Iodine determination in mineral water using ICP-MS: method development and analysis of brands available in Israeli stores

Vasiliy Rosen[a,*], **Orit Gal Garber**[a], **Yona Chen**[b],

[a]The Scientific Service Core Facility (ZBM Analytical Lab), The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel

[b]Department of Soil and Water Sciences, The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel

*Corresponding author. Email: vasiliyr@savion.huji.ac.il; icpaes@gmail.com

Abstract

Reliable iodine determination in drinking water samples has gained importance in the last few decades, mostly due to intensive use of both desalinized water that lacks several important nutritional elements, and bottled mineral water. ICP-MS is a sensitive, high-throughput method for iodine determination that must be performed under alkaline conditions because of the volatile nature of some iodine species. However, in water samples with high pH (>10), slow precipitation of calcium (Ca) and/or magnesium (Mg) carbonates leads to clogging of the ICP-MS nebulizer. We propose preventing this precipitation by adding the chelating agent ethylenediaminetetraacetic acid (EDTA) at 0.1% to a 2% ammonium hydroxide matrix. This concentration of EDTA sufficed for most drinking water samples studied, as long as a 1:1 molar ratio of EDTA to Ca+Mg concentration in the water was maintained. The limit of quantitation of the developed method for iodine was <0.1 µg L^{-1}. The average iodine concentration in various brands of bottled mineral water sold in Israel was relatively low (7.67 ± 6.38 µg I L^{-1}). Regular consumption of either desalinated water or bottled mineral water may induce iodine deficiency in Israeli consumers. Therefore, continuous follow-up of the iodine status in both tap and bottled water is strongly recommended.

Keywords: iodine, drinking water, ICP-MS, alkaline matrix, bottled water, desalinized water

1. Introduction

Iodine is a relatively rare element in the earth's crust, averaging around 0.45 mg kg^{-1} and usually found in minerals as the anion iodate (Neal et al., 2007). It occurs naturally in water in the form of iodide. Traces of iodine are produced by oxidation of iodide during water treatment (WHO, 2011). The micronutrient iodine is critical to good human health at all stages of life. It is essential for proper functioning of the thyroid, especially before and during pregnancy, to ensure normal development of the fetal and newborn brain (Oliveira et al., 2010; Ovadia et al., 2017). Estimates of the dietary requirement for adult humans range from 80 to 150 mg iodine (I) day^{-1}. Dietary deficiencies of iodine have been recorded in many parts of the world, most commonly resulting in severe adverse effects on neurological development (WHO, 2011). Nevertheless, no guidelines for iodine concentration in drinking water have been established to date because data available in the literature are inadequate to permit derivation of health-based guideline values, and determine lifetime minimum exposure to iodine through water (WHO, 2011). Rosborg and Kozisek (2015) suggested that although risk-reducing concentrations of iodide in drinking water are difficult to determine, they appear to range from 5 to 50 µg L^{-1}.

Several national surveys conducted in Israel have led to the conclusion that most Israelis, adults and children alike, do not consume enough iodine (Barzilai and Harris, 1965; Brand et al., 1961; Israel Ministry of Health, 2017; Sack et al., 2000).

An investigation conducted by Benbassat et al. (2004) in a coastal area in Israel with 102 subjects revealed what appeared to be satisfactory iodine intake in the population group studied, although mild deficiency might have occurred in up to 26% of this group. They also found the mean iodine concentration in manufactured mineral water to be only 7 ± 5.7 µg L^{-1} (Benbassat et al., 2004). In 2020, Israeli researchers conducted a cross-sectional study among 105 pregnant women living in an area primarily receiving desalinated drinking water (Rosen et al., 2020). It was found that this drinking water, with low iodine concentrations, provided only about 9% of the recommended daily iodine intake. These researchers also found that only 52% of the participating individuals took supplements containing iodine. Among those who did not take supplements, 92% had iodine deficiency.

Thus, one possible reason for the increase in iodine deficiency observed in recent years is the growing use of desalinated water in Israel, now constituting approximately 70–80% of the drinking and municipal water supply (Israel Ministry of Health, 2017; Rosen et al., 2020). Drinking water contains essential minerals that serve as micronutrients in human nutrition and in the food chain. Desalinated seawater is low in mineral content because minerals are removed during the desalination process, which is based on reverse osmosis. Consumption of drinking water with low concentrations of certain minerals, such as calcium (Ca), magnesium (Mg), iodine (I), and fluoride (F), may have adverse effects on health (Berman and Barnett-Itzhaki, 2020).

Among the iodine species found in water, the volatile species are molecular iodine (I_2) and organic iodides, and the nonvolatile species are I^-, HOI, I_3^- and IO_3^- . The volatile species formed in the aqueous phase can be transferred to the gas phase under prevailing conditions (Clément et al., 2007).

The primary species of iodine in water is most frequently determined by a titrimetric procedure which can be used for solutions containing 2–20 mg I L^{-1}. A leuco crystal violet method may be used to determine iodide or molecular iodine in water. This photometric method is applicable to iodide concentrations of 50–6000 μg L^{-1}; the detection limit for iodine is 10 μg L^{-1} (WHO, 2003). Another method is catalytic reaction based on the catalytic effect of iodide on the redox reaction between Ce^{4+} (yellow) and As^{3+}, which yields the colorless ions Ce^{3+} and As^{5+} (known as the Sandell–Kolthoff reaction) (Oliveira et al., 2010). Other analytical techniques that have been used include ion-selective electrodes, X-ray fluorescence spectrometry, neutron activation analysis, ion chromatography, gas chromatography mass spectrometry, and cathodic stripping voltammetry (Mesko et al., 2010).

