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Water-Based Microwave-Assisted Digestion Method for Electrochemical and Chromatographic Determination of Total Fluoride Ions in Toothpaste Samples

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Abstract: Fluoride ions are the major constituents of dental products because they prevent cavities through bacterial growth inhibition. However, excessive consumption of fluoride ions results in fluorosis, thereby causing tooth staining and roughness. Therefore, there is a crucial need to develop rapid and effective methods for monitoring fluoride levels in dental products. The current study describes a greener water-based microwave-assisted digestion (WB-MAD) prior to fluoride-ion-selective electrode (F-ISE) measurement for the determination of fluoride ions in various toothpaste products. The optimum conditions of the developed WB-MAD method were 180 °C digestion temperature, 60 min digestion time, 0.05 g toothpaste amount and 10 mL distilled water. Under the optimum conditions, the method detection limit (MDL) of 0.00302 µg/kg and the method quantification limit (MQL) of 0.01007 µg/kg obtained were favorably comparable with the literature reports. The proposed WB-MAD method was both accurate (99.2 to 101%) and precise (≤0.75%) for the quantitative determination of F^- in toothpaste samples using F-ISE. Furthermore, the newly developed WB-MAD method showed better accuracy (97–100%) than the traditional microwave-assisted acid digestion methods (71–92%). It is worth indicating that since water was used as the only digestion reagent, it was possible to validate the F-ISE results with ion chromatography (IC). The percentage recoveries obtained from IC (91–104%) and F-ISE (93–100%) were statistically insignificant. In view of the validation data, the proposed WB-MAD method can be considered as an alternative to the conventional microwave-assisted acid digestion (MAAD) methods for the determination of F^- in toothpaste samples containing sodium monofluorophosphate.

Keywords: water-based microwave-assisted digestion; fluoride-ion-selective electrode; method detection limit; method quantification limit; ion chromatography; toothpaste samples

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1. Introduction

Although fluoride is known to prevent cavities in dental products, overexposure leads to fluorosis, kidney failure, and skeletal defects [1,2]. Fluoride ions are added to dental products in the form of various dissolved salts such as sodium fluoride (NaF), tin(II) fluoride (SnF_2), 2-[3-[bis (2-hydroxyethyl) amino]propyl-octadecylamino]ethanol;dihydrofluoride (olafur, $C_{27}H_{60}F_2N_2O_3$), and sodium mono-fluorophosphate (Na_2PO_3F) [3]. Dental products are also made of active and inactive ingredients such as abrasives, solvents, humectants, detergents, surfactants, thickening or binding agents, flavoring agents, therapeutic agents, coloring agents and preservatives [3,4]. It must be noted that toothpastes and mouthwashes frequently contain NaF and Na_2PO_3F. Moreover, NaF dissociates completely in an aqueous solution; that is why it is more effective in inhibiting dental caries than Na_2PO_3F [3–8]. However, the margin between the amount of fluoride ions that convey health benefits and the amount that causes toxicity is very minimal. Therefore, there is a need for the development of a simple, reliable, accurate and rapid analytical method to monitor F^- concentration levels, thereby resolving this ambiguity [1,2].

Various analytical techniques such as laser-induced breakdown spectroscopy (LIBS) [8,9], X-ray fluorescence spectrometry (XRF) [10], electrothermal vaporization coupled to inductively coupled plasma optical emission spectrometry (ETV-ICP-OES) [11] and high-resolution graphite furnace molecular absorption spectrometry (HR-GF-MAS) [12] have been used for the direct determination of F^- in different solid sample matrices. Even though direct analytical techniques are non-destructive, sensitive and rapid, they have limitations such as the need for sophisticated calibration curves, especially in the absence of matrixed-matched certified reference materials (CRMs), and evenly homogenous samples to obtain acceptably accurate and reproducible results, and they are also costly, which is a serious drawback for routine analysis in developing countries like South Africa [13]. To resolve some of the disadvantages of the direct analytical methods, researchers have made use of indirect analytical techniques such as fluoride-ion-selective electrode (F-ISE) measurement [14], gas chromatography (GC-MS) [15] and ion chromatography [16–18]. However, the indirect analytical techniques are only compatible with aqueous solutions; therefore, there is the requirement of a sample preparation step to convert solid matrices into solutions prior to analysis [8]. The most documented sample preparation methods for halogen determination in solid matrices are acid digestion [19] pyrohydrolysis [20], combustion in bombs [21] and microwave-induced combustion [22]. Classical combustion and wet digestion methods use different acidic reagents for digestion, which result in loss of F^- as volatile HF gas, and corrosive acidic matrices can cause interferences and damage nebulization systems and chromatographic columns. The nitrous oxides normally produced during acid digestion when using HNO_3 as a reagent are carcinogenic [8,22].

Therefore, the aim of the current study was to develop a greener sample preparation method prior to total F^- determination by using F-ISE potentiometric and IC analytical devices. To the best of our knowledge, this is the first time the use of water as the sole green reagent to digest toothpaste containing monofluorophosphate under microwave radiation has been reported. A fluoride-ion-selective electrode (F-ISE) device was selected due to its high sensitivity, selectivity, and simplicity [23,24]. The high selectivity of F-ISE measurement is enhanced using an electrode that is specifically designed for F^- ions with a wide range of concentration measurements [25–27]. Moreover, IC has rapidly developed over the years; therefore, reproducible determination of halides is widely reported to be possible in a single analytical run [28].

2. Experimental Method

2.1. Materials, Reagents and Standards

Ultrapure deionized water with a resistivity of 18.2 MΩ cm was obtained by using Millipore RiOs 5 reverse osmosis and a Millipore Milli-Q academic deionizer system (Millipore, Bedford, MA, USA). All glass and plasticware were soaked in soapy water overnight, washed and rinsed with deionized water. Analytical-grade NaF salt purchased from Sigma-Aldrich, Modderfontein, South Africa, was used to prepare stock solution. A series of dilutions was conducted by using deionized water to prepare appropriate fluoride calibration standards for both F-ISE and IC measurements. A total of twelve samples of South African toothpaste (8 for adults and 4 for toddlers) were purchased in local supermarkets, Florida Park, Johannesburg, South Africa (see Table 1). All prepared solutions were stored in polyethylene flasks at ±4 °C.

2.2. Instrumentation

A microwave digester system from Anton Paar Multiwave that allows a maximum of twenty-four 50 mL microwave digester polytetrafluoroethylene (PTFE-TFM) samples and a 24 HVT rotor, including a control, was used to digest the toothpaste samples. Each vessel assembly had a vessel body, safety relief valve, cap, and venting hole for pressure release to prevent explosions. The microwave system was also equipped with an advanced reaction sensor for the temperature (maximum 250 °C) regulator.

