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Systematic Review

Identification of Factors Influencing Fluoride Content in Tea Infusions: A Systematic Review

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Abstract: Tea is one of the most widely consumed beverages globally and a significant dietary source of fluoride. This systematic review aimed to identify and evaluate the factors influencing fluoride concentration in tea infusions. A comprehensive literature search was conducted in March 2025 across PubMed, Scopus, and Web of Science databases, following PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and the PICO framework. Eligible studies investigated fluoride release in tea infusions, published in English from the year 2000 onward. Thirty articles met the inclusion criteria, and the risk of bias in the articles was assessed using the Joanna Briggs Institute (JBI) quality checklist. Fluoride concentration in tea infusions varied widely across studies, ranging from 0.008 to over 8 mg/L. Key factors influencing fluoride release included tea type (with black and green teas showing the highest values), leaf form (powdered and bagged teas released more fluoride than loose leaves), brewing time and temperature, water composition, and the presence of additives such as spices. A longer brewing time and higher temperature consistently increased fluoride extraction. Lower pH or water hardness also significantly affected fluoride availability. Regional origin of tea and production methods were additional sources of variation. Fluoride release in tea is influenced by a complex interplay of botanical, environmental, and preparation-related factors. These findings are clinically relevant, particularly for populations at risk of fluoride overexposure. Further standardized research is needed to inform safe consumption guidelines and public health recommendations.

Keywords: beverages; fluoride; tea; infusion

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1. Introduction

Fluoride is an element commonly found in the natural environment and is classified as a microelement. It enters the human body through the digestive and respiratory tracts and, in small amounts, through the skin. The main sources are water, food, and everyday hygiene products such as toothpastes and mouthwashes [1–4]. The recommended daily intake of fluoride varies according to age and gender. It is 0.7 mg for children and 3–4 mg for

adults. These values are considered to be the adequate daily intake of fluoride. The tolerable upper intake level (UL) for adults, beyond which the risk of fluorosis increases, is 10 mg per day [2,5]. Fluoride is an element that performs important systemic and local functions in the human body [6]. It is a component of enzymes involved in the metabolism of proteins, carbohydrates, and lipids [3]. Ninety-nine percent of the fluoride absorbed by the human body is found in bones and teeth, where hydroxyapatites have been converted by the presence of fluoride into more valuable fluoroapatites and/or hydroxyfluoroapatites [1,2]. In addition, fluoride plays a very important role in dentistry as a component of an anti-caries substance [7,8]. In addition to being added to drinking water and milk, fluoride is found in everyday hygiene products such as toothpastes and mouthwashes. It is also used professionally in the form of varnishes, foams, and gels [9,10]. Its cariostatic action is based on the prevention of enamel demineralization, its remineralization (stopping caries at an early stage), and its antibacterial action. These properties have contributed significantly to the worldwide reduction in dental caries [8,9,11]. It is also worth mentioning the risks associated with overdosing on fluoride. Excess fluoride leads to enamel fluorosis, which is a disorder of the quality and/or quantity of enamel. Studies show that exceeding the daily intake of fluoride has a systemic toxic effect and, in extremely high doses, can lead to death [12,13].

Tea infusion is a beverage commonly consumed by humans. It is produced worldwide from the leaves of the *Camellia sinensis* tree. Apart from water and some foods such as fish and seafood, tea is the main source of fluoride in the human diet [3,14]. The amount of tea consumed varies depending on the region of the world and cultural habits. A 250 mL infusion can provide up to 1.5 mg of fluoride, which is a significant part of the recommended daily intake of this element [15]. Therefore, tea should be considered as a significant source of fluoride in the human diet, and it should be borne in mind that the accumulation of fluoride from all sources creates a risk of dental fluorosis, skeletal fluorosis, and chronic poisoning with this element [16]. Studies show that there is considerable variation in the fluoride content of teas. This is affected by many variables. The amount of fluoride depends on the type of tea. For example, black teas release the most fluoride into the infusion, followed by white and green teas [17,18]. Herbal products release the least fluoride [14,19]. The same type of tea may also have different fluoride levels depending on the region of origin [20]. The age of the plant has a major effect on the fluoride content of tea trees. Older specimens have been shown to have higher levels of fluoride due to the accumulation of fluoride over time. The pH of the soil in which the plant is grown is also important, as the lower the pH of the environment, the greater the deposition of fluoride in the stems and leaves [14,21]. In some regions of the world, frequent consumption of tea because of cultural behavior creates a situation in which a given population is exposed to exceeding the daily limit of fluoride intake [15,22]. This can result in dental and/or skeletal fluorosis and chronic poisoning leading to cardiac, neuro, and nephrotoxicity [13,15]. Finally, it should be noted that a person's fluoride intake from tea infusions is influenced by the concentration of fluoride in the water and by factors related to the preparation of the infusion, which affect the amount of fluoride released from the leaves [13,22,23] (see Figure 1).

The release of fluoride from tea is influenced by a multitude of factors. These factors are diverse and related to the plant itself, including its growing environment, brewing circumstances and parameters, the form of the tea, and the technique of processing the leaves and the addition of various spices. The age of the plant itself has been demonstrated to affect the fluoride concentration. Consequently, as the plant matures, the fluoride concentration increases. This assertion is corroborated by studies undertaken by Vakdevi et al., which demonstrated a higher fluoride content in older tea leaves [21].

A closer examination of the plant itself, the soil type, or more precisely, the pH level, is clear in our considerations. It has been demonstrated that elevated levels of fluoride in the foliage are associated with acidic soil [23,24]. Consequently, the level of fluoride will be elevated. The bioavailability of ions, such as fluorine and aluminum, in soil is subject to variation and correlation with its acidity. At a pH of 5.5, aluminum ions in conjunction with fluorine ions form a stable Al-F complex, which is efficiently absorbed by tea plants [25]. The region of cultivation from which tea comes also affects the fluoride concentration [26]. The form of tea has been demonstrated to influence the quantity of fluoride released. Specifically, tea bags have been found to release a higher concentration of fluoride compared to loose-leaf tea varieties during the infusion process. This phenomenon can be attributed to the utilization of older leaves in the production of tea bags [27]. A similar trend was observed in the study by Jin et al., where it was found that the use of mature leaves resulted in a higher fluoride release during the pressing process [27]. In this instance, too, older leaves are utilized, resulting in these teas exhibiting a higher fluoride concentration [24,28].

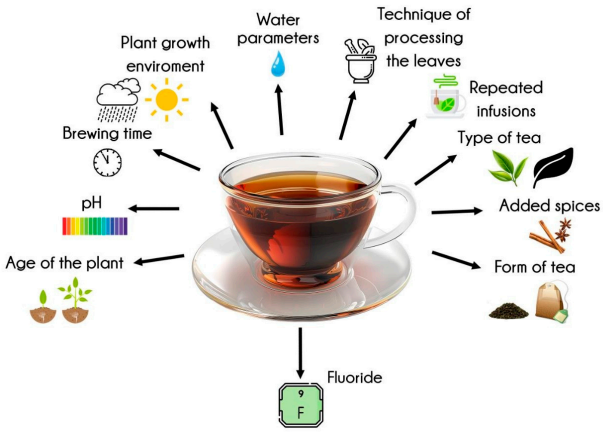

Figure 1. Factors influencing fluoride levels in tea infusions (created with Freepik.com).

The fluoride concentration is observed to vary depending on the type of tea. It is black tea in the infusion that—as a rule—contains the highest concentration of this element [19]. In descending order, green tea, Earl Grey, pu-erh, and white tea follow. Fluoride is present in trace amounts in herbal teas. Brick tea, as previously referenced, has been observed to contain elevated levels of fluoride, while white tea, in comparison to black, green, and oolong varieties, has been found to exhibit reduced levels [29]. Numerous studies have indicated a direct proportionality between brewing time and the fluoride concentration in the infusion. The concentration of fluoride in the infusion increases in proportion to the duration of the infusion process [30]. Furthermore, the repeated infusion of the same quantity of tea has been shown to increase the fluoride content [31]. Conversely, the infusion resulting from a single, continuous infusion contains a lower amount of fluoride. It has been demonstrated that multiple infusions of the same quantity of tea result in an increase in the amount of fluoride released. Of particular interest is the observation that the initial infusion of a given quantity of tea releases the greatest amount of fluoride. The extraction of fluoride ions into the infusion is influenced by the temperature of the water used for preparation, with boiling water being the standard [32]. The total fluoride content will also be influenced by the quality of the water itself. Endemic water may contain higher or lower concentrations of fluoride ions. Furthermore, it is imperative to acknowledge the significance of water treatment within the water supply network. Groundwater intakes are distinguished by their varying fluorine content [33]. It has been observed that the addition of spices, such as ginger or cloves, to the infusion can modify the amount of fluorine extracted [34].