The application of inductively coupled plasma mass spectrometry (ICP-MS) to iodine determination is considered difficult because the ionization efficiency of iodine is low, resulting in lower sensitivity. However, even though the sensitivity to iodine is lower than that to other elements, it is still higher than that of any other traditional method (Takaku et al., 1995). Today, ICP-MS is successfully used by many researchers for the determination of iodine in drinking water, and is considered a sufficiently sensitive and accurate high-throughput technique (Mesko et al., 2010; Larsen and Ludwigsen, 1997; Sayess and Reckhow, 2017; Todorov et al., 2018). Dilute nitric acid (1–2%) is usually used as the main matrix for elemental analysis in ICP-MS (EPA, 2014). However, this methodology cannot be applied for iodine determination. The main species of iodine in water samples, namely I^- and IO_3^-, have different volatilities in solution. Takaku et al. (1995) showed that the rate of I^{127} signal increase in an acidic solution was higher for the I^- form than the IO_3^- form with increasing nitric acid (HNO_3) concentration. This was because the population of free iodine (I_2) in the gas phase, which is vaporized from the fine drops of the sample mist in the spray chamber, increases with increasing acid concentration, due to increasing iodine volatility (Takaku et al., 1995). This phenomenon leads to a high memory effect and overestimation of iodine (Tagami and Uchida, 2005; Takaku et al., 1995).

Iodine vaporization is usually restricted by the addition of alkalis. In most cases, the substances used are sodium hydroxide, ammonium carbonate, tetramethyl ammonium hydroxide (TMAH) and ammonium solution (NH_4OH) (Gao et al., 2021; Takaku et al., 1995; Tagami and Uchida, 2005; Rasmussen et al., 2000; Oliveira et al., 2010; Flores et al., 2020). The last two chemicals are the most widely used. The standard method recommended by the US Food and Drug Administration (FDA, 2017) and used by many researchers not only for determination of iodine in foodstuffs, but also in drinking water samples, is based on the use of a TMAH alkaline matrix for iodine extraction and measurement by ICP-MS (Oliveira et al., 2010; Flores et al., 2020). However, TMAH is an extremely toxic chemical. In addition to alkalinity-related chemical burn, dermal exposure to TMAH may result in respiratory failure and/or sudden death (Lin et al., 2010). Exposure of rat skin to 2.38% or 25% TMAH generated LD_{50} values of 85.9 mg kg^{-1} and 28.7 mg kg^{-1}, respectively (Lee et al., 2011). Thus, an alternative “green” method should be sought. In several studies (Analytik Jena, 2015; Analytik Jena, 2020; Limchoowong et al., 2016), the use of 2–3% NH_4OH solution has been recommended to prevent iodine loss.

The goals of the present investigation were to: (i) develop a reliable method of iodine determination in different water samples using ICP-MS; and (ii) evaluate iodine status in the various brands of bottled mineral water available in the Israeli market.

2. Materials and methods

2.1. Reagents, instruments and samples

The following reagents were used to set up the proposed method: NH_4OH 25% (Merck, Germany); ethylenediaminetetraacetic acid (EDTA) disodium salt (Sigma-Aldrich, USA); deionized (DI) water (Milli-Q, <18 MΩ cm); iodine, ICP-grade stock standard (1000 mg L^{-1}, Sigma-Aldrich, USA); germanium (Ge), ICP-grade stock standard (1000 mg L^{-1}, Inorganic Ventures, USA), used as an internal standard; Triton X-100 (Merck, Germany); customized standard ICP-grade mixture of Ca, Mg, sodium (Na), potassium (K), sulfur (S) (1000 mg L^{-1}, AccuStandard, USA).

A PlasmaQuant Elite ICP-MS spectrometer (Analytik Jena, Germany) was used for the determination of iodine concentrations in mineral water samples. All analyses were conducted in an optimized sensitivity mode that was set up using a manual optimization routine (Supplementary Table S1 and Supplementary Fig. S1). Since no interference influencing the ^{127}I isotope is expected, no collision or reaction gas was applied to manage potential interference (Analytik Jena, 2015). Internal standard ^{72}Ge was used at 10 µg L^{-1}. The internal standard solution was prepared with the following matrix: 2% NH_4OH, 0.1% EDTA, and 0.01% Triton X-100 (w/w).

The HR dual-view ICP-OES PQ9000 (Analytik Jena), equipped with concentric nebulizer and cyclonic spray chamber, was used for macroelement concentration measurements in the mineral water samples. The method's limit of quantitation (LOQ) and calibration parameters are presented in Supplementary Fig. S2 and Supplementary Table S2.

JMP 16.1.0 (SAS Institute, USA) was used for statistical calculations.

To develop the procedure for iodine determination, we used various brands of bottled mineral water that is available commercially in Israel. According to the Nature Resources Committee of the State of Israel, there are about 10 local and imported bottled water brands on the market. The local producers are: Ein Gedi (market share 20%), Mei Eden (37%), Neviot (26.5%) and Tempo (12%). Tempo also produces distilled mineralized water—Aqua Nova brand—and imports the San Benedetto brand. Other imported brands (Evian, San Pellegrino, and others) maintain a market share of about 4.5% (Firshtman and Weiner, 2013). San Pellegrino and Tempo water was carbonated (sparkling) and pretreated in a UV bath (10 min in “degas” mode) prior to ICP-OES/MS analysis. Other samples were of still water.