Table 1. Toothpaste samples with varied F^- concentration levels as declared by the manufacturer.

Toothpaste Sample	Declared F^- Concentration (mg/kg)	Age Group	F^- Source
A	1450	Adult	Na_2FPO_3
B	1000	Adult	Na_2FPO_3
C	1450	Adult	Na_2FPO_3
D	1450	Adult	Na_2FPO_3
E	1000	Adult	Na_2FPO_3
F	1450	Adult	Na_2FPO_3
G	1450	Adult	Na_2FPO_3
H	1450	Adult	Na_2FPO_3
I	500	Toddler	Na_2FPO_3
J	500	Toddler	Na_2FPO_3
K	500	Toddler	Na_2FPO_3
L	500	Toddler	Na_2FPO_3

The F-ISE was used throughout the experiments for the total determination of fluoride ions in toothpaste samples. The choice of F-ISE was motivated by the fact that it is cost-effective, available, sensitive, selective, and portable [29,30]. Determination of fluoride ion concentration with F-ISE potentiometry was carried out by using a CPI-502 Ion Meter and an ion-selective electrode (ISE) from Analytical Solutions, South Africa. To prepare for TISAB solution, 2.5 g of NH_4Cl was accurately weighed and mixed with 100 mL of deionized water in a volumetric flask. The 1000 mol/L solution of NaF was prepared by dissolving 0.4199 g salt in 1 L deionized water. From this solution, two appropriate dilutions were conducted to prepare two standard solutions of 0.0001 mol/L and 0.00001 mol/L NaF, which were used for the two-point calibration [31].

An Eco Ion chromatography instrument (Metrohm, Switzerland) was used for validation purposes, and the instrumental conditions were as follows: data source, conductivity detector 1 (Eco IC 1); recording time, 12.00 min; integration, automatic type; column type, Metrosep A Supp 17-150/4.0; elution composition, 17^{-5} mM Na_2CO_3 and 0.2 mM $NaHCO_3$; flow rate, 1.200 mL/min; pressure, 14.41 MPa. The fluoride calibration standards in the range of 0.2–10 mg/L were prepared through appropriate dilutions from 1000 mg/L F^- stock solution purchased from Sigma-Aldritch, South Africa.

2.3. Water-Based Microwave-Assisted Digestion (WB-MAD) Procedure

The current study was performed on twelve different brands of toothpaste. The toothpaste brands contained monofluorophosphate, as indicated by the manufacturers. All samples were prepared by accurately weighing known aliquots of toothpaste (previously homogenized in the case of striped toothpaste) and mixing with 10 mL of deionized water in a microwave Teflon vessel [32,33]. The latter was closed, and the digestion was conducted under optimum conditions. After digestion, the Teflon vessels were cooled at room temperature and digests were quantitatively transferred into 10 mL plastic volumetric flasks, which were topped up to the mark using deionized water. Thereafter, 5 mL of the digest solution was mixed with 5 mL of TISAB. The latter provides a constant ionic strength and similar diffusion potentials at the reference electrode in standard and test samples [34,35].

3. Results and Discussion

3.1. Optimization of Toothpaste Sample Mass

These experiments were carried out to examine the highest amount of toothpaste sample A feasible to be fully digested. It is pertinent to note that while optimizing sample amount, temperature and time were kept constant at 180 °C and 60 min, respectively. The results for this investigation are illustrated in Figure 1. The latter shows that satisfactory agreement (100.06–99.65%) was obtained when low toothpaste amounts (0.025–0.1 g) were weighed and mixed with 10 mL of deionized water. An increase in toothpaste amounts

(0.15, 0.20, 0.25 and 0.30 g) led to a decrease in the digestion efficiencies, which resulted in low agreements of 83.04, 73.89, 69.64 and 69.18%, respectively. Based on the above information, 0.05 g of toothpaste sample was then considered as the optimum mass for obtaining a clear digest with good precision (≤0.7%) and accuracy (≤96.56%).