The objective of this systematic literature review is to identify the factors influencing fluoride release from tea during infusion preparation. A comprehensive analysis of the extant literature pertaining to fluoride content measurements in infusions from diverse tea varieties, the water utilized, the spices employed, and the physical parameters of the extraction process was conducted. The findings revealed a paucity of systematic reviews addressing this subject in the literature. This constitutes a compelling rationale for the consolidation of extant scientific evidence. The present study will undoubtedly provide dietitians, medical practitioners, and, most crucially, consumers with a comprehensive framework for selecting tea as a substantial source of fluoride supplementation. A significant element of the systematic review is to ascertain the algorithms for preparing tea infusions so that the fluoride concentration is optimal. This comprehensive approach will facilitate a more profound comprehension of the entire process of fluoride extraction from tea during the preparation of the beverage.

2. Materials and Methods

2.1. Focused Question

The systematic review was conducted using the PICO framework [35], which guided the formulation of the following focused question: In the case of tea infusions (population), what are the factors (investigated condition) influencing the fluoride content (outcome) compared to infusions prepared under different conditions or with varying tea types and preparation methods (comparison condition)?

2.2. Protocol

The article selection process for this systematic review was thoroughly documented using the PRISMA flow diagram [36] (Figure 2). The review was also registered on the Open Science Framework at the following link: https://osf.io/8ayuz (accessed on 24 April 2025).

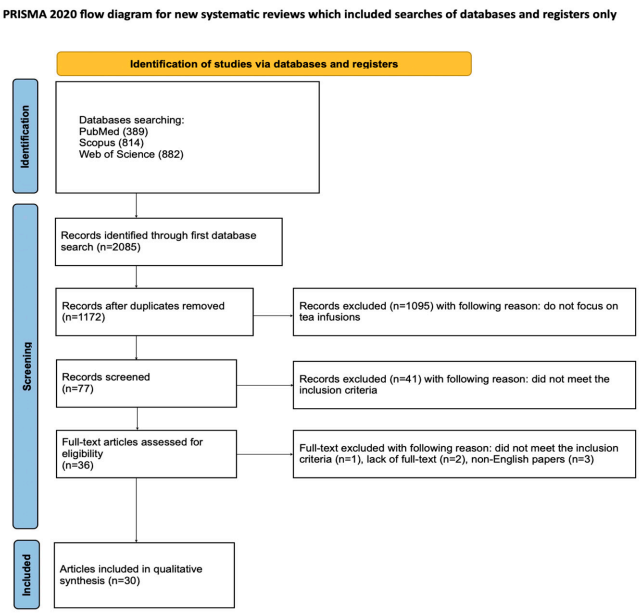

Figure 2. The PRISMA 2020 flow diagram.

2.3. Eligibility Criteria

The researchers chose to include only those articles that met the following criteria [36–44]:

- Investigation of tea infusions;
- Fluoride release evaluation;
- In vitro studies;

- Studies in English;
- Full-text articles.

The exclusion criteria the reviewers agreed upon were as follows [36–44]:

- Not a tea infusion investigation;
- Evaluation of properties other than fluoride release;
- Non-English papers;
- Systematic review articles;
- Review articles;
- Full-text not accessible;
- Duplicated publications.

Only studies published in the year 2000 or later were considered eligible for inclusion.

2.4. Information Sources, Search Strategy, and Study Selection

In March 2025, a comprehensive literature search was conducted in the PubMed, Scopus, and Web of Science (WoS) databases to find studies that matched the established inclusion criteria. To target research on factors influencing fluoride content in tea infusions, the search was restricted to titles and abstracts containing the keywords: fluoride AND tea. All results were screened based on predefined eligibility standards, and only accessible full-text articles were considered for inclusion.

2.5. Data Collection Process and Data Items

Six independent reviewers (A.M., J.K., A.K., J.K., S.K., and M.M.) carefully selected articles that met the inclusion criteria. The extracted data included the first author, publication year, study design, article title, tea infusion, and its fluoride content. All relevant information was recorded in a standardized Excel file.

2.6. Risk of Bias and Quality Assessment

During the initial phase of study selection, each reviewer independently screened the titles and abstracts to reduce potential bias. The level of inter-reviewer agreement was assessed using Cohen's k test. Any disagreements regarding article inclusion or exclusion were resolved through discussion among the authors [45].

2.7. Quality Assessment and Risk of Bias

The procedural quality of each study included in the article was independently assessed by two blinded reviewers (J.M. and M.D.) using the Joanna Briggs Institute (JBI) checklist designed for quasi-experimental studies (i.e., nonrandomized experimental studies) [46]. This tool includes nine specific questions:

- Is it clear in the study what is the 'cause' and what is the 'effect'?
- Were the participants included in any similar comparisons?
- Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?
- Was there a control group?
- Were there multiple measurements of the outcome both before and after the intervention/exposure?
- Was a follow-up completed, and if not, were differences between groups in terms of their follow-up adequately described and analyzed?
- Were the outcomes of participants included in any comparisons measured in the same way?
- Were the outcomes measured in a reliable way?
- Was an appropriate statistical analysis used?

Each question could be answered with "yes", "no", "unclear", or "not applicable". Any discrepancies between the reviewers' responses were resolved through discussion until consensus was achieved. Cohen's kappa test was performed to assess inter-rater reliability using MedCalc version 23.1.7 (MedCalc Software Ltd., Ostend, Belgium). The test results showed a kappa value of 0.87 ($p < 0.001$), indicating almost perfect agreement and high consistency among the reviewers' assessments.

The quality of each study was assessed using a 0–9 point scale, where a "Yes" response earned 1 point, and all other answers received 0 points. Studies scoring 0–3 points were considered to have a high risk of bias, those with 4–6 points had a moderate risk, and scores between 7–9 indicated a low risk of bias.

3. Results

3.1. Study Selection

The initial search of PubMed, Scopus, and WoS databases yielded 2085 potentially relevant articles. After removing duplicates, 1172 articles remained, and studies not related to tea infusions were excluded. The remaining 77 articles were screened. After an initial search of titles and abstracts, 41 articles that did not meet the inclusion criteria were excluded. Of the remaining 36 studies, full text could not be accessed for 2 studies, 3 were written in a language other than English, and one did not meet the inclusion criteria after full text analysis. Ultimately, a total of 30 articles were included in the qualitative synthesis of this review. The considerable heterogeneity of the included studies prevented the conduct of a meta-analysis.

3.2. General Characteristics of the Qualified Articles

In the eligible articles, a significant proportion of authors examined more than one type of tea [19,28,31,32,34,47–60]. Black tea was the most frequently studied, appearing in 20 articles [19,28,32,34,47,49,51,52,54–58,60–65]. Green tea was investigated in 14 studies [19,28,31,32,47,49,51,52,54–57,59,60], followed by pu-erh tea in 7 articles [19,28,51,52,55,57,66], herbal teas in 5 articles [19,31,49,55,58], and white tea in 4 articles [28,32,47,55]. Some authors additionally assessed oolong tea [52,55].

Regarding the form of tea used, 15 studies analyzed loose leaves [19,28,31,32,34,47,50–52,57,58,62,63,66,67], 12 studies assessed tea in bags [19,28,31,32,49–52,54,56,58,63], and tea powder was used in 5 studies [49,54,55,65,68]. Importantly, 11 articles compared multiple tea forms [19,28,31,32,49–52,54,58,63].

