

Comparative Evaluation of the Microleakage of Glass Ionomers as Restorative Materials: A Systematic Review of In Vitro Studies

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Featured Application: Results from the present systematic review are applicable in the field of restorative dentistry. Differences in microleakage between glass ionomers and the factors that influence it are crucial for restorative material selection.

Abstract: This study aimed to perform a qualitative synthesis of the available in vitro evidence on the microleakage of commercially available conventional glass ionomer cements (GICs), resin-modified glass ionomer cements (RMGICs), and modified glass ionomer cements with nano-fillers, zirconia, or bioactive glasses. A systematic review was conducted according to the PRISMA 2020 (Preferred Reporting Items for Systematic Review and Meta-Analysis) statement standards. The literature search was performed in Medline (via PubMed), Embase, Web of Science, and Scopus to identify relevant articles. Laboratory studies that evaluated microleakage of GICs, RMGICs, and modified glass ionomer cements with nano-fillers, zirconia, or bioactive glasses were eligible for inclusion. The QUIN risk of bias tool for the assessment of in vitro studies conducted in dentistry was used. After the study selection process, which included duplicate removal, title and abstract screening, and full-text assessment, 15 studies were included. A qualitative synthesis of the evidence is presented, including author data, year of publication, glass ionomer materials used, sample characteristics, microleakage technique and values, and main outcome measures for primary and permanent teeth. Although no statistically significant differences were found in numerous studies, most results showed that RMGICs exhibited less leakage than conventional GICs. All studies agreed that leakage was significantly higher at dentin margins. It was also higher at the gingival margin than at the occlusal margin. Nano-filled RMGICs Ketac N100, Equia Forte, and Zirconomer appear to have less microleakage than conventional GICs and RMGICs. Further investigations using a standardized procedure are needed to confirm the results.

Keywords: dentistry; dental materials; glass ionomers; microleakage; in vitro; laboratory; systematic review



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1. Introduction

Glass ionomer cements (GICs), developed during the late 1960s [1], are one of the most important groups of dental materials due to their ionic exchange with the dental substrate and their continuous fluoride release. GICs do not mimic tooth color or composites and show faster surface loss with wear. However, because they are less technique-sensitive, they may act as the material of choice in many restorative cases [2]. On the other hand, GICs not only possess a remineralizing action but can also increase their hardness in contact with the oral environment over time, and their ability to incorporate calcium and phosphate has been demonstrated by SEM-EDX, suggesting an additional mineralization process [3]. The main disadvantages attributed to GICs are their poor mechanical properties [4], poor esthetics due to their lack of translucency [5], and moisture sensitivity while setting [6]. GICs have undergone multiple modifications in their structure and composition to overcome these disadvantages, increasing their usefulness as restorative materials in

dental treatments [7]. Among these modifications, the following can be highlighted: the incorporation of resin, usually 2-hydroxy-ethyl methacrylate (HEMA) [8]; metallic fiber particles [9,10], such as titanium dioxide, zirconia, or alumina nanoparticles [11–13]; and other inorganic compounds, such as hydroxyapatite, fluorapatite, or bioactive glass [14,15].

Resin-modified glass ionomer cements (RMGICs) were developed to improve the physical and mechanical properties of GICs [16]. These materials undergo a dual-setting reaction, the typical acid–base reaction of GICs, and photopolymerization [17]. The remineralizing potential of RMGICs can be improved by incorporating bioactive glasses into their composition, which also confer bioinductive and regenerative potential to the material [18]. The calcium-fluor-aluminosilicate content in the glass powder is responsible for the remineralizing ability of the materials [19]. Fluoride promotes the formation of fluorapatite, which is less soluble than hydroxyapatite [20]. When fluoride ions are released, they can saturate the liquid phase in and around the surface of the restorative tooth, resulting in the precipitation of CaF_2 crystals, which reduces the chances of demineralization and accelerates the remineralization process [21]. This process can be considered bioactive [22]. An *in vitro* study demonstrated that at 37 °C, maximum fluoride release was observed from Equia Forte HT filling, regardless of pH conditions [23]. Modified forms of glass ionomers are available in the form of resin-modified glass ionomer cements (RMGICs) [24], zirconia-reinforced glass ionomers [25], nano-filled modified GICs [26], bioactive glasses [27], and glass carbomers [24].

During the setting process, resin composite materials may undergo shrinkage, which causes difficulties in effectively sealing against the tooth surface, potentially leading to the infiltration of bacteria [28]. This phenomenon, known as microleakage, is frequently manifested as marginal staining, postoperative sensitivity, and the development of secondary caries around the restoration site [29]. Applying an elastic shrinking material layer combined with bulk fill composite reduces the stress magnitude in dentin and enamel to replace dental tissues in Class I and II posterior cavities [30]. On the other hand, less microleakage was reported from Equia Forte in Class II restorations than with GC G-aenial Posterior in an *in vitro* study [31].

The current minimally invasive treatment approach involves removing infected dentin but preserving affected tissue that is partially demineralized [32]. The dentin remineralization process involves a complex mechanism of mineral gain and its interaction with the collagen matrix [33]. This biomimetic remineralization process represents an approach based on creating nanocrystals that are small enough to fit into the gap zones between adjacent collagen molecules and establish a hierarchical order in the mineralized collagen [34]. Modified and unmodified GICs have the potential to remineralize dentin at different depths [35].

Modified formulations of GICs can also improve marginal adaptation and reduce microleakage. Based on this hypothesis, the present systematic review performs a qualitative synthesis of the available *in vitro* evidence on the microleakage of commercially available glass ionomer cements (GICs); resin-modified glass ionomer cements (RMGICs); and modified glass ionomer cements with nano-filled, zirconia, or bioactive glasses.

2. Materials and Methods

The present systematic review followed the established Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement standards [36]. The PRISMA 2020 checklist of items is presented in Supplementary Table S1. The protocol for the systematic review was previously registered in the Prospective Registry of Systematic Reviews (PROSPERO) under the number CRD42023415453.

2.1. Eligibility Criteria

According to the PECOS strategy [37], P: human extracted primary or permanent teeth, E: newly modified GICs, C: conventional GICs, O: microleakage or dental leakage, and S: *in vitro* or laboratory studies. Laboratory studies comparing the microleakage of

conventional and newly modified commercially available glass ionomer materials used as dental restorative materials were eligible for inclusion. Animal and in vivo studies were excluded. Studies that assessed materials other than glass ionomers, added experimental materials to commercial GICs, or did not include a comparison between the traditional and at least one of the newly modified GICs were also excluded.

2.2. Search Strategy

A comprehensive electronic literature search was performed in Medline (via PubMed), Embase, Web of Science, and Scopus) to identify relevant articles published up to March 2023 without year and language limitations. Search strategies were structured with keywords based on each section of the PECOS question, separated by the Boolean operator “OR”; then, all sections were combined with the Boolean operator “AND”, as shown in Table 1. The last search was performed on 29 June 2023.

Table 1. Search strategy.

