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ORIGINAL RESEARCH

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Fluoride concentration in semi-solid infant foods and institutional soups in a Southern Ecuadorian population: implications for dental fluorosis risk

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Abstract

Background: Excessive systemic fluoride (F^-) exposure during early childhood is a recognized risk factor for dental fluorosis. In addition to drinking water, commercially processed infant foods and institutional meals may contribute to total dietary fluoride intake. This study aimed to determine and compare fluoride concentrations in commercial infant foods and semi-solid institutional preparations in Cuenca, Ecuador, and to estimate their potential contribution to dietary fluoride exposure among children aged 6 months to 3 years. **Methods**: A total of 41 samples, including commercial infant foods and institutional soups, were analyzed. Fluoride concentrations were determined using the hexamethyldisiloxane (HMDS) acid microdiffusion technique coupled with a fluoride ion-selective electrode (ISE). Fluoride intake was estimated for a standardized 125 mL serving and expressed as fluoride intake per serving, body weight-adjusted intake, and percentage of the European Food Safety Authority (EFSA) tolerable upper intake level (UL). Statistical significance was established at $p < 0.05$. **Results**: Institutional soups exhibited significantly higher and more variable fluoride concentrations than commercial infant foods, ranging from <LOD to 2.66 mg F^-/L and from <LOD to 0.73 mg F^-/L, respectively ($p < 0.001$). Fluoride intake per serving reached 0.333 mg in institutional soups compared with 0.091 mg in commercial infant foods. The estimated fluoride intake represented 4.92% of the EFSA UL per serving for institutional soups and 0.16% for commercial infant foods. **Conclusions**: Institutional semi-solid preparations contained higher and more variable fluoride concentrations than commercial infant foods, indicating a greater potential contribution to dietary fluoride exposure during early childhood. These findings highlight the importance of monitoring fluoride concentrations in foods intended for young children, particularly in institutional settings, to strengthen dietary fluoride surveillance and support strategies aimed at preventing dental fluorosis while preserving the caries-preventive benefits of fluoride.

Keywords

Fluoride; Infant foods; Semi-solid foods; Dietary exposure; Dental fluorosis

1. Introduction

Fluoride (F^-) has long been recognized as a key factor in dental caries prevention, primarily through its topical action in reducing enamel demineralization and enhancing remineralization processes [1, 2]. However, excessive systemic exposure during amelogenesis may interfere with enamel formation and maturation, resulting in dental fluorosis (DF), a developmental defect caused by altered enamel mineralization [3]. The susceptibility period extends from birth to approximately eight years of age, coinciding with the formation of the permanent dentition [4, 5]. During this stage, ameloblasts are particularly sensitive to fluoride-related metabolic disturbances, and prolonged exposure may lead to the enamel porosity characteristic of DF [6]. The risk of DF appears to be associated with cumulative F^- exposure during early childhood rather than with a single exposure period, particularly in populations exposed to elevated F^- concentrations in drinking water (>1.5 mg/L) [4]. In this context, diet represents an important source of systemic F^- exposure, as industrialized infant foods and preparations made with fluoridated water may contribute to total daily F^- intake [7, 8]. Recent evidence has further emphasized that infant formulas, prepared foods, and early-childhood dietary matrices may contribute variably to total fluoride exposure depending on product composition, preparation water, and food matrix characteristics [9, 10].

Fluoride (F^-) exposure during early childhood may arise from multiple sources [11]. In addition to drinking water, fluoride-containing toothpastes, dietary supplements, infant formulas, and commercially processed foods and beverages

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intended for infants and young children may contribute cumulatively to total fluoride intake during early childhood [2, 8]. Dental fluorosis has also been reported in populations with low fluoride concentrations in drinking water or in areas without community water fluoridation, highlighting the potential contribution of fluoride exposure from sources other than drinking water [12, 13]. The World Health Organization (WHO) has established a guideline value of 1.5 mg F^-/L for fluoride in drinking water [14], whereas the European Food Safety Authority (EFSA) has established tolerable upper intake levels (ULs) of 1.0 mg/day for infants (<1 year), 1.6 mg/day for children aged 1–3 years, and 2.0 mg/day for children aged 4–8 years [15]. Similarly, the Institute of Medicine (IOM) has proposed Adequate Intake (AI) and ULs adjusted for body weight, with an empirical reference range of 0.05–0.07 mg/kg/day commonly cited as an approximation of safe exposure in the pediatric population [8, 13, 16, 17].

In parallel, shifts in consumption patterns associated with globalization, urbanization, and the increasing availability of ready-to-eat (RTE) products have substantially modified infant dietary habits. In multiple countries, considerable variability in the F^- content of infant foods and beverages has been documented, attributable to differences in manufacturing processes, the origin of raw ingredients, and the use of fluoridated water during production or reconstitution [18]. Studies conducted in Iran and Poland, for example, have reported fluoride concentrations reaching levels comparable to or even exceeding those found in drinking water in infant formulas and beverages for young children, highlighting that these foods may contribute substantially to systemic F^- exposure [19].