Significant differences were observed in the brewing parameters. The water temperature during brewing ranged from 60 °C [68] to 100 °C [19,28,55,66], and the brewing time varied considerably, from as short as 1 min [31,56] to as long as 24 h [31]. Only three studies reported brewing according to the ISO 3103 standard [28,63,69], whereas none declared using brewing methods strictly based on manufacturer recommendations.

Fluoride concentrations were most commonly determined using a fluoride ion-selective electrode (FISE), employed in 24 studies [19,28,31,34,49–54,56–58,60–64,66–70]. Alternative methods included ion chromatography [32,57], molecular absorption spectrometry [10,31], ion-exclusion chromatography [57], single quadrupole ICP-MS [47], and MIP-OES techniques [59].

Several studies also examined the influence of external factors on fluoride release, such as water hardness [32], the pH of the infusion [31,55,67], or the fluoride concentration in the brewing water [54,56,65]. Brewing time and water temperature consistently appeared as significant factors affecting fluoride levels [19,28,32,49,51,52,54–56,58,60,63–65,68]. In some cases, additives like milk or spices were also considered [34,50]. The general information about the included studies is demonstrated in Table 1.

Table 1. General characteristics of the included studies.

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Erdemoglu [67]	To assess how pH and time affect Al-F salt formation and how other metals influence free F content in the infusion.	The infusion was prepared by brewing 2 g tea in 100 mL deionized water, then filtered after 10 min at pH = 5. Al was measured via FAAS while free and total F were determined using FISE with ALCOA buffer to release F from complexes.	Higher pH increases free F in tea infusion. Elevated Al and F(III) concentrations reduce free F. Fe(II) ions react negligibly with F. Fe(III) ions increasingly bind F as pH decreases. Mn^{2+} and Mg^{2+} have statistically insignificant reactions with F due to low tea concentrations.	The amount of free fluoride in the infusion is influenced by its pH and the concentration of Al, Fe(III) ions present.
Liu [68]	To evaluate the effect of temperature, brewing time, and tea-to-water ratio on the release of F and Al in the infusion.	Tea cubes were ground, dried, and 1 g brewed in appropriate amounts of deionized water. To 5 mL of centrifuged tea liqueur, either 10 mL TISAB buffer (for F quantification) or 0.1 ml HNO_3 (for Al quantification) was added.	F and Al release decreases with successive brewings but increases with higher temperatures. F release peaks at 40 min of brewing. Greater water volume reduces F release.	Brewing parameters: time, temperature, and amount of water influence the amount of F released into the infusion.
Mahvi [62]	To compare the amount of F released into the infusion depending on the tea brand.	60 black Iranian tea samples (10 brands, 2 g each) were brewed in 50 mL water for 10 min at 80 °C, then diluted to 100 mL with distilled water. F content was measured using FISE method.	The amount of fluoride released into the infusion ranged from 0.57 mg/L to 2.6 mg/L.	The amount of F released varies depending on the brand of tea.
Li [22]	To examine the fluoride content in drinking water, tea infusion, and urine of inhabitants of a specific region of China.	F content was measured with a CSBF-1 fluoride electrode in tap water and with an Orion 868 Electrode in urine and brick tea infusion samples. All samples were diluted with TISAB buffer.	One of three tested water sources exceeded the F norm (1 mg/L); 82% of infusions contained above-normal F levels. Higher drinking water F correlated with increased urinary F.	The sum of fluoride from drinking water and tea infusion may reach values that pose a risk of fluorosis in the studied regions of China.
Morés [48]	To develop a simple tea fluorine detection method using molecular absorption spectrometry with high-resolution continuum source AAS and electrothermal vaporization.	10 tea samples were prepared by three methods: microwave HNO_3 digestion, TMAH alkaline solubilization, and 90 °C/5-min infusion. Fluoride was measured via CaF molecular absorption using high-resolution continuum source AAS with a graphite furnace. All preparations were performed in triplicate, with measurements repeated at least 3 times.	Fluorine in tea was determined via CaF molecular absorption at 606.440 nm, yielding 42–87 µg/g in leaves and 21–56 µg/g in infusions, with 48–74% extraction rates. Method validation showed comparable results between acid digestion and alkaline solubilization.	The method proved accurate and reliable, with acid digestion and alkaline solubilization yielding comparable results, offering a simple, effective approach for routine tea fluorine analysis.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Yuwono [49]	To establish a technique for measuring fluoride concentrations in black, green, and herbal tea infusions.	Fluoride in 12 tea brands was analyzed using a fluoride ion-selective electrode after 5 min hot water infusion, filtration, and dilution. Potentiometry with Gran's plot was used for concentration determination.	After a 5 min infusion, fluoride concentrations varied from 0.95 to 4.73 mg/L in black tea, 0.70 to 1.00 mg/L in green tea, and 0.26 to 0.27 mg/L in herbal tea.	Black and green teas are major sources of daily fluoride intake, and children at risk of dental fluorosis should refrain from consuming black teas with high fluoride levels.
Giljanović [31]	To analyze fluoride content in various teas from markets in Split, Croatia.	Fluoride content was analyzed in 43 tea infusions, including mint, lemon balm, green tea, and pomegranate from tea bags, bottled beverages, and bulk samples. Fluoride concentration was measured using FISE.	Average fluoride: 0.116 ± 0.211 mg/L. Highest in green tea (0.393 ± 0.23 mg/L), lowest in pomegranate (0.008 ± 0.002 mg/L) and mint (0.011 ± 0.004 mg/L). Tea bags contained more fluoride than bulk tea, with green tea bags showing the highest levels (0.558 ± 0.12 mg/L vs. 0.161 ± 0.12 mg/L bottled). Packaging had no effect on mint tea fluoride levels.	Fluoride content varies by tea type and packaging, highest in green tea and tea bags/bottled drinks.
Gupta [50]	Assess fluoride variation in tea infusions across different tea forms prepared in 3 different methods.	16 tea brands (3 dip, 2 leafy, 11 granulated) were analyzed for fluoride using an ion-selective electrode after preparing infusions via 3 methods: hot water steeping, water boiling, and boiling with milk and sugar.	Tea infusions had mean fluoride concentrations of 1.437, 3.375, and 3.437 mg/L, depending on the preparation method, with tea granules showing statistically significant fluoride levels regardless of preparation.	Fluoride in tea can contribute to dietary intake, potentially aiding in cavity prevention or increasing the risk of fluorosis.
Zhu [51]	Fluoride release properties of 3 common tea types consumed in Hong Kong and Hangzhou were investigated.	72 water samples (Hong Kong, Hangzhou, deionized) were used to brew pu-erh, black, and green teas via repeated and continuous infusion methods, with fluoride measured by selective electrode.	Fluoride was highest in Hong Kong's drinking water versus Hangzhou's. Black tea bags released the most fluoride, followed by pu-erh and green tea leaves. Repeated infusions increased fluoride concentration over time.	Fluoride release from tea depends on water composition, brewing time, and infusions, but not on pH.
Chan [52]	To examine the fluoride intake from tea consumption in the UK.	38 tea products in 5 groups (Black, Green, Pure, Oolong/Pu'er, Economy) were analyzed with FISE after brewing 2 g in 100 mL boiling water for 2, 10, and 30 min.	Fluoride in tea infusions ranged from 0.43 to 8.85 mg/L. The fluoride release order was Economy > Green > Black > Pure > Oolong/Pu'er teas. Fluoride concentration increased with time brewing.	Economy tea contains high fluoride levels (3.60–7.96 mg/L), with 1 L providing 75–150% of the recommended daily intake.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Lv [66]	To assess the safety of Chinese Pu-erh tea consumption by analyzing the levels of microelements (fluoride, lead, copper, chromium, arsenic, cadmium).	56 Pu-erh teas (26 loose, 30 compressed) from 5 Yunnan regions were analyzed for fluoride and heavy metals after drying, grinding, and sieving. Infusions from 20 selected samples were prepared by brewing 5 g in 250 mL boiled water for 5 min twice, combined, freeze-dried, and analyzed.	Highest fluoride in Dali and Dehong samples; lowest in Lincang. Compressed tea had 30% less lead than loose tea. Infusions contained mean concentrations: fluoride (523.86 μg/L), copper (43.18 μg/L), chromium (13.67 μg/L), lead (5.70 μg/L), arsenic (0.43 μg/L), and cadmium (0.17 μg/L), with dissolving rates of 24.6–45.8%.	Regional variations were significant except for copper. Fluoride had the highest dissolving rate (45.8%). All elements were below safety thresholds, suggesting no health risk from Pu-erh tea infusions, though chromium warrants monitoring due to high contribution (92.2%).
Fojo [53]	To determine the fluoride levels in various drinks marketed in Portugal for children.	183 samples were collected from markets (106 soft drinks, 23 juices, 37 nectars, 6 juice drinks, 5 concentrates, 3 teas, and 3 infusions), then FISE was used.	Extract-based soft drinks contained the highest fluoride levels (0.86 mg/L), while tea (0.16 mg/L) and tea infusions had the lowest (0.12 mg/L). Tea and tea infusion had higher pH values (6.0 and 5.7) compared to other pH values around 3.4.	All drinks contain fluoride levels below toxic thresholds, with typical consumption contributing only 7.4% of a child's recommended daily intake.
Embiale [54]	To assess how water fluoride levels affect fluoride release from tea leaves during infusion and evaluate potential fluoride absorption by leaves.	Water from 5 fluoride-rich Ethiopian Rift Valley locations and Addis Ababa University tap water was used. 9 tea brands (3 green tea bags, 3 black tea powders, 3 black tea bags) were tested by adding 1 g to 100 mL boiling water (92 °C) for 3, 5, and 10 min. Fluoride was measured using FISE.	Fluoride ranged from 0.254–30.2 mg/L in water to 0.51–20.57 mg/L in tea infusions. Moderately fluoride-rich water (12.5 mg/L) decreased to <5 mg/L when used for tea, while highly fluoride-rich water (30.2 mg/L) reduced to <10 mg/L in most infusions after 3 min brewing. Ethiopian teas contained higher fluoride than imported ones.	Tea brands showed varying fluoride absorption capacities (30–80%), demonstrating that tea leaves can reduce fluoride in high-fluoride water. Absorption rates varied by tea brand and brewing time. Drinking tea prepared with fluoride-rich water could lower daily fluoride intake compared to direct water consumption.
