Fluoride Release by Restorative Materials after the Application of Surface Coating Agents: A Systematic Review

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Abstract: Background: Fluoride is vital in dentistry for caries prevention, enhancing remineralization, and inhibiting bacteria. Incorporating fluoride into restorative materials like glass-ionomer cements, compomers, and giomers has significantly increased fluoride availability in the oral cavity. This review assesses how surface coatings influence fluoride release from various dental restorative materials. Methods: In December 2023, we conducted electronic searches in PubMed, Scopus, and Web of Science (WoS) databases. In the Scopus database, the results were refined to titles, abstracts, and keywords, while in PubMed, they were narrowed down to titles and abstracts. In WoS, the results were refined only to abstracts. The search criteria were based on the terms fluoride AND release AND (coating OR glaze OR layer OR film OR varnish) AND (composite OR glass OR compomer), following PRISMA guidelines and the PICO framework. Twenty-three studies were rigorously selected and analyzed for fluoride release from coated versus uncoated materials. Results: Surface coatings typically reduce the rate of fluoride release. Glass-ionomer cements had the highest release, followed by giomers and compomers. The initial release was greater in uncoated materials but stabilized over time, influenced by variables like artificial saliva and deionized water. Conclusions: Surface coatings generally decrease fluoride release rates from dental materials. Although initial rates are high, contributing to caries prevention, more standardized research is needed to better understand the impact of coatings and optimize materials for maximum preventive benefits.

Keywords: composite; compomer; film; glass ionomer; glaze; layer; varnish

1. Introduction

Fluorine is a light-yellow gas that, due to its high chemical activity, is not freely available in nature. The main sources of fluoride in the daily diet are water, tea, cereal products, leafy vegetables, nuts, fish, and potatoes [1]. The incorporation of fluoride in public health measures, such as water fluoridation and the use of fluoride toothpaste, has significantly reduced the prevalence of dental caries in many parts of the world. Fluoride works by promoting the remineralization of tooth enamel and inhibiting the demineralization process. It also has antibacterial properties that help reduce the levels of harmful oral bacteria [2].
However, excessive fluoride intake during tooth development can lead to dental fluorosis, a condition characterized by discoloration and the mottling of the enamel. Dental fluorosis ranges from mild forms, which present as white spots on the teeth, to severe forms that result in brown stains and surface pitting. While mild fluorosis does not typically affect oral health-related quality of life, severe cases can lead to aesthetic concerns and social discomfort [3]. Fluoride is considered the key component of caries prevention. It limits the impact of cariogenic bacteria by extenuating the production of acids and the deposition of bacterial plaque on tooth surfaces and holding back the metabolic transformation of carbohydrates in bacterial cells. It inhibits demineralization by the constant presence of low concentrations of fluoride ions, enabling the repositioning of mineral compounds lost during repeated acid attacks with the formation of fluoroapatite crystals that are less susceptible to dissolution. It supports and accelerates remineralization by providing higher concentrations of fluoride ions, which ensure the formation of calcium fluoride (CaF2), which is a reservoir of fluoride ions released during the action of acids on the enamel [4].

By leveraging the therapeutic role of fluoride, manufacturers of materials used in restorative dentistry have introduced a wide range of products that influence the increase in fluoride concentration in the oral cavity. Starting with conventional glass-ionomer cements (CGICs), progressing through compomers and giomers, and ending with composites coated with a fluoride-containing binding component. Glass-ionomer cements used in dentistry for over 30 years have undergone numerous changes and enhancements. CGICs consist of a liquid and a powder containing a fluoro-alumino-silicate glass filler, which serves as a base containing fluoride. The liquid contains acrylic acid or its copolymers with a possible content of aliphatic polycarboxylic acids. There are also water-activated glass-ionomer cements (WAGICs) that have the addition of an acidic polymer in powder. Upon mixing with water, an acid–base reaction occurs, influencing the material’s hardening [5–7]. These cements have the ability to replenish the pool of fluorides from the environment, acting as a fluoride reservoir and ensuring long-term fluoride release [8].

Compomers are another type of restorative material that combines the advantages of composites and glass ionomers [9]. In the latest versions of this product, silicon–calcium–aluminum–fluoride glass particles (42–67% by volume) are embedded in a conventional methacrylate matrix. This material hardens through two types of reactions: polymerization and acid–base reaction [10,11]. These materials exhibit high aesthetics and fluoride-releasing capabilities, albeit to a lesser extent than CGICs [12]. In turn, hybrid materials derived from glass ionomers and composites are also known as giomers. They contain fluoro-alumino-silicate filler particles that have undergone a prior (partial or complete) reaction with polyacrylic acid, known as pre-reacted glass-ionomer filler (PRG) technology [8,13]. Giomers demonstrate superiority over compomers in terms of releasing a greater amount of fluoride and absorbing more from the oral cavity environment [14,15].