From an analytical perspective, the determination of F^- in semi-solid food matrices represents a methodologically complex process, since the ion may be present either in free form or bound to proteins, calcium, and other organic components within the food matrix [20]. This characteristic may hinder its quantification and lead to underestimation when direct analytical methods are used without adequate sample preparation [20]. For this reason, the ion-selective electrode (ISE) remains one of the most widely used techniques in population-based studies due to its sensitivity, accessibility, and analytical applicability. However, the reliability of the measurements depends on strict analytical conditions, including appropriate control of pH, ionic strength, and the complete release of F^- from the food matrix [20].

The acid microdiffusion technique using hexamethyldisiloxane (HMDS), originally described by Taves (1968), enables the release of total fluoride through conversion into volatile species under strongly acidic conditions, thereby separating it from matrix interferences and subsequently capturing it for potentiometric quantification using an ion-selective electrode (ISE) [21]. This procedure has been validated and standardized as an ISE-based reference method for F^- analysis, demonstrating appropriate performance parameters for complex matrices [20]. Studies evaluating infant foods and ready-to-eat beverages have employed this methodology, reporting significant variability in F^- content attributable to differences in technological processes and the use of water during production or preparation [8, 19].

Recent studies have demonstrated considerable variability in the F^- content of infant foods and beverages, associated with both manufacturing processes and the water used during preparation [7]. In addition, the high consumption of processed and ultra-processed foods among young children, including semi-solid infant products, may increase dietary F^- exposure [22]. Similarly, Casarin *et al*. [7] reported that cooking foods with fluoridated water can significantly increase their final F^- content.

In Ecuador, DF exhibits a heterogeneous distribution that does not appear to be determined exclusively by fluoride concentrations in drinking water. In the southern region of Ecuador, an overall DF prevalence of 50.1% has been reported among schoolchildren from Azuay, Cañar, and Morona Santiago [13], whereas higher prevalence rates have been documented in other Ecuadorian regions, including Chimborazo, Pichincha, and Imbabura [23]. In Cuenca, fluoride concentrations in the public water supply have been reported to range from 0.01 to 0.11 mg/L [24], indicating relatively low fluoride levels in drinking water and supporting the need to consider additional sources of fluoride exposure. These findings suggest that additional sources of fluoride exposure may contribute to the overall fluoride burden during childhood. Accordingly, evaluating the potential contribution of processed infant foods and institutional semi-solid preparations is particularly relevant, especially during the early years of life, when systemic fluoride exposure may influence the development of dental fluorosis.

Despite this evidence, a substantial information gap persists in Ecuador regarding the F^- content in semi-solid infant foods, both commercial and institutional. In addition, no standardized system is currently implemented to routinely assess or monitor F^- concentrations in these products. This situation contrasts with the increasing reliance on ready-to-eat foods during early childhood and limits the ability of healthcare professionals to accurately estimate total F^- exposure and to provide recommendations grounded in local evidence.

In this context, the present study aimed to determine and compare F^- concentrations in commercial infant purées and soups prepared in Child Development Centers (CDCs) administered by the Ministry of Economic and Social Inclusion (MIES) in the city of Cuenca, Ecuador. Using the acid microdiffusion technique coupled with a F^- ion-selective electrode, the study further sought to analyze their potential contribution to dietary F^- exposure among children aged 6 months to 3 years. By addressing a largely understudied dietary component in the country, this work aims to provide original evidence relevant to understanding potential DF risk in early childhood and to serve as a foundation for future research.

2. Materials and methods

2.1 Study design

This study was based on a detailed chemical analysis conducted within a descriptive observational design. An acid microdiffusion process was employed to quantify fluoride using a fluoride ISE.

The study was conducted at the facilities of the Research, Innovation and Technology Transfer Centre (CIITT) of the

Catholic University of Cuenca under controlled laboratory conditions to ensure analytical precision and reproducibility. The research protocol was reviewed and approved by the Bioethics Committee of the Universidad Hemisferios, which granted ethical approval under approval code CEUHE24-1 on 07 October 2024 (Quito, Ecuador), ensuring compliance with relevant ethical and scientific standards.

2.2 Sample

A total of 41 food samples were analyzed, including packaged semi-solid products and soups provided by CDCs administered by the Ministry of Economic and Social Inclusion (MIES) for children aged 6 months to 3 years. Due to the exploratory and descriptive nature of the study, purposive sampling was conducted according to product availability and observed consumption patterns within the urban area of Cuenca.

Institutional samples were collected from four CDCs located in different urban sectors of Cuenca (El Valle, Sayausí, Baños, and Ricaurte) over five consecutive days. Menus corresponding to the four daily meals were reviewed to capture variability in routine food preparations. However, semi-solid soups, which constituted the food matrix of interest for fluoride determination, were offered during only one of the four daily meals and were not included on every sampling day at all centers. Consequently, only 15 samples met the predefined inclusion criteria and were included in the final analysis.

Packaged products included infant purées, fruit compotes, and cereals formulated for children aged 0 to 3 years that were commercially available in supermarkets and retail establishments in Cuenca. Selection prioritized the brands most widely marketed and readily accessible at the time of collection, including Supermaxi, Gerber, Heinz, Vivo Mifrut, Baby's Paap, Yummy Baby, Nutrimonster, Nestum, Cerelac, and Vita Health Digest.