Maleki [32]	To assess fluoride levels in various Iranian tea leaves and analyze how brewing duration and water hardness impact the fluoride release.	100 tea samples (white, green, oolong, black) from one Iranian manufacturer in leaf and bag forms were prepared. 1 g of each sample was steeped in 100 mL boiling water in Teflon teapots at 80 °C for 3–120 min. Water hardness varied from 0 to 350 mg $CaCO_3$/L. Fluoride, phosphate, sulfate, nitrate, and chloride concentrations were measured using a Metrohm 882 compact IC plus ion chromatography system.	Tea bags released more fluoride than loose leaves. Black tea contained the highest fluoride levels, and oolong the lowest. Fluoride release increased with brewing time. Water hardness reduced fluoride extraction, especially above 100 mg $CaCO_3$/L.	Brewing time and water hardness significantly influence fluoride release from tea, with longer brewing increasing and harder water decreasing fluoride extraction.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Fan [70]	Investigate the frequency and severity of brick-tea fluorosis in Tibet, and assess fluoride exposure from varying sources.	416 child and 1287 adult urine samples, 1227 brick tea infusions, 29 drinking water samples, and 107 brick tea samples were analyzed for fluoride concentration using FISE.	106/107 samples exceeded national fluoride standards (median: 732.81 mg/kg). Median daily brick tea consumption was 3.2 L, providing 24.73 mg fluoride daily—7× the national safety standard (3.5 mg). Dental fluorosis affected 33.57% of children, while skeletal fluorosis affected 46.06% of adults.	Tibetans have high fluoride exposure due to their consumption of brick tea. The study identified altitude and occupation as key risk factors.
Das [55]	Evaluation of potential health risk factors associated with fluoride exposure from tea consumption.	47 tea samples (15 herbal mixes, 15 black, 9 green, 4 oolong, 3 pu-erh, 1 white) from 13 countries were analyzed. 500 mg tea powder was infused in 50 mL boiling water for 5 min, filtered, and adjusted to pH 4.25–4.75 before fluoride analysis.	Herbal teas had the lowest fluoride (0.06–0.69 mg/L). Traditional teas contained higher concentrations: green (2.43–6.94 mg/L), black (1.47–5.45 mg/L), oolong (3.08–5.63 mg/L), pu-erh (2.87–4.96 mg/L), white (5.39 mg/L). Traditional teas released 18–99% of fluoride during brewing versus 6–96% for herbal teas. All infusions were acidic (pH 3.5–5.5).	10 traditional teas exceeded recommended daily intake limits, though no teas showed immediate health risks (HQ < 1). Combined with other fluoride sources, regular consumption of high-fluoride teas may increase fluorosis risk.
Linhares [56]	To compare fluoride content in commercial teas and analyze release rates based on brewing time and water type used.	F content was determined using the FISE method in 30 drinking water samples from three Azores locations and 450 tea samples (black and green) from three commercial brands. Infusions were prepared using 5 brewing times (1, 2, 3, 5, and 10 min).	F- concentration in water samples ranged from 0.29 to 1.56 ppm. F- concentration in tea infusions increased with brewing time. A negative correlation existed between tea F- content and water pH used for infusion preparation. F- in infusions was significantly associated with baseline F- present in the water.	In regions with naturally high F- levels in water supplies and prevalent tea consumption, rigorous monitoring of F- concentrations in both water sources and commercial tea brands is advisable.
Janda [34]	To determine polyphenol, F- content, and antioxidant potential in black tea infusions with added spices.	Infusions of black tea with selected spices were prepared at 80 °C. Polyphenol content and antioxidant activity were determined spectrophotometrically, while F- concentration was measured using an ion-selective electrode.	The highest polyphenol content and strongest antioxidant properties were observed in tea infused with cloves. The highest F- content was detected in tea with turmeric, and the lowest in the clove infusion. The addition of spices and F- content influenced the antioxidant properties and polyphenol levels in tea infusions. High F- concentrations were associated with decreased antioxidant capacity of tea infusions.	Antioxidant activity is a significant determinant of black tea infusions' health-related quality. Adding spices influences the infusion's composition and properties. Elevated F- levels diminish black tea infusions' antioxidant capacity.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Zhou [57]	Development and evaluation of a novel ion-exclusion chromatography method for determining F- ions in tea infusions.	Ion-exclusion chromatography was performed using 2 connected Metrosep organic acid columns. The method was validated with standard samples and Chinese tea samples, with accuracy confirmed through recovery tests and comparison with ion-selective electrode measurements.	Two columns in series provided better F- separation than a single column. The method showed good sensitivity and a wide linearity range, with results matching those from ion-selective electrode measurements.	Ion-exclusion chromatography offers a novel, rapid, accurate, and direct method for F- determination in tea infusions, effectively separating fluoride ions from interfering organic acids.
Guo [47]	Development of a method for total F determination (both F- and covalently bonded F) in tea infusions using single quadrupole ICP-MS, with assessment of associated health risks.	ICP-MS measured BaF^+ ions generated from fluorine and barium in plasma. 100 tea samples of various types were analyzed, with chronic daily intake (CDI) and target hazard quotient (THQ) of F- assessed for adults.	The developed ICP-QMS method accurately determined total F- with a low detection limit. Brick tea showed the highest F- concentration. Estimated chronic daily intake (CDI) and target hazard quotient (THQ) values indicated that F- exposure from tea consumption is within safe levels for adults.	ICP-QMS coupled with online aerosol dilution and mathematical correction provides a viable method for determining total F- in tea infusions.
Satou [58]	Estimation of daily fluoride intake from beverages.	31 tea infusions were prepared by extracting 1.0 g of tea leaves with 100 mL of distilled water at 80 °C for 5 min. After cooling to 25 °C, fluoride levels were measured using a fluoride ion-selective electrode.	The concentration of fluoride ions in green tea infusion was the highest: 0.26–4.09 mg/L, while in herbal tea it was 0.07–0.17 mg/L.	Regular consumption of certain beverages requires management of the risk of dental fluorosis.
Akhdhar [59]	To evaluate using CaF for determining total fluorine in tea infusion without sample preparation using microwave-induced plasma optical emission spectrometry (MIP-OES).	7 samples were prepared by brewing 0.15 g of tea in 15 mL of water at 90 °C for 5 min. Fluoride levels were measured using MIP-OES and a high-resolution continuum source atomic absorption spectrometer (HR GF-MAS).	Fluoride concentrations in the tea samples tested ranged from <3.8 to 7.8 mg/L and were similar between both methods.	The MIP-OES method is sufficiently sensitive, and the results obtained are comparable to those obtained with the reference method.
Szmagara [19]	Determining which brand/type of tea and tea products release the highest levels of fluoride and how brewing time affects this.	The samples were prepared by brewing 2 g of tea in 200 mL of distilled water at 100 °C for 5 or 15 min. After cooling the samples to 18–20 °C, the fluorine content was measured using an ion-selective electrode.	The highest fluoride levels were obtained from black tea infusions, with more infusions prepared from tea bags than from leaves. Green tea followed, and white tea and rooibos had the lowest levels. In each case, longer brewing times were associated with higher fluoride content.	Even if tea is brewed with a high fluoride content or brewed longer than necessary, the public's exposure to fluoride is negligible.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Chandrajith [63]	To assess F- exposure via commercially available tea in regions affected by kidney disease with undetermined origin (CKDu) and the effect of different brewing times and repeated tea brewing.	Samples were prepared by brewing 2 g of black tea in 100 mL of distilled water at a temperature of >95 °C for 2, 5, 10, or 15 min. Some infusions were prepared by brewing the tea 4 times for 5 min. An ion-selective electrode was used to assess the amount of fluoride.	There is a significant difference in the amount of fluoride in the infusion prepared from tea leaves and tea bags, and with each subsequent brewing, the amount of fluoride in the infusion decreases. However, the effect of brewing time on the amount of fluoride has not been demonstrated.	The study found elevated levels of F- in tea infusions. The effect is increased when using water with a higher F- content.
Mazurek [28]	Assessment of fluoride content in tea infusion based on tea type, leaf fragmentation, brewing time, and evaluation of health risks for Polish consumers.	Samples were prepared by brewing covered 2 g of tea leaves between 1.5 and 2 mm in 100 mL of deionized water at 100 °C for 6 min. Fluoride levels were measured using the potentiometric method, according to Shyu.	The fluoride level increases with the degree of leaf fragmentation and the lengthening of the brewing time. The most fluoride is found in the infusion of black tea, then green, and the least in pu-erh.	There is a potential for negative health effects from fluoride consumption, particularly from black and green tea infusions purchased in tea bags.
Edussurya [64]	To investigate the content of selected ions, including fluoride, in black tea consumed in areas of Sri Lanka where CKDu occurs, and to assess the risk of dietary exposure.	Samples were prepared by adding 200 mL of boiling deionized water to 2 g of black tea and brewing for 5, 10, 20, 30, 45, 60, or 120 min, maintaining the temperature between 80 and 85 °C. Fluoride levels were assessed using an ion-selective electrode.	The amount of fluoride increased with brewing time.	Frequent drinking of black tea contributes to increasing the daily intake of fluoride.
Rajiv [65]	To assess fluoride levels in tea after different brewing times and compare them between different tea brands.	Samples were prepared by brewing 1 g of black tea powder in 100 mL of boiling demineralized water or Mettur water. Fluoride concentration was assessed by spectrophotometry.	Higher amounts of fluoride were released into the infusion brewed with Mettur water than with demineralized water.	The fluoride content of tea depends on the fluoride content of the water that is used to brew it.
Aktug [61]	Determining the effect of tea brewing time on its color, brightness, and fluoride ion concentration in the infusion.	Samples were prepared by brewing 6 g of tea in 250 mL of boiling water, heating for 15 to 18 min. Fluoride concentration was determined using an ion-selective electrode.	At 15 min, the fluoride ion concentration reaches a maximum and remains constant, but the color of the infusion continues to darken.	The fluoride concentration in tea infusions reaches a plateau after 20 min of brewing using the Turkish method.