Database	Search String	Findings
PubMed	#1 “glass ionomer cement” OR GIC	4712
	#2 Microleakage	3327
	#3 “in vitro” OR laboratory	4,608,981
	#1 AND #2 AND #3	168
Embase	#1 ‘glass ionomer cement’/exp OR ‘glass ionomer cement’ OR ‘gic’	10,662
	#2 ‘microleakage’/exp OR microleakage	3090
	#3 ‘in vitro’/exp OR ‘in vitro’ OR ‘laboratory’/exp OR laboratory	10,476,800
	#1 AND #2 AND #3	331
Scopus	#1 “glass ionomer cement” OR GIC	13,689
	#2 microleakage	3712
	#3 “in vitro” OR “laboratory”	4,279,048
	#1 AND #2 AND #3	325
Web of Science	#1 “glass ionomer cement” OR GIC (Topic)	9484
	#2 microleakage (Topic)	6432
	#3 “in vitro” OR laboratory (Topic)	9,237,722
	#1 AND #2 AND #3	283

2.3. Study Selection Process

Study records were imported into a reference manager software (Mendeley 1.19.8; Elsevier, Amsterdam, The Netherlands), and duplicate records were discarded. Subsequently, the titles and abstracts of the resulting records were screened based on the previously established eligibility criteria. Eligible articles were then read in full text, and the eligibility criteria were applied again to determine whether the article was appropriate for inclusion in the qualitative synthesis. Additionally, the references and citations of the selected articles were manually reviewed to check for potentially eligible studies. All databases had alerts set up to retrieve recently published articles. The search strategy, study selection process, data extraction, and quality assessment (risk of bias assessment) were performed by two independent investigators (A.A. and M.M.). In case of doubt, a third investigator was consulted (J.L.S.).

2.4. Data Extraction

The following data were extracted from the selected articles: information about the authors, year of publication, glass ionomer materials used, sample characteristics (sample

size, primary or permanent teeth, number of groups, and cavity classification), materials or specific techniques used, main outcome, and additional outcome measures.

2.5. Risk of Bias Assessment

The QUIN risk of bias tool for the assessment of in vitro studies conducted in dentistry was used [38]. This tool consists of 12 criteria that must be rated and given a score, as follows: adequately specified = 2, inadequately specified = 1, not specified = 0, and not applicable = exclude criteria from the calculation. The scores obtained were used to categorize an in vitro study as having a high, medium, or low risk of bias (>70% = low risk of bias, 50% to 70% = medium risk of bias, and <50% = high risk of bias). Final score = (total score × 100)/(2 × number of applicable criteria).

3. Results

3.1. Study Selection

The search yielded a total of 1107 studies. Of these, 472 duplicate records were excluded by the reference manager software. A further 621 studies were excluded after title and abstract screening because they did not meet the eligibility criteria. The remaining 14 studies were selected for full-text review, which concluded with the exclusion of 1 study because it compared only two conventional GICs. Then, 1 study was added from citation research and 1 study from a Google Scholar search. Finally, 15 articles were included in this study for qualitative synthesis. The PRISMA 2020 statement flow diagram summarizing the selection process is shown in Figure 1 [36].

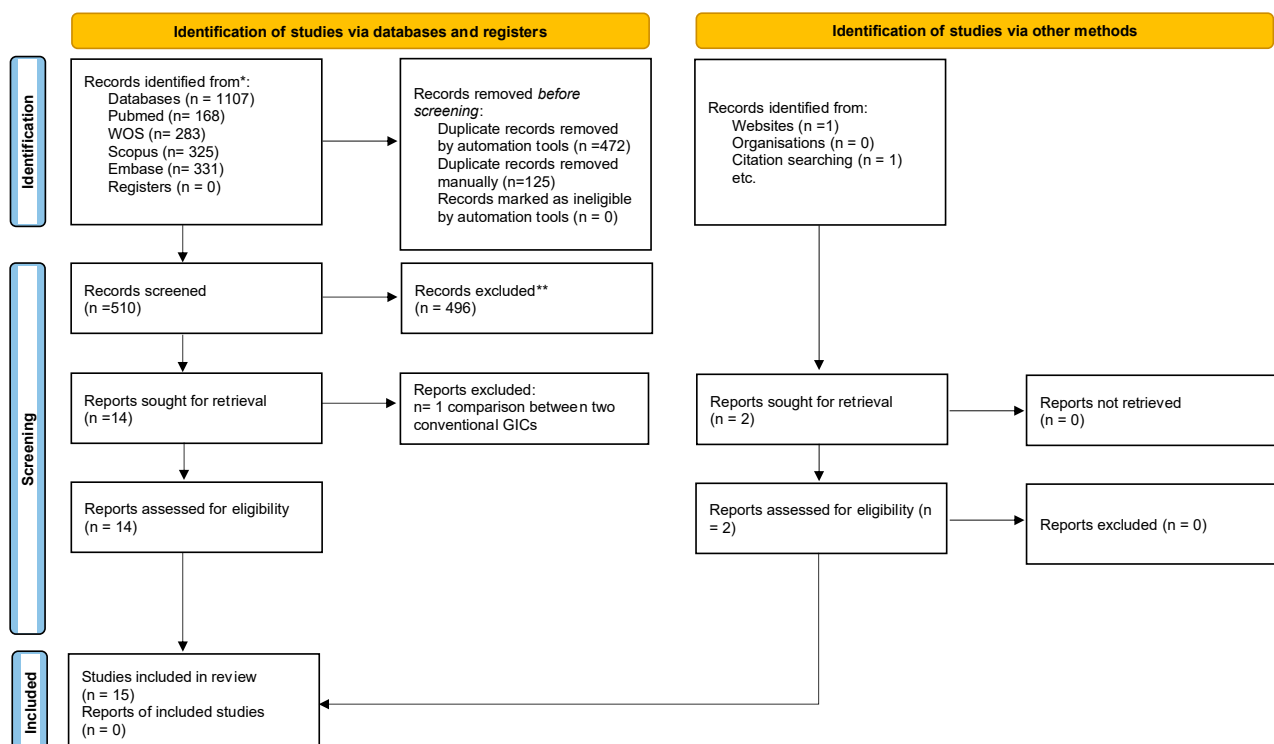


Figure 1. Schematic representation of the study selection process. Based on the PRISMA 2020 flow diagram [36]. * Records identified from each database. ** Records were excluded by a human and automation tools.

3.2. Study Characteristics

The characteristics of the included studies are summarized in Table 2a,b.

Table 2. (a) General outcomes in primary teeth. (b) General outcomes in permanent teeth.