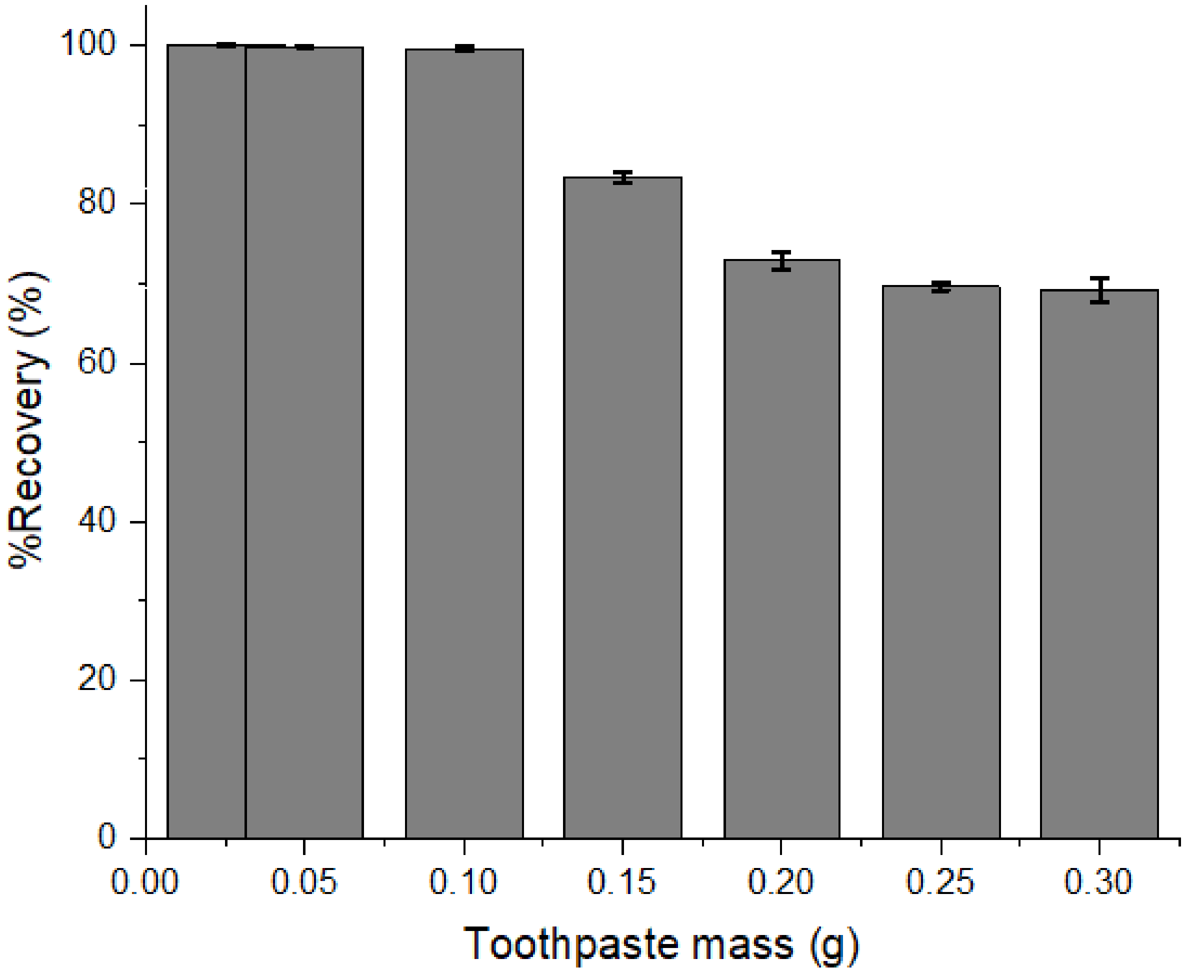

Figure 1. Influence of sample weight on fluoride determination in toothpaste samples using F-ISE after WB-MAD. Digestion conditions: digestion temperature, 180 °C; digestion time, 60 min; water volume, 10 mL and *n* = 3.

3.2. Optimization of Digestion Temperature

Since the amount of energy used for the digestion of sodium monofluorophosphate in the toothpaste sample is an important factor, five temperature levels (100, 120, 140, 160 and 180 °C) were evaluated. It is worth indicating that sample mass was kept at 0.05 g and time at 60 min. As can be observed in Figure 2, low agreements (50–67%) were obtained when toothpaste samples were subjected to lower temperatures of 100, 120 and 140 °C. These observations suggest that temperatures less than or equal to 140 °C are insufficient to break the covalent bond between phosphorus and fluoride in monofluorophosphate (Figure 3). Therefore, an increase in temperature to 180 °C drastically increased agreement from 50% to 100%. Thus, the optimum digestion temperature was 180 °C, as agreed in other studies in the literature [26,27]. Therefore, temperature was directly proportional to the digestion efficiency of toothpaste samples using deionized water.

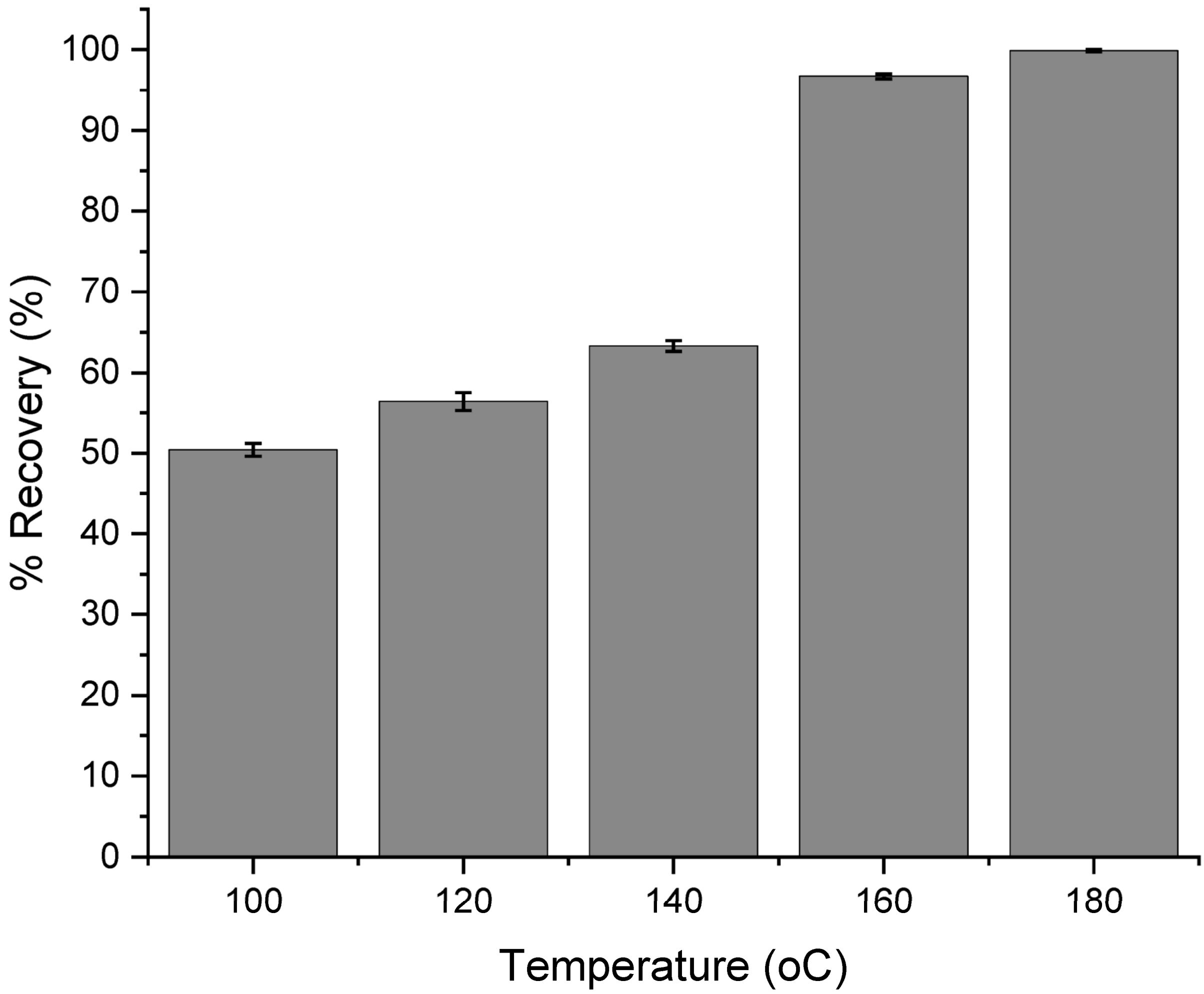

Figure 2. Influence of digestion temperature on fluoride determination in toothpaste samples using F-ISE after WB-MAD. Digestion conditions: sample amount, 0.05 g; digestion time, 60 min; water volume, 10 mL and *n* = 3.