Table 1. *Cont.*

Study	Aim of the Study	Materials and Methods	Results	Conclusions
Essebbahi [60]	To determine the fluoride content in green and black tea and well water consumed by the population of seven rural regions of Morocco.	A total of 12 samples of green and black tea were prepared. Each was brewed for 10 and 30 min. Fluoride levels were determined using the Belcher–West colorimetric method.	Fluoride levels tested after 30 min of brewing are higher than those after 10 min of brewing. The fluoride content of tea and the way it is consumed pose a risk of dental fluorosis.	The fluoride content of boiled teas is higher than that of teas brewed for 30 or 10 min. Three types of green tea and one black tea have fluoride levels above recommended standards.
Kanrar [69]	Evaluation of fluoride content in Indian tea produced in north-eastern India.	Samples were prepared by brewing 3 g of tea in 150 mL of boiling deionized water for 5 min. Fluorine content was measured using an ion-selective electrode.	The highest fluoride concentration was found in Upper Assam samples, followed by Dooars, South Bank, Cachar, Darjeeling, and Tripura.	The concentration increased with the brewing time and decreased with each subsequent brewing.

3.3. Main Study Outcomes

3.3.1. Variability in Fluoride Concentration Across Samples

Numerous studies demonstrated substantial variability in fluoride concentrations across different tea samples, with values spanning over three orders of magnitude—even under comparable brewing conditions (see Figure 2). For instance, Szmagara et al. [19] reported values ranging from 0.04 to 6.76 mg/L, while Satou et al. [58] observed a similar spread among black and green teas (approximately 0.06 to 5.99 mg/L). Zhu et al. [51] and Guo et al. [47] documented particularly high levels in Chinese teas, reaching up to 11.05 mg/L and 7.25 mg/L, respectively. Das et al. [55], Chan et al. [52], and Linhares et al. [56] highlighted the impact of tea type (e.g., black, green, herbal), form (powder, leaves, bags), and geographical origin on fluoride release. Fan et al. [70] reported high fluoride exposure from brick tea, especially among Tibetan populations. Embiale et al. [54] demonstrated that using highly fluoridated water during brewing can significantly increase final fluoride content in the infusion. Beyond composition and origin, technological and chemical factors also influence fluoride levels. Chandrajith et al. [63] found that fermentation increases fluoride content in black tea, while Mazurek et al. [28] reported higher levels in granulated and bagged teas compared to loose-leaf forms. In addition, Janda et al. [34] observed an inverse correlation between fluoride concentration and antioxidant potential, suggesting a trade-off between fluoride exposure and potential health benefits. Essebbahi et al. [60] and Morés et al. [48] further emphasized the role of tea matrix composition, reinforcing the multifactorial nature of fluoride variability across samples. (see Figure 3) A detailed description of the included studies is presented in Supplementary Table S1.