(a)					
Author/Year	Glass Ionomer/Other Materials	Sample Characteristics and Cavity Size	Groups	Microleakage Technique and Values	Main Outcome
Alwan and Al-Waheb 2021 Iraq [39]	RMGIC: Fuji II LC GIC: Fuji IX Hybrid GI: Equia Forte	36 sound primary molars 3 groups (n = 12)	G1. Fuji II LC G2. Fuji IX + G-Coat Plus G3. Equia Forte + Equia Coat	2% methylene blue (score 0–4) Mean/SD G1. 0.9487/0.5393 G2. 1.0718/0.4502 G3. 0.2318/0.2522 p value = 0.000	Equia Forte showed significantly less microleakage than the other groups.
	20% acrylic acid conditioner G-Coat Plus Equia Coat	Class V buccal surface (2 × 4 × 2 mm depth)			
Deshpande et al., 2021 India [40]	GIC: Fuji II RMGIC: Fuji II LC	40 anterior primary teeth 2 groups (n = 20) 8 subgroups (n = 5)	G1a. Fuji II G2a. Fuji II LC G1b. Fuji II + Fuji Varnish G2b. Fuji II LC + Fuji Varnish G1c. Fuji II + G-Coat G2c. Fuji II LC + G-Coat G1d. Fuji II + Icon DMG G2d. Fuji II LC + Icon DMG	Methylene blue (score 0–3) Mean/SD G1a. 2.8/0.44/G2a. 2.6/0.54/p = 0.25 G1b. 2/0.0/G2b. 1.8/0.44/p = 0.02 G1c. 0.4/0.54 G2c. 0.2/0.44/p = 0.25 G1d. 1.2/0.44 G2d. 1/0.70/p = 0.78	No significant differences were found between Fuji II and Fuji II LC. Subgroups G1b and G2b showed significant differences between them.
	GC Dentine Conditioner Fuji Varnish G-Coat Plus Icon DMG	Class V labial surface (3 × 2 × 2 mm depth with the incisal margin in enamel and the gingival margin in dentin)			
Arthilakshmi et al., 2018 India [41]	GIC: Fuji IX RMGIC: Fuji II LC	120 caries/exfoliated primary molars 4 groups (n = 30)	G1. Fuji IX G2. Fuji IX + G-Coat Plus G3. Fuji II LC G4. Fuji II LC + G-Coat Plus	2% basic fuchsin dye (score 0–3) Microleakage % G1. 100% G2. 13.3% G3. 26.6% G4. 0% p = 0.040	RMGIC showed less microleakage than GIC with and without G-Coat Plus.
	G-Coat Plus	Class V buccal surface (4 × 2 × 1.5 mm depth)			
Dissenha et al., 2016 Brazil [42]	GIC: Ketac Molar Easymix Nano-filled RMGIC: Ketac N100	60 sound primary canines 6 groups (n = 10)	G1. Ketac N100 + water G2. Ketac N100 + orange juice G3. Ketac N100 + Coca-Cola G4. Easymix + water G5. Easymix + orange juice G6. Easymix + Coca-Cola	0.5% methylene blue (score 0–4) Microleakage % G1. 40% G2. 100% G3. 100% G4. 50% G5. 90% G6. 100%	Ketac N100 showed less microleakage than Ketac Molar Easymix, but it was non-significant. Erosive challenges with orange juice and Coca-Cola could affect the marginal adaptation of the tested GIC.
	Orange juice Coca-Cola	Class V buccal surface with margins only in enamel (2 × 3 × 1.5 mm depth)			
Madyarani et al., 2014 Indonesia [43]	GIC: Fuji IX RMGIC: Fuji II LC Nano-filled RMGIC: Ketac N100	21 sound primary canines 3 groups (n = 7) Class V (3 × 2 × 2 mm depth) on the labiocervical surface	G1. Fuji IX G2. Fuji II LC G3. Ketac N100	2% methylene blue (score 0–4) Mean/SD G1. 1.29/0.488 G2. 1.57/1.134 G3. 2.57/1.397 p = 0.119	No significant differences were found between the groups.

Table 2. Cont.

(b)					
Author/Year	Glass Ionomer/Other Materials	Sample Characteristics and Cavity Size	Groups	Microleakage Technique and Values	Main Outcome Measures
Ebaya et al., 2019 Egypt [27]	GIC: Equia Fil + G-Coat Plus RMGI: Fuji II LC + G-Coat Plus BIR: Activa Bioactive Restorative	60 sound third molars 3 groups (n = 20) 3 subgroups (n = 10) Class V buccal surfaces (4 × 3 × 2 mm depth)	G1a. Equia Fil + G-Coat Plus (Immediately) G2a. Fuji II LC + G-Coat Plus (Immediately) G3a. Activa Bioactive Restorative (Immediately) G1b. Equia Fil + G-Coat Plus (6 months + thermocycling) G2b. Fuji II LC + G-Coat Plus (6 months + thermocycling) G3b. Activa Bioactive Restorative (6 months + thermocycling)	2% methylene blue (score 1–4) Median (IQR) G1a. enamel 0.0 (0.00–0.0)/dentin 0.5 (0.0–3.0) G2a. enamel 0.0 (0.00–0.0)/dentin 0.5 (0.0–1.0) G3a. enamel 0.00 (0.00–0.00)/dentin 3.0 (0.0–3.0) G1b. d.namel 0.50 (0.0–1.0)/dentin 2.5 (0.0–3.0) G2b. enamel 0.0 (0.0–3.0)/dentin 2.5 (1.0–3.0) G3b. enamel 0.0 (0.0–0.0)/dentin 3.0 (3.0–3.0)	No significant differences were found between the materials. The dentin substrate revealed greater microleakage than enamel, especially with BIR material. Water aging had a negative effect on RMGI.
Meral and Baseren 2019 Turkey [44]	GIC: Equia Fil + Equia Fil Coat Glass carbomer: Glass Fill + GCP Gloss ZRGIC: Zirconomer GIC: Riva Self Cure + Riva Coat	32 sound third molars 4 groups (n = 16) Class V buccal and lingual surfaces (4 × 3 × 2 mm depth)	G1. Equia Fil G2. Carbomer Glass Fill G3. Zirconomer G4. Riva Self Cure	0.5% basic fuchsin (score 0–4) Microleakage % G1.enamel 87.5%/dentin 43.75% G2.enamel 75%/dentin 87.5% G3.enamel 68.75%/dentin 50% G4.enamel. 56.25%/dentin 62.5%	No significant differences were allowed at the enamel margins. Carbomer Glass Fill showed significantly more microleakage than Equia Fil and Zirconomer.
Diwanji, A. et al., 2014 India [45]	GIC: Fuji IX RMGIC: Fuji II LC Nano-filled RMGIC: Ketac N100	120 sound young maxillary permanent first premolars Class I (n = 60) 3 groups (n = 20) Class V (n = 60) 3 groups (n = 20)	Class I G1. Fuji IX G2. Fuji II LC G3. Ketac N Class V: G4. Fuji IX G5. Fuji II LC G.6 Ketac N 100	Acridine dye (score 0–4) Microleakage % G1.70%/G2. 40%/G3.50% $p \leq 0.05$ between G1 and G2/G1 and G3 G4. 80%/G5.60%/G6. 50% $p < 0.05$ between G4 and G6/G5 and G6	In Class I restorations, Fuji IX showed significantly more microleakage than the other glass ionomers. In Class V restorations, Fuji IX and Ketac N100 and Fuji LC II showed significant differences.
Pavuluri et al., 2014 India [46]	GIC: Fuji IX Nano-filled RMGIC: Ketac N100	100 carious mandibular first molars Conventional caries removal (CCR) (n = 50) 2 subgroups (n = 25) Chemomechanical Carisolv removal (CMR) (n = 50) 2 subgroups (n = 25) Class I	G1. CCR +Fuji IX G2. CCR +Ketac N100 G3. CMR +Fuji IX G4. CMR + Ketac N100	0.5% basic fuchsin solution (score 0–3) Mean/±SD (%) G1. 0.04/±0.2 (4%) G2. 0.16/±0.4 (12%) G3. 0.08/±0.2 (8%) G4. 0.2/±0.5 (16%)	No significant differences between groups.

Table 2. Cont.

