12 h: CSC: ≅ 8.8 CSC + ZrO_2-micro: ≅ 8.5 CSC + ZrO_2-nano: ≅ 8.4 CSC + Nb_2O_5-micro: ≅ 8.3 CSC + Nb_2O_5-nano: ≅ 8.8 CSC + Bi_2O_3: ≅ 8.7 CSC + $CaWO_4$: ≅ 7.3 CSCR: ≅ 7.5 CSCR + ZrO_2-micro: ≅ 6.8 CSCR + ZrO_2-nano: ≅ 6.7 CSCR + Nb_2O_5-micro: ≅ 6.6 CSCR + Nb_2O_5-nano: ≅ 6.8 CSCR + Bi_2O_3: ≅ 7.7 CSCR + $CaWO_4$: ≅ 7.3 White MTA: ≅ 7.7 24 h: CSC: ≅ 8.0 CSC + ZrO_2-micro: ≅ 8.0 CSC + ZrO_2-nano: ≅ 8.0 CSC + Nb_2O_5-micro: ≅ 7.9 CSC + Nb_2O_5-nano: ≅ 7.5 CSC + Bi_2O_3: ≅ 8.5 CSC + $CaWO_4$: ≅ 8.2 CSCR: ≅ 7.5 CSCR + ZrO_2-micro: ≅ 6.8 CSCR + ZrO_2-nano: ≅ 6.6 CSCR + Nb_2O_5-micro: ≅ 6.6 CSCR + Nb_2O_5-nano: ≅ 6.6 CSCR + Bi_2O_3: ≅ 7.2 CSCR + $CaWO_4$: ≅ 7.3 White MTA: ≅ 7.7	CSCR + ZrO_2 micro IV: 33.83 (±4.0) ^{de} FV: 163.50 (±53.8) ^{d} CSCR + ZrO_2 nano IV: 36.67 (±1.5) ^{d} FV: 342.30 (±12.7) ^{a} CSCR + Nb_2O_5 micro IV: 40.50 (±1.7) ^{d} FV: 191.70 (±48.3) ^{cd} CSCR + Nb_2O_5 nano IV: 57.50 (±2.7) ^{bc} FV: 379.20 (±18.8) ^{a} CSCR + Bi_2O_3 IV: 61.50 (±9.2) ^{b} FV: 226.50 (±26.3) ^{c} CSCR + $CaWO_4$ IV: 51.17 (±8.1) ^{c} FV: 188.50 (±16.6) ^{cd} White MTA IV: 24.33 (±4.1) ^{e} FV: 175.20 (±4.1) ^{cd}	CSC: 0.73 (±0.2) ^{a} CSC + ZrO_2-micro: 0.99 (±0.8) ^{a} CSC + ZrO_2-nano: 1.91 (±1.0) ^{a} CSC + Nb_2O_5-micro: 1.93 (±1.6) ^{a} CSC + Nb_2O_5-nano: 1.71 (±0.7) ^{a} CSC + Bi_2O_3: 2.01 (±1.5) ^{a} CSC + $CaWO_4$: 0.52 (±0.1) ^{a} White MTA: 0.30 (±0.0) ^{a} CSCR: 0.82 (±0.5) ^{a} CSCR + ZrO_2-micro: 1.02 (±1.3) ^{a} CSCR + ZrO_2-nano: 1.15 (±0.4) ^{a} CSCR + Nb_2O_5-micro: 1.21 (±1.1) ^{a} CSCR + Nb_2O_5-nano: 1.67 (±0.7) ^{a} CSCR + Bi_2O_3: 0.89 (±0.5) ^{a} CSCR + $CaWO_4$: 0.92 (±0.8) ^{a} White MTA: 0.30 (±0.0) ^{a}