2.2. Preliminary experiment: solution stability study

We used 2% NH_4OH as an alkaline matrix (matrix A) for calibration standard preparation, internal standard preparation (with the addition of 0.01% Triton X-100), and water sample dilution (at least 2-fold). The pH of the diluted samples was controlled using pH indicator strips (Merck, pH range 5–14), as the volume of each prepared sample (2–5 mL) was too low to use a pH meter; moreover, only approximate pH levels needed to be detected (>10), because introducing acidic solution into the ICP-MS leads to a strong iodine memory effect. The analytical calibration curve was built using the following iodine concentrations: 0.1, 0.5, 1, 5 and 10 µg L^{-1}. The calibration parameters were: $r = 0.998$, LOQ = 0.01 µg I L^{-1}, and intensity of 1 µg I L^{-1} = 150.5K cps; these fit the FDA method criteria (FDA, 2017). The first series of iodine determinations in drinking water was successful (data not shown), but we quickly faced the problem of nebulizer clogging. The problem of precipitate formation in water samples with elevated pH has been reported, for example, by Tagami (Tagami and Uchida, 2005). We assumed that this is due to precipitation of insoluble carbonates (primarily of Ca and Mg) at high pH. The pH value for calcium carbonate ($CaCO_3$) precipitation has been shown to range from 8.1 to 8.8 (Korchef and Touaibi, 2020). The increased pH causes HCO_3^- ion conversion to CO_3^{2-} ion and rapid precipitation as solid $CaCO_3$ according to the following equation (Korchef and Touaibi, 2020; Saksono et al., 2010):

$$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3\,(s) + CO_2 + H_2O \qquad (1)$$

Solution temperature, time of exposure, and concentrations of CO_2 and other ions in the solution (for example, Fe^{2+}, SO_4^{2-} and Mg^{2+}, which may inhibit $CaCO_3$ formation) all influence the stability of the mineral water sample at elevated pH (Coto et al., 2012; Korchef and Touaibi, 2020; Boyd, 2012).

To prevent the precipitation of Ca and Mg as carbonates, we proposed adding EDTA to the matrix solution. The large EDTA molecule forms a complex with the calcium ion according to the following equation (Bruttel et al., 2015):

$$Ca^{2+} + Na_2H_2EDTA + 2H_2O \rightarrow [CaEDTA]^{2-} + 2Na^{+} + 2H_3O^{+} \qquad (2)$$

The same is true for the Mg^{2+} ion. A concentration of 0.1% w/w EDTA was selected (2.67 mM) as recommended in the ICP-MS manufacturer for applications dedicated to direct iodine determination in biological matrices using alkali dilution (Analytik Jena, 2020). Thus, matrix E, containing 2% NH_4OH and 0.1% EDTA, was used for calibration and internal standard preparation, as well as for water sample dilution.

The following experiment was conducted to verify our suggestion for preventing carbonate precipitation: eight brands of bottled mineral water, bought in local supermarkets, and one sample of tap water (city of Rehovot, Israel) were separated into three groups: matrices W (water as is), A (diluted 2-fold with 2% NH_4OH), and E (diluted 2-fold with a solution of 2% NH_4OH + 0.1% EDTA). The samples were mixed thoroughly and stored in closed polypropylene flasks overnight at room temperature (approximately 23–25 ºC).

After the overnight exposure, precipitate was observed in all matrix A samples and only in San Pellegrino mineral water with matrix E. All samples were filtered using a 0.45-µm Millex filter and analyzed by ICP-OES. The following elements were measured: Ca, K, Mg, Na and S. The cations of these elements (and the sulfate anion) are responsible for mineral water hardness and are considered macrominerals (Rosborg and Kozisek, 2015). The W matrix samples were acidified with HNO_3 (1%) prior to analysis for matrix matching. Matrices A and E were analyzed as is. To correct for possible matrix effects in samples with high pH and EDTA addition, a spike (fortification) with concentrations that were 3–10 times higher than the analyte concentration was employed for samples in groups A and E. The high-concentration spike (100 mg L^{-1}) demonstrated recovery of about 100% (no correction was applied to the results); however, the low-concentration spike (10 mg L^{-1}) demonstrated recovery of about 83% for Ca and Mg. This means that when matrices A and E were analyzed by ICP-OES using the external calibration method, a signal decrease of about 15% was observed for the low concentrations measured (several milligrams per liter or less). In this case, a spike correction factor was applied to the results. The concentrations of all macroelements measured in matrices W, A and E are presented in the Supplementary Table S3.

The concentration of each element was submitted to one-way ANOVA to reveal possible differences among the three matrices studied. For S and K, there were no significant differences between the three groups ($p = 0.95$ and 0.74, respectively). The t-test employed on the Na results did not show any difference between matrices W and A (matrix E was not analyzed for Na because of the high Na content in the added EDTA).

3. Results and discussion

3.1. Solution stability at elevated pH

A significant difference was only recorded for Ca and Mg ($p < 0.001$, Table 1), indicating that these two elements precipitated as carbonates at the elevated pH values.

Table 1

One-way ANOVA and post-hoc test results for macroelement concentrations in matrices W, A and E.

Element	Matrix	F-ratio	*p*-value	Tukey–Kramer test
Ca	W	8.7348	0.0005	a[1]
	A			b
	E			a
Mg[2]	W	91.58	<0.0001	a
	A			b
	E			a

[1] Matrices sharing the same letters do not differ significantly at an alpha level of 0.05.

[2] The concentration of Mg in the San Pellegrino sample was excluded from the statistical calculations.