(b)					
Author/Year	Glass Ionomer/Other Materials	Sample Characteristics and Cavity Size	Groups	Microleakage Technique and Values	Main Outcome Measures
Gupta et al., 2012 India [47]	GIC: Fuji II + Fuji Varnish RMGI: Fuji II LC + Fuji Varnish Nano-filled RMGIC: Ketac N100	45 sound molars 3 groups (n = 15) Class V (5 × 3 × 2 mm depth) on the buccal surface	G1. Fuji II + GC Fuji Varnish G2. Fuji II LC + GC Fuji Varnish G3. Ketac N100	2% rhodamine-B (score 0–3) Microleakage % Occlusal margins: G1. 20%/G2. 13.3%/G3. 33.3%/p = 0.464 Gingival margins: G1. 100%/G2. 93.3%/G3. 60%/p ≤ 0.05	KN 100 showed less microleakage than the other two cements at gingival margins.
	GIC: Fuji II GIC: Fuji IX RMGIC: Fuji II LC RMGIC: Fuji VIII	160 sound permanent molars 320 cavities Er:YAG laser caries remotion (n = 160) 8 subgroups (n = 20) Conventional caries removal (CCR) (n = 160) 8 subgroups (n = 20) Class V (4 × 3 × 1.5 depth) on buccal and lingual surfaces with the occlusal margins in enamel and the cervical margins 1.5 mm apical to the cementoenamel junction	Er:YAG laser caries remotion G1a. Fuji II G2a. Fuji IX G3a. Fuji II LC G4a. Fuji VIII Er:YAG laser caries remotion + Ketac conditioner G1b. Fuji II G2b. Fuji IX G3b. Fuji II LC G4b. Fuji VIII CCR G5a. Fuji II G6a. Fuji IX G7a. Fuji II LC G8a. Fuji VIII CCR + Ketac conditioner G5b. Fuji II G6b. Fuji IX G7b. Fuji II LC G8b. Fuji VIII	2% methylene blue Median (IQR) %microleakage Er:YAG laser caries remotion Occlusal G1a. 1.5 (0.0–18.0) G2a. 0.0 (0.0–20.0) G3a. 0.0 (0.0–0.0) G4a. 5.0 (0.0–22.0) Gingival G1a. 20.0 (8.0–45.0) G2a. 18.0 (0.0–35.0) G3a. 7.5 (0.0–12.0) G4a. 11.0 (0.0–25.0) Er:YAG laser caries remotion + Ketac conditioner Occlusal G1b. 1.0 (0.0–33.0) G2b. 7.5 (0.0–50.0) G3b. 0.0 (0.0–12.0) G4b. 2.0 (0.0–25.0) Gingival G1b. 21.0 (0.0–50.0) G2b. 15.5 (0.0–50.0) G3b. 2.0 (0.0–30.0) G4b. 5.0 (0.0–25.0) CCR Occlusal G5a. 12.0 (0.0–25.0) G6a. 5.5 (0.0–50.0) G7a. 5.0 (0.0–13.0) G8a. 5.0 (0.0–15.0) Gingival G5a. 22.5 (10.0–50.0) G6a. 12.4 (4.0–20.0) G7a. 15.0 (0.0–43.0) G8a. 18.5.0 (8.0–26.0) CCR + Ketac conditioner Occlusal G5b. 0.0 (0.0–9.0) G6b. 0.0 (0.0–3.0) G7b. 0.0 (0.0–10.0) G8b. 0.0 (0.0–33.0) Gingival G5b. 12.0 (0.0–31.0) G6b. 10.5 (0.0–30.0) G7b. 1.0 (0.0–35.0) /G8b. 1.0 (0.0–17.0)	RMGICs allowed less microleakage than GICs. Dentin conditioning or Er:YAG laser reduced microleakage in both gingival and occlusal margins.
Delme et al., 2008 Belgium [48]	Ketac conditioner				

Table 2. *Cont.*

(b)					
Author/Year	Glass Ionomer/Other Materials	Sample Characteristics and Cavity Size	Groups	Microleakage Technique and Values	Main Outcome Measures
Delme et al., 2010 Belgium [49]	GIC: Ketac Fil Plus GIC: Ketac Molar GIC: Ionofil Molar GIC: Ionofil Molar Quick RMGIC: Photac Fil Quick	200 sound permanent molars 400 cavities Er:YAG laser caries remotion (n = 200) 10 subgroups (n = 20) Conventional caries removal (CCR) (n = 200) 10 subgroups (n = 20) Class V (4 × 3 × 1.5 depth) on buccal and lingual surfaces with the occlusal margins in enamel and the cervical margins 1.5 mm apical to the cementoenamel junction	Er:YAG laser caries remotion G1a. Ketac Fil Plus G2a. Ketac Molar G3a. Ionofil Molar G4a. Ionofil Molar Quick G5a. Photac Fil Quick Er:YAG laser caries remotion + Ketac conditioner G1b. Ketac Fil Plus G2b. Ketac Molar G3b. Ionofil Molar G4b. Ionofil Molar Quick G5b. Photac Fil Quick CCR G6a. Ketac Fil Plus G7a. Ketac Molar G8a. Ionofil Molar G9a. Ionofil Molar Quick G10a. Photac Fil Quick CCR + Ketac conditioner G6b. Ketac Fil Plus G7b. Ketac Molar G8b. Ionofil Molar G9b. Ionofil Molar Quick G10b. Photac Fil Quick	2% methylene blue Median (IQR) %microleakage Er:YAG laser caries remotion Occlusal G1a. 0.0 (0.0–22.0) G2a. 0.0 (0.0–17.0) G3a. 4.5 (0.0–24.0) G4a. 8.0 (2.0–60.0) G5a. 0.0 (0.0–8.0) Gingival G1a. 29.5 (0.0–52.0) G2a. 9.0 (0.0–30.0) G3a. 14.0 (2.0–30.0) G4a. 14.0 (8.0–34.00) G5a. 6.0 (0.0–14.0) Er:YAG laser caries remotion + Ketac conditioner Occlusal G1b. 0.0 (0.0–13.0) G2b. 0.0 (0.0–15.0) G3b. 7.0 (0.0–11.0) G4b. 6.0 (0.0–12.0) G5b. 0.0 (0.0–14.0) Gingival G1b. 19.5 (0.0–33.0) G2b. 10. (0.0–33.0) G3b. 22.0 (4.0–26.0) G4b. 21.0 (10.0–27.0) G5b. 4.5 (0.0–12.0) CCR Occlusal G6a. 8.0 (2.0–13.0) G7a. 18.0 (8.0–36.0) G8a. 5.0 (0.0–17.0) G9a. 9.0 (0.0–33.0) G10a. 6.0 (0.0–10.0) Gingival G6a. 22.5 (10.0–50.0) G7a. 12.4 (4.0–20.0) G8a. 15.0 (0.0–43.0) G9a. 18.5. (8.0–26.0) G10a. 6.0 (5.0–22.0) CCR + Ketac conditioner Occlusal G6b. 0.0 (0.0–12.0) G7b. 0.0 (0.0–25.0) G8b. 8.0 (0.0–15.0) G9b. 5.0 (0.0–30.0) G10b. 0.0 (0.0–8.0) Gingival G6b. 16.0 (0.0–33.0) G7b. 9.5 (0.0–33.0) G8b. 16.5 (0.0–26.0) G9b. 15.0 (9.0–28.0) G10b. 2.0 (0.0–10.0)	RMGIC showed less microleakage than GICs at both occlusal and gingival margins, irrespective of the preparation method used. Conventionally prepared cavities should be conditioned before being filled, except for Ionofil Molar and Ionofil Molar Quick.
	Ketac conditioner				

Table 2. Cont.