Coatings that prevent the development of caries and strengthen filling materials used in modern dentistry include varnishes; resins; glaze; and, for example, vaseline, depending on the method used. When using fluoride varnishes, fluorine ions diffuse from the tooth coating to its surface, improving the acid resistance of the tooth surface. Applying a coating to some surfaces of filling materials allows clinicians to modify the color of the tooth/filling and its susceptibility to staining. The most important and basic purpose of using coatings is to change the surface properties of the original substrate. The main problem that arises when using various coatings, and at the same time the greatest challenge, is the issue of interaction and cooperation between the applied coating, the substrate, and the surrounding environment [16]. Despite the many advantages of using coating materials, it is also necessary to mention the downside aspect of their use, which is the negative impact on some properties of filling materials. Research shows that despite the improvement in the properties of glass-ionomer materials, e.g., their hardness, there is also a risk of a negative impact on the release and absorption of fluorine ions from the environment [17] (Figure 1).
is also a risk of a negative impact on the release and absorption of fluoride ions from the environment [17] (Figure 1).

Figure 1. Materials used in restorative dentistry.

The aim of this systematic review was to investigate the fluoride release from restorative materials subsequent to the application of surface coating agents. To date, no comparable study has been conducted. It is imperative to underscore the significance of this research area, as its thorough exploration has the potential to yield manifold benefits. Specifically, elucidating this aspect may enhance the efficacy of dental procedures, mitigate caries susceptibility, and thereby positively impact patient oral health outcomes.

2. Materials and Methods

2.1. Focused Question

This systematic review followed the PICO framework as follows [18]:

PICO question: In the case of restorative materials (population), will the addition of surface coating (investigated condition) cause a change in fluoride release (outcome) compared to restorative materials without surface coating (Comparison Conditions)?

2.2. Protocol

The article selection process for this systematic review was meticulously outlined according to the PRISMA flow diagram (see Figure 2).
2.3. Eligibility Criteria

All studies included in this systematic review had to meet the following criteria: They had to investigate fluoride release by dental materials, explore fluoride release with different coating materials, and be published in English with no restrictions regarding the date of publication. The reviewers established the following exclusion criteria: studies in non-English languages, clinical reports, opinions, editorial papers, review articles, and studies without a full-text version available [20–23].

2.4. Information Sources, Search Strategy, and Study Selection

In December 2023, we conducted electronic searches in PubMed, Scopus, and Web of Science (WoS) databases. In the Scopus database, the results were refined to titles, abstracts, and keywords, while in PubMed, they were narrowed down to titles and abstracts. In WoS, the results were refined only to abstracts. The search criteria were based on the terms fluoride AND release AND (coating OR glaze OR layer OR film OR varnish) AND (composite OR glass OR compomer), following PRISMA guidelines and the PICO framework. The search parameters were constrained to studies meeting eligibility criteria. Additionally, a supplementary literature search was conducted to identify any articles not captured during the initial database search. Only articles with full-text versions were included in the analysis.

2.5. Data Collection and Data Items

Seven reviewers (J.K., J.K., M.S., O.T., D.T., T.D., and W.D.) diligently selected the articles that fulfilled the previously established criteria. The essential data were then compiled into a standardized Excel file.
2.6. Assessing Risk of Bias in Individual Studies

During the initial stage of study selection, the authors independently reviewed the titles and abstracts of each study to minimize potential reviewer bias. The level of agreement among reviewers was assessed using Cohen’s \( \kappa \) test [24]. Any discrepancies regarding the inclusion or exclusion of a study were resolved through discussions between the authors.

2.7. Quality Assessment

Two independent assessors (J.M. and M.D.) conducted an evaluation of the procedural quality for each study included in the article. The criteria used to evaluate study design, implementation, and analysis included research conducted on molds, differentiation of materials used, use of artificial saliva, usage of fluoride ion electrodes, adherence to manufacturer’s instructions for material use, and frequency of checkups (hours/days cycle). Studies were scored on a scale of 0 to 6 points, where a higher score indicated better study quality. The risk of bias was categorized as follows: 0–2 points denoted a high risk, 3–4 points denoted a moderate risk, and 5–6 points indicated a low risk. Any discrepancies in scoring were resolved through discussion until a consensus was reached [25–31].