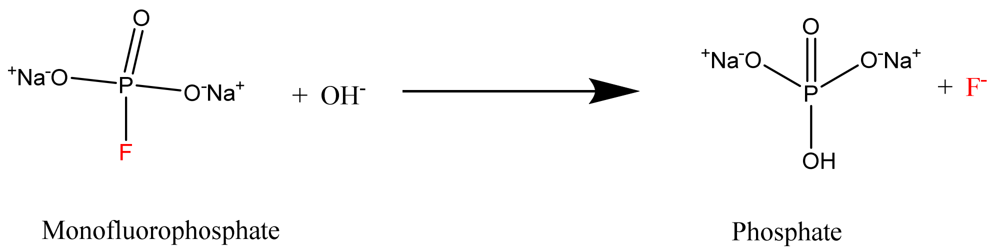

Figure 3. Break of the covalent bond between phosphorus and fluoride in monofluorophosphate.

3.3. Optimization of Digestion Time

Time is one of the critical parameters in any sample preparation method, because it is associated with cost, and less time-consuming digestion methods are appealing as they save energy [27,36]. Therefore, the different digestion time intervals of 10, 20, 30, 40 and 60 min were investigated, while sample mass (0.05 g) and digestion temperature (180 °C) were kept at optimum levels. The results presented in Figure 4 show that 60 min digestion time was the optimum, as it resulted in the highest agreement of 100%.

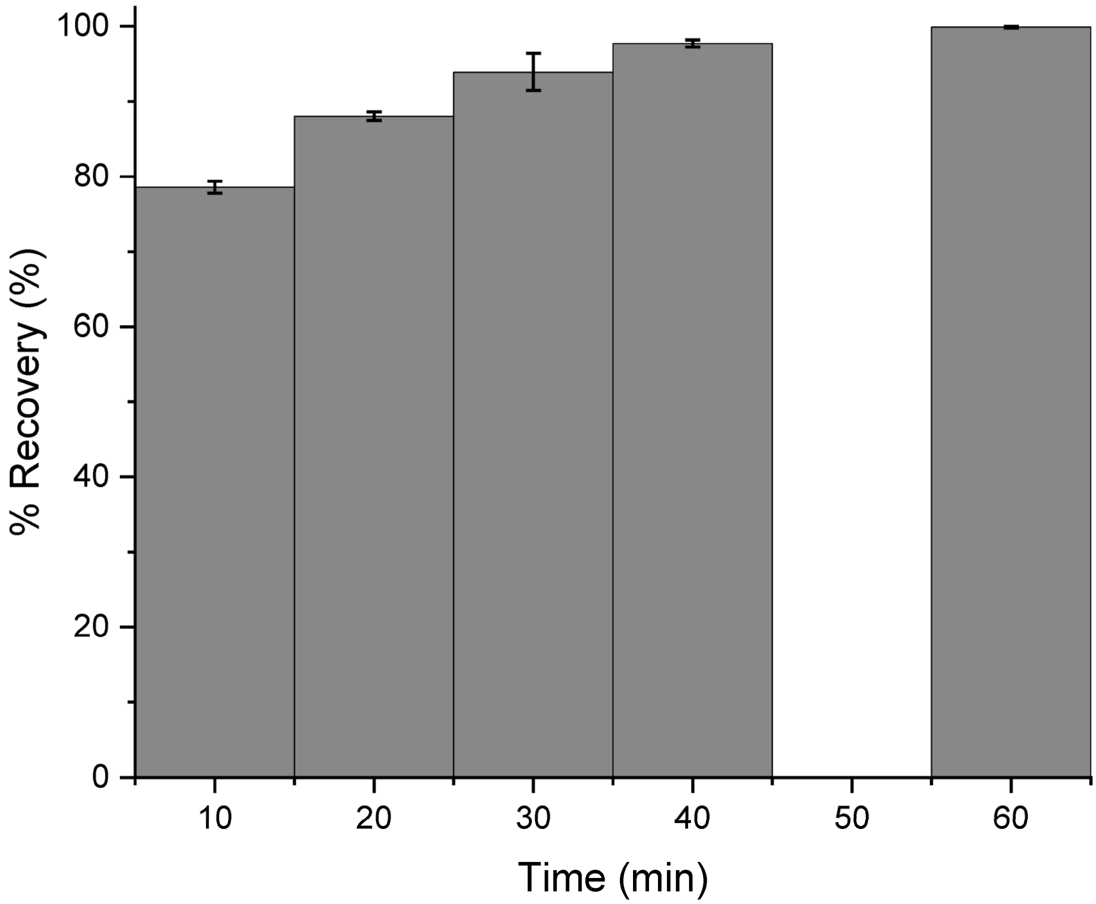

Figure 4. Influence of digestion time on fluoride determination in toothpaste samples using F-ISE after WB-MAD. Digestion conditions: sample amount, 0.05 g; digestion temperature, 180 °C; water volume, 10 mL and *n* = 3.

3.4. Analytical Performance of Water-Based Microwave-Assisted Digestion Method

Under the optimum conditions, analytical figures of merit for the proposed WB-MAD method were investigated. The studied parameters include sensitivity, correlation coefficient (R^2), limit of detection (LOD), Equation (2), limit of quantification (LOQ), Equation (3), method detection limit (MDL), Equation (4), method quantification limit (MQL), Equation (5), precision and accuracy. The LOD is the lowest signal that can be detected using the instrument, the LOQ is the lowest concentration that can be quantified using the instrument or using MQL and the MDL is the minimum measured concentration [37]. These analytical figures of merit are extremely important to determine whether the newly developed analytical method is more efficient than the ones used in previous studies [1]. Firstly, the calibration curve was obtained by analyzing a series of seven standard solutions prepared through WB-MAD followed by F-ISE analysis.