(b)					
Author/Year	Glass Ionomer/Other Materials	Sample Characteristics and Cavity Size	Groups	Microleakage Technique and Values	Main Outcome Measures
Mello et al., 2006 Brazi [50]	GIC: Ketac Fil Plus RMGIC: Vitremer	45 molars and premolars Conventional caries removal (CCR) (n = 15) Er:YAG caries removal (n = 15) Er:YAG caries removal + dentin conditioner (n = 15)	CCR G1. Ketac Fil Plus G2. Vitremer Er:YAG laser G3. Ketac Fil Plus G4. Vitremer Er:YAG caries removal + dentin conditioner G5. Ketac Fil Plus G6. Vitremer	2% methylene blue (score 0–3) Mean scores: G1. 2.5 G2. 3 G3. 3 G4. 0.7 G5. 2.7 G6. 1.5 $p < 0.05$	RMGIC showed less microleakage than GIC, independently of the caries removal technique used. Lower microleakage scores were observed in cavities prepared with a laser when combined with restoration by RMGIC.
	Artificial root caries were induced using a microbiological model (Streptococcus mutans)	n = 3 for SEM n = 12 microleakage			
Corona et al., 2005 Brazil [51]	GIC: Ketac Fil RMGIC: Vitremer RMGIC: Fuji II LC	15 sound third molars 30 cavities (n = 10) Class V (3 × 3 × 1.5 mm depth) the occlusal margin in enamel and the cervical margin located 1 mm below the amelocemental junction	G1. Ketac Fil G2. Vitremer G3. Fuji II LC	Rhodamine-B (%) Mean mm/SD: Occlusal margin G1. 25.76/34.35 G2. 20.00/42.16 G3. 28.25/41.67 Cervical margin G1. 23.72/41.84 G2. 44.22/49.69 G3. 39.27/50.74 $p > 0.05$	No statistically significant differences were assessed between groups or margins.
	Aluminum oxide air-abrasion device for cavity preparation				
Hallett and Garcia-Godoy 1993 USA [52]	GIC: Fuji II GIC: Ketac Fil RMGIC: Fuji II LC RMGIC: Photac Fil	45 sound molars 3 groups (n = 15 cavities in buccal and n = 15 cavities in lingual) Class V (5 × 3 × 2 mm depth) on buccal and lingual surfaces, the occlusal margin in the enamel, and the cervical margin in dentin at the cementoenamel junction	G1a. buccal Fuji II LC G1b. buccal Photac Fil G2a. buccal Fuji II G2b. lingual Ketac Fil G3a. buccal Fuji II LC G3b. lingual Photac Fil	2% basic fuchsin (score 0–3) Values not available	RMGICs showed less microleakage than GICs. Photac Fil had a significantly more reliable seal than Ketac Fil both against enamel and dentin cementum. Fuji LC II performed worse than Fuji II in enamel but comparable at the dentin cementum.

All the included studies were in vitro studies published between 1993 and 2021. Of them, 1 study was conducted in Turkey [44], 1 in the USA [52], 1 in Egypt [27], 1 in Iraq [39], 1 in Indonesia [43], 2 in Belgium [48,49], 3 in Brazil [42,50,51] and 5 in India [40,41,45–47]. The sample size varied from 15 to 200 teeth; a total of 1159 teeth were evaluated. The number of assessed samples in each subgroup ranged from 5 to 30 cavities. In all studies, Black’s cavity classification was reported [53]. The prepared cavities were classified as Class V except in two studies, where Class I was also used [45,46], and in one study, where the authors performed restorations of bacterial artificial root caries [50]. The selected

teeth varied, with 5 studies on extracted primary teeth [39–43] and 10 studies on extracted permanent teeth [27,44–52]. Sound teeth were selected in most studies except one study on primary teeth [41] and one on permanent teeth [46], where caries teeth were selected.

Conventional GIC restorative materials used were Fuji II [40,47,48,52], Fuji IX [39,41,43,45,46,48], Equia Fil [27,44], Riva Self Cure [44], Ketac Fil [52], Ketac Fil Plus [49,50], Ketac Molar Easymix [42], and Ionofil Molar [49]. RMGICs used were Fuji II LC [27,39–41,43,45,47,48,51,52], Fuji VIII [48], Vitremer [50,51], and Photac Fil [49,52]. Other materials used were GICs reinforced with nano-zirconia fillers (Zirconomer Improved) [44], nano-filled carbonized glass (glass carbomer: Glass Fill) [44], bioactive ionic resin (Activa Bioactive Restorative) (27), highly reactive glass (hybrid GIC: Equia Forte) (41), and nano-filled RMGIC (Ketac N100) [42,43,45–47]. Other materials evaluated in the selected studies were Vitremer finishing gloss, Fuji Coat LC, G-Goat Plus, Ketac Primer, Icon, and Fuji Varnish II. The manufacturers and compositions of the mentioned materials are shown in Tables 3–5.

Table 3. Commercially available conventional GICs evaluated in the included studies.

CGIC	Manufacturer	Composition	Studies
Fuji II	GC Corporation	Powder: calcium fluoroalumino silicate (FAS) glass. Liquid: polyacrylic acid, itaconic acid, maleic acid, tartaric acid, and water.	Diwanji et al., 2014 [45]; Arthilakshmi et al., 2018 [41]; Alwan and Al-Waheb 2021 [39]
Fuji IX GP	GC Corporation	Powder: fluoroaluminosilicate glass and polyacrylic acid. Liquid: polyacrylic acid and polybasic carboxylic acid.	Delme et al., 2008 [48]; Madyarani et al., 2014 [43]; Pavuluri et al., 2014 [46]; Diwanji et al., 2014 [45]; Vishnurekha et al., 2018 [41]; Alwan and Al-Waheb 2021 [39]
EQUIA Fil	GC Corporation	Powder: 95% strontium fluoroalumino silicate (FAS) glass and 5% polyacrylic acid. Liquid: 40% aqueous polyacrylic acid liquid.	Ebaya et al., 2019 [27]; Meral and Baseren. 2019 [44]
Riva Self Cure	SDI Ltd.	Powder: strontium fluoroaluminosilicate glass, polyacrylic acid copolymer powders, and pigment.	Meral and Baseren 2019 [44]
Ketac Fil	3M ESPE	Power: calcium aluminum lanthan fluorosilicate glass and strontium. Liquid: water, acrylic and maleic acid copolymer, tartaric acid, and benzoic acid.	Hallett and Garcia-Godoy 1993 [52]; Corona et al., 2005 [51]; Mello et al., 2006 [50]; Delme et al., 2010 [49]
Ketac Molar Easymix	3M ESPE	Ketac Conditioner: polyacrylic acid (25%). Powder: calcium aluminum–lanthanumfluorosilicate glass, acrylic acid, maleic acid copolymer, and pigments. Liquid: water, acrylic acid, maleic acid copolymer, and tartaric acid.	Dissenha et al., 2016 [42]; Delme et al., 2010 [49]
Ionofil Molar AC	VOCO	Fluoroaluminosilicate glass, polyacrylic acid, and tartaric acid.	Delme et al., 2010 [49]

Table 4. Commercially available RMGICs evaluated in the included studies.