3. Results

3.1. Study Selection

The initial search of the electronic databases generated 645 records. Subsequently, 261 duplicates were identified and removed, leaving 384 unique records for abstract screening. Following the process, 69 articles were excluded based on abstracts, which resulted in 27 articles remaining for full-text evaluation. Three articles were excluded due to the unavailability of full-text versions, and one was removed because of failure to meet predefined inclusion criteria. This culminated in a final selection of 23 articles for both qualitative and quantitative analyses.

3.2. General Characteristics of the Included Studies

The overarching objective of the included studies was to assess the fluoride release capabilities of various dental materials, encompassing glass-ionomer cements [17,32–53], resin-based composites [34,38,40,41,45,47], giomers [33,36,40,45], bioactive glass [35], and compomers [48] under different conditions. These conditions included the application of surface coatings [17,32,37,40,43,44,46,53], bonding agents [38–41,46–48], fluoride varnishes or concentrated gels [32–35,39,45], nail varnishes [49,50], and resin liners [31]. Additionally, two studies aimed to assess the reabsorption capabilities and the impact of fluoride release [17,34]. Methods varied across studies but typically involved preparing in vitro samples of dental materials under study conditions. Twenty-two studies utilized molds [17,32–44,46–53], applying different surface coatings, and then immersing them to create an experimental medium in solutions that simulated various oral environments, including the effects of brushing, saliva substitutes, and varying pH levels.

Various types of solutions were utilized, such as deionized water [17,32,34,35,37–41,43–46,48,49,51–53] in eighteen studies, synthetic saliva [33,39,47] in three studies, acetate buffer [43,51] and remineralizing solution [47,50] in two studies, and lactic acid solution [36], deionized water containing hydroxyapatite [39], maleic acid–KOH buffer [48], 5% sucrose solution [47], and amine fluoride gel [47] in one study each. Techniques for fluoride measurement commonly included the use of ion-selective electrodes [17,32–35,37–41,43,45–49,51–53] in twenty studies, ion analyzers [32–35,38–41,43,45,49,52] in twelve studies, pH meters [17,37,51,53] in four studies, and gas–liquid chromatography in one study [50]. In twenty-two studies [17,33–53], there were hours/days cycles of multiple checkups. Notably, in twenty articles [17,32–36,38–40,43–53], the materials were used according to the manufacturer’s instructions.

The results revealed a broad spectrum of fluoride release behaviors influenced by material composition, surface coating, and environmental conditions. Overall, uncoated samples exhibited higher fluoride release compared to coated samples across all cases [17,32–53].
Glass-ionomer cements typically exhibited higher fluoride release compared to other materials [33,34,38,40,41,46,49]. Surface coatings, such as varnishes and resins, generally reduced fluoride release, although the extent of reduction varied depending on the material and type of coating. The initial fluoride release was typically higher but decreased over time. Additionally, studies explored fluoride recharging abilities and the impact of external fluoride sources, such as toothpaste and varnish, revealing their potential to enhance fluoride release from dental materials [33,34] (see Supplementary Table S1).

3.3. Main Study Outcomes

The objective of this study was to assess the fluoride release of different materials, after applying a coating agent. The findings across studies revealed diverse outcomes. Various materials and coatings were used to measure the amount of the cumulative fluoride ions released. In most papers, the most frequently examined material is glass ionomer [17,32–53], while the next common material is composite [34,38,40,41,45,47]. In four studies, giomers were mentioned [33,36,40,45], two studies analyzed compomers [38,48], and only one study was conducted on bioactive glass [46].

In terms of a system to check the amount of released fluoride, SEM analysis was used, in addition to a fluoride ion-selective electrode type 96-09 (Boston, MA, USA) and a microprocessor analyzer ORION EA 940 (Orion Res Inc., Salt Lake City, UT, USA).

Nevertheless, twelve papers [32,38–45,47,48,53] provided a clear answer, affirming that uncoated materials presented significantly greater fluoride release in comparison with coated specimens. In those articles [52], it was noted that even high fluoride release and neutralization capacity are unable to stop secondary caries around the fillings.

In one article, the authors stated that freshly set glass ionomer released the highest number of fluoride ions, which decreased every 24 h till day 21st [43]. In another study, we found data indicating that sealant emission led to the highest fluoride ion release during the first day, which then steadily decreased until the fifteenth day [33] (see Table 1).

Table 1. Detailed characteristic table.