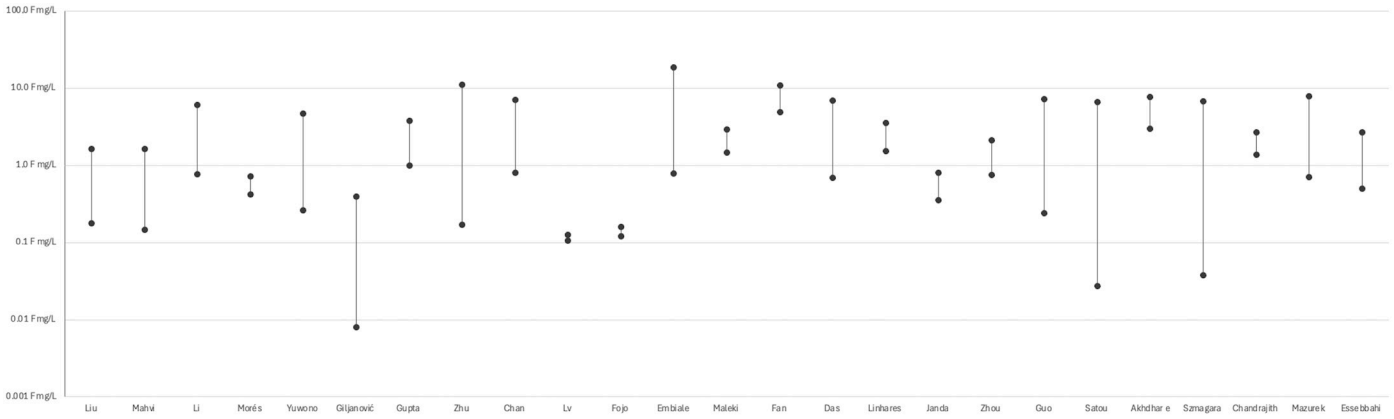

Figure 3. Variability in fluoride levels among tea samples reported in selected studies (Liu et al. [68], Mahvi et al. [62], Li et al. [22], Morés et al. [48], Yuwono [49], Giljanović et al. [31], Gupta et al. [50], Zhu et al [51], Chan et al. [52], Lv et al. [66], Fojo et al. [53] Embiale et al. [54], Maleki et al [32], Fan et al. [70], Das et al. [55], Linhares et al. [56], Janda et al. [34], Zhou et al. [57], Akhdhar et al. [59], Szmagara et al. [19], Chandrajith et al. [63], Mazurek et al. [28], Essebbahi et al. [60]).

3.3.2. Fluoride Content by Tea Type and Geographic Origin

The included studies demonstrate substantial variability in fluoride concentrations across tea infusions, even when the same plant species and similar brewing conditions are used. This variability appears to be primarily influenced by the type of tea, country of origin, processing methods, and brand. For example, Satou et al. [58] reported fluoride levels in black tea ranging from 1.057 mg/L (Sri Lanka) to 6.68 mg/L (India), while Szmagara et al. [19] also identified black tea as having the highest fluoride concentrations among tested varieties. Guo et al. [47] observed concentrations as high as 7.25 mg/L in Chinese green teas, consistent with findings by Zhu et al. [51] for black tea bags.

Although average values often fall within safe consumption limits [19,20,28], Chan et al. [52] highlighted that consuming 1 L of certain teas could provide up to 150% of the recommended daily fluoride intake. Fan et al. [70] reported excessive fluoride exposure among Tibetans consuming up to 3.2 L of tea daily. Other studies [22,55] confirmed that chronic tea consumption can contribute to dental or skeletal fluorosis, particularly among vulnerable populations. Yuwono et al. [49] even recommended that children already affected by fluorosis should avoid black and green teas.

For studies on black tea in bag form brewed for 3–5 min, fluoride concentrations vary significantly across tea samples of different geographic origins. The highest fluoride content was observed in India (Assam Nr. 4) with a maximum level nearing 4.8 mg/L, followed by Sri Lankan blends such as Ceylon-Assam Mischung and Ceylon-Indien Mischung, both exceeding 3 mg/L in mean values. Teas from the Azores (Portugal) and Kenya also exhibited relatively high fluoride levels, with mean concentrations above 2.5 mg/L. Moderate fluoride levels were noted in samples from Sri Lanka (Ceylon Hochland), Lipton—Best English (Sri Lanka), and India (general samples), typically around 2.3–2.5 mg/L. Lower fluoride concentrations were recorded in teas from China, Sri Lanka (Embiale), and Ethiopia, ranging between 1.3 and 1.9 mg/L, while the lowest levels were found in the Sri Lanka (Darjeeling, Messmer) sample, which remained under 1 mg/L across all measures (min, mean, and max) (see Figure 4).

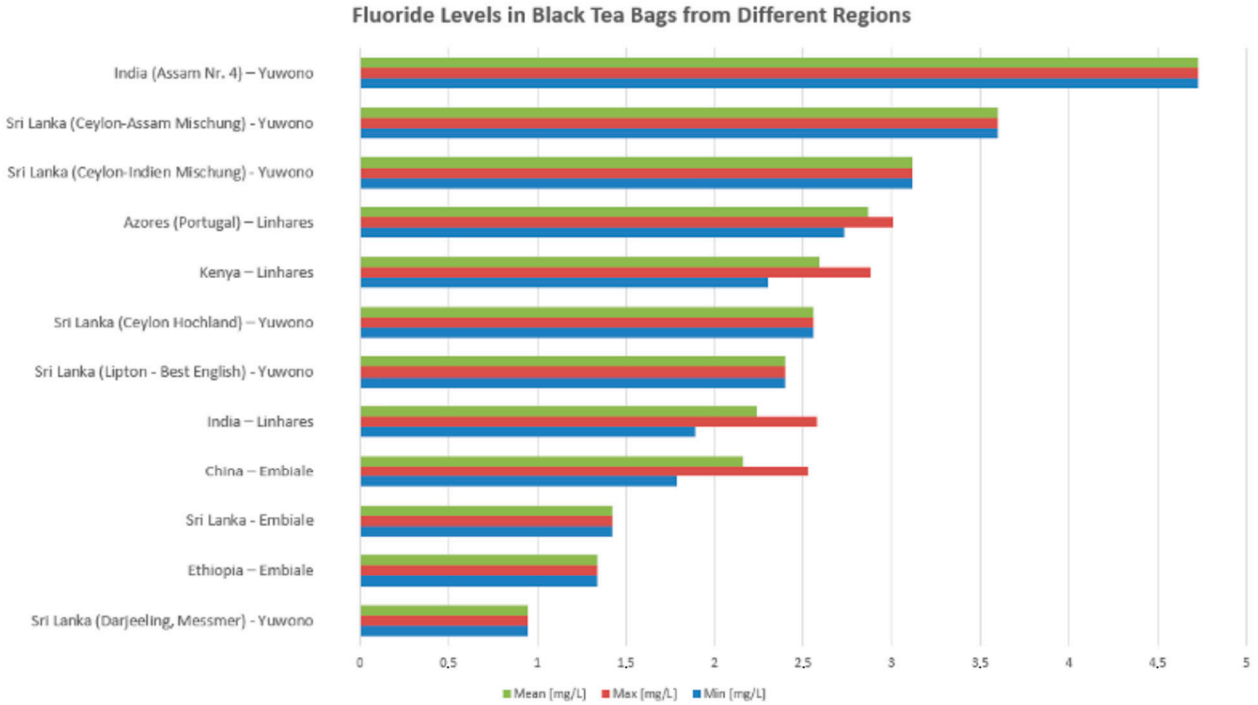

Figure 4. Variability in fluoride levels among tea samples from different regions reported in selected studies (Yuwono [49], Linhares et al. [56], Embiale et al. [54]).

3.3.3. Effect of Brewing Time on Fluoride Release

There is strong agreement across studies that fluoride release increases with longer brewing times [19,31,32,51,52,54,56,61,63,64,68]. Aktug et al. [61] demonstrated that after approximately 20 min, fluoride concentrations tend to reach a plateau—a finding corroborated by Liu et al. [68] and Linhares et al. [56]. This supports the view that extended infusion times enhance fluoride extraction, though the marginal gain diminishes over time.

3.3.4. Influence of Tea Mass and Leaf Fragmentation

The degree of leaf fragmentation is another important factor influencing fluoride content. Teas in bagged or powdered form—characterized by finer particle size and greater surface area—release significantly more fluoride than loose leaf teas [19,28,31,32,49–52,54,58,63]. Mazurek et al. [28] reported particularly high fluoride levels in infusions made from granulated or bagged black teas, highlighting the role of processing in fluoride release. (see Table 2)

Table 2. Influence of Tea Mass and Leaf Fragmentation on Fluoride Content.