3.1.1. Calcium

For Ca concentrations, Tukey–Kramer test showed a significant difference between pairs W–A and A–E, but not between W–E. Thus, addition of EDTA prevented the formation of insoluble $CaCO_3$. A decrease of about 10% Ca concentration was observed in matrix E (Table 2), which could also be attributed to analysis uncertainty due to the difference between W and E matrices (high pH and EDTA addition). In the sample of San Pellegrino water, the decrease in Ca concentration was even more pronounced (Table 2), but note that the concentration of macrominerals in the San Pellegrino mineral water was about 2–3 times higher than in the other investigated samples (Figs. 1, 2). The reaction between EDTA and Ca(Mg) ions proceeded at a molar ratio of 1:1 (Bruttel et al., 2015). The sum of Ca+Mg in all studied waters was 0.85–2.5 mM, whereas in San Pellegrino it was 6.15 mM Ca+Mg. The EDTA concentration added to the samples (ratio 1:1) was 2.67 mM (Supplementary Table S4), which was sufficient to react with all Ca and Mg in all water samples excluding the San Pellegrino sample, where at least double the concentration (or quantity) of EDTA solution would be needed to prevent carbonate precipitation. Consequently, when determining iodine content in highly mineralized waters, additional analytical effort is needed to select the appropriate EDTA concentration that will prevent the formation of insoluble Ca and Mg carbonates. However, it must be noted that in the frame of our investigation, analysis of the San Pellegrino sample shortly after pH elevation did not lead to quick carbonate formation or the resultant ICP-MS nebulizer clogging.

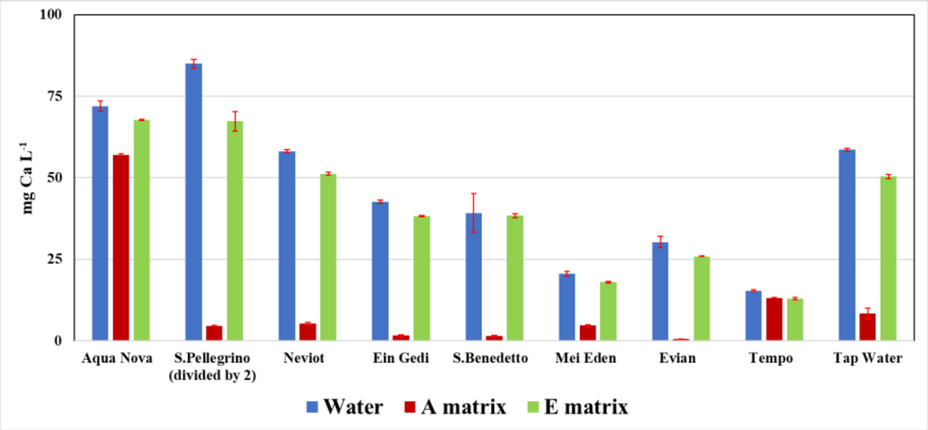

Fig. 1. Calcium concentrations in W, A and E matrices.

Table 2

Decrease in calcium concentration (% of W matrix concentration) after overnight exposure to high pH.

Water brand	Decrease in matrix (% of matrix W)	
	Matrix A	Matrix E
Aqua Nova	20.7	5.9
San Pellegrino	94.6	20.8
Neviot	90.9	12.0
Ein Gedi	96.1	10.3
San Benedetto	96.2	12.5
Mei Eden	77.2	12.6
Evian	98.3	14.3
Tempo	14.4	15.5
Tap water	85.7	14.0

3.1.2. Magnesium

One-way ANOVA and Tukey–Kramer test revealed differences between the three matrices for Mg (Table 3) that were similar to those found for Ca, but the calculations were performed without data from the San Pellegrino sample.

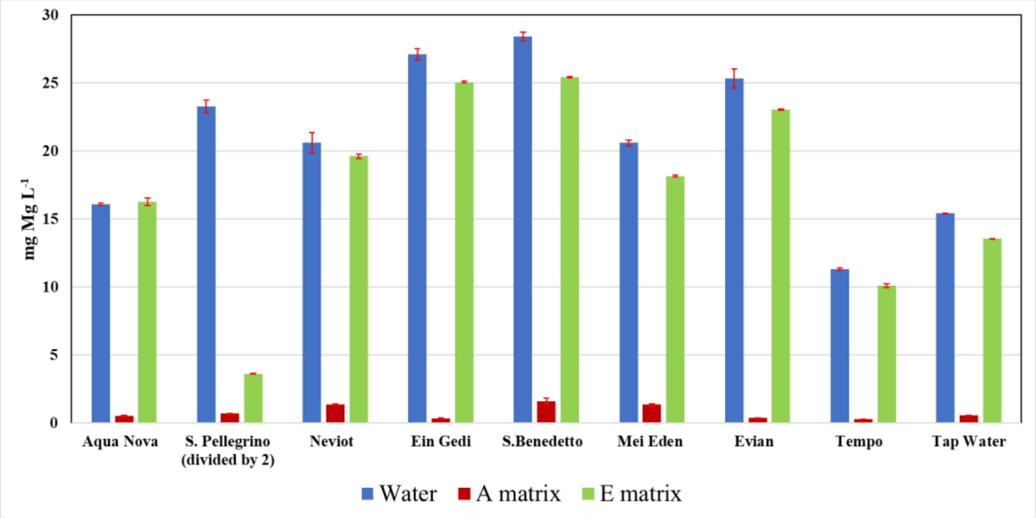

Fig. 2. Magnesium concentrations in W, A and E matrices.

Table 3

Decrease in magnesium concentration (% of W matrix concentration) after overnight exposure to high pH level.

Water brand	Decrease in matrix (% of matrix W)	
	Matrix A	Matrix E
Aqua Nova	96.7	no decrease
San Pellegrino	97.1	84.4
Neviot	93.3	4.7
Ein Gedi	98.7	7.5
San Benedetto	94.4	10.4
Mei Eden	93.3	11.9
Evian	98.5	9.0
Tempo	97.7	10.8
Tap water	96.5	12.3

The San Pellegrino sample showed a strong decrease in Mg concentration in both the A and E groups (Table 3), whereas other samples decreased in group A at a rate of 93–98% and in group E, 4.7–12% (Table 3). When the San Pellegrino sample was excluded from the ANOVA calculations, the difference between W and E groups was insignificant. It could be concluded that the behavior of Mg was similar to that of Ca in water samples under elevated pH conditions.