<table>
<thead>
<tr>
<th>Study</th>
<th>Studied Material</th>
<th>Type of Coating (Composition)</th>
<th>Experimental Medium</th>
<th>Fluoride Release Measurement Technique</th>
<th>Length of Measurement Period</th>
<th>Amount of Cumulative Fluoride Ion Released (Coated vs. Non-Coated Specimen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rajić et al. [32]</td>
<td>Glass ionomer</td>
<td>1. Equia Forte Coat (EC) (low-viscosity monomer methyl methacrylate, phosphoric acid ester monomer, and photoinitiator)</td>
<td>Deionized water</td>
<td>A fluoride ion-selective electrode type 96-09 (Boston, MA, USA) and a microprocessor analyzer ORION EA 940 (Orion Res Inc., USA)</td>
<td>64 days</td>
<td>Equia + EC (66.01 mg/L) &lt; EQUIA + VC (123.54 mg/L) &lt; EQUIA non-coated (203.22 mg/L)</td>
</tr>
<tr>
<td>Senthilkumar et al. [33]</td>
<td>GIS (Fuji VII), 1. GIS (Fuji VII), 2. resin sealant (Voco Twinkys star), 3. Giomer sealant (Shofu Beautisealant),</td>
<td>1. Cheerio gel fluoride toothpaste 2. GC Fuji Fluoride Varnish</td>
<td>Synthetic saliva (pH 5.3).</td>
<td>An expandable ion analyzer and a fluoride ion selective electrode</td>
<td>30 days</td>
<td>After 30 days: 1) (Sealants with toothpaste) giomer &gt; GIS &gt; resin sealant 2) (sealants with varnish) GIS &gt; giomer &gt; resin sealant 3) Without toothpaste and sealant GIS &gt; giomer &gt; resin sealant</td>
</tr>
</tbody>
</table>
Table 1. Cont.

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<tr>
<td>Poggio et al. [34]</td>
<td>1. Fuji Triage (glass-ionomer cement)  2. Fissurit FX (composite resin) 3. Grandio Seal (composite resin)</td>
<td>1. Profluorid Varnish (varnish) 2. MI Paste Plus (varnish)</td>
<td>Deionized water</td>
<td>Combination of fluoride electrode (Orion GP 1 S/N 13824, Orion Research, Inc., Boston, MA, USA) connected to an expandable ion analyzer (Orion 720A, Orion Research Inc., Boston, MA, USA).</td>
<td>84 days</td>
<td>The GIC-based sealant Fuji Triage/GC &gt; Fissurit FX/Voco &gt; Grandio Seal/Voco. The sealants tested were significantly more recharged by exposure to the fluoridated varnish (Profluorid Varnish) than by the CPP-ACPF toothpaste (MI Paste Plus).</td>
</tr>
<tr>
<td>Nassar et al. [35]</td>
<td>1. GC Fuji IX, GC America, Alsip, IL, USA (P9) 2. 3M ESPE Ketac-fil Plus Aplicap, 3M, St. Paul, MN, USA (KF)</td>
<td>1. Fluoride slurry 2. Fluoride varnish</td>
<td>Deionized water</td>
<td>Fluoride electrode (Orion Research, Inc., Boston, MA, USA) connected to an ion analyzer</td>
<td>-</td>
<td>3M ESPE Ketac-fil Plus Aplicap &gt; GC Fuji IX. The varnish-coated groups generally exhibited higher fluoride release compared to the non-varnish groups.</td>
</tr>
<tr>
<td>Par et al. [36]</td>
<td>The fillers for experimental composites: inert glass, silica, and two types of Bioactive Glass (BG): The conventional BG 45S5 formulation The low-Na F-containing BG 3 commercial restorative materials: Gicmer (Beautifil II, Shofu, Kyoto, Japan; shade: A2, LOT: 041923), Reinforced glass-ionomer (ChemFil Rock, Dentsply Sirona, Konstanz, Germany; shade: A2, LOT: 190300819), “alkasite” material (Cercon, Ivoclar Vivadent, Schaan, Liechtenstein; shade: universal, LOT: XL7102).</td>
<td>No data</td>
<td>Lactic acid solution of pH = 4.0</td>
<td>No data</td>
<td>32 days</td>
<td>No data</td>
</tr>
<tr>
<td>Tiwari et al. [37]</td>
<td>1. Hydroxyapatite Glass-ionomer Cement (HA-GIC): This was created by replacing 8 weight percent of conventional glass-ionomer with hydroxyapatite powder (HA), mixed with polyacid liquid.</td>
<td>No data</td>
<td>Distilled water</td>
<td>Combination ion-selective electrode (ISE) from HACH Company with Sension4 pH/ISE/MV Laboratory Meter.</td>
<td>21 days</td>
<td>Materials that were not coated released more fluorine.</td>
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</tbody>
</table>
### Table 1. Cont.