Figure 5 shows a linear least-squares fit plot of E_meas (mV) versus log [F^-], and the slope was found to be 56.397 mV. Therefore, the results suggest that the sensitivity for F^- was 56.397 mV. It is pertinent to note that for an ideal F-ISE, the cell potential is linearly related to the logarithm of the fluoride ion concentration ($[F^-]$) and should increase by 59.16 mV for every 10-fold decrease in the [F^-] [38,39]. In the present study, an increase of 59 mV in the cell potential was observed, and this is acceptable [38]. The other figures of merit were determined by using the standard deviation (SD) of 20 blank samples and their responses for F^-. The average of the twenty measurements was 0.0668 µg/kg and the standard deviation (SD) was 0.0104 mV. By comparing the obtained slope (56.397 mV) with the theoretical (57.93 mV) at 19 °C, it can be clearly seen that there is a deviation of around 2%, which is acceptable [39]. Furthermore, the observed analytical figures of merit presented in Table 2 were comparable with the literature reports, but with better accuracy and precision [39,40].

$$\textbf{Limit of detection (LOD)} = \frac{3 * \text{SD}}{\text{Method calibration slope}} \tag{1}$$

$$\textbf{Limit of quantification (LOQ)} = \frac{10 * \text{SD}}{\text{Method calibration slope}} \tag{2}$$

$$\textbf{Method detection limit (MDL)} = \frac{\text{LOD} * \text{Final volume}}{\text{Optimum mass}} \tag{3}$$

$$\textbf{Method quantification limit (MQL)} = \frac{\text{LOD} * \text{Final volume}}{\text{Optimum mass}} \tag{4}$$

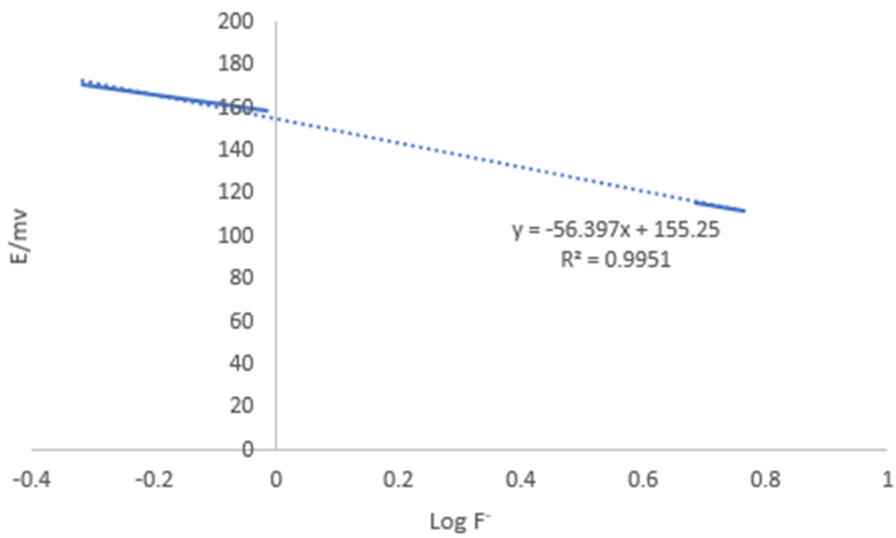

Figure 5. A two-point calibration plot of the mV reading for the diluted fluoride standards versus the log of the actual fluoride ion concentration.

Table 2. Determined analytical figures of merit for the proposed WB-MAD method using sample A. Digestion conditions: sample amount, 0.05 g; digestion time, 60 min; digestion temperature, 180 °C; water volume, 10 mL and *n* = 3.

Analytical Features	**Specification**
Correlation coefficient (R^2)	0.995
Standard deviation (SD) in mV	0.01039.
Limit of detection (LOD) in µg/kg	0.10070
Limit of quantification (LOQ) in µg/kg	0.33820
Method detection limit (MDL) in µg/kg	0.00302
Method quantification limit (MDQ) in µg/kg	0.01007
Precision based on intraday (%)	≤0.7
Accuracy (%)	≤96.56

3.5. Validation of Water-Based Microwave-Assisted Digestion Method

Firstly, the validation of the proposed method was conducted by comparing the fluoride concentration levels obtained through F-ISE after WB-MAD and classical microwave-assisted acid digestion (MAAD) of sample A. The latter made use of diluted HNO_3. The description of the literature-reported method is as follows: weigh 0.3 g of toothpaste sample and dissolve it in 10 mL of HNO_3 (0.05% HNO_3) for digestion at 190 °C, over 20 min [4]. The results are illustrated in Figure 6, where agreement of the literature-reported MAAD method was low (71.33 to 92.10%) compared to that of the WB-MAD method (96.56 to 99.88%) The low digestion efficiency of MAAD is attributed to the reaction of fluoride ions in the presence of acid, which forms HF, as illustrated in Figure 7 [8]. The HF gas is highly volatile, and it is easily released into the atmosphere [41].

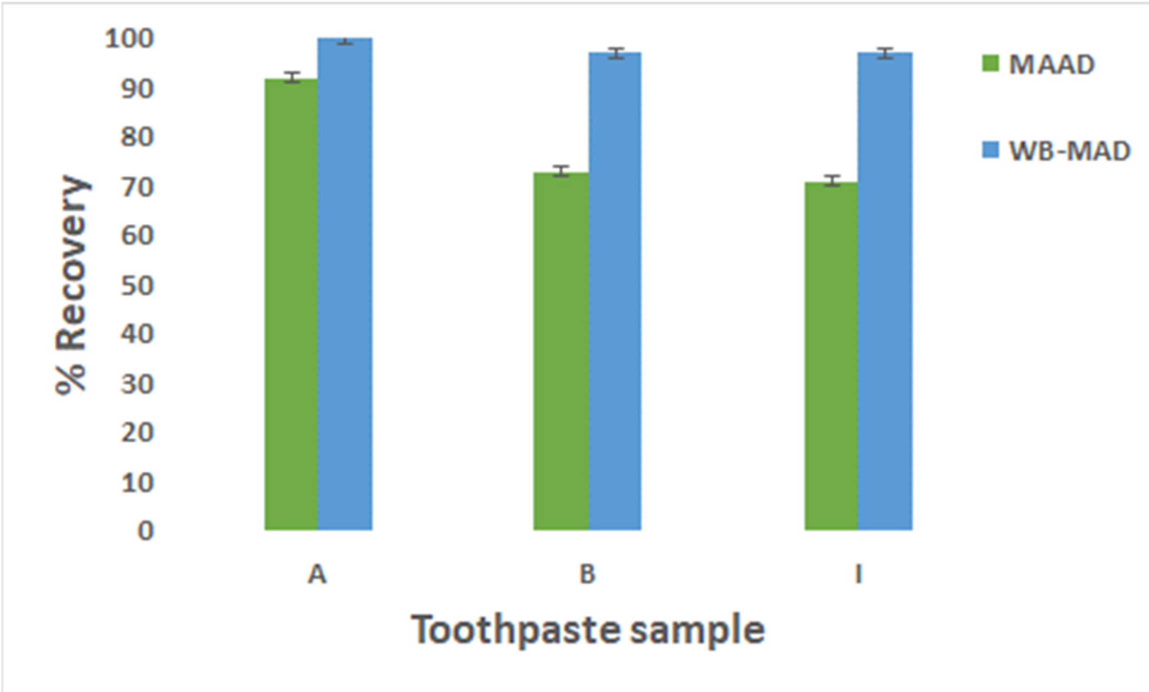

Figure 6. Comparison of microwave-assisted acid digestion (MAAD) with newly developed water-based microwave-assisted digestion (WB-MAD).

$$H^+ + F^- \longrightarrow HF$$

Figure 7. Reaction of fluoride in an acid environment to form HF.