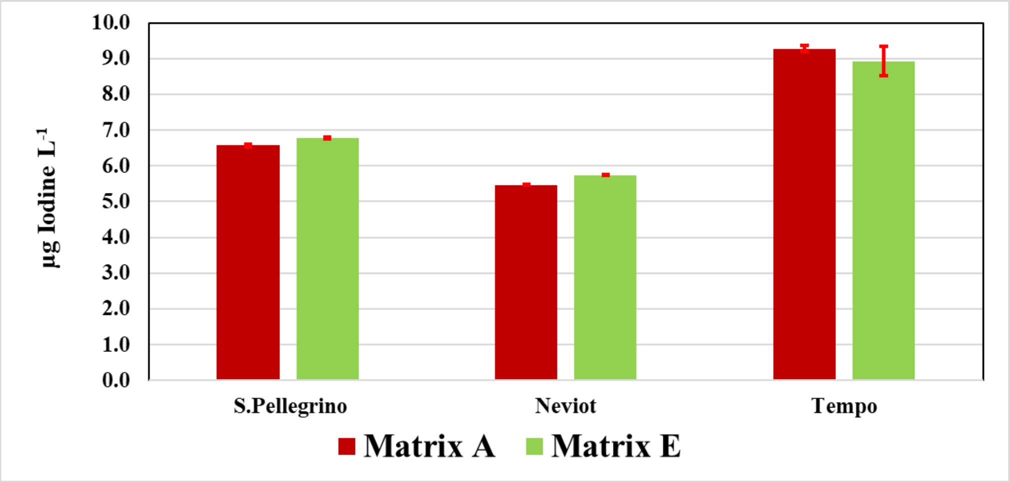

Fig. 3. Iodine concentration in A and E matrices of three mineral waters.

3.1.3. Iodine

Iodine concentration was determined by ICP-MS in the samples diluted with matrices A and E after overnight incubation (Fig. 3). This measurement was performed for brands San Pellegrino, Neviot and Tempo. No significant difference in iodine concentration was found by t-test between the two matrices (p = 0.95). It could be concluded that EDTA use has no effect on the iodine concentration in the tested water samples.

4. “Green” method development and validation

Based on the presented data, it was concluded that the 2-fold dilution of mineral water samples (or more, if Ca+Mg was high [>2.67 mM] and/or high iodine concentrations were expected) with matrix E (2% NH_4OH + 0.1% EDTA) can serve as a general sample-pretreatment method for iodine determination using ICP-MS. This matrix is less toxic than the TMAH that is recommended in standard methods and may therefore be considered a “green” alternative.

We used a series of iodine concentrations for calibration (0.1–10 µg L^{-1}; section 2.2). The iodine stock was diluted with matrix E. The calibration was performed daily with a freshly prepared set of standards. The following calibration parameters were obtained: r = 1.0, limit of detection (LOD) = 0.004 µg L^{-1}, LOQ = 0.013 µg L^{-1}, Background Equivalent Concentration = 0.077 µg L^{-1} (each value is the average of 4 successive working days).

To evaluate the actual LOQ, a series of low-concentration iodine standards (<1 µg L^{-1}) was measured (Table 4).

Table 4

Actual LOQ determination for iodine measured by ICP-MS in matrix E.

Standard	Measured concentration (µg I L^{-1})	SD	%RSD	c/s	S/N
Blank solution	0.0004	0.0006	136	11458	
0.025 µg I L^{-1}	0.0215	0.0013	5.91	14261	1.2
0.05 µg I L^{-1}	0.0471	0.0026	5.45	18007	1.6
0.1 µg I L^{-1}	0.1062	0.0022	2.1	28809	2.5
1 µg I L^{-1}	0.9674	0.0105	1.08	163207	14.2

% RSD – relative standard deviation (%); c/s – signal intensity, counts per second; S/N – signal to noise ratio.

The RSD of the five measurements dropped from 5.45 to 2.1% between the iodine concentrations of 0.05 and 0.1 µg L^{-1}. Taking into consideration the memory effect, a concentration of 0.05 µg I L^{-1} should be assigned as the instrument LOQ for matrix E. Because the method LOQ considers the water sample dilution, in the case of 2-fold dilution, it should be assigned as 0.1 µg L^{-1}.

Table 5

Evaluation of iodine determination method accuracy, using spike.

Sample diluted 2-fold			Added spike	Recovery
	Avg.	SD	(µg I L^{-1})	(%)
Evian	0.6877	0.0131	1.0	97
San Benedetto	1.7597	0.0249	5.0	95
Mei Eden	3.1133	0.0867	10.0	100
Tap water	0.8529	0.0354	5.0	100

Avg – average of five measurements.

To evaluate the method accuracy, a portion of iodine standard solution was added to several water samples, diluted 2-fold with matrix E. The added spike concentration was 2–3 times higher than the measured sample concentration. The recovery value was 95–100% (Table 5).

The precision of the method was determined by measuring the iodine concentration in 10 samples of Tempo water diluted 2-fold with matrix E. The result was about 4.2 µg I L^{-1}, which is approximately the middle of the calibration curve (0–10 µg I L^{-1}). The final calculated result was 8.43 ± 0.08 µg I L^{-1} (n = 10) and precision, expressed as RSD (%), was 0.997.