<table>
<thead>
<tr>
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</tr>
</thead>
</table>
| Pamir et al. [38]            | 1. Hytac Aplitip (polyacid modified resin composite)  
2. Ketac-fil (Conventional glass-ionomer cement)  
3. Photac-fil (Resin-modified glass-ionomer cement)  
4. Ecusit (resin composite)  
5. Ariston pHc (fluoridated resin composite) | Prompt L-Pop (Fluoridated adhesive) | Deionized water     | Combination fluoride ion-selective electrode (Orion 96-09 BN) connected to an ion analyzer (Orion Bench Top pH/ISE Meter, 720 A Model). | 28 days | Uncoated materials after 28 days:  
Ariston pHc > Photac-fil > Ketac-fil > Hytac Aplitip > Ecusit  
Uncoated materials after 1 day:  
Ketac-fil > Photac-fil > Ariston pHc > Hytac Aplitip > Ecusit  
Coated materials after 28 days:  
Ketac-fil > Photac-fil > Ariston pHc > Hytac Aplitip > Ecusit |
| Hattab et al. [39]           | 1. conventional glass-ionomer Ketac-Fil (KF; ESPE, Seefeld/Oberbay, Germany)  
2. conventional glass-ionomer Fuji II (FJ; G-C Dental Industrial Corp., Tokyo, Japan)  
3. cermet Ketac-Silver (KS; ESPE, Seefeld/Oberbay, Germany)  
1. Varnish  
2. light-cured bonding resin (Visio-bond)  
1. Deionized Water  
2. Artificial saliva (pH was adjusted to 5.5).  
3. Deionized water containing hydroxyapatite. | 1. Deionized Water  
2. Artificial saliva (pH was adjusted to 5.5).  
3. Deionized water containing hydroxyapatite. | 28 days | F-specific electrode (Model 96-09-00, Orion Research Inc., Cambridge, MA, USA) coupled with microprocessor ion analyzer (Orion model 901). | Non-coated: FJ (405 g/cm) > KF (391 g/cm) > KS (132 g/cm)  
Coated with Varnish: KF: Reduction in fluoride release by 74.6%  
KS: Reduction in fluoride release by 65.0%  
FJ: Reduction in fluoride release by 51.1%  
KS: Reduction in fluoride release by 44.0%  
Deionized water: Higher fluoride release rates were observed in deionized water, initially rapid, then stabilizing to near-zero order kinetics after two weeks.  
Artificial saliva: Fluoride release in artificial saliva was significantly lower than in deionized water, with a similar pattern but stabilizing earlier. |
| Kelić et al. [40]            | 1. Beautifil II (BF) Giomer  
2. Cention (CN) Alkasite  
3. Fuji IX Extra (FUJ) Glass ionomer  
2. Clearfil Universal Bond Quick (CB) Universal fluoride-releasing adhesive  
3. GC Fuji Coat LC (FC) Glass-ionomer coat | Deionized water | An ion-selective electrode Orion 9609BNWP was connected to an Expandable Ion Analyzer EA 940 (Orion Research, Beverly, MA, USA) | non coated: FUJ > CN > BF  
Materials treated with GB > Materials treated with CB  
FIL emitted fluoride only with the fluoride-emitting adhesive CB. FUJ, on the other hand, exhibited a notable fluoride release increase over time, with uncoated samples releasing 30 times more fluoride than those coated with FC. |
<table>
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<tbody>
<tr>
<td>Mazzaoui et al. [41]</td>
<td>1. Ketac-Molar</td>
<td>Aplicap (capsulated self-cured glass ionomer)</td>
<td>Floride ion electrode (Orion research electrode, Orion Research Inc., Boston, MA, USA) connected to an ion analyzer (Ion 85 Radiometer, Copenhagen, Denmark)</td>
<td>28 days</td>
<td>Ariston pHc (uncoated) = 85.4 ppm &gt; Photac-Fil (uncoated) = 58.0 ppm &gt; Ketac-Molar (uncoated) = 41.1 ppm &gt; Ketac Molar (coated) = 24.1 ppm &gt; Fuji II LC (uncoated) = 26.9 ppm &gt; Fuji IX GP (uncoated) = 24.4 ppm &gt; Photac-Fil (coated) = 12.5 ppm &gt; Fuji IX GP (coated) = 9.9 ppm &gt; Fuji II LC (coated) = 6.6 ppm &gt; Ariston pHc (coated) = 3.3 ppm &gt; Solitaire (uncoated) = 2.3 ppm &gt; Solitaire (coated) = less than 0.2 ppm</td>
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<td>2. Fuji IX GP</td>
<td>(capsulated self-cured glass ionomer)</td>
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<td>3. Fuji II LC</td>
<td>(capsulated resin-modified glass ionomer)</td>
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<td>4. Photac-Fil</td>
<td>(capsulated resin-modified glass ionomer)</td>
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<td></td>
<td>5. Ariston pHc</td>
<td>(Light-cured resin composite)</td>
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<td></td>
<td>6. Solitaire</td>
<td>(light-cured resin composite)</td>
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<tr>
<td>Ariffin et al. [42]</td>
<td>1. Fuji IX</td>
<td></td>
<td>1. deionized distilled water (DDW)</td>
<td>Fluoride-specific ion electrode (Orion, USA)</td>
<td>9 days</td>