Table 2. *Cont.*

Author	Groups	Radiopacity mmAI	Analyses of pH	Setting Time (min)	Solubility (%)
Bosso-Martelo et al. 2016 [31]	CSC CSC + ZrO_2-micro CSC + ZrO_2-nano CSC + Nb_2O_5-micro CSC + Nb_2O_5-nano CSC + Bi_2O_3 CSC + $CaWO_4$ White MTA (Angelus) CSCR CSC + ZrO_2-micro CSC + ZrO_2-nano CSC + Nb_2O_5-micro CSC + Nb_2O_5-nano CSCR + Bi_2O_3 CSCR + $CaWO_4$ White MTA (Angelus)	CSC: 1.51 ± 0.1 ^{c} CSC + ZrO_2-micro: 5.94 ± 0.9 ^{a} CSC + ZrO_2-nano: 4.34 ± 0.2 ^{b} CSC + Nb_2O_5-micro: 4.09 ± 0.4 ^{b} CSC + Nb_2O_5-nano: 4.02 ± 0.5 ^{b} CSC + Bi_2O_3: 5.78 ± 0.5 ^{a} CSC + $CaWO_4$: 5.67 ± 0.5 ^{a} White MTA: 5.96 ± 0.7 ^{a} CSCR: 1.05 (±0.2) ^{c} CSCR + ZrO_2-micro: 5.28 (±1.0) ^{a} CSCR + ZrO_2-nano: 3.91 (±0.1) ^{b} CSCR + Nb_2O_5-micro: 3.45 (±0.3) ^{b} CSCR + Nb_2O_5-nano: 3.61 (±0.4) ^{b} CSCR + Bi_2O_3: 5.32 (±0.4) ^{a} CSCR + $CaWO_4$: 5.18 (±0.6) ^{a} White MTA: 5.96 (±0.7) ^{a}	7 d: CSC: ≅ 9.7 CSC + ZrO_2-micro: ≅ 8.9 CSC + ZrO_2-nano: ≅ 9.1 CSC + Nb_2O_5-micro: ≅ 9.5 CSC + Nb_2O_5-nano: ≅ 9.5 CSC + Bi_2O_3: ≅ 9.8 CSC + $CaWO_4$: ≅ 9.0 CSCR: ≅ 9.5 CSCR + ZrO_2-micro: ≅ 9.7 CSCR + ZrO_2 nano: ≅ 9.4 CSCR + Nb_2O_5-micro: ≅ 9.3 CSCR + Nb_2O_5-nano: ≅ 9.3 CSCR + Bi_2O_3: ≅ 8.8 CSCR + $CaWO_4$: ≅ 8.4 White MTA: ≅ 10.1 14 d: CSC: ≅ 9.6 CSC + ZrO_2-micro: ≅ 8.0 CSC + ZrO_2-nano: ≅ 8.7 CSC + Nb_2O_5-micro: ≅ 9.0 CSC + Nb_2O_5-nano: ≅ 8.7 CSC + Bi_2O_3: ≅ 8.8 CSC + $CaWO_4$: ≅ 8.4 CSCR: ≅ 8.3 CSCR + ZrO_2-micro: ≅ 7.5 CSCR + ZrO_2-nano: ≅ 8.9 CSCR + Nb_2O_5-micro: ≅ 8.0 CSCR + Nb_2O_5-nano: ≅ 8.3 CSCR + Bi_2O_3: ≅ 9.0 CSCR + $CaWO_4$: ≅ 7.9 White MTA: ≅ 9.4 21 d: CSC: ≅ 8.8 CSC + ZrO_2-micro: ≅ 8.2 CSC + ZrO_2-nano: ≅ 8.7 CSC + Nb_2O_5-micro: ≅ 8.9 CSC + Nb_2O_5-nano: ≅ 8.2 CSC + Bi_2O_3: ≅ 8.0 CSC + $CaWO_4$: ≅ 7.5 CSCR: ≅ 8.2 CSCR + ZrO_2-micro: ≅ 7.4 CSCR + ZrO_2-nano: ≅ 8.5 CSCR + Nb_2O_5-micro: ≅ 8.6 CSCR + Nb_2O_5-nano: ≅ 8.6 CSCR + Bi_2O_3: ≅ 8.5 CSCR + $CaWO_4$: ≅ 7.9 White MTA: ≅ 8.5 All the associations of CSC showed an alkaline pH.	CSCR + ZrO_2 micro IV: 33.83 (±4.0) ^{de} FV: 163.50 (±53.8) ^{d} CSCR + ZrO_2 nano IV: 36.67 (±1.5) ^{d} FV: 342.30 (±12.7) ^{a} CSCR + Nb_2O_5 micro IV: 40.50 (±1.7) ^{d} FV: 191.70 (±48.3) ^{cd} CSCR + Nb_2O_5 nano IV: 57.50 (±2.7) ^{bc} FV: 379.20 (±18.8) ^{a} CSCR + Bi_2O_3 IV: 61.50 (±9.2) ^{b} FV: 226.50 (±26.3) ^{c} CSCR + $CaWO_4$ IV: 51.17 (±8.1) ^{c} FV: 188.50 (±16.6) ^{cd} White MTA IV: 24.33 (±4.1) ^{e} FV: 175.20 (±4.1) ^{cd}	CSC: 0.73 (±0.2) ^{a} CSC + ZrO_2-micro: 0.99 (±0.8) ^{a} CSC + ZrO_2-nano: 1.91 (±1.0) ^{a} CSC + Nb_2O_5-micro: 1.93 (±1.6) ^{a} CSC + Nb_2O_5-nano: 1.71 (±0.7) ^{a} CSC + Bi_2O_3: 2.01 (±1.5) ^{a} CSC + $CaWO_4$: 0.52 (±0.1) ^{a} White MTA: 0.30 (±0.0) ^{a} CSCR: 0.82 (±0.5) ^{a} CSCR + ZrO_2-micro: 1.02 (±1.3) ^{a} CSCR + ZrO_2-nano: 1.15 (±0.4) ^{a} CSCR + Nb_2O_5-micro: 1.21 (±1.1) ^{a} CSCR + Nb_2O_5-nano: 1.67 (±0.7) ^{a} CSCR + Bi_2O_3: 0.89 (±0.5) ^{a} CSCR + $CaWO_4$: 0.92 (±0.8) ^{a} White MTA: 0.30 (±0.0) ^{a}