Author	Tea Mass/Form	Granules and Tea Bags Had the Highest Fluoride Levels.
Mazurek et al. [28]	2 g; leaves, bags, granules	Granulated and tea bag samples had higher fluoride content than loose-leaf tea.
Giljanović et al. [31]	2 g (leaves and bags); bottled teas analyzed directly	Tea bags contained higher fluoride concentrations than loose-leaf and bottled tea.
Maleki et al. [32]	1 g; leaves and bags	Tea bags released more fluoride than loose leaves; extraction efficiency reached up to 73.5%.
Yuwono et al. [49]	1 g powder, 1.75–2.25 g bags	Highest fluoride concentrations were found in black tea, followed by green and herbal teas.
Chan et al. [52]	2 g; leaves and bags	Fluoride content was highest in economy blends, followed by green and black teas.
Embiale et al. [54]	1 g; powder and bags	Black tea powder released more fluoride than tea bags; values varied with water fluoride content.
Satou et al. [58]	1 g; leaves and bags	Loose green teas showed higher fluoride levels than bagged herbal teas.
Chandrajith et al. [63]	2 g; loose vs. packed tea	Loose tea had higher fluoride concentrations than bagged tea.
Gupta et al. [50]	2 g; bags, leaves, granules	Granules > leaves > bags in fluoride content.
Szmagara et al. [19]	2 g; leaves and bags	Fluoride content was highest in black tea bags and increased with brewing time.
Das et al. [55]	500 mg powder	Traditional powdered teas showed elevated fluoride levels (up to 6.9 mg/L); herbal teas contained significantly less.
Linhares et al. [56]	2.0 ± 0.5 g bags	Fluoride levels varied by tea origin and were negatively correlated with the pH of brewing water.

3.3.5. Impact of Brewing Temperature and Water Composition

Several physicochemical parameters of the brewing process also affect fluoride concentrations. Lower pH values have been associated with increased fluoride release [22,55,56,58,67], although Zhu et al. [51] did not find a consistent pH effect, suggesting that its influence may depend on other variables.

Repeated brewing of the same tea leaves typically results in decreased fluoride release with each successive infusion [56,63,68,69]. Furthermore, the fluoride content of the brewing water itself plays a critical role: Li et al. [22], Chandrajith et al. [63], and Rajiv et al. [65] demonstrated a positive correlation between fluoride concentrations in water and tea infusion. Interestingly, Embiale et al. [54] observed that tea leaves can adsorb fluoride from high-fluoride water, occasionally resulting in lower concentrations in the infusion than in the original water.

Water hardness and ion content further modulate fluoride extraction. High calcium carbonate concentrations significantly reduced fluoride release [32,48]. Likewise, elevated

levels of aluminum and iron (III) ions were found to bind fluoride and reduce its availability in the infusion [67]. (see Table 3).

Table 3. Impact of Temperature and Water Composition on Fluoride Release; ↑- increase, ↓-decrease.

Author	Parameter(s)	Effect on Fluoride	Results
Liu et al. [68]	Temperature (60–95 °C), repeated brewing	↑ with temperature, ↓ with each brew	Detailed temperature profile and brewing ratios studied
Zhu et al. [51]	Water type (DI vs. drinking), repeated brewing	↑ with time, variation by water type	Fluoride release higher in drinking water
Embiale et al. [54]	Water fluoride content (0.25–30.2 mg/L)	Complex—sometimes ↓ due to absorption	Tea leaves absorb fluoride from highly fluoridated water
Chandrajith et al. [63]	Repeated brewing, fermentation	↓ with each brew, ↑ with fermentation	Loose vs. packed tea also compared
Linhares et al. [56]	Water source (different pH/fluoride levels)	↓ fluoride release with ↑ pH	Water origin matters
Rajiv et al. [65]	Water type (distilled vs. natural)	↑ in natural water	Higher fluoride release in mineralized water
Maleki et al. [32]	Water hardness ($CaCO_3$ 0–350 mg/L)	↑ hardness = ↓ fluoride release	Significant reduction in extraction with hard water
Morés et al. [48]	Calcium presence	↓ fluoride extraction	Tea with calcium-rich solution released less fluoride
Erdemoglu et al. [67]	pH, Al, and Fe^{3+} ion concentration	↑ pH = ↑ fluoride; ↑ Al/Fe = ↓ fluoride	Ion competition affects free fluoride
Essebbahi et al. [60]	Brewing time (10 vs. 30 min)	↑ fluoride with longer time	Limited temperature data
Kanrar et al. [69]	Repeated infusion	↓ fluoride with more brews	Region of origin also noted

3.4. Quality Assessment and Risk of Bias of the Included Studies

For all of the 9 questions, 8 papers received a positive answer to 8 of them [31,32,48,50,52,54,64,67], 10 papers received a positive answer to 7 of them [22,34,49,51,53,56,62,66,68,70], 9 papers received a positive answer to 6 of them [19,28,47,55,58,59,63,65,69], and 3 remaining papers received a positive answer to 6 of them [57,60,61] (see Supplementary Table S2.)

Among the thirty studies included in this systematic review, thirteen were classified as having a low risk of bias, with total scores ranging from 7 to 9 points [22,28,31,32,34,48,50–54,64,67]. The remaining seventeen studies were rated as having a moderate risk of bias, scoring 5 or 6 points [19,47,49,55–63,65,66,68–70]. None of the studies were classified as high risk, as no score fell below the threshold of five points (see Figure 5).

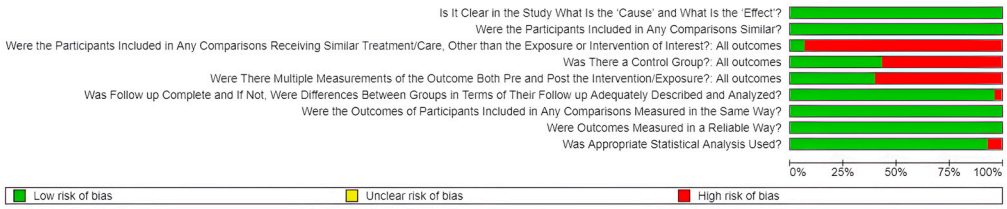

Figure 5. Risk of bias across the included studies, assessed using the JBI checklist for quasi-experimental studies. Green indicates low risk, red indicates high risk.

4. Discussion

This systematic review sought to answer the research question: What factors influence the fluoride content in tea infusions? The findings consistently demonstrate that fluoride release is not uniform but rather modulated by multiple interacting variables, including tea type, form of tea, brewing parameters, and external modifiers such as the water's properties or the addition of spices. While wide variations in fluoride concentrations were observed, common trends were identified. Black and green teas tended to release the highest amounts of fluoride, particularly when processed into bagged or powdered forms. A particular threat in the context of fluorosis risk is the consumption of economy tea, which is a blend of teas from China, Sri Lanka, and India. Chan et al. [52] proved that after 2 min, the infusion contains almost twice as much fluoride as black tea, which, according to most studies, is considered the greatest source of fluoride among all types of tea. Consumption of 1 L of economy tea, which is about 4 cups, can lead to up to 150% of the daily recommended fluoride intake. This dietary exposure is further supported by systemic data. In addition to the variability in fluoride levels found in tea infusions, some studies have also explored systemic fluoride exposure resulting from high tea consumption. For example, Fan et al. [70] examined fluoride levels in urine samples from more than 1700 individuals in Tibet and found that excessive intake of brick tea (up to 3.2 L/day) was associated with elevated fluoride concentrations in the body and a high prevalence of dental and skeletal fluorosis. These findings highlight the value of integrating biomarker-based assessments—such as fluoride levels in urine or blood—into future research to better evaluate the health risks linked to chronic tea consumption. Longer brewing times and higher water temperatures consistently increased fluoride release, although a plateau was often observed beyond a certain point. Moreover, the mineral composition and pH of the water used for infusion emerged as additional significant factors. These results highlight the multifactorial nature of fluoride release during tea preparation and suggest that both intrinsic properties of the tea and extrinsic brewing conditions must be considered when evaluating potential fluoride exposure from tea consumption. Some publications draw attention to the significant effect of drinking tea infusion on the concentration of fluoride in the blood [71–74]. It has been proven that drinking significant amounts of brewed tea, in the amount of several cups or 30 glasses of iced tea per day, is equivalent to 13–14 mg of fluoride [71]. Such amounts lead to reaching a toxic level of fluoride in the blood, i.e., >15 umol/L, which leads to osteosclerosis, pain, bone fractures, kidney disorders, and digestive system disorders [72]. It is worth mentioning that the above symptoms are influenced by the sum of fluoride from water and tea, as well as from drugs such as flucoxentine, and the accumulation of fluoride can be intensified by kidney diseases [73]. Disorders related to excessive tea consumption are usually caused by drinking habits practiced for even 30 years, and in some cases, restoring the correct level of fluoride in the plasma (0–4 umol/L) is impossible despite radical treatment lasting even more than 10 years [71,74]. Future studies should also focus on the above issue to accurately assess

what amounts of tea are safe to consume in people for whom it is a significant component of the diet.