<td>Vitrebond (uncoated) &gt; Fuji VII (uncoated) &gt; Fuji IX (uncoated) &gt; Vitrebond + AgF (coated) &gt; Fuji VII + AgF (coated) &gt; Fuji IX + AgF (coated) In this summary, uncoated Vitrebond exhibited the highest cumulative fluoride release, followed by Fuji VII and Fuji IX. With the application of a 10% AgF coating, there was an increase in fluoride release, but the release patterns varied, with Vitrebond + AgF eventually reaching almost the same levels of cumulative release as the uncoated GIC versions.</td>
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<td></td>
<td>2. Fuji VII</td>
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<td>2. acetate buffers (pH 3, 5, 7)</td>
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<td>3. Vitrebond</td>
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<tr>
<td>Rekhlahshimi et al. [44]</td>
<td>Fuji II (Conventional GIC)</td>
<td>1. Cavity Varnish</td>
<td>Distilled water</td>
<td>Combination of fluoride electrode (Orion 9609BN, Orion Research Inc) and an ion analyzer (Orion EA 940, Orion Research Inc)</td>
<td>15 days</td>
<td>Glass-ionomer cement uncoated &gt; glass-ionomer cement coated with petroleum jelly &gt; Glass-ionomer cement coated with varnish</td>
</tr>
<tr>
<td>Kelic et al. [45]</td>
<td>1. Alkasite composite (Cention)</td>
<td>1. Universal Adhesive System (G-aenial Bond)</td>
<td>Deionized water</td>
<td>Deionized water</td>
<td>168 days</td>
<td>Cention non-coated &gt; Beautiful II non-coated &gt; Fuji IX Extra non coated &gt; Filtek Z250 non coated &gt; Cention coated Clearfil Bond &gt; Beautiful II (coated) &gt; (Fujix IX Extra) (coated) &gt; Filtek Z250 (coated)</td>
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<tr>
<td></td>
<td>2. Giomer (Beautifil II)</td>
<td>2. Glass-ionomer coat (GC Fuji Coat LC)</td>
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<td></td>
<td>3. Conventional glass-ionomer cement (GIC) (GC Fuji IX Extra)</td>
<td>3. Universal Fluoride-Releasing Adhesive System (Clearfil Universal Bond Quick)</td>
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<td>4. Conventional composite (Filtek Z250)</td>
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<td>Study</td>
<td>Studied Material (Composition)</td>
<td>Experimental Medium</td>
<td>Fluoride Release Measurement Technique</td>
<td>Length of Measurement Period</td>
<td>Amount of Cumulative Fluoride Ion Released (Coated vs. Non-Coated Specimen)</td>
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<td>Wang et al. [46]</td>
<td>Vitremer (P: Fluoro-aluminosilicate glass, potassium persulphate, ascorbic acid)</td>
<td>1. demineralizing solution (Ca 2.0 mM, PO4 2.0 Mm, and acetate buffer 75 mM, pH 4.3, containing Na N3 0.02%)</td>
<td>Ion-specific electrode (Orion Research, Cambridge, MA, USA, model 9609)</td>
<td>15 days</td>
<td>Coated with Vitremer Primer &gt; non-coated &gt; coated with Single Bond &gt; coated with Prime and Bond 2.1 Groups coated with Vitremer Primer and Non-Coated released a greater amount with no statistical differences in all periods ($p &gt; 0.05$).</td>
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<td>Seppä et al. [47]</td>
<td>1. Ketac-Fil Aplicap®  2. Fuji II LC®  3. Vitremer®  4. Silux Plus</td>
<td>1. Distilled water  2. maleic-acid-KOH buffer,  3. 5% sucrose solution  4. amine fluoride gel (Elmex Gel)</td>
<td>Fluoride-specific electrode (Orion 960 Autochemistry-system, Orion Research, Boston, MA, USA).</td>
<td>29 days</td>
<td>Ketac-Fil (initially)—highest fluoride release at the beginning but diminishes over time. Vitremer (after 29 days)—fluoride release still high after aging, higher than other materials. Fuji II LC—lower fluoride release compared to Vitremer after aging.</td>
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<td>Exterkate et al. [49]</td>
<td>1. Fuji II LC, a conventional GIC  2. Experimental GIC, RK-141  3. Non-fluoride-releasing disc of polymethylmethacrylate (Vertex)</td>
<td>Nail varnish</td>
<td>1. Remineralization Buffer: Composed of 1.5 mmol/L CaCl2, 0.9 mmol/L KH2PO4, 130 mmol/L KCl, and 20 mmol/L HEPES at pH 7.0.  2. 1 mL 1 mol/L KOH for 24 h  3. 1.5 mL 0.4 mol/L HCl for 1 h  4. 5 mL 4 mol/L HCl</td>
<td>10 weeks</td>
<td>Experimental GIC &gt; Conventional GIC</td>
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<td>Iota et al. [50]</td>
<td>1. Lining cement (LC) (FASG, polyacrylic acid, etc.)  2. RK-141A (FASG, polyacrylic acid, etc.)</td>
<td>1. Resin liner containing 5 wt% NaF (RF) (bis-GMA, TEGDMA, NaF, etc.)  2. Resin liner without fluoride (bis-GMA, TEGDMA, etc.)</td>
<td>Fluoride-specific electrode attached to an ion meter</td>
<td>10 weeks</td>
<td>Highest: RF—268.0 ppm (1 week), 450.6 ppm (5 weeks), and 525.2 ppm (10 weeks) LC—54.4 ppm (1 week), 130.4 ppm (5 weeks), and 176.6 ppm (10 weeks) RK—50.2 ppm (1 week), 154.0 ppm (5 weeks), and 230.8 ppm (10 weeks).</td>
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Table 1. Cont.