2.3 Inclusion criteria

Food samples were selected according to predefined criteria to ensure sample traceability, sample integrity, and analytical suitability for fluoride determination.

Commercially available semi-solid foods intended for children aged 0–3 years were included. Eligible products were required to have complete labeling information, including ingredient composition, batch identification, and expiration date. Samples with intact packaging, adequate storage conditions, and no evidence of contamination, deterioration, or other alterations that could affect sample integrity were selected. Product categories included fruit-based preparations (purées/compotes) and infant cereals.

Institutional samples consisted of semi-solid soup preparations provided through CDCs administered by MIES in Cuenca, Ecuador. Samples were collected on the day of preparation and consumption to ensure that they represented routine institutional meals and preserved the original food characteristics.

2.4 Exclusion criteria

Samples were excluded if they did not meet the predefined requirements for age suitability, sample integrity, or analytical evaluation.

Commercial products were excluded if they were not intended for children aged 0–3 years, lacked complete labeling information, or presented damaged packaging, contamination, deterioration, or other changes that could compromise sample quality.

Institutional preparations were excluded if they were not part of the CDC food service system, including foods prepared outside the institutional setting or obtained from external sources not following standardized distribution procedures. Liquid and solid food preparations were excluded, as well as semi-solid samples showing evidence of manipulation, degradation, or changes in their physicochemical characteristics that could interfere with the reliability of fluoride measurements.

2.5 Calibration

In order to ensure the accuracy, precision, and reproducibility of the results, a calibration and analytical validation of the potentiometric method was performed using a fluoride ion-selective electrode (F^- ISE) connected to an Orion Dual Star™ pH/ISE Meter 9609BNWP (Thermo Scientific™, Waltham, MA, USA), purchased from Elicrom, Ecuador.

In the initial phase, the measurement procedure was standardized by preparing F^- standard solutions at concentrations of 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 mg/L. These standards were prepared using sodium F^- (NaF; Merck, $\geq$99.0% purity) dissolved in ultrapure water (resistivity 18.2 MΩ·cm). A Total Ionic Strength Adjustment Buffer (TISAB II) solution was used to control the pH (5.0–5.5) and minimize ionic interferences.

The limit of detection (LOD) and limit of quantification (LOQ) were calculated based on the standard deviation of blank measurements and the slope of the calibration curve, yielding values of 0.02 mg/L and 0.05 mg/L, respectively. The calibration curve demonstrated excellent linearity (R^2 = 0.9995) within the range of 0.1–5.0 mg/L, confirming the appropriate electrode response. Analytical reporting followed a sub-LOD/LOQ convention: values below the LOD were reported as <LOD, values between the LOD and LOQ were considered detected but below the limit of reliable quantification, and values below the lower validated calibration point were interpreted as extrapolated estimates.

Intra-day precision (repeatability) was assessed through three consecutive replicates of a 1.0 mg/L standard solution, resulting in a coefficient of variation (CV%) of 2.3%. Inter-day precision (reproducibility), calculated over three consecutive days, yielded a CV% of 3.1%, indicating adequate method stability.

As part of the quality control procedures, verification solutions at concentrations of 0.5 and 2.0 mg/L were prepared independently from the calibration standards. Additionally, internal quality controls were performed after every ten measurements to assess potential electrode drift. All measurements were conducted at 25 ± 1 °C, and the electrode was periodically reconditioned with a 0.1 M NaF solution to maintain

consistent sensitivity.

2.6 Sample preparation and fluoride concentration analysis

The F^- content of the analyzed foods was determined using the acid microdiffusion method combined with electrochemical detection using of a fluoride ISE. Direct measurements of F^- concentration in the water used for food preparation were not performed during the study period. Therefore, previously reported values for the public water supply network of Cuenca were used only as contextual reference data. Vélez León *et al.* [24] analyzed 36 water samples from urban and rural parishes of Cuenca and reported F^- concentrations ranging from 0.01 to 0.11 mg/L.

This information was considered exclusively to contextualize the interpretation of the results obtained from institutional preparations, since these foods are commonly prepared using water from the public distribution network. However, these water values were not incorporated into the quantitative analyses and were not added to the F^- concentrations experimentally determined in the food samples. Consequently, all F^- concentrations reported in this study correspond exclusively to fluoride quantified in the analyzed food matrices by acid microdiffusion coupled with a F^- ISE.

Samples obtained from the CDCs were collected in sterile 50 mL Falcon tubes containing approximately 30 mL of each preparation. The samples were stored in sterile, hermetically sealed tubes at −80 °C until analysis to preserve their physicochemical stability and minimize potential changes before F^- determination.

Fruit compotes and purées did not require prior processing due to their semi-solid consistency. By contrast, cereals were reconstituted with deionized water according to the manufacturer's instructions prior to analysis. All samples were analyzed in duplicate to ensure precision and reproducibility of the results.