Table 2. *Cont.*

Author	Groups	Radiopacity mmAI	Analyses of pH	Setting Time (min)	Solubility (%)
Gomes-Cornélio et al. 2017 [32]	MTA Plus (Avalon Biomed) Biodentine (Septodont) CSCR + 30% ZrO_2 CSCR + 30% Nb_2O_5	n.a.	n.a.	n.a.	n.a.
Fen et al. 2018 [33]	MAWPC + BS MAWPC + NO MAWPC + BO	n.a.	0 d: MAWPC + NO: 7.0 (±0.1) MAWPC + BO: 6.4 (±0.1) MAWPC + BS: 6.1 (±0.0) 1 d: MAWPC + NO: 9.9 (±0.0) MAWPC + BO: 10.3^{a} (±0.1) MAWPC + BS: 10.1 (±0.1) 3 d: MAWPC + NO: 10.6 ^{a,A} (±0.2) MAWPC + BO: 10.8 ^{a,b,B} (±0.0) MAWPC + BS: 10.8 ^{a,A,B} (±0.1) 7 d: MAWPC + NO: 10.9 ^{A} (±0.0) MAWPC + BO: 10.9 ^{a,A} (±0.1) MAWPC + BS: 10.9 ^{b,A} (±0.1) 14 d: MAWPC + NO: 10.5 ^{a} (±0.1) MAWPC + BO: 10.7 ^{b,A} (±0.0) MAWPC + BS: 10.8 ^{a,b,B} (±0.0)	n.a.	n.a.
Queiroz et al. 2021 [26]	MTA Repair HP (Angelus) TCS + ZrO_2 TCS + $CaWO_4$ TCS + Nb_2O_5	MTA HP: 3.20 (±0.18) ^{d} TCS + ZrO_2: 4.20 (±0.13) ^{b} TCS + $CaWO_4$: 4.61 (±0.01) ^{a} TCS + Nb_2O_5: 3.55 (±0.17) ^{c}	3 h: MTA HP: 10.5 (±0.3) ^{b} TCS + ZrO_2: 10.9 (±0.4) ^{a,b} TCS + $CaWO_4$: 10.9 (±0.2) ^{a,b} TCS + Nb_2O_5: 10.7 (±0.3) ^{b} 12 h: MTA HP: 9.9 (±0.4) ^{a,b} TCS + ZrO_2: 10.0 (±0.4) ^{a} TCS + $CaWO_4$: 9.0 (±0.6) ^{b} TCS + Nb_2O_5: 9.4 (±0.4) ^{b} 24 h: MTA HP: 9.3 (±0.4) ^{ab} TCS + ZrO_2: 9.0 (±0.5) ^{ab} TCS + $CaWO_4$: 8.8 (±0.5) ^{b} TCS + Nb_2O_5: 8.7 (±0.5) ^{b} 7 d: MTA HP: 10.3 (±0.3) ^{a} TCS + ZrO_2: 9.2 (±0.9) ^{c} TCS + $CaWO_4$: 9.8 (±0.7) ^{ab} TCS + Nb_2O_5: 9.4 (±0.9) ^{b}	MTA HP: 32.50 (±1.80) ^{d} TCS + ZrO_2: 40.06 (±2.45) ^{b,c} TCS + $CaWO_4$: 61.78 (±4.07) ^{a} TCS + Nb_2O_5: 38.00 (±4.96) ^{c}	n.a.