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<tr>
<th>Study</th>
<th>Studied Material</th>
<th>Type of Coating (Composition)</th>
<th>Experimental Medium</th>
<th>Fluoride Release Measurement Technique</th>
<th>Length of Measurement Period</th>
<th>Amount of Cumulative Fluoride Ion Released (Coated vs. Non-Coated Specimen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castro et al. [51]</td>
<td>1. Ketac-Fil Aplicap 2. Variglass</td>
<td>1. Visibond (ESPE-Premier) 2. Scotchbond II LC Dental Adhesive (3M Dental Products, St Paul, MN) 3. Ketac Varnish (ESPE-Premier)</td>
<td>Fluoride-free distilled water</td>
<td>Combination Fluoride Electrode and an Orion Digital Ionometer (Orion Research Inc., Cambridge, MA 02139, USA)</td>
<td>4 weeks</td>
<td>Non-coated &gt; Visibond (57% of the non-coated group) &gt; Scotchbond (39% of the non-coated group) &gt; Variglass (37% of the non-coated group) &gt; Ketac varnish (26% of the non-coated group)</td>
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<td>Iota et al. [52]</td>
<td>Experimental dental resin-based material, which included a filler made of fluoro-boro-alumino-silicate glass</td>
<td>3-Methacryloxypropyltrimethoxysilane (KBM-503, Shin-Etsu Chemical Co., Ltd., Tokyo, Japan) (MS) 2. 3-amino-npropiyl methoxyxysilane (KBM-45, Shin-Etsu Chemical Co., Ltd.) (AS)</td>
<td>Deionized water</td>
<td>fluoride-specific electrode attached to an ion meter (Model 290A, Orion Research Inc., Boston, MA, USA).</td>
<td>10 weeks</td>
<td>group AS: Highest at 1 and 10 weeks. Fluoride emission was similar for the control and MS groups; no notable difference.</td>
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</table>