For the analytical procedure, 1 g of each sample was weighed and placed in 60 mm diameter Petri dishes, together with 2 mL of double-distilled water. The dishes were previously prepared by perforating the lid and applying petroleum jelly along the inner rim to ensure an airtight seal. On the inner surface of the lid, 50 μL of 0.05 N sodium hydroxide (NaOH) solution was deposited to capture volatilized F^- generated during the chemical reaction. Once the Petri dish was sealed, a 3 N sulfuric acid solution containing hexamethyldisiloxane (H_2SO_4 3N/HMDS) was added through the perforation, which was immediately resealed with petroleum jelly, thereby inducing the hydrolysis and volatilization of fluoride ions present in the sample (Fig. 1).

The microdiffusion reaction was maintained at a constant temperature of 25 °C for a period of 16 to 24 hours. Upon completion of this period, the NaOH droplets accumulated on the lid were neutralized with 50 μL of 0.1 M acetic acid, followed by electrochemical analysis. Potential readings, expressed in millivolts (mV), were obtained using a F^- ISE, whose operation is based on the Nernst equation, which establishes a logarithmic relationship between electrode potential and F^- ion concentration in the sample.

For the conversion of potential values into F^- concentrations expressed in mg F^-/L, a calibration curve was constructed using standard F^- solutions of known concentrations. This curve provided a linear relationship between the recorded potential and F^- concentration within the validated calibration range. Concentrations below the lower validated calibration point were retained only as extrapolated estimates and interpreted with caution.

2.7 Estimated fluoride exposure

Potential F^- intake per serving was estimated by multiplying the measured F^- concentration (mg/L) by a standardized serving volume of 125 mL (0.125 L). Body weight–adjusted exposure was calculated for reference body weights of 9, 12, and 14 kg, and the percentage contribution to the EFSA tolerable upper intake level for children aged 1–3 years (1.6 mg/day) was estimated [15]. A repeated-consumption scenario of two standardized servings per day was considered only as an exploratory estimate for contextual discussion of potential daily exposure; it was not treated as an estimate of measured individual intake and does not imply that all sampled soups were consumed twice daily.

2.8 Statistical analysis

The Shapiro–Wilk test was used to assess the normality of fluoride concentration data, and descriptive statistics were calculated using measures of central tendency and dispersion, presented as mean ± standard deviation and median with interquartile range, as appropriate. Because the data did not follow a normal distribution, the comparison between commercial infant foods and institutional soups was performed using a non-parametric test; specifically, the Kruskal–Wallis test was applied to evaluate differences in fluoride concentrations between the two independent groups. A confidence level of 95% and a significance threshold of $p < 0.05$ were adopted for all analyses.

3. Results

Table 1 summarizes the descriptive statistics for both food groups. In the commercial infant foods group (n = 26), the mean F^- concentration was 0.10 ± 0.18 mg/L. The median concentration was 0.02 mg/L, with an interquartile range (IQR) of 0.02–0.05 mg/L. Observed values ranged from <LOD to 0.73 mg/L. Values below the analytical limit of detection were not interpreted as true zero concentrations; values below the LOQ or below the validated calibration range were interpreted with caution. The median estimated F^- intake per serving was 0.003 mg, corresponding to 0.16% of the EFSA tolerable upper intake level (UL).

In the institutional soups group (n = 15), the mean F^- concentration was 0.82 ± 0.70 mg/L. The median concentration was 0.63 mg/L (IQR: 0.34–1.28 mg/L), with values ranging from <LOD to 2.66 mg/L. The median estimated intake per serving was 0.079 mg, representing 4.92% of the EFSA UL.

The table provides descriptive statistics for both groups, including sample size, mean, standard deviation, median, in-