https://doi.org/10.3390/app16041722

Table 2. *Cont.*

Author	Groups	Radiopacity mmAI	Analyses of pH	Setting Time (min)	Solubility (%)
Queiroz et al. 2021 [26]	MTA Repair HP (Angelus) TCS + ZrO_2 TCS + $CaWO_4$ TCS + Nb_2O_5	MTA HP: 3.20 (±0.18) [d] TCS + ZrO_2: 4.20 (±0.13) [b] TCS + $CaWO_4$: 4.61 (±0.01) [a] TCS + Nb_2O_5: 3.55 (±0.17) [c]	14 d: MTA HP: 10.3 (±0.4) [a] TCS + ZrO_2: 9.1 (±0.7) [b] TCS + $CaWO_4$: 10.0 (±0.6) [a] TCS + Nb_2O_5: 9.8 (±0.6) [ab] 21 d: MTA HP: 9.1 (±0.5) [a] TCS + ZrO_2: 9.3 (±0.4) [a] TCS + $CaWO_4$: 9.0 (±0.6) [a] TCS + Nb_2O_5: 9.0 (±0.7) [a]	MTA HP: 32.50 (±1.80) [d] TCS + ZrO_2: 40.06 (±2.45) [b,c] TCS + $CaWO_4$: 61.78 (±4.07) [a] TCS + Nb_2O_5: 38.00 (±4.96) [c]	n.a.

Bi_2O_3: Bismuth oxide, BS: Barium sulfate, CaO: Calcium oxide, $CaWO_4$: Calcium tungstate, CSC: Calcium silicate cement, CSCR: Calcium silicate experimental cement with resin, D: Day, ES: Experimental sealer, FV: Final value, H: Hour, IV: Initial value, MAWPC: Malaysian white Portland cement, Min: Minutes, mmAI: Thickness of aluminum (in millimeters), MTA: Mineral trioxide aggregate, n.a.: Not applicable, Nb: Niobium, Nbμ: Microparticles of niobium, Nb_2O_5: Niobium pentoxide, Nbη: Nanoparticles of niobium, NO: Niobium oxide, PC: Portland cement, pH: Potential of hydrogen, TCS: Tricalcium silicate-based, Zr: Zirconium, ZrO_2: Zirconium oxide. Significant differences are represented by different letters in each study ($p < 0.05$).

Seven studies evaluated the radiopacity of the materials [2,26–31]. In all studies, radiopacity was assessed based on the thickness of the aluminum (in mm) using a conversion equation and all specimens were standardized in size (internal diameter = 10 mm; height = 1 mm).

A total of seven studies carried out pH analysis. The period of analysis was 3 [25,26,31] and 12 h [25,26,31] and 1 [2,25–27,30,31,33], 3 [27,33], 7 [2,25–28,30,31,33], 14 [2,25–27,30,31,33], 21 [2,25–27,31] and 28 days [2,27,30]. All the studies used polyethylene tubes filled with 10 mL of distilled water that were stored at 37 °C.

Five studies evaluated the setting time [25,26,29–31] of the materials in accordance with international standards, including ISO 6876 (2012), American Dental Association (ADA) Specification n^0 57 [34], and ASTM C266-03 [35]. Specimens with a diameter of 10 mm and a thickness ranging from 1 to 2 mm were maintained at 37 °C and 95% relative humidity. The initial setting time was determined using a Gillmore needle weighing 100 g with a 2 mm tip, whereas the final setting time was assessed using a 456 g needle with a 1 mm tip. Setting times were calculated as the mean interval between the mixing of the materials and the point at which the needles no longer produced indentations.