GI	Manufacturer	Composition	Studies
RMGIC Fuji II LC	GC Corporation	Powder: FAS glass. Liquid: polyacrylic acid, 2-HEMA (hydroxylethyl methacrylate; 30–35%), bicarbonate, and proprietary ingredient.	Alwan and Al-Waheb 2021 [39]; Deshpande et al., 2021 [40]; Ebaya et al., 2019 [27]; Arthilakshmi et al., 2018 [41]; Diwanji, et al., 2014 [45]; Madyarani et al., 2014 [43]; Delme et al., 2008 [48]; Corona et al., 2005 [51]; Hallett and Garcia-Godoy 1993 [52]
Hybrid glass ionomer Equia Forte	GC Corporation	Powder: 95% strontium fluoroaluminosilicate glass, highly reactive small particles, and 5% polyacrylic acid. Liquid: 40% aqueous polyacrylic acid.	Alwan and Al-Waheb 2021 [39]
RMGIC Fuji VIII GP	GC Corporation	2-HEMA (25–50%); tartaric acid (5–10%); 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxo-5,12-diazahexadecane-1,16-diyl bismethacrylate 1–5%; and 2-hydroxy-1,3 dimethacryloxypropane (1–5%).	Delme et al., 2008 [48]
RMGIC Vitremer	3M ESPE	Powder: fluoroaluminosilicate powder. Contains pigments. Liquid: polycarboxylic acid modified with a methacrylate group.	Corona et al., 2005 [51]; Mello et al., 2006 [50]
RMGIC Photac Fil	3M ESPE	Polyethylene polycarbonic acid, 2-hydroxyethyl methacrylate, water, and diurethane dimetharylate.	Delme et al., 2010 [49]; Hallett and Garcia-Godoy 1993 [52]
Ketac N100 Nano RMGIC	3M ESPE	Primer: water (40–50%); HEMA (35–45%), acrylic/itaconic acid copolymer (10–15%), and photo-initiators. Ketac™ N100: de-ionized water, HEMA, vitrebond copolymer/methacrylate-modified polyalkenoic acid, fluoroaluminosilicate glass, nanomers, and nanoclusters.	Dissenha et al., 2016 [42]; Diwanji et al., 2014 [45]; Madyarani et al., 2014 [43]; Pavuluri et al., 2014 [46]; Gupta et al., 2012 [47]
Activa Bioactive Restorative RMGIC	Pulpdent	Powder: diurethane dimethacrylate, bis (2-(methacryloyloxy) ethyl) phosphate, barium glass, ionomer glass, sodium fluoride, and colorants. Liquid: polyacrylic acid/maleic acid copolymer.	Ebaya et al., 2019 [27]
Glass carbomer: Glass Fill	GCP Dental	Powder: fluoroaluminosilicate glass and apatite. Liquid: polyacrylic acids and silica.	Meral and Baseren 2019 [44]
Zirconia GIC: Zirconomer Improved	SHOFU Dental	Powder: fluoroaluminosilicate glass, zirconium oxide, pigment, etc. Liquid: polyacrylic acid and tartaric acid.	Meral and Baseren 2019 [44]

Table 5. Other commercially available dental materials evaluated in the included studies.

Coat	Manufacturer	Studies
Vitremer finishing gloss	3M ESPE	Corona et al., 2005 [51]
GC Fuji Coat LC	GC Corporation	Delme et al., 2008 [48]
Ketac Primer	3M ESPE	Madyarani et al., 2014 [43]

Table 5. *Cont.*

Coat	Manufacturer	Studies
Icon	DMG Dental Milestones Guaranteed	Deshpande et al., 2021 [40]
GC Fuji Varnish II	GC Corporation	Deshpande et al., 2021 [40]; Gupta et al., 2012 [47]
Carisolv system	Swedish Medi Team	Pavuluri et al., 2014 [46]

Various methods are used to evaluate the microleakage of GIC restorative materials. These include using the following dyes: 2% methylene blue [27,39,43,48–50], 0.5% methylene blue [42], 2% basic fuchsin [41,52], 0.5% basic fuchsin [44,46], rhodamine B [47,51], and acridine dye [45]. The studies used various methods to assess microleakage; in some, a score number between 0–4 [39,42–45], 0–3 [46,47,50,52], and 1–4 [27] was assigned; in others, quantitative assessment of dye penetration in millimeters was expressed as a percentage of the total length of the restorative interface in three studies [48,49,51]. SEM was employed in three studies for morphological analysis of cavities prepared by Er:YAG laser irradiation [48–50]. Additionally, SEM was utilized in one study to evaluate marginal gap formation and analyze the adhesion mechanism [52].

3.3. Results of Individual Studies

The studies showed conflicting results when comparing conventional GICs with RMGICs with regards to microleakage. Although no statistically significant differences were found in numerous studies [27,40,43,46,51], the results of most studies showed that RMGICs exhibited less leakage than conventional GICs [39,41,43,48–50,52]. Only two studies showed that conventional GICs had lower microleakage scores than RMGICs [43,51]. The included studies agreed that the most significant leakage was observed at the gingival margin compared to the occlusal margin [47–49,52], which was also significantly higher on dentin/cementum than on enamel margins [27,44].

In primary teeth, RMGIC (Fuji II LC and Ketac N100) showed less microleakage than conventional GIC (Fuji II, Fuji IX, and Ketac Molar Easymix) [39–41]. However, it is noteworthy that in one study [43], conventional Fuji IX exhibited slightly better results than Fuji II LC and Ketac N100, although the findings were not statistically significant. Also, one study on hybrid GIC (Equia Forte with Equia Coat) showed a significant reduction in microleakage compared to Fuji II LC and Fuji IX [39].

In permanent teeth, two studies showed that Ketac N100 exhibited less leakage, performed better than conventional GICs and RMGICs, and was more consistent in Class I and Class V cavities [45,47]. However, in one study, non-significant results were obtained compared to conventional GIC Fuji IX in Class I cavities [46]. Likewise, non-statistically significant differences were observed when comparing Aactiva Bioactive Restorative (RMGIC) to conventional GIC Equia Fil and RMGIC Fuji II LC with coating material G-Coat Plus [27]. Only one study comparing Zirconomer Improved GIC, conventional GIC, and glass carbomer showed that Zirconomer Improved and conventional GIC exhibited better results than glass carbomer [44].

Different methods for caries removal, like chemomechanical agents, air abrasion, and Er:YAG lasers, were also assessed in the included studies. The results of one study demonstrated no significant difference in microleakage between conventional GIC and Ketac N100 following conventional and chemomechanical caries removal methods [46]. Er:YAG laser irradiation was evaluated in three studies. In one study, after root caries removal, lower microleakage was observed in cavities prepared with a laser when combined with RMGIC restorative materials [50]. Two studies on Class V cavities restored with conventional GICs and RMGICs following conventional bur preparation and Er:YAG laser irradiation found that RMGICs showed less microleakage than GICs, regardless of the preparation method [48,49]. One study on cavities prepared with aluminum oxide air

abrasion observed that conventional GIC and RMGIC used as restorative materials had similar behavior [51].