3.4. Quality Assessment

The reviewers conducted a quality assessment of the 23 included studies. Nine studies were characterized by a moderate risk-of-bias scoring of 3/6 [32,37] or 4/6 [41–45,49,51] points. Furthermore, twelve studies were considered high-quality studies with a low risk of bias, scoring 5/6 [17,34–36,38,40,46–48,50,52,53] or 6/6 [33,39] points. None of the studies was excluded due to a high risk of bias. A summary of the conducted quality assessment is presented in Figure 3.

![Quality assessment chart](chart.png)

Figure 3. Quality assessment.

4. Discussion

In the present systematic review, our objective was to investigate the fluoride release by restorative materials following the application of surface coating agents. The findings of the studies indicate that the utilization of coating agents impacts the release of fluoride ions from filling materials, with coating materials demonstrating a significant reduction in fluoride ion release [17,36,37,39–41,44,45,49]. Moreover, the quantity of released fluoride ions also varied depending on the material utilized in the study. In the analyzed studies, researchers also examined how the release of fluoride ions from filling materials changed...
over time. The studies have shown that the release of fluoride ions is highest in both coated and uncoated samples in the first few days of observation and then decreases, maintaining a steady level [32,33,37,39,44,47,52]. It was also found that the use of coating agents can improve the ability of filling materials to absorb fluoride ions from the surroundings [48]. The release of fluoride ions also varied depending on the conditions in which research was carried out. The influence of deionized water, artificial saliva, or specific demineralization conditions caused the release of fluorine ions from the tested materials to be different, and the highest number of ions were released in deionized water [39]. Deionized water was the most commonly used solution in studies utilizing the fluoride ion electrode at the same time [17,32,34,35,37–41,44–46,48,49,51–53], allowing for standardization and an accurate comparison of results across these studies.

Various adhesive systems, particularly when used in conjunction with glass-ionomer cements, exert a significant influence on the fluoride release process. This suggests that certain adhesive systems may function as mechanical barriers, thereby resulting in a reduction in the quantity of fluoride released [47]. Variations in the efficacy of fluoride release are contingent upon the formulation of a particular adhesive system, encompassing factors such as its viscosity, thickness, pH, and uniformity of application. The emphasis placed on these parameters implies that, beyond the quantity of fluoride released, other inherent properties of adhesive systems are pivotal for their effectiveness within a clinical milieu. The functionality of these adhesive systems as potential barriers prompts discourse regarding their role in safeguarding tooth structure and modulating remineralization processes.

An essential facet explored in contemporary research is the influence of fluoride release on bacteria, specifically those implicated in the caries process. Numerous investigations have elucidated the capacity of fluoride emanating from diverse dental materials to impede the metabolic processes of cariogenic bacteria, thereby mitigating acidogenesis [47,50]. For example, findings from the study conducted by Seppä et al. [47] revealed substantial quantities of fluorine ions released by freshly mixed glass-ionomer cements, resulting in a marked suppression of pH decline within the liquid phase. Conversely, aged samples exhibited significantly diminished fluoride release and failed to exert any discernible impact on attenuating acid production by Streptococcus mutans. Furthermore, the application of fluoride gel induced a noteworthy augmentation in fluoride release and associated inhibitory efficacy across all the tested glass-ionomer cements. Notably, variability in the degree of inhibition was observed among different formulations of glass-ionomer cements. Nevertheless, the scientific literature consistently underscores the potential of sustained fluoride release, particularly facilitated by specialized fluoride preparations, to sustain a bacteriostatic effect [47,50]. Consequently, these findings show the potential merits of employing dental materials that not only facilitate remineralization but also actively deter bacterial proliferation within the oral milieu.

The primary limitation of this systematic review stems from the notable lack of standardized methodologies across the dental research conducted. Discrepancies in experimental conditions, including variations in the type of water utilized, the composition of artificial saliva, and specific demineralization parameters, can introduce considerable variability in outcomes. This lack of uniformity complicates the comparison and generalization of findings. Additionally, disparities in methodologies for assessing fluoride release further compound the complexity of interpreting results across studies. Hence, it is imperative to conduct further research aimed at investigating the effect of coatings on fluoride release with stringent experiment standardization. This will be instrumental in substantiating the findings obtained in various studies.

5. Conclusions

In conclusion, this systematic review focused on the fluoride release from different restorative materials both with and without coatings. The results show that coating a filling material with coatings such as bonds or varnishes tends to reduce the fluoride release, which leads to the conclusion that fluoride release is dependent only on the
filling material type. However, the fluoride released from various dental materials has demonstrated antibacterial properties, inhibiting the metabolic activities of cariogenic bacteria and reducing acid production, which is crucial for caries prevention. However, due to the lack of homogeneity of research, there is a need to conduct more accurate and heterogeneous research in order to draw more specific and thorough conclusions.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14114956/s1, Table S1: General characteristics of studies.


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**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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