3.6. Application of WB-MAD Method for the Determination of Fluoride in Twelve Different Toothpastes

The World Health Organization (WHO) established dental decay prevention by limiting concentration levels of fluoride ions to a maximum of 1500 mg/kg for adults and the maximum of 550 mg/kg for children [42]. In the interest of counterchecking whether the declared fluoride ions in the toothpaste brands that are used daily comply with the recommended concentrations established by WHO or not, twelve different brands of toothpaste were purchased in a South African local supermarket (sample A–L) and subjected to the optimum conditions of the proposed WB-MAD method. Table 3 shows that all F^- concentration levels detected using F-ISE after WB-MAD agree with the manufacturer's concentrations recorded on the product label and are within the acceptable ranges as prescribed by WHO [43–45]. Secondly, validation was carried out by comparing fluoride concentration levels obtained by using F-ISE and ion chromatography (IC) after the WB-MAD method. Table 3 shows that the F^- concentration levels obtained from IC and F-ISE were insignificantly different, with excellent precision. Furthermore, Figure 8 presents chromatograms of three different digests from toothpaste samples A, B and I. The F^- ions were eluted at 2.5 min, while Cl^- and $CO_3{}^{-2}$ ions were delayed and appeared at 4.3 and 8.4 min, respectively [41].

Table 3. Concentration levels of F⁻ determined in 12 toothpaste digests using ISE and IC.

Toothpaste Sample	F⁻ Content Determined Using ISE		F⁻ Content Determined Using IC		Declared F⁻ Concentration
	(mg/kg ± SD), *n* = 3	(%R)	(mg/kg ± SD), *n* = 3	(%R)	(mg/kg)
A	1448.36 ± 1.74	99.9	1443.34 ± 0.34	99.5	1450
B	970.21 ± 1.90	97.0	997.31 ± 0.36	99.7	1000
C	1452.13 ± 3.99	100.1	1447.17 ± 1.07	99.8	1450
D	1437.72 ± 4.34	99.2	1460.61 ± 2.17	100.7	1450
E	989.41 ± 3.78	98.9	908.01 ± 0.24	90.9	1000
F	1449.17 ± 2.86	99.9	1454.83 ± 3.53	100.3	1450
G	1353.31 ± 4.85	93.3	1445.76 ± 1.56	99.7	1450
H	1456.85 ± 4.76	100.5	1452.31 ± 0.84	100.2	1450
I	482.81 ± 0.103	96.6	508.22 ± 0.98	101.6	500
J	499.33 ± 1.70	99.9	495.65 ± 1.05	99.1	500
K	496.71 ± 1.25	99.2	518.44 ± 1.11	103.7	500
L	500.12 ± 1.05	100	497.01 ± 0.78	99.4	500

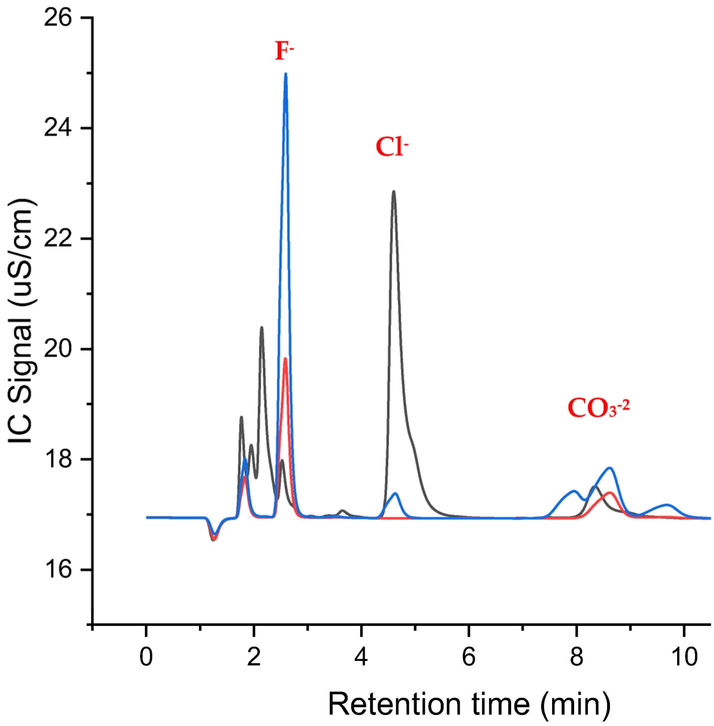

Figure 8. Chromatograms of digested toothpaste samples A (Blue), B (Red) and I (Black) showing different anionic peaks using a mixture of 5 × 10^{-3} M Na_2CO_3 and 0.2 × 10^{-3} M $NaHCO_3$ as an eluent, at a flow rate of 1.200 mL/min. The peak assignments are as follows: 1 is fluoride, 2 is chloride and 3 is carbonate.

4. Conclusions

The novel and greener WB-MAD method was successfully developed for complete digestion of toothpaste samples containing sodium monofluorophosphate prior to F⁻ determination using a fluoride-ion-selective electrode (F-ISE). The newly developed acid-free digestion method resulted in water-based digests that were also compatible with ion chromatographicanalysis. The proposed WB-MAD method was accurate (96.0–100.1%) and precise (≤0.7), with a low method detection limit of 0.0159 µg/kg. The F⁻ concentration levels in all the investigated samples (A–L) were within the regulation limits (500 to 1500 mg/kg) specified by the World Health Organization (WHO) and thereby safe for consumption by both toddlers and adults. The proposed WB-MAD method showed better accuracy (96.6 to 99.9%) compared to the classical microwave-assisted acid digestion method (MAAD) (71.3 to 92.1%). Moreover, Table 3 shows that the F^- concentration levels obtained from both F-ISE and IC were statistically insignificant. In view of the validation results and the figures of merit discussed, the WB-MAD method can be considered as an alternative to substitute the conventional acid digestion methods for decomposition of sodium monofluorophosphate (Na_2PO_3F) in any dental or oral hygiene products.