3.4. Quality Assessment (Risk of Bias)

The final scores among the included studies ranged from 50% to 70%, indicating a medium risk of bias. All the authors clearly stated the aims; provided a detailed explanation of the methodology, method of measurement of outcomes, and statistical analysis; and adequately presented the results. The sampling size calculation, the sampling technique, the criteria of outcome assessor details, and blinding needed to be adequately specified in most studies, as shown in Table 6.

Table 6. QUIN tool risk of bias results.

Study [Ref.]	Country/Date	1	2	3	4	5	6	7	8	9	10	11	12	Score	%
Ebaya et al. [27]	Egypt 2019	●	●	●	●	●	●	●	●	●	●	●	●	15 (100)/24	62.5
Meral and Baseren [44]	Turkey 2019	●	●	●	●	●	●	●	●	●	●	●	●	14 (100)/24	58.3
Hallett and Garcia-Godoy [52]	USA 1993	●	●	●	●	●	●	●	●	●	●	●	●	15 (100)/24	62.5
Alwan and Al-Waheb [39]	Iraq 2021	●	●	●	●	●	●	●	●	●	●	●	●	16 (100)/24	66.67
Madyarani et al. [43]	Indonesia 2014	●	●	●	●	●	●	●	●	●	●	●	●	16 (100)/24	66.67
Delme et al. [48]	Belgium 2008	●	●	●	●	●	●	●	●	●	●	●	●	17 (100)/24	70.83
Delme et al. [49]	Belgium 2010	●	●	●	●	●	●	●	●	●	●	●	●	16 (100)/24	66.67
Corona et al. [51]	Brazil 2005	●	●	●	●	●	●	●	●	●	●	●	●	13 (100)/24	54.1
Dissenha et al. [42]	Brazil 2016	●	●	●	●	●	●	●	●	●	●	●	●	16 (100)/24	66.67
Mello et al. [50]	Brazil 2006	●	●	●	●	●	●	●	●	●	●	●	●	13 (100)/24	54.1
Deshpande et al. [40]	India 2021	●	●	●	●	●	●	●	●	●	●	●	●	17 (100)/24	70.83
Gupta et al. [47]	India 2012	●	●	●	●	●	●	●	●	●	●	●	●	15 (100)/24	62.5
Arthilakshmi et al. [41]	India 2018	●	●	●	●	●	●	●	●	●	●	●	●	16 (100)/24	66.67
Diwanji et al. [45]	India 2014	●	●	●	●	●	●	●	●	●	●	●	●	15 (100)/24	62.5
Pavuluri et al. [46]	India 2014	●	●	●	●	●	●	●	●	●	●	●	●	12 (100)/24	50.0

Risk of bias: low (green), moderate (yellow), or high (red). (1) Clearly stated aims and objectives, (2) detailed explanation of sample size calculation, (3) detailed explanation of sampling technique, (4) details of comparison group, (5) detailed explanation of methodology, (6) operator details, (7) randomization, (8) method of measurement of outcome, (9) outcome assessor details, (10) blinding, (11) statistical analysis, (12) presentation of results.

4. Discussion

The use of GICs in posterior teeth has traditionally been limited by their physical properties [6]. The new GIC restorative materials have improved some of their mechanical properties without reducing their ion release [54]. This improvement could make them suitable in certain clinical situations, such as the restoration of primary teeth [55], cervical restorations [56], and teeth affected by molar incisor hypomineralization [57], among others. A recent systematic review and meta-analysis stated that high-viscosity GICs are comparable to composite resins for posterior restorations at least for 3 years, especially in patients at high risk of caries [58].

4.1. Study Methodology

Standardized and updated guidelines must be followed when performing in vitro studies [59]. Variations in the sample preparation methods could alter the results obtained. For example, bovine and swine substrates allow higher marginal leakage than human substrates [60]. Therefore, to maintain consistency in the findings, animal teeth studies were excluded from this study to reduce methodological heterogeneity. The use of human substrates was considered more relevant to the study's objectives, and this decision contributes to the consistency of the results. Furthermore, primary teeth differ from permanent ones because they have thinner enamel, dentin, and longer pulp horns [40]. Therefore, the qualitative results were synthesized into two parts, primary and permanent teeth, to analyze the difference in the results.

Determining the appropriate sample size is crucial for achieving scientifically and statistically valid outcomes [61]. It is worth noting that among the studies reviewed, there was a lack of reporting or incomplete reporting of sample size calculations, and only two reported calculating the necessary sample size for the teeth used [40,41]. Additionally, two studies with small sample sizes produced different results from other included studies and demonstrated no statistical differences in their outcomes [43,51]. However, inadequate sample sizes can compromise the ability to detect differences between groups, leading to potentially falsely adverse outcomes and an elevated risk of a type II error [62].

The results of microleakage studies can be affected by cavity design. Notably, the U-shaped Class V cavity demonstrated superior performance in minimizing microleakage compared to the V-shaped design [63], a finding not mentioned in the studies.

Penetration may also be affected by the chosen dye material, the dye material's concentration and diffusion coefficient, the dentin's thickness, and the dentin's available surface area for diffusion [63]. For example, rhodamine B dye has a molecular size smaller than the diameter of a dentinal tubule. It presents greater diffusion on human dentin than methylene blue, resulting in a higher leakage score [47]. The tested teeth were immersed in dye material for 24 h in all selected studies except for one study, in which the sample was immersed in 2% methylene blue dye for 4 h [43].

Thermocycling is a widely used method in laboratory dental studies to simulate temperature changes in the oral environment. The International Organization for Standardization (ISO) recommends thermal cycling between 5 and 55 °C as an accelerated aging test [64]. Accordingly, most authors chose cycling temperatures between 5 and 55 °C except in one study by Madyarani et al. [43], where no thermocycling was applied. Concerning the methods used to detect microleakage, the authors opted for semi-quantitative assessment by different scores and quantitative assessment as a percentage in millimeters, allowing for precise measurements of the extent of leakage. The microleakage assessment using stereomicroscope methods featured high intra- and inter-examiner reproducibility levels [64]. However, a few studies referenced the level of inter-examiner agreement [39,40,42,45,48], indicating almost perfect inter-examiner reliability.

4.2. Study Results

The decrease in microleakage observed in RMGIC compared to conventional GIC could be attributed to differences in their setting reactions. In conventional GIC, if it encounters intraoral fluid during the initial setting, the matrix-forming ions (Ca and Al) may be washed out, resulting in improper matrix formation with inferior mechanical properties and increased microleakage. In contrast, RMGIC undergoes two setting processes: acid-base reaction and photopolymerization. In this process, hydroxyl ethyl methacrylate partially replaces water. The structure of RMGIC includes a matrix of metal polyacrylate salts and a polymer matrix. Consequently, RMGICs are generally considered less affected by moisture, exhibiting reduced microleakage compared to conventional GICs [41].

However, Hallet and Garcia-Godoy [52] also concluded that Fuji II LC performed worse than Fuji II at the enamel margin but was comparable at the dentin cementum margin. However, in the same study, Photac Fil showed a significantly more reliable seal than Ketac

Fil at both the occlusal and gingival margins. The authors proposed that this could be attributed to the encapsulation of ESPE materials (Photac Fil and Ketac Fil). Meanwhile, the Fuji II LC and Fuji II were not encapsulated, and individual hand proportions and mixing can affect the results.