Three studies employed similar methodologies to evaluate the solubility of materials [22,25,29]. Specimens with a thickness of 1.5 mm and a diameter of 7.75 mm were prepared, with nylon threads embedded in the fresh material to allow suspension during testing. The specimens were maintained at 37 °C, with variations in storage time, and immersed in 7.5 mL of distilled and deionized water. After the immersion period, the samples were dried, stabilized in a desiccator, and weighed using a precision balance (HM-200, A & D Engineering, Inc., Bradford, MA, USA). Solubility was calculated as the percentage of mass loss relative to the initial mass, ensuring rigor and reproducibility of the applied protocols.

3.3. Radiopacity, pH, Setting Time and Solubility Analysis

In the radiopacity test [26–31], cements containing Nb showed lower (four studies) or equal (four studies) values compared to white MTA and cements with ZrO_2 or other radiopacifiers.

Of the seven studies that carried out pH analysis [2,25–27,30,31,33], all tested materials showed an alkaline pH. Although some variability in the results was observed across studies, most reported an alkaline pH throughout all evaluation periods, which was not influenced by the presence of Nb.

In the setting time test [25,26,29–31], most studies (four studies) showed that there was no difference in setting time between the different radiopacifiers.

In the solubility test [25,29,31], Nb increased the solubility of the materials compared to zirconium in one study, reduced solubility in another study, and showed no difference in a third study.

3.4. Risk of Bias

Figure 2 summarizes the results of the risk of bias assessment of the eligible studies. All included articles showed the possibility of comparing control and experimental groups at the outset and a reliable measurement method. Overall, a low risk of bias was observed in domains related to the clear definition of objective of the studies, identical treatment of the groups, appropriate description of the treatment protocol, consistent outcome measurement across groups, and appropriate statistical analysis. On the other hand, a high risk of bias was observed for some items, such as the assignment to truly random treatment groups and the blindness of those assessing the outcomes to the treatment allocation.