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References

1. Guimarães, I.C.; Rezende, C.C.; da Silva, J.A.F.; de Jesus, D.P. Simultaneous determination of free fluoride and monofluorophosphate in toothpaste by capillary electrophoresis with capacitively coupled contactless conductivity detection. *Talanta* **2009**, *78*, 1436–1439. [CrossRef]
2. Borremans, M.; Van Loco, J.; Van Den Meerssche, P.; Meunier, J.; Vrindts, E.; Goeyens, L. Analysis of fluoride in toothpastes on the Belgian market. *Int. J. Cosmet. Sci.* **2008**, *30*, 145–152. [CrossRef]
3. Iqbal, K.; Asmat, M.; Jawed, S.; Mushtaque, A.; Mohsin, F.; Hanif, S.; Sheikh, N. Role of different ingredients of tooth pastes and mouthwashes in oral health. *JPDA* **2011**, *20*, 163–170.
4. Gleisner, H.; Einax, J.W.; Morés, S.; Welz, B.; Carasek, E. A fast and accurate method for the determination of total and soluble fluorine in toothpaste using high-resolution graphite furnace molecular absorption spectrometry and its comparison with established techniques. *J. Pharm. Biomed. Anal.* **2011**, *54*, 1040–1046. [CrossRef] [PubMed]
5. Michalski, R.; Mathews, B. Simultaneous determination of fluoride and monofluorophosphate in toothpastes by supressed ion chromatography. *Cent. Eur. J. Chem.* **2006**, *4*, 798. [CrossRef]
6. Michalski, R. Ion chromatography as a reference method for determination of inorganic ions in water and wastewater. *Crit. Rev. Anal. Chem.* **2006**, *36*, 107–127. [CrossRef]
7. Xiang, Q.; Liang, Y.; Chen, L.; Wang, C.; Chen, B.; Chen, X.; Zhou, M. Effect of fluoride in drinking water on children's intelligence. *Floride* **2003**, *36*, 84–94.
8. Tjabadi, E.; Mketo, N. Recent developments for spectrometric, chromatographic and electroanalytical determination of the total sulfur and halogens in various matrices. *TrAC Trends Anal. Chem.* **2019**, *118*, 207–222. [CrossRef]
9. Tang, Z.; Zhou, R.; Hao, Z.; Zhang, W.; Li, Q.; Zeng, Q.; Li, X.; Zeng, X.; Liu, Y. Determination of fluorine in copper ore using laser-induced breakdown spectroscopy assisted by the SrF molecular emission band. *J. Anal. At. Spectrom.* **2020**, *35*, 754–761. [CrossRef]
10. Li, X.; Wang, Y.; Zhang, Q. Determination of halogen levels in marine geological samples. *Spectrosc. Lett.* **2016**, *49*, 151–154. [CrossRef]
11. Maung, P.; Beauchemin, D. Development of a method for the direct determination of fluorine in solid samples using electrothermal vaporization coupled to inductively coupled plasma optical emission spectrometry. *Anal. At. Spectrom.* **2020**, *35*, 1097–1102. [CrossRef]
12. Cadorim, H.R.; de Gois, J.S.; Borges, A.R.; Vale MG, R.; Welz, B.; Gleisner, H.; Ott, C. Determination of fluorine in copper concentrate via high-resolution graphite furnace molecular absorption spectrometry and direct solid sample analysis—Comparison of three target molecules. *Talanta* **2018**, *176*, 178–186. [CrossRef]