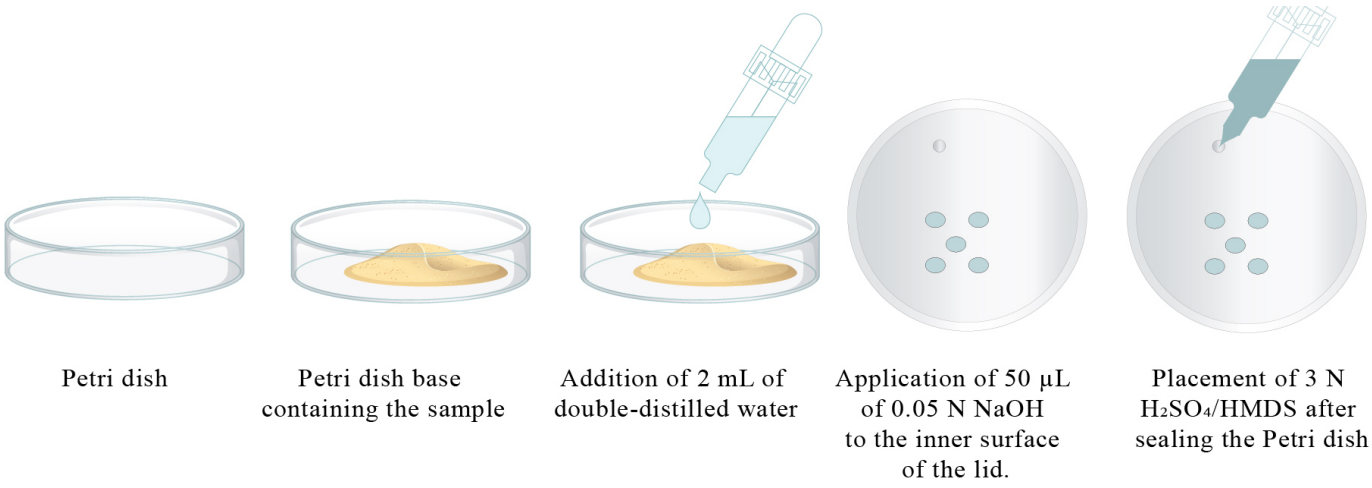


FIGURE 1. Schematic illustration of the acid microdiffusion system used for F^- determination. The setup allows the volatilization of F^- from the sample under acidic conditions and its subsequent trapping in an alkaline medium placed on the inner surface of the lid prior to quantification with a F^- ISE. NaOH, sodium hydroxide; H_2SO_4, sulfuric acid; HMDS, hexamethyldisiloxane.

TABLE 1. Descriptive statistics of fluoride concentration and estimated fluoride intake per serving in commercial semi-solid infant foods and institutional preparations.

Food origin	n	Mean ± SD (mg/L)	Median (IQR)	Min–Max	mg/serving (median)	% UL (median)
Commercial foods	26	0.10 ± 0.18	0.02† (0.02†–0.05‡)	<LOD–0.73	0.003	0.16
Institutional soups	15	0.82 ± 0.70	0.63 (0.34–1.28)	<LOD–2.66	0.079	4.92

Fluoride concentrations are expressed as mg F^-/L. A standard serving size of 125 mL (0.125 L) was used. Fluoride per serving and % UL were calculated relative to the EFSA tolerable upper intake level for children aged 1–3 years (1.6 mg/day). Data are presented as mean ± SD or median (IQR). LOD = 0.02 mg/L; LOQ = 0.05 mg/L. Values below the LOD were reported as <LOD rather than 0.00. Values between the LOD and LOQ were considered detected but below the reliable quantification limit (†). Values at or above the LOQ but below the lowest validated calibration point were interpreted as extrapolated estimates (‡). For descriptive calculations, values below the LOD were substituted by LOD/√2. Abbreviations: F^-, fluoride ion; UL, tolerable upper intake level; SD, standard deviation; IQR, interquartile range; LOD, limit of detection; Min, minimum; Max, maximum.

terquartile range, minimum and maximum values, as well as the estimated F^- intake per serving and its relative contribution to the UL for the reference age group. Sub-LOD and sub-LOQ values were handled according to the analytical reporting convention described in the table note.

An inferential comparison between the two food groups was performed using a non-parametric test. Prior to between-group comparisons, the distribution of F^- concentration data was assessed using the Shapiro–Wilk test. After classifying the samples according to origin—commercial infant foods (including reconstituted cereals) and non-commercial institutional soups—the data did not follow a normal distribution in either group (commercial infant purées: $p = 2.2 \times 10^{-6}$; institutional soups: $p = 0.022$). Accordingly, non-parametric tests were used for the between-group comparison (Table 2).

The between-group comparison using the Kruskal–Wallis test revealed statistically significant differences in fluoride concentrations according to food origin ($p < 0.001$). These results indicate that fluoride concentrations differed significantly between commercial infant foods and institutional soup preparations.

In Table 3, the F^- concentration values for 15 non-commercial institutional soup preparations are presented. Concentrations ranged from <LOD to 2.66 mg F^-/L, demonstrating substantial variability among preparations. The highest value corresponded to barley with milk soup (2.66 mg/L), whereas one preparation had a fluoride concentration below the analytical limit of detection. Values below the validated calibration range were interpreted cautiously as extrapolated estimates. When standardized to a 125 mL (0.125 L) serving, quantifiable F^- per portion ranged up to 0.333 mg. In terms of body weight–adjusted exposure, the quantifiable values reached 0.037 mg/kg for a 9 kg child, 0.028 mg/kg for a 12 kg child, and 0.024 mg/kg for a 14 kg child.

The percentage of the tolerable upper intake level per serving (% UL), calculated only for quantifiable concentrations, reached 20.78%, with the highest values associated with the preparation with the highest F^- concentrations. Overall, the data demonstrate a heterogeneous distribution of both F^- concentrations and estimated exposure across the different soups analyzed.

Table 4 presents the F^- concentrations in commercial infant foods, which ranged from <LOD to 0.73 mg F^-/L. The highest value was observed in Heinz apple (0.73 mg/L), whereas several products showed concentrations below the LOD or below

TABLE 2. Assessment of normality and selection of statistical analysis for comparing fluoride concentrations between food groups according to origin.

Food group	Normality test (Shapiro–Wilk) *p*	Distribution	Selected analysis type	Test applied
Commercial infant foods (including reconstituted cereals)	2.2×10^{-6}	Non-normal	Non-parametric	Kruskal–Wallis
Non-commercial institutional soups	0.022	Non-normal	Non-parametric	Kruskal–Wallis
Between-group comparison	—	—	Non-parametric	Kruskal–Wallis

Normality was assessed using the Shapiro–Wilk test. Cereals were included within the commercial infant purées group, as they are industrialized products that were reconstituted into a semi-solid form. As the groups did not exhibit a normal distribution, non-parametric tests were employed for between-group comparisons.