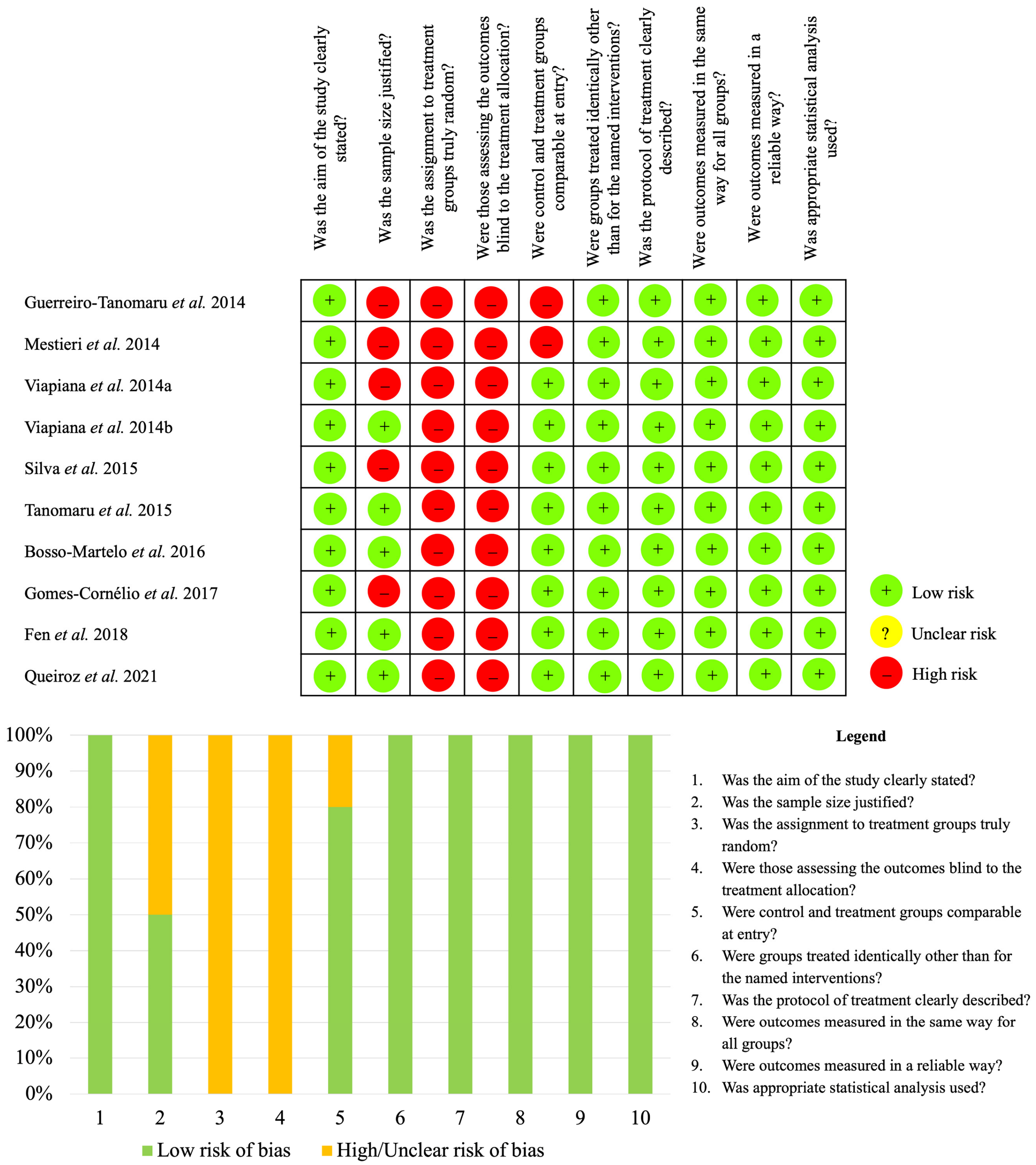

Figure 2. Evaluation of the risks of bias of the included studies. Legend: Guerreiro-Tanomaru et al. 2014 [27], Mestieri et al. 2014 [28], Viapiana et al. 2014a [2], Viapiana et al. 2014b [29], Silva et al. 2015 [30], Tanomaru et al. 2015 [25], Bosso-Martelo et al. 2016 [31], Gomes-Cornélio et al. 2017 [32], Fen et al. 2018 [33], Queiroz et al. 2021 [26].

4. Discussion

This systematic review investigated the use of niobium as a radiopacifying agent in endodontic cements. Ten studies were selected, evenly distributed between sealer and repair cements, with niobium oxide being the predominant radiopacifying agent. Seven studies evaluated the radiopacity of the materials, showing that niobium-containing cements exhibited radiopacity values equal to or lower than those of other radiopacifying agents, while still meeting the requirements established by ISO/ADA standards. Regarding pH analysis, which was performed in 7 of the 10 studies included in this review, all evaluated materials exhibited alkaline behavior, indicating that niobium did not influence this property, and this alkalinity was maintained over time in the included studies. Four studies analyzed the setting time. These studies reported that niobium did not influence setting time when compared with other radiopacifying agents. Regarding solubility, the results were variable: one study indicated that niobium increased the solubility of the materials compared with zirconium, another study showed a reduction in solubility, and a third found no significant differences between the radiopacifiers.

An ideal radiopacifying material should provide adequate radiopacity to the cement while maintaining favorable physicochemical and biological properties [36–38]. Previous studies [39,40] have shown that the incorporation of Nb_2O_5 and ZrO_2 nanoparticles into dental materials has been primarily aimed at improving biological properties, particularly antibacterial activity, while minimizing genotoxic risks.

Radiopacity is one of the key characteristics of endodontic materials as it allows for the detection of failures in fillings and facilitates treatment evaluation through clinical radiographs [41,42]. In this study, the addition of Nb_2O_5 and ZrO_2 as radiopacifying agents influenced the radiopacity of the tested materials in distinct ways. Although materials containing niobium as a radiopacifying agent exhibited lower radiopacity in four of the seven evaluated studies, this radiopacity may not represent a limitation, as these values still meet the requirements set by ISO/ADA standards.

Alkalinity is another important characteristic of endodontic materials and plays a critical role in their biological profile and antimicrobial properties [27,41]. Camilleri et al. [41] demonstrated that the addition of various radiopacifying agents to PC resulted in an alkaline pH from day 1 to day 28. In this review, all studies that analyzed pH reported elevated pH, which is desirable for the inactivation of bacterial endotoxins and the induction of biomineralization [43–46].

Tanomaru-Filho et al. [25] demonstrated that the addition of Nb_2O_5 decreased the setting time of tricalcium silicate-based cement, which is consistent with the findings of Bosso-Martelo et al. [31]. However, the addition of calcium tungstate ($CaWO_4$) increased the setting time of this material, corroborating the results reported by Hungaro Duarte et al. [47]. Based on studies investigating the hydraulic hydration of calcium silicate cement, it can be suggested that the addition of the radiopacifiers Nb_2O_5 and $CaWO_4$ interferes with the hydration process of tricalcium silicate, thereby accelerating and delaying setting, respectively [48].