Among the factors analyzed, tea type emerged as one of the most significant determinants of fluoride release. Across the majority of included studies, black teas exhibited the highest fluoride concentrations, followed closely by green teas [19,28,32,47,51,52,55]. This pattern is likely linked to the maturity of the tea leaves utilized; older leaves, commonly used for black and green teas, accumulate fluoride over time due to prolonged environmental exposure. Moreover, the regional origin of the tea plants strongly influenced fluoride accumulation, as areas with acidic soils and high environmental fluoride levels contributed to higher internal fluoride content [22,53,58]. Interestingly, some studies, such as that by Satou et al. [58], found green tea to release more fluoride than black tea, suggesting that local agricultural practices and specific cultivars could shift the typical trend. In contrast, white, pu-erh, and herbal teas consistently demonstrated lower fluoride levels. Herbal teas, in particular, released minimal fluoride, confirming that non-*Camellia sinensis* infusions are generally a safer choice for individuals needing to limit fluoride intake [19,31,49,57]. Nonetheless, variability among tea types also reflects different processing techniques; for instance, extensive fermentation processes, typical for pu-erh teas, may alter fluoride availability [19,66]. Overall, tea type remains a crucial, but not sole, predictor of fluoride content in the infusion.

The form of tea and degree of leaf fragmentation significantly influenced fluoride release. Fragmented tea, such as powders and tea bags, consistently yielded higher fluoride concentrations than loose-leaf teas [19,28,31,32,49–52,54,58,63]. The greater surface area provided by fragmented tea particles facilitates more efficient ion extraction into the water. Studies by Mazurek et al. [28] and Giljanović et al. [31] directly confirmed that tea bags and instant tea products released substantially higher fluoride concentrations compared to whole-leaf forms. Additionally, industrial processing methods, including mechanical pressing and cutting of leaves during tea bag production, contribute to increased cellular disruption and subsequent fluoride liberation. Gupta et al. [50] highlighted that granulated teas contained fluoride concentrations comparable to or exceeding those of bagged teas, emphasizing the role of mechanical processing. These findings are critical from a public health perspective, as tea bags and powdered teas are often preferred for their convenience, potentially exposing frequent consumers to higher fluoride levels unknowingly. Thus, the form of tea preparation must be considered when assessing individual fluoride intake from tea beverages.

Brewing conditions—particularly time, temperature, and water composition—further modulated fluoride release. A robust relationship was observed between longer brewing times and increased fluoride extraction [19,31,32,51,52,54,56,61,63,64,68]. Aktug et al. [61] and others showed that fluoride concentrations rose steeply during the first 20 min of brewing, after which the rate of release plateaued. This suggests that most available fluoride is solubilized early in the brewing process, and prolonged brewing does not proportionally increase fluoride concentrations. Similarly, higher water temperatures enhanced fluoride extraction due to increased solubility and diffusion rates [51,54,68]. Beyond brewing parameters, the chemical composition of the brewing water played a vital role. Studies revealed that using water with higher baseline fluoride levels led to increased fluoride content in the resulting tea infusion [22,63,65]. However, Embiale et al. [54] observed that in water with extremely high fluoride content, tea leaves could absorb part of the fluoride, thus slightly reducing the infusion's fluoride concentration compared to the original water. Moreover, water hardness negatively correlated with fluoride extraction: higher concentrations of calcium carbonate precipitated fluoride ions, thereby lowering their availability in the infusion [32,48]. These findings emphasize that

not only tea characteristics but also water quality must be accounted for in fluoride exposure assessments. Furthermore, one of the included studies—Gupta et al. [50]—examined different methods of tea preparation: plain tea, tea with milk, and tea with milk and sugar, and found that the addition of milk slightly decreased the concentration of fluoride in the infusion. This reduction is likely due to the binding of fluoride ions with calcium and other minerals present in milk.

Despite the strengths of this systematic review, several limitations must be acknowledged. The included studies displayed considerable methodological heterogeneity regarding tea types, brewing protocols, measurement techniques, and reporting standards. Differences in the use of fluoride ion-selective electrodes versus more sophisticated methods such as ion chromatography or ICP-MS [28,47,59] likely contributed to variability between reported fluoride concentrations. Furthermore, many studies lacked detailed information about the specific origin, cultivar, or processing methods of the tea samples, limiting the possibility of fully disentangling botanical from environmental influences. The absence of standardized brewing protocols (e.g., differences in leaf-to-water ratios, brewing vessels, agitation methods) further complicates comparisons. Future research should prioritize standardized methodologies, particularly in experimental design and fluoride quantification, to allow more robust comparisons and meta-analyses. In addition, more studies should explore the effects of additives (e.g., milk, spices) and consider the impact of habitual versus occasional tea consumption patterns in different populations. In medicine, serum fluoride levels are often used as an indicator of exposure to skeletal fluorosis. Further studies by using this marker could therefore confirm whether consuming a certain amount of fluoride from tea poses an actual risk of fluorosis or chronic poisoning. Understanding cumulative fluoride exposure from multiple sources remains critical for refining public health recommendations, particularly in regions where tea consumption is culturally significant.

5. Conclusions

This systematic review of thirty studies demonstrated that the fluoride content in tea infusions is influenced by a wide range of factors. A consistent finding across the reviewed studies was that fluoride concentration increases with longer brewing times, regardless of the temperature used. Additionally, a positive correlation between higher brewing temperatures and elevated fluoride concentrations was frequently observed. The presence of other ions, such as aluminum, iron, calcium, and fluoride itself, in the brewing water significantly affected the amount of free fluoride released into the infusion, highlighting the importance of considering both water hardness and fluoride content when preparing tea. It is also noteworthy that repeated brewing of the same tea leaves results in progressively lower fluoride concentrations in subsequent infusions.

The global diversity and variety of teas available on the market contribute to the observed variability in fluoride concentrations among tea infusions. Nevertheless, irrespective of the country of origin or specific tea variety, black tea infusions consistently exhibited the highest fluoride levels. Tea bags and loose tea leaves were the most frequently studied forms, with tea bag infusions consistently releasing higher fluoride concentrations than loose-leaf counterparts. Regarding analytical techniques, fluoride determination was most commonly performed using potentiometry with an ion-selective electrode. However, more precise and reliable measurements can be achieved using methods such as ion chromatography.

The findings of this systematic review demonstrate that the fluoride content in tea infusions ranges from 0.008 to over 8 mg/L, while the recommended daily intake for adults is 3–4 mg. Based on these results, regular consumption of teas with high fluoride

content (particularly black and green teas in bagged or powdered form) could potentially contribute significantly to exceeding the daily fluoride requirements for adults, especially when prepared with longer brewing times and higher water temperatures.Several studies, including Chan et al. [52], indicated that drinking 1 L of tea could provide up to 150% of the daily fluoride requirement, while Fan et al. [70] reported that populations consuming up to 3.2 L of tea daily were at risk of excessive fluoride intake. Conversely, herbal teas, white teas, and loose-leaf preparations generally contain lower fluoride levels and are less likely to cause overconsumption. Based on these findings, the recommendation are for the tea consumers, particularly those who drink multiple cups daily, to choose herbal teas, white teas, or loose-leaf preparations, which generally contain lower fluoride levels; limit consumption of bagged or powdered black and green teas, which consistently show the highest fluoride concentrations; consider shorter brewing times (under 5 min) to reduce fluoride extraction; and be aware that tea brewing in areas with naturally high-fluoride water compounds the total exposure.

Given the widespread consumption of tea worldwide, understanding these factors is critical for assessing potential fluoride exposure through diet. Further standardized research is necessary to refine safe consumption guidelines, especially for populations at higher risk of fluoride overexposure.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15115974/s1, Table S1: Detailed characteristics of the included studies; Table S2: Quality assessment—JBI checklist for quasi-experimental studies (nonrandomized experimental studies).

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