TABLE 3. Fluoride content in institutional soups and estimated fluoride exposure per standard serving.

Code	Preparation	F^- (mg/L)	Serving (L)	F^- per serving (mg)	mg/kg (9 kg)	mg/kg (12 kg)	mg/kg (14 kg)	% UL
S1	Sambo with beans soup	<LOD	0.125	NC	NC	NC	NC	NC
S2	Quinoa with peas and carrots soup	0.34	0.125	0.042	0.005	0.004	0.003	2.66
S3	Vegetables with chicken (potato and carrot) soup	0.07‡	0.125	0.009	0.001	0.001	0.001	0.55
S4	Potatoes and zucchini soup	0.27	0.125	0.034	0.004	0.003	0.002	2.11
S5	Plantain and corn soup	0.62	0.125	0.078	0.009	0.006	0.006	4.84
S6	Spinach soup	0.64	0.125	0.080	0.009	0.007	0.006	5.00
S7	Broad beans with potatoes and spinach soup	0.96	0.125	0.120	0.013	0.010	0.009	7.50
S8	Barley with milk soup	2.66	0.125	0.333	0.037	0.028	0.024	20.78
S9	Quinoa with potatoes and peas soup	0.36	0.125	0.045	0.005	0.004	0.003	2.81
S10	Sambo, potato and tender corn soup	1.35	0.125	0.169	0.019	0.014	0.012	10.55
S11	Vegetables (broccoli, cauliflower and peas) soup	1.26	0.125	0.158	0.018	0.013	0.011	9.84
S12	Homemade noodles soup	1.44	0.125	0.180	0.020	0.015	0.013	11.25
S13	Turnip soup	0.33	0.125	0.041	0.005	0.003	0.003	2.58
S14	Vegetables with peas and herbs soup	0.63	0.125	0.079	0.009	0.007	0.006	4.92
S15	Meat soup	1.30	0.125	0.163	0.018	0.014	0.012	10.16

F^-, fluoride ion; mg/L, milligrams per litre; L, litre; UL, tolerable upper intake level; % UL, percentage of the tolerable upper intake level; NC, not calculated; LOD, limit of detection. Fluoride intake per serving was calculated using a standardized serving size of 125 mL (0.125 L). The percentage of the tolerable upper intake level (% UL) was calculated based on the EFSA recommendation for children aged 1–3 years (1.6 mg/day). LOD = 0.02 mg/L; LOQ = 0.05 mg/L. Values below the LOD are reported as <LOD and were not interpreted as zero. Values at or above the LOQ but below the validated calibration range were considered extrapolated estimates (‡).

TABLE 4. Fluoride concentration in commercial infant purées and cereals and estimated fluoride intake per standard serving (125 mL).

Code	Preparation	F^- (mg/L)	Serving (L)	F^- per serving (mg)	mg/kg (9 kg)	mg/kg (12 kg)	mg/kg (14 kg)	% UL*
C1	Gerber Banana	0.03†	0.125	0.004	<0.001	<0.001	<0.001	0.23
C2	Gerber Apple (glass jar)	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C3	Gerber Peach (glass jar)	0.11	0.125	0.014	0.002	0.001	0.001	0.86
C4	Gerber Pear	0.37	0.125	0.046	0.005	0.004	0.003	2.89
C5	San Jorge Mixed fruits	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C6	San Jorge Apple	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C7	San Jorge Pear	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C8	San Jorge Mango	<LOD	0.125	NC	NC	NC	NC	NC
C9	San Jorge Peach	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C10	Quinua Kids	0.05‡	0.125	0.006	0.001	0.001	<0.001	0.39
C11	Baby's Paap Pure Mix	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C12	Baby's Paap Peach & Mango	<LOD	0.125	NC	NC	NC	NC	NC
C13	Baby's Paap Apple	0.03†	0.125	0.004	<0.001	<0.001	<0.001	0.23
C14	Supermaxi Banana	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C15	Supermaxi Apple	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C16	Supermaxi Peach	0.03†	0.125	0.004	<0.001	<0.001	<0.001	0.23
C17	Supermaxi Pear	0.03†	0.125	0.004	<0.001	<0.001	<0.001	0.23
C18	Heinz Apple	0.73	0.125	0.091	0.010	0.008	0.007	5.70
C19	Heinz Peach	0.39	0.125	0.049	0.005	0.004	0.003	3.05
C20	Heinz Pear	0.50	0.125	0.063	0.007	0.005	0.004	3.91
C21	Nutrimonsters Carrot & Amaranth	0.05‡	0.125	0.006	0.001	0.001	<0.001	0.39
C22	Nutrimonsters Z Q	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16
C23	Nutrimonster BA	0.03†	0.125	0.004	<0.001	<0.001	<0.001	0.23
C24	Vita Health Digest ++ (cereal)	<LOD	0.125	NC	NC	NC	NC	NC
C25	Cerelac (cereal)	<LOD	0.125	NC	NC	NC	NC	NC
C26	Nestum (cereal)	0.02†	0.125	0.003	<0.001	<0.001	<0.001	0.16