13. Machado, R.C.; Andrade, D.F.; Babos, D.V.; Castro, J.P.; Costa, V.C.; Sperança, M.A.; Garcia, J.A.; Gamela, R.R.; Pereira-Filho, E.R. Solid sampling: Advantages and challenges for chemical element determination-a critical review. *J. Anal. At. Spectrom.* **2020**, *35*, 54–77. [CrossRef]
14. Hoehne, L.; Picoloto, R.S.; Enders, M.S.; Druzian, G.T.; Muller, E.I.; Flores, E.M. Feasibility of pyrohydrolysis as a clean method for further fluorine determination by ISE and IC in high purity nuclear grade alumina. *Microchem. J.* **2019**, *146*, 645–649. [CrossRef]
15. Kaykhaii, M.; Ghalehno, M.H. Rapid and sensitive determination of fluoride in toothpaste and water samples using headspace single drop microextraction-gas chromatography. *Anal. Methods* **2013**, *5*, 5622–5626. [CrossRef]
16. Muhammad, N.; Zhang, Y.; Subhani, Q.; Intisar, A.; Mingli, Y.; Cui, H.; Zhu, Y. Comparative steam distillation based digestion of complex inorganic copper concentrates samples followed by ion chromatographic determination of halogens. *Microchem. J.* **2020**, *158*, 105176. [CrossRef]
17. Li, T.; Min, H.; Li, C.; Yan, C.; Zhang, L.; Liu, S. Simultaneous Determination of Trace Fluorine and Chlorine in Iron Ore by Combustion-Ion Chromatography (C-IC). *Anal. Lett.* **2021**, *54*, 2498–2508. [CrossRef]
18. Pereira, L.S.F.; Pedrotti, M.F.; Dalla Vecchia, P.; Pereira, J.S.F.; Flores, E.M.M. A simple and automated sample preparation system for subsequent halogens determination: Combustion followed by pyrohydrolysis. *Anal. Chimi. Acta* **2018**, *1010*, 29–36. [CrossRef] [PubMed]
19. He, T.; Xie, J.; Hu, Z.; Liu, T.; Zhang, W.; Chen, H.; Liu, Y.; Zong, K.; Li, M. A Rapid Acid Digestion Technique for the Simultaneous Determination of Bromine and Iodine in Fifty-Three Chinese Soils and Sediments by ICP-MS. *Geostand. Geoanal. Res.* **2018**, *42*, 309–318. [CrossRef]
20. Taflik, T.; Duarte, F.A.; Flores, L.M.; Antes, F.G.; Paniz, J.N.G.; Flores, M.M.; Dressler, V.L. Determination of bromine, fluorine and iodine in mineral supplements using pyrohydrolysis for sample preparation. *J. Braz. Chem. Soc.* **2012**, *23*, 488–495. [CrossRef]
21. Sredović Ignjatović, I.D.; Onjia, A.E.; Ignjatović, L.M.; Todorović, Ž.N.; Rajaković, L.V. Experimental Design Optimization of the Determination of Total Halogens in Coal by Combustion–Ion Chromatography. *Anal. Lett.* **2015**, *48*, 2597–2612. [CrossRef]
22. Mesko, M.F.; Balbinot, F.P.; Scaglioni, P.T.; Nascimento, M.S.; Picoloto, R.S.; da Costa, V.C. Determination of halogens and sulfur in honey: A green analytical method using a single analysis. *Anal. Bioanal. Chem.* **2020**, *412*, 6475–6484. [CrossRef] [PubMed]
23. Itota, T.; Carrick, T.E.; Rusby, S.; Al-Naimi, O.T.; Yoshiyama, M.; McCabe, J.F. Determination of fluoride ions released from resin-based dental materials using ion-selective electrode and ion chromatograph. *J. Dent.* **2004**, *32*, 117–122. [CrossRef] [PubMed]
24. Švarc-Gajić, J.; Stojanović, Z.; Vasiljević, I.; Kecojević, I. Determination of fluorides in pharmaceutical products for oral hygiene. *J. Food Drug Anal.* **2013**, *21*, 384–389. [CrossRef]
25. Yildiz, Y.; Patel, S.; Jan, A. Potentiometric determination of % fluoride ion content (w/v) in toothpastes by ion selective electrode. *Anal. Chem. Ind. J.* **2018**, *18*, 132.
26. Gupta, R.; Kumar, A.N.; Bandhu, S.; Gupta, S. Skeletal fluorosis mimicking seronegative arthritis. *Scand. J. Rheumatol.* **2007**, *36*, 154–155. [CrossRef] [PubMed]
27. Bralić, M.; Buljac, M.; Prkić, A.; Buzuk, M.; Brinić, S. Determination Fluoride in Products for Oral Hygiene Using Flow-Injection (FIA) and Continuous Analysis (CA) with HomeMade FISE. *Int. J. Electrochem. Sci.* **2015**, *10*, 2253–2264. [CrossRef]
28. Costa, V.C.; Pereira, R.M.; Mello, J.E.; Brum, J.R.; Picoloto, R.S.; Mesko, M.F. Indirect determination of chlorine and fluorine in eye shadow by ion chromatography after an eco-friendly sample preparation method based on combustion reaction. *Microchem. J.* **2019**, *150*, 104125. [CrossRef]
29. World Health Organization. *Preventing Disease through Healthy Environments: Inadequate or Excess Fluoride: A Major Public Health Concern*; WHO: Geneva, Switzerland, 2019. Available online: https://apps.who.int/iris/handle/10665/329484 (accessed on 1 June 2023).
30. Tokalioğlu, Ş.; Kartal, Ş.; Şahin, U. Determination of fluoride in various samples and some infusions using a fluoride selective electrode. *Turk. J. Chem.* **2004**, *28*, 203–212.
31. Introduction to Ion-Selective Measurement. Available online: https://us.vwr.com/assetsvc/asset/en_US/id/7979405/contents#:~:text=Calibration%2520%25E2%2580%2593%25202%252Dpoints,2%252Dpoint%2520calibration%2520is%2520sufficient (accessed on 1 June 2023).
32. Masanabo, N.M.; Zinyemba, O.; Mketo, N. A greener microwave-assisted extraction method for rapid spectroscopic determination of selected metals in river and freshwater sediment certified reference materials. *Int. J. Environ. Anal. Chem.* **2019**, *99*, 33–46. [CrossRef]
33. Mketo, N.; Nomngongo, P.N.; Ngila, J.C. Development of a novel and green microwave-assisted hydrogen peroxide digestion method for total sulphur quantitative extraction in coal samples prior to inductively coupled plasma-optical emission spectroscopy and ion chromatography determination. *Talanta* **2015**, *15*, 567–573. [CrossRef]
34. Patel, S.; Omid, N.; Zohoori, F.V.; Maguire, A.; Waldron, K.J.; Valentine, R.A. Comparison of total ionic strength adjustment buffers III and IV in the measurement of fluoride concentration of teas. *Nutr. Health* **2018**, *24*, 111–119. [CrossRef] [PubMed]
35. Forsido, T.; Ndibewu, P. Comparison of Different Total Ionic Strength Adjustment Buffer Compositions for Determination of Low Level Fluoride in Environmental Water Samples with Fluoride Ion Selective Electrode. *Res. Sq.* 2021, *preprint*. [CrossRef]
36. Johansson, R. Optimization. In *Numerical Python*; Apress: Berkeley, CA, USA, 2019. [CrossRef]
37. Bazaraa, M.S.; Shetty, C.M. *Nonlinear Programming: Theory and Algorithms*; John Wiley and Sons: Hoboken, NJ, USA, 1979.
38. Cheng, M.-D. Atmospheric chemistry of hydrogen fluoride. *J. Atmos. Chem.* **2018**, *75*, 1–16. [CrossRef]
39. Rundle, C.C. *A Beginners Guide to Ion-Selective Electrode Measurements*; Nico2000 Ltd.: London, UK, 2006.

40. Barzingi, A.N.A. Potentiometric determination of fluoride in various brands of toothpaste. *ZANCO J. Pure Appl. Sci. Off. Sci. J. Salahaddin Univ.* **2021**, *33*, 12–20. [CrossRef]
41. Farcas, F.; Chaussadent, T.; Fiaud, C.; Mabille, I. Determination of the sodium monofluorophosphate in a hardened cement paste by ion chromatography. *Anal. Chim. Acta* **2002**, *472*, 37–43. [CrossRef]
42. Skoog, D.A.; Holler, F.J.; Crouch, S.R. *Principles of Instrumental Analysis*, 7th ed.; Cengage Learning: New York, NY, USA, 2017; ISBN 978-1-305-57721-3.
43. WHO. *Summary of Principles for Evaluating Health Risks in Children Associated with Exposure to Chemicals*; World Health Organization: Geneva, Switzerland, 2011. Available online: https://apps.who.int/iris/handle/10665/44533 (accessed on 1 June 2023).
44. WHO. Fluorides. In *Air Quality Guidelines for Europe*, 2nd ed.; World Health Organization Regional Office for Europe: Copenhagen, Denmark, 2000; pp. 143–146.
45. WHO. *Guidelines for Drinking-Water Quality*, 4th ed.; Incorporating the First Addendum; World Health Organization: Geneva, Switzerland, 2017; pp. 370–373. Available online: https://apps.who.int/iris/bitstream/handle/10665/254637/9789241549950-eng.pdf (accessed on 1 June 2023).