Nano-filled RMGIC (Ketac N100) is a new RMGIC that was introduced in 2007. Two studies [45,47] performed on permanent teeth provided valuable insights on the performance of Ketac N100 compared to conventional GICs and other RMGICs. However, the study by Diwanji et al. [45] observed that there was no significant difference between the Fuji LC II and KN100 in Class I restoration. In contrast, a significant difference was obtained in Class V restorations. These results are consistent with those obtained by Gupta et al. [47], who found that Ketac N100 showed less leakage than conventional GIC and RMGIC at gingival margins. This could be due to smaller particle sizes providing better material flow and better adaptation to the tooth interface; also, the higher filler loading in the nano-filled type may result in lower polymerization shrinkage and a lower coefficient of thermal expansion, thus improving long-term bonding to the tooth structure. Additionally, the incremental layer technique used to place Ketac N100 may have further improved adaptation, leading to Ketac N100 showing less leakage and better performance than conventional GICs and other RMGICs.

The manufacturer and some authors refer to Activa Bioactive Restorative as a bioactive composite [65–67], but others consider it an RMGIC [27,68]. The components of Activa Bioactive Restorative are a proprietary bioactive ionic resin, a proprietary rubberized resin, and a bioactive glass ionomer; therefore, it was included in our research. We found only one study [27] that compared it with the GIC Equia Fil and the RMGIC Fuji II LC and demonstrated that they exhibited the same marginal adaptation and microleakage.

Carbomer Glass Fil is a new material that consists of nanosized hydroxyapatite–fluorapatite particles in powder form. Only one study evaluating permanent teeth [44] found higher microleakage and crack lines filled with dye in the glass carbomer. Despite the advantages of glass carbomer material, there is a need for improvements, particularly in its sealing capacity, for it to be considered a reliable restorative material.

Zirconomer Improved, a new restorative glass ionomer material (also called white amalgam because it combines the strength of amalgam with the biocompatibility and fluoride release of GICs), was evaluated in one study, and it was observed that they offer better leakage resistance than glass carbomer, conventional GICs, and RMGICs and might be considered as a reliable posterior restorative material, especially for patients with high caries activity [44].

Equia Forte is a glass hybrid restorative system that combines the benefits of GIC and composite resin. It is designed for anterior and posterior restorations, offering ease of use and esthetic results. The material comprises two components: a glass hybrid restorative and a nano-filled coating [69]. Alwan and Al Waheb's study [39] on primary teeth revealed that Equia Forte with nano-coating (Equia Coat) demonstrated lower microleakage than both conventional GICs and RMGICs. Nevertheless, the limited available literature on Equia Forte, carbomer Glass Fil, and Activa Bioactive Restorative makes comparing the results to others difficult.

4.3. Factors Influencing Microleakage

Coating agents have a role in the prevention of microleakage; G-Coat Plus was studied in some studies with primary [39–41] and permanent teeth [27]. Alwan and Al-Waheb [39], in their study, concluded that conventional GIC (Fuji IX) with nano-coating (G-Coat Plus) has microleakage values equal to RMGIC (Fuji II LC) without coating. These outcomes are consistent with the results of the study conducted by Arthilakshmi et al. [41], who found that conventional GIC and RMGIC without G-Coat Plus coating showed more microleakage when compared to conventional GIC and RMGIC with G-Coat Plus. These findings were also confirmed in the study by Deshpande et al. [40]. Thus, using nano-coating with all types of GICs is preferred to minimize microleakage.

The different preparation techniques in the cavity may be another factor influencing the microleakage score results. In studies using laser cavity preparation [48–50], the researchers found that RMGICs performed better than conventional GICs in conditioned cavities treated with Er:YAG laser. Scanning electron microscopy (SEM) was applied to visualize the effect of the conditioner on the lasered tooth structure. Photographs demonstrated that the edges of the cavities obtained by Er:YAG laser irradiation were irregular, wrinkled, and free of a smear layer. Based on the authors' opinions, this irregularity in cavity outlines and crater-like character free of the smear layer can improve the adhesion mechanism of GICs as it is favorable for micromechanical retention. Furthermore, conditioning is recommended to obtain a smoother surface with partial occlusion of dentinal tubules, which may improve contact between the GIC and the tooth. Pavuluri et al. also described that the chemomechanical removal of caries with Cariosolv in Class I cavities in young primary teeth did not affect the microleakage results in the GIC materials Fuji IX and Ketac N100. Furthermore, Cariosolv helps preserve dental tissue, although the clinical time is longer than when high-speed excavation is used [46].

There is weak evidence about the margin-sealing ability of GICs subjected to erosive challenges, and only one study [42] evaluated the behavior of GICs after subjecting them to Coca-Cola and orange juice. The results showed that they have a negative effect on the marginal sealing in both conventional and RMGIC materials. However, *in vitro* tests performed with composite materials have demonstrated that other variables can have a significant influence on long-term durability, such as depth of cure [70], curing type [71], and interface contamination [72]. Therefore, future studies on the influence of these factors on GICs are needed to expand our knowledge of these materials.

The results of many studies indicate that the gingival margins show more leakage than the occlusal margins. This behavior could be attributed to the fact that adhesion to enamel is stronger than dentin due to differences in morphologic, histologic, and compositional characteristics between the two because dentin has high organic and water content, low surface energy, and the presence of a smear layer [27,44,48,49].

In short, there are many factors that can affect the microfiltration of the materials, derived from the characteristics of the substrate, the conditioning of the fabrics, and the characteristics and handling of the material itself.

4.4. Limitations and Future Perspectives

The inherent laboratory nature of the included studies can serve as a limitation. *In vitro* studies do not replicate chewing load conditions or the thermal changes that occur orally. Likewise, setting conditions at a clinical level are not as controllable as in a laboratory and may affect microleakage. Due to the heterogeneity of the included studies, a meta-analysis could not be performed. Diverse materials were tested under different situations (different study groups, methodologies in manipulating the sample, primary or permanent, Class I and Class V, microleakage assessment method, and additional outcome measures). In addition, regarding newly modified GICs, only one study was included in the review for each assessed formulation, hindering the comparison of the obtained results. Therefore, *in vitro* studies and clinical trials are necessary to complete the information regarding their properties and clonal applications.

Another limitation could be the sample size of the studies included in the review, given that an adequate sample size calculation was presented in only two studies. Studies could also be influenced by reporting bias, as shown by the unfulfilled items in the quality assessment. At a review level, studies not included in the databases used could have been left out of the quality assessment.

The findings of the present systematic review represent the available evidence on the microleakage of various types of GICs in primary and permanent human teeth and may serve for future studies. Future investigations should use standardized laboratory procedures to evaluate the microleakage of newly modified GICs as restorative materials for primary and permanent human teeth in order to confirm the obtained results.

5. Conclusions

Based on the results of the in vitro studies included in the present review, Ketac N100, Equia Forte, and Zirconomer appear to exhibit less microleakage than conventional GICs and RMGICs. The use of nano-coating materials can significantly reduce microleakage in all glass ionomers. Further investigations using standardized procedures are needed to confirm the obtained results.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app14051729/s1>, Table S1: PRISMA 2020 checklist.

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