*F^-, fluoride ion; mg/L, milligrams per litre; L, litre; UL, tolerable upper intake level; NC, not calculated; LOD, limit of detection; LOQ, limit of quantification. F^- intake per serving was calculated using a standardized serving size of 125 mL (0.125 L). * The percentage of the tolerable upper intake level (% UL) was calculated based on the EFSA tolerable upper intake level for children aged 1–3 years (1.6 mg/day). Values <LOD are reported as <LOD. Values between the LOD and LOQ were considered detected but below the reliable quantification limit (†). Values at or above the LOQ but below the lowest validated calibration point were retained as extrapolated estimates and interpreted with caution (‡). Positive body weight–adjusted estimates that rounded below 0.001 mg/kg are displayed as <0.001.*

the LOQ. Thus, low values should be interpreted as trace-level detections or extrapolated estimates, as applicable, rather than exact quantitative concentrations. When standardized to a 125 mL (0.125 L) serving, quantifiable F^- content per portion reached 0.091 mg. In terms of body weight–adjusted exposure, the estimated exposure reached 0.010 mg/kg for a 9 kg child, 0.008 mg/kg for a 12 kg child, and 0.007 mg/kg for a 14 kg child. The percentage of the tolerable upper intake level per serving (% UL) reached 5.70%, with the highest values associated with the products with the highest F^- concentrations. Positive body weight–adjusted values that rounded to less than 0.001 mg/kg are shown as <0.001.

4. Discussion

The objective of the present study was to determine and compare F^- concentrations in commercial semi-solid infant foods and soups prepared in CDCs administered by the MIES for children aged 6 months to 3 years in Cuenca, Ecuador, using the HMDS microdiffusion technique coupled with a F^- ion-selective electrode (ISE), and to describe their potential contribution to dietary F^- exposure during early childhood.

Compared with alternative analytical techniques such as ion chromatography or inductively coupled plasma mass spectrometry (ICP-MS), the ISE method combined with HMDS microdiffusion offers important operational advantages for nutritional surveillance studies, including lower cost, simple instrumentation, rapid processing, and the ability to analyze large numbers of samples with adequate sensitivity [20]. Moreover, numerous epidemiological studies evaluating dietary F^- exposure from infant formulas, beverages, and prepared foods have employed similar methodological approach, facilitating international comparability of findings [8, 18, 19].

However, this method has certain limitations that should be considered when interpreting the findings. The measurements obtained represent total F^- concentrations and did not allow differentiation between free and complexed fractions; therefore, actual F^- absorption may be lower in foods with high calcium or fiber content [20]. Recent evidence further indicates that fluoride bioaccessibility in foods consumed during early childhood is highly variable and strongly influenced by the food matrix and accompanying beverages. Kronic *et al.* [9] reported mean fluoride bioaccessibility values well below 100% for most foods and meals consumed by children under four years of age, highlighting that total fluoride concentration does not necessarily reflect the fraction potentially available for gastrointestinal absorption. Consequently, total fluoride measurements should be interpreted cautiously when estimating dietary fluoride exposure and potential biological availability. Although the use of TISAB helps minimize analytical interferences, elevated concentrations of aluminum or iron could slightly affect measurement accuracy [20]. In addition, although fluoride concentrations were directly measured in the institutional soup samples, the specific contribution of the water used during food preparation could not be quantified because fluoride concentrations in the cooking water were not measured directly during sample collection.

Our findings identified differences in fluoride content between commercial infant foods and the institutional Semi-solid preparations analyzed. Commercial infant food showed low and relatively homogeneous fluoride concentrations, whereas institutional soups exhibited greater variability and substantially higher concentrations, reaching up to 2.66 mg/L. The highest fluoride concentrations were observed in several different types of institutional preparations, suggesting that recipe composition, ingredient characteristics, preparation practices, and the water used during cooking may all contribute to the variability observed [7, 19].

These findings suggest that semi-solid foods consumed during early childhood in institutional settings may represent a variable dietary source of F^- exposure during a developmental stage in which fluoride provides preventive benefits against dental caries [25], while excessive systemic exposure may increase the risk of dental fluorosis [16]. Exposure estimates based on standardized 125 mL servings, reference body weights, and the exploratory repeated-consumption scenario defined in the Methods suggest that some institutional preparations may represent a potentially relevant source of F^- intake during early childhood. This finding is relevant in the context of complementary feeding, which generally begins at approximately 6 months of age and continues through 23 months, during a period in which foods make an increasingly important contribution to overall dietary intake [26]. Under the predefined hypothetical scenario of consuming two standardized servings per day, a soup with the median F^- concentration observed (0.63 mg/L) would provide approximately 0.16 mg of F^- per day, corresponding to an estimated intake of 0.011–0.018 mg/kg/day in children weighing between 9 and 14 kg. For preparations with higher F^- concentrations (1.34–2.66 mg/L), estimated exposure could reach approximately 0.05–0.074 mg/kg/day under the same repeated-consumption scenario [17]. Although the individual servings analyzed did not independently exceed the tolerable upper intake levels established for this age group [15], the findings suggest that certain institutional preparations could increase total F^- exposure when consumed regularly alongside other concurrent sources, such as drinking water, fluoride-containing toothpaste, beverages, and processed foods [2, 8, 17]. This interpretation is consistent with the updated EFSA consumer risk assessment, which recommends evaluating fluoride exposure as aggregate oral exposure, integrating contributions from food, drinking water, discretionary salt, and ingested dental care products rather than considering individual sources in isolation. This aggregate approach provides a more comprehensive framework for assessing fluoride exposure during early childhood [15]. Nevertheless, these results should be interpreted with caution, as the present study does not allow a direct causal relationship with DF to be established or individual clinical risk to be inferred.