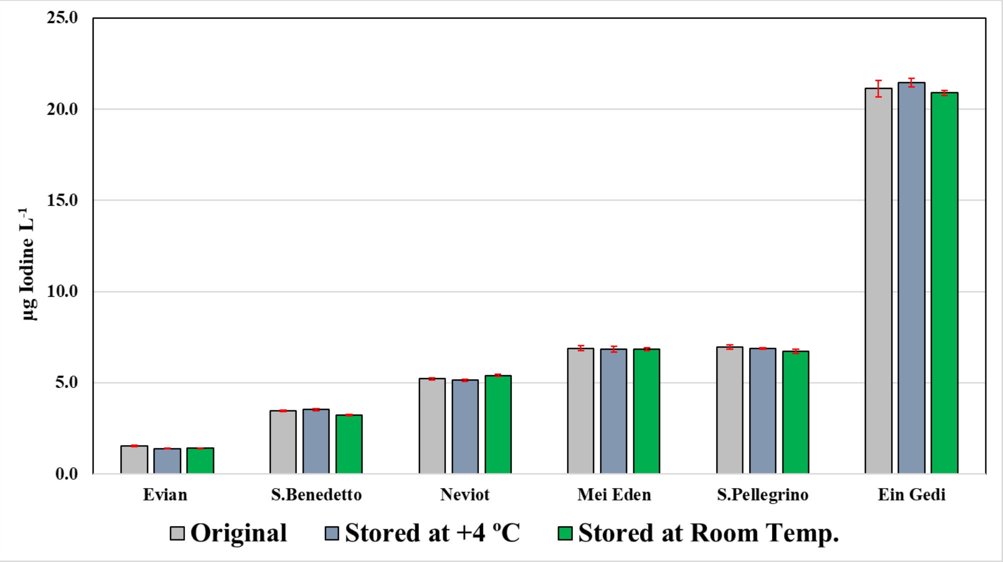

Fig. 4. Stability of iodine in the mineral water samples stored for 2 weeks under different conditions.

To evaluate the stability of iodine in mineral water, the following experiment was conducted: six samples of mineral water were divided into three groups: (1) original sample diluted 2-fold with matrix E and analyzed as described above; (2) a second undiluted group stored in closed polypropylene flasks at 4 ºC; and (3) a third undiluted portion stored in the same flasks for 2 weeks at room temperature (about 23 ºC). The results of the iodine analysis of all three groups are presented in Fig. 4 (samples of groups 2 and 3 were diluted 2-fold with matrix E just before the ICP-MS measurement). One-way ANOVA did not reveal any significant difference between the tested groups ($p = 0.999$). It could be concluded that samples of mineral water for iodine determination can be placed in polypropylene flasks and stored without addition of any chemical for at least 2 weeks at either room temperature or 4 ºC.

The detailed "green" protocol for iodine measurement in alkali media using ICP-MS is presented in the Supplementary File 1.

5. Iodine concentration in bottled mineral water available on the Israel market

The average result for the seven mineral water brands analyzed (excluding Aqua Nova which was found to be <LOQ) was 7.67 ± 6.38 µg I L^{-1}, consistent with Benbassat (2004), where four local and one imported brand of mineral water available in Israel were

studied. Iodine intake from drinking water depends on its concentration in the water. Gao et al. (2021) compared the intake of iodine between two groups of pregnant women: the first group consumed drinking water containing <10 µg I L^{-1} and the second consumed drinking water containing 50–99 µg I L^{-1}. The rate of contribution to total iodine intake increased from 3.0% in the first group to 45.7% in the second group (Gao et al., 2021). The bulk of the daily iodine requirement (around 80%) is from food, the remainder from drinking water. However, the range of iodine concentrations in drinking water identified as goitrous in many studies is about 5–10 µg L^{-1} or less (Smedley, 2000). From the data in Table 6, it can be concluded that the concentration of iodine in tap water samples and in most mineral water brands can be considered low. If the analyzed samples are the primary source of drinking water for Israeli citizens, we can predict a high likelihood of iodine deficiency.

The total iodine concentration in sea and ocean waters is about 50–60 µg L^{-1} (Tsunogai and Henmi, 1971; Ito et al., 2009; Smedley, 2000). Our result (60.0 ± 1.25 µg I L^{-1}) corresponds with this, suggesting that the proposed analytical method provides data that are within reason.

Table 6

Iodine concentration found in bottled mineral water available in the Israeli market and in several miscellaneous water samples.

Sample	μg I L^{-1}	
	Avg[1]	SD
Bottled mineral water		
Aqua Nova	<0.1	
Evian	1.53	0.03
San Benedetto	3.47	0.03
Neviot	5.22	0.07
Mei Eden	6.89	0.13
San Pellegrino	6.96	0.12
Tempo	8.46	0.11
Ein Gedi	21.13	0.45
Miscellaneous samples		
Milli-Q DI water	<0.1	
Ion-exchange column DI water	<0.1	
Tap water (Faculty campus, Rehovot)	2.99	0.06
Tami Bar water (Faculty campus)	3.14	0.07
Sea water[2] (Mediterranean Sea)	60.00	1.25

[1] Average of five measurements.

[2] Sea water was sampled from the coast of Rishon LeZion and analyzed under 500-fold dilution with an alkali matrix, then this diluted sample, containing 0.12 μg I L^{-1}, was spiked with 1 μg I L^{-1} standard, and recovery of 94.5% was found.

6. Conclusions

- An accurate and precise method of iodine determination in drinking water using ICP-MS was developed. The method LOQ (considering 2-fold dilution of the sample and possible memory effect) was <0.1 µg I L^{-1}. Use of an alkaline matrix (2% NH_4OH + 0.1% EDTA) for sample dilution and calibration standard preparation prevented carbonate precipitation and, as a result, nebulizer clogging.
- Sampling of the bottled mineral water brands available in the Israeli market demonstrated relatively low average iodine content. The single tap water sample showed even lower iodine concentration.
- Because tap water and bottled mineral water are the primary drinking water sources in Israel, an additional investigation of iodine content in tap water is considered necessary. We conclude that the evaluation of iodine concentration in the end user's tap water, and of the consistency of tap water iodine concentration with time, and an analysis of water produced by desalination facilities, are essential and appropriate and can be achieved using the developed iodine determination method.

Acknowledgements

We gratefully acknowledge Yuliana Andrushchenko, M.Sc., for her effort and contribution to the laboratory analyses performed in this study, and Camille Vainstein (“Camille Vainstein Scientific Copy Editing”) for providing excellent language support.

Research funding

This research did not receive any specific grant from a funding agency — public, commercial, or in the nonprofit sector.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

References

Analytik Jena, 2015. Application Note: Iodine analysis in biological matrices using the PlasmaQuant MS. Jena, Germany.

Barzilai, D., Harris, P., 1965. The problem of endemic goiter in Wadi Ara and the Jordan Valley - northern Israel. Isr J Med Sci 1, 62-70. PMID: 14252800

Benbassat, C., Tsvetov, G., Schindel, B., Hod, M., Blonder, Y., Sela, B.A., 2004. Assessment of iodine intake in the Israel coastal area. Isr Med Assoc J 6(2), 75-77. PMID: 14986461

Berman, T., Barnett-Itzhaki, Z., 2020. Environmental Health in Israel 2020, Israel Ministry of Health, Jerusalem. https://www.ehf.org.il/sites/default/files/Env_Health_Israel_2020_Eng.pdf. Accessed on September 17, 2021.

Boyd, V., 2012. The effect of calcium and magnesium on carbonate mineral precipitation during reactive transport in a model subsurface pore structure. M.Sc. Thesis. University of Illinois at Urbana-Champaign Urbana, Illinois. https://core.ac.uk/download/pdf/10201015.pdf. Accessed on August 24, 2021.

Brand, N., Gedalia, I., Jungreis, E., Levitus, Z., Maayan, M., 1961. Endemic goiter in Upper Galilee. Isr Med J 20, 206-214. PMID: 13872462.

Bruttel, P., Kalkman, I., Meier, L., 2015. Complexometric (Chelometric) Titrations, Metrohm, Herisau, Switzerland. https://partners.metrohm.com/GetDocumentPublic?action=get_dms_document&docid=2416715. Accessed on April 10, 2021.

Clément, B., Cantrel, L., Ducros, G., Funke, F., Herranz, L., Rydl, A., Weber, G., Wren, C., 2007. State of the art report on iodine chemistry. Nuclear Energy Agency Committee on the Safety of Nuclear Installations. https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/035/44035206.pdf?r=1 Accessed on January 29, 2021.

Coto, B., Martos, C., Peña, J.L., Rodríguez, R., Pastor, G., 2012. Effects in the solubility of $CaCO_3$: Experimental study and model description. Fluid Phase Equilibria 324, 1-7. https://doi.org/10.1016/j.fluid.2012.03.020.

EPA, U.S., 2014. Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry, Revision 2., U.S. EPA, Washington, DC. https://www.epa.gov/esam/epa-method-6020b-sw-846-inductively-coupled-plasma-mass-spectrometry. Accessed on December 14, 2021.

FDA, 2017. Inductively Coupled Plasma-Mass Spectrometric determination of iodine in food using tetramethyl ammonium hydroxide extraction. Official Methods of Analysis of AOAC International., U.S. Food and Drug Administration. https://www.fda.gov/media/103112/download. Accessed on September 27, 2021.

Firshtman, C. , Weiner, T., 2013. The economic rationale for imposing royalties on the use of natural mineral water (in Hebrew). Committee, N.R. (ed). https://www.gov.il/BlobFolder/unit/nature_resources_committee/he/Vaadot_ahchud_NatureResourcesCommittee_HazagatEmdotTzibur_MineralWater.pptx. Accessed on February 23, 2021.

Flores, E.M.M., Mello, P.A., Krzyzaniak, S.R., Cauduro, V.H., Picoloto, R.S., 2020. Challenges and trends for halogen determination by inductively coupled plasma mass spectrometry: A review. Rapid Communications in Mass Spectrometry 34(S3), e8727. 1-19. https://doi.org/10.1002/rcm.8727.

Gao, M., Chen, W., Dong, S., Chen, Y., Zhang, Q., Sun, H., Zhang, Y., Wu, W., Pan, Z., Gao, S., Lin, L., Shen, J., Tan, L., Wang, G., Zhang, W., 2021. Assessing the impact of drinking water iodine concentrations on the iodine intake of Chinese pregnant women living in areas with restricted iodized salt supply. European Journal of Nutrition 60(2), 1023-1030. DOI: 10.1007/s00394-020-02308-y.

Israel Ministry of Health, 2017. Iodine nutrition and iodine survey in drinking water sources (in Hebrew). Israel Ministry of Health, Jerusalem, Israel. https://www.health.gov.il/PublicationsFiles/IodineMarch2017.pdf. Accessed on April 21, 2021.

Ito, K., Hirokawa, T., Preedy, V.R., Burrow, G.N., Watson, R., 2009. Comprehensive handbook of iodine. Academic Press, San Diego, USA. 1334 p.

Analytik Jena. 2020. Application Note: Multi-element analysis of biological materials by icp-ms using alkali dilution. Jena, Germany. https://www.analytik-jena.com/fileadmin/import/assets/12562392_AppNote_ICPMS_0017_multielement_body_fluids_en.pdf. Accessed on September 22, 2021.

Korchef, A., Touaibi, M., 2020. Effect of pH and temperature on calcium carbonate precipitation by CO_2 removal from iron-rich water. Water and Environment Journal 34(3), 331-341. https://doi.org/10.1111/wej.12467.

Larsen, E.H., Ludwigsen, M.B., 1997. Determination of iodine in food-related certified reference materials using wet ashing and detection by Inductively Coupled Plasma Mass Spectrometry. Journal of Analytical Atomic Spectrometry 12(4), 435-439. DOI https://doi.org/10.1039/A607581I.

Lee, C.H., Wang, C.L., Lin, H.F., Chai, C.Y., Hong, M.Y., Ho, C.K., 2011. Toxicity of tetramethylammonium hydroxide: review of two fatal cases of dermal exposure and development of an animal model. Toxicol Ind Health 27(6), 497-503. DOI: 10.1177/0748233710391990.

Limchoowong, N., Sricharoen, P., Techawongstien, S., Kongsri, S., Chanthai, S. 2016. A green extraction of trace iodine in table salts, vegetables, and food products prior to analysis by Inductively Coupled Plasma Optical Emission Spectrometry. Journal of the Brazilian Chemical Society 28, 540-546. https://doi.org/10.5935/0103-5053.20160193.

Lin, C.C., Yang, C.C., Ger, J., Deng, J.F., Hung, D.Z., 2010. Tetramethylammonium hydroxide poisoning. Clin Toxicol (Phila) 48(3), 213-217. DOI: 10.3109/15563651003627777.

Mesko, M.F., Mello, P.A., Bizzi, C.A., Dressler, V.L., Knapp, G., Flores, É.M.M., 2010. Iodine determination in food by inductively coupled plasma mass spectrometry after digestion by microwave-induced combustion. Analytical and Bioanalytical Chemistry 398(2), 1125-1131. DOI:10.1007/s00216-010-3766-9.

Neal, C., Neal, M., Wickham, H., Hill, L., Harman, S., 2007. Dissolved iodine in rainfall, cloud, stream and groundwater in the Plynlimon area of mid-Wales. Hydrol. Earth Syst. Sci. 11(1), 283-293. https://doi.org/10.5194/hess-11-283-2007.

Oliveira, A.A., Trevizan, L.C., Nóbrega, J.A. 2010. Review: Iodine determination by Inductively Coupled Plasma Spectrometry. Applied Spectroscopy Reviews 45(6), 447-473. https://doi.org/10.1080/05704928.2010.502207.

Ovadia, Y.S., Arbelle, J.E., Gefel, D., Brik, H., Wolf, T., Nadler, V., Hunziker, S., Zimmermann, M.B., Troen, A.M., 2017. First Israeli national iodine survey demonstrates iodine deficiency among school-aged children and pregnant women. Thyroid 27(8), 1083-1091. DOI: 10.1089/thy.2017.0251.

Rasmussen, L.B., Larsen, E.H., Ovesen, L. 2000. Iodine content in drinking water and other beverages in Denmark. European Journal of Clinical Nutrition 54(1), 57-60. https://doi.org/10.1038/sj.ejcn.1600893.

Rosborg, I., Kozisek, F., 2015. Drinking water minerals and mineral balance: importance, health significance, safety precautions. Springer International Publishing, Switzerland. 137 p. DOI 10.1007/978-3-319-09593-6.

Rosen, S.R., Ovadia, Y.S., Anteby, E.Y., Fytlovich, S., Aharoni, D., Zamir, D., Gefel, D., Shenhav, S., 2020. Low intake of iodized salt and iodine containing supplements among pregnant women with apparently insufficient iodine status - time to change policy? Israel Journal of Health Policy Research 9(1), 9, 1-12. DOI: 10.1186/s13584-020-00367-4.

Sack, J., Kaiserman, I., Tulchinsky, T., Harel, G. and Gutekunst, R. 2000. Geographic variation in groundwater iodine and iodine deficiency in Israel, The West Bank and Gaza. J Pediatr Endocrinol Metab 13(2), 185-190. DOI: 10.1515/jpem.2000.13.2.185.

Saksono, N., Yuliusman, Y., Bismo, S., Soemantojo, R., Manaf, A., 2009. Effects of pH on calcium carbonate precipitation under magnetic field. Makara Journal of Technology; Vol 13, No 2, 79-85. http://journal.ui.ac.id/technology/journal/article/download/479/255. Accessed on November 15, 2021.

Sayess, R., Reckhow, D.A., 2017. An improved method for total organic iodine in drinking water. Water Res., 108, 250-259. DOI: 10.1016/j.watres.2016.10.079.

Smedley, P., 2000 Water quality fact sheet: Iodine, 4 pp., British Geological Survey. http://nora.nerc.ac.uk/id/eprint/516302/1/Iodine.pdf. Accessed on August, 23, 2021.

Tagami, K., Uchida, S., 2005. Sample storage conditions and holding times for the determination of total iodine in natural water samples by ICP-MS. Atomic Spectroscopy 26(6), 209-214. DOI: 10.46770/AS.2005.06.002.

Takaku, Y., Shimamura, T., Masuda, K., Igarashi, Y., 1995. Iodine determination in natural and tap water using Inductively Coupled Plasma Mass Spectrometry. Analytical Sciences 11(5), 823-827. DOI: 10.2116/analsci.11.823.

Todorov, T.I., Smith, T., Abdalla, A., Mapulanga, S., Holmes, P., Hamilton, M., Lewis, T., McDonald, M., 2018. Comparison of ICP-MS and Spectrophotometry Methods for the Analysis of Iodine in 2013 US FDA Total Diet Study Samples. Food Analytical Methods 11(11), 3211-3223. https://doi.org/10.1007/s12161-018-1301-3.

Tsunogai, S., Henmi, T., 1971. Iodine in the surface water of the ocean. Journal of the Oceanographical Society of Japan 27(2), 67-72. https://doi.org/10.1007/BF02109332.

WHO, 2003. Iodine in Drinking-water: Background document for development of WHO Guidelines for Drinking-water Quality. https://www.who.int/water_sanitation_health/dwq/chemicals/iodine.pdf. Accessed on January, 23, 2021.

WHO, 2011. Guidelines for Drinking-water Quality (4th edition), WHO. https://www.ncbi.nlm.nih.gov/books/NBK442376. Accessed on December, 15, 2020.