Another factor that may be associated with the setting process is the powder-to-liquid ratio, which is established for each material according to the consistency required for clinical applicability [49]. However, most studies included in this review reported no differences in setting time among the different radiopacifiers.

The studies included in this review showed conflicting results regarding the effect of niobium oxide on material solubility. While some findings suggest that the addition of radiopacifiers such as niobium oxide may reduce solubility and thereby contribute to greater clinical durability [25], other studies reported either an increase [29] or no significant difference [31] when compared to zirconium-based formulations. Low solubility is generally desirable to ensure that the material remains at the application site long enough to exert its therapeutic effects [50,51]. However, considering that only three studies have evaluated this property, further research is necessary to clarify the actual influence of niobium oxide on the solubility of these materials.

It is noteworthy that most of the studies included in this systematic review were conducted by the same group of authors [2,25–32]. This may be considered a limitation of the present review, as the strong influence of methodological characteristics of a single research group could have affected the overall findings.

However, this systematic review included studies with a low risk of bias in most assessed domains. Nevertheless, some critical methodological aspects, particularly random allocation to treatment groups and blinding of outcome assessment, showed a high risk of bias. This finding indicates that, despite an overall acceptable methodological quality, important limitations remain in study design. Addressing these issues in future studies would strengthen the internal validity of the evidence. Minimizing the risk of bias is essential to ensure that the available data are reliable and applicable to clinical practice [52,53].

It is important to highlight that this systematic review focused exclusively on the physicochemical properties of endodontic materials containing niobium. However, previous studies suggest that niobium may also positively influence biological properties, including tissue and cellular biocompatibility, antimicrobial activity, and osteogenic potential [26]. These aspects were not addressed in the present review, highlighting the need for a complementary systematic review specifically aimed at evaluating the biological effects of niobium in endodontic materials. A comprehensive understanding of these properties is essential to determine the full potential of niobium-based compounds in promoting repair in endodontic therapies.

5. Conclusions

Niobium-based radiopacifiers demonstrated a physicochemical performance comparable to that of other radiopacifying agents with respect to radiopacity, alkalinizing ability, setting time, and solubility of endodontic cements.

The available evidence is limited, particularly for setting time and solubility, and most studies were conducted by the same research group. Therefore, current data are insufficient to support the superiority of niobium for any specific physicochemical property.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app16041722/s1, Supplementary File S1: Search strategies used for the electronic databases.

Author Contributions: Conceptualization, H.G.d.S.C., L.F.d.S.A.M. and F.B.; methodology, H.G.d.S.C., M.A.H.D., L.T.A.C., L.F.d.S.A.M. and J.M.M.d.S.; software, H.G.d.S.C., P.C.G.T. and A.C.S.M.; validation, H.G.d.S.C., P.C.G.T. and C.B.A.; formal analysis, H.G.d.S.C., C.B.A. and F.B.; investigation, H.G.d.S.C., A.C.S.M., V.C.M.D., P.C.G.T., B.F. and F.B.; resources, M.A.H.D., L.T.A.C., C.B.A. and L.F.d.S.A.M.; data curation, A.C.S.M., P.C.G.T., V.C.M.D., B.F. and F.B.; writing—original draft preparation, H.G.d.S.C., P.C.G.T. and B.F.; writing—review and editing, J.M.M.d.S., C.B.A. and F.B.; visualization, H.G.d.S.C., A.C.S.M., V.C.M.D. and B.F.; supervision, J.M.M.d.S., C.B.A. and F.B.; project administration, M.A.H.D., L.T.A.C., L.F.d.S.A.M. and F.B.; funding acquisition, H.G.d.S.C., C.B.A. and F.B. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ADA	American Dental Association
AlF_3	Aluminum fluoride
Bi_2O_3	Bismuth oxide
C	Comparison
$CaWO_4$	Calcium tungstate
I	Intervention
JBI	Joanna Briggs Institute
MTA	Mineral trioxide aggregate
Nb	Niobium
Nb_2O_5	Niobium pentoxide
O	Outcome
OSF	Open Science Framework
P	Population
PC	Portland cement
pH	Hydrogen potential
Zr	Zirconium

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