The implications derived from these findings are particularly relevant in the Ecuadorian context, where several epidemiological studies have reported a high prevalence of DF even among populations exposed to low or moderate F^- concentrations in drinking water [24]. This scenario suggests that systemic F^- exposure during early childhood is likely multifactorial, with dietary sources potentially playing a complementary but still insufficiently characterized role.

However, the results should be interpreted in light of certain methodological limitations. The descriptive cross-sectional design and the number of samples analyzed ($n = 41$) limit the assessment of potential variations associated with batch-to-batch differences, changes in product formulations, or modifications in production and preparation processes. In the case of the institutional preparations, factors inherent to recipe preparation, such as ingredient proportions, cooking conditions, and the raw materials used, may have contributed to the observed variability. Furthermore, although fluoride concentrations were directly determined in the analyzed samples, exposure estimates were based on standardized serving sizes considered representative of this age group. The repeated-consumption scenario was included only as a contextual estimate and should not be interpreted as a measured intake pattern. Consequently, the values obtained reflect the potential F^- contribution of the evaluated food matrices, without accounting for individual variations in consumption patterns or concurrent exposure from other dietary and non-dietary sources. Additionally, the absence of direct measurements of F^- concentration in the water used for food preparation and the inability to differentiate between total F^- and potentially bioavailable F^- represent additional sources of uncertainty in

the exposure assessment. This distinction is particularly relevant because recent evidence has shown that fluoride bioaccessibility varies substantially among food matrices and does not necessarily correspond to total fluoride concentration [9]. An additional analytical limitation concerns the interpretation of low fluoride concentrations. Although the method showed limits of detection and quantification of 0.02 mg/L and 0.05 mg/L, respectively, the validated calibration range was 0.1–5.0 mg/L. Therefore, values below the lower validated calibration point should be considered extrapolated estimates. Results below the LOD were not interpreted as true zero concentrations, and values between the LOD and LOQ were regarded as detected but below the reliable quantification range. This limitation may particularly affect the interpretation of low fluoride concentrations observed in commercial infant foods.

The differences observed between commercial foods and institutional preparations should also be interpreted in the context of the specific characteristics of the food categories evaluated. Commercial products consisted primarily of fruit purees, vegetable purees, and infant cereals manufactured under standardized industrial processes, whereas the institutional preparations included semi-solid mixtures of cereals, legumes, vegetables, dairy products, and protein sources prepared locally. Therefore, the differences observed in F^- concentrations likely reflect the combined influence of ingredient composition, food matrix characteristics, and the preparation processes involved in each category.

From a public health perspective, these findings underscore the importance of including F^- content assessment in monitoring programs for foods intended for young children. Regular monitoring of F^- concentrations in institutional meals and commonly consumed infant foods could provide a clearer understanding of dietary sources of F^- exposure and complement current surveillance efforts, which have traditionally focused on drinking water.

5. Conclusions

Institutional soups exhibited higher and more variable fluoride concentrations than commercial infant foods, with maximum values reaching 2.66 mg/L compared with 0.73 mg/L in purées. The fluoride contribution per standardized serving (125 mL) was also greater in institutional preparations, providing up to 0.333 mg of fluoride per standardized serving, whereas commercial infant foods contributed substantially lower amounts. Accordingly, the fluoride intake per serving represented a higher proportion of the EFSA tolerable upper intake level (UL) in institutional soups (4.92%) compared with commercial infant foods (0.16%), suggesting a greater potential contribution to dietary fluoride exposure from institutional preparations. These findings highlight the importance of continued monitoring and surveillance of fluoride concentrations in foods intended for young children, particularly in settings where repeated exposure from multiple dietary and non-dietary sources may occur. Low-concentration results should be interpreted according to the reported LOD/LOQ convention and, when below the validated calibration range, as extrapolated estimates.

AVAILABILITY OF DATA AND MATERIALS

All data generated or analyzed during this study are included in this published article.

AUTHOR CONTRIBUTIONS

GPH and EVL—Study conception and design; Data analysis and/or interpretation; Critical revision of the manuscript for important intellectual content; Approval of the manuscript version for publication. EVL and DT—Data acquisition. GPH, EVL and DT—Drafting of the manuscript. All authors contributed to editorial revisions of the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The research protocol was reviewed and approved by the Bioethics Committee of Universidad Hemisferios. Ethical approval was granted under approval code CEUHE24-1 on 07 October 2024 (Quito, Ecuador), in accordance with applicable ethical principles and scientific standards.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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