Chilean J. Agric. Anim. Sci., ex Agro-Ciencia (2024) 40(3): 485-493.
https://doi.org/10.29393/ CHJAAS40-40EATE70040

ISSN 0719-3890 online

EFFECT OF AGRONOMIC BIOFORTIFIATION WITH IODINE ON THE YIELD AND NUTRACEUTICAL QUALITY OF SALADETTE TOMATO (*Solanum lycopersicum* L.)

Tomás Juan Álvaro Cervantes-Vázquez[1a], Pablo Preciado-Rangel[2a], Erika Lagunes-Fortiz[3a], Cirilo Vázquez-Vázquez[1b], María Gabriela Cervantes-Vázquez[1c], Manuel Fortis-Hernández[2b*], and Edgar O. Rueda-Puente[4a*]

[1a] Universidad Juárez del Estado de Durango, Facultad de Agricultura y Zootecnia. Carretera Gómez Palacio-Tlahualilo km 35, ejido Venecia. 35111 Gómez Palacio, Durango, Mexico
https://orcid.org/0000-0003-0479-1404
[2a] Tecnológico Nacional de México, Instituto Tecnológico de Torreón (ITT), Torreón, Coahuila, 27170, Mexico
https://orcid.org/0000-0002-3450-4739
[3a] Autonomous University of Chapingo, Phytotechnics Department, Carretera Mexico-Texcoco km 38.5 Chapingo, Texcoco 56230, State of Mexico, Mexico
https://orcid.org/0000-0002-6961-4284
[1b] Universidad Juárez del Estado de Durango, Facultad de Agricultura y Zootecnia. Carretera Gómez Palacio-Tlahualilo km 35, ejido Venecia. 35111 Gómez Palacio, Durango, Mexico
https://orcid.org/0000-0002-8545-8381
[1c] Universidad Juárez del Estado de Durango, Facultad de Agricultura y Zootecnia. Carretera Gómez Palacio-Tlahualilo km 35, ejido Venecia. 35111 Gómez Palacio, Durango, Mexico
https://orcid.org/0000-0003-0402-3894
[2b*] Tecnologico Nacional de México, Instituto Tecnológico de Torreón (ITT), Torreón, Coahuila, 27170, Mexico
https://orcid.org/0000-0002-7374-8779
[4a*] Universidad de Sonora, Departamento de Agricultura y Ganadería, Boulevard Luis Encinas y Rosales s/n, Colonia Centro, Hermosillo, Sonora C.P. 83000, Mexico
https://orcid.org/0000-0002-9724-0558
* Corresponding author: fortismanuel@hotmail.com; edgar.rueda@unison.mx

ABSTRACT

Iodine is not considered an essential nutrient for terrestrial plants like tomato. However, it can increase the concentration of secondary metabolites as a reactive mechanism to oxidative stress in tomato fruit. In humans, iodine is essential for thyroid metabolism and the development of cognitive abilities, being associated with lower risks of certain types of cancer. The objective of this research was to evaluate the effect of foliar applications of iodine on the yield, commercial and nutraceutical quality, and iodine concentration in tomato fruits. The treatments were five increasing concentrations of potassium iodide (0, 5, 10, 15 and 20 μM L^{-1}). The results showed that the foliar application of high doses of iodine improved crop yield, but had no influence on some commercial quality variables, such as soluble solids and firmness. Nutraceutical quality concentrations improved, except for lycopene content, which decreased with foliar applications of iodine. Therefore, iodine biofortification can be a viable alternative to improve the nutritional quality of tomato fruits, being a potential strategy to reduce or prevent iodine deficiency.

Keywords: *Solanum lycopersicum* L., potassium iodide, antioxidants, phenols, lycopene.

Received: September 8, 2024 Accepted: November 30, 2024

INTRODUCTION

Biofortified foods can be obtained through different approaches such as agronomic practices (Malézieux et al., 2024), with biofortification being a sustainable and profitable strategy for agricultural production (Panwar et al., 2024). Specifically, biofortification is the process of increasing the concentration of essential elements in the edible part of harvested products through agronomic intervention, being recognized as an effective way to combat iodine deficiency (Duborská et al., 2020; Gulyas et al 2024). Biofortification with microelements has proved useful to increase minerals and bioactive compounds in different crops such as chili, lettuce, carrot and tomato (Li et al., 2017; Buendía-García et al., 2021; Rakoczy-Lelek et al., 2021; Lima et al., 2023). There are 30 microelements essential for public health in the development and growth of children; however, the global deficiency of vitamin A, iodine and iron is especially worrying in developing countries, which underscores the need for effective strategies to increase the content of these micronutrients (Latham, 2002). Micronutrient deficiency affects around 2 billion people worldwide (Krela-Kaźmierczak et al., 2021). Iodine is required in recommended daily doses of 150 μg for adults (Landini et al., 2011), being a necessary microelement in the human diet for the synthesis of thyroid hormones, as well as for the induction and modulation of thyroid autoimmunity (Mikulska et al., 2022).

Tomato crop has been biofortified with inorganic chemical forms (KI and KIO_3) (Medrano-Macías et al., 2016; Lima et al., 2023; Mejía-Ramírez et al., 2023) and organic forms (iodine benzoates, acid iodosalicylic) (Halka et al., 2018). The most effective is the inorganic form KI, since the iodide is distributed more easily in the upper parts of the plants due to it its simpler structure, which results in greater absorption (Halka et al., 2020). In the case of potassium iodide, biofortification would allow obtaining plants with a greater antioxidant capacity and greater tolerance to stress, in addition to substantially improving the nutritional value of their fruits when applied in low concentrations (Fuentes et al., 2022; Halka et al., 2018). Favorable responses have been observed with the application of iodine by foliar spray in cereals and tomato fruits (Cakmak et al., 2017; Somma et al., 2024), particularly considering the complex interactions of this element with the components of the soil. In fact, it has been shown that iodine is capable of being absorbed by the aerial structures (waxy cuticle) of the plant with high efficiency (Suh et al., 2002) due to the high permeability of the cuticle around the guard cells (Eichert and Goldbach, 2008). Additionally, higher absorption rates have been reported when a surfactant is added to the iodine solution. Therefore, the present study aimed to evaluate the effect of foliar applications of iodine on the yield, commercial and nutraceutical quality, and iodine concentration of tomato fruits.

MATERIALS AND METHODS

The work was carried out at the Torreon Technological Institute (ITT), Torreon, Coahuila, Mexico (26°30′15″N, 103°22′07″W, altitude 1120 m). Five increasing doses of KI were evaluated: 0, 5, 10, 15 and 20 μM L^{-1}, potassium iodide (KI) (Fagalab ®), which was dissolved in tridistilled water (TQE ®), adding a surfactant (Charlotte Chemical Inc. ®), adherent (Cofolmex ®) and acidifying (Spander Pluss ®) agent for application for agricultural use. The applications were made in the mornings using a spray bottle, applying the product to the entire plant at 15-day intervals. A completely randomized experimental design was used with five repetitions per treatment.

Sahel hybrid Saladette type tomato plants (Syngenta ®) were used. The plants were germinated under shade netting in 200-cavity polyethylene germination trays, using peat moss (Floragard ®) and vermiculite (Hidroflora ®) as a substrate. The transplant was carried out 47 days after sowing (DAS), when the seedlings presented six true leaves. Black plastic hydroponic gutters (Nature Hydro ®) of 20x20x200 cm in size (height, width and length) were filled with substrate using a mixture of sand and perlite in a ratio of 80:20, respectively. The sand was sterilized with a 5% sulfuric acid solution, allowed to stand for 24 hours, and then washed with tridistilled water (TQE ®).

The plants were guided to a single stem, and pruning was carried out by eliminating the axillary buds to improve aeration and light penetration in the lower part of the plants. Nutrient solution (Steiner, 1984) was applied based on fertilizers: MKP, $CaNO_3$, $MgNO\text{-}_3$ and KNO_3. The Steiner solution was applied in three physiological stages with different concentrations, from the moment of transplantation to harvest (Table 1).

The irrigation applied throughout the experiment was a function of the water demand of the crop for each phenological stage, considering the climatic factors during the study period. The plants were irrigated from the moment of transplant at a rate of 250 mL of solution daily per plant, applying up to 1.2 L day^{-1}, for a period of 15 days. At 65 days after transplanting (DAT), the first fruits were harvested based on their commercial maturity.

The variables evaluated were performance, commercial quality, and nutraceutical quality. Firmness was determined for each fruit with a penetrometer (Fruit Hardness Tester FHT200); total soluble solids (TSS) using a manual refractometer (Master Refractometer Automatic Atago); and weight and size with a digital vernier (Sendowtek model LCD IP54). For nutraceutical quality, the extracts were obtained using the method of Molina-Quijada et al. (2010). The antioxidant capacity was determined using the in vitro DPPH+ method (Brand-Williams et al., 1995). Total phenolic compounds were measured using a modification of the Folin-Ciocalteu method (Singleton et al., 1999), while total flavonoid content was determined using the technique described by Lamaison and Carnet (1990). In addition, lycopene concentration was measured according to the methodology proposed by Perkins-Veazie et al. (2001) and Fish et al. (2002). For the determination of iodine in the fruit, the catalytic method by plasma mass spectrometry (ICP-MS) was used (Krishna et al., 1992; Landini et al., 2011).

For foliar sampling, fully developed mature leaves without any damage were collected from the middle part of the plant during the flowering stage of the crop, selecting two leaves from each of the repetitions and forming a composite sample for each treatment. Subsequently, the leaves were oven-dried at 70 °C on brown paper and then macerated in a mortar. Cu, Fe, Mn, Zn and Ni were quantified in the atomic absorption spectrophotometer (AAS, iCE 3000 Series, Thermo Scientific, Waltham, MA, USA) (Alcantar and Sandoval, 1999).

The results obtained were analyzed by an analysis of variance, while means were compared with the Tukey test ($P \leq 0.5$), using the SAS statistical package version 9.1 (SAS, 1990).

RESULTS AND DISCUSSION

The analysis of variance showed significant differences ($P \leq 0.05$) in terms of equatorial diameter, polar diameter and fruit weight. This indicates that iodine applications influenced the development of tomato plants, generating good-sized fruits with weight ranges from 44.09 g to 51.91 g. As observed in Table 2, which shows the comparison of means of these variables, all treatments with different doses of iodine were statistically different from the control.

The treatment with 20 μM L^{-1} of iodine exceeded the control by 13.70% and 25% in terms of polar diameter and weight of the fruit, respectively. Regarding soluble solids, the trend was reversed, high concentrations of iodine decreased the concentration of sugars in the fruit. This agrees with Halka et al. (2019), who found that sugar content decreased with foliar application at doses of 5, 10 and 50 μM L^{-1}. Lima et al. (2023) mentioned that the increase in soluble solids in tomato fruit can be attributed mainly to an environmental factor, such as water stress and to a lesser extent to KI, reporting that the doses used improved the quality parameters of the fruit. Furthermore, Halka et al. (2018) and Andrade-Sifuentes et al. (2024) pointed out that KI doses of 25 μM L^{-1} and 10 mM L^{-1} applied in tomato and melon, respectively, do not lead to damage to plants or a decrease in yield, and found that doses higher than 25 μM L^{-1} may trigger symptoms of toxicity, including chlorosis or wilting plants. Córtes-Flores et al. (2016) reported that applications of 50 mM L^{-1} in pepper crops produced plants with smaller leaves and some toxicity symptoms. Similar results have been reported in the biofortification of lettuce since doses of 40 mM L^{-1} decreased plant growth and biomass production (Blasco et al., 2008).

Regarding nutraceutical quality, the results obtained showed significant statistical differences ($P \leq 0.05$) between the different concentrations of iodine. In addition, the treatment with 20 μM L^{-1} recorded the highest antioxidant capacity, surpassing the control by 32%, whereas the results of the treatments with 10 and 15 μM L^{-1} iodine were statistically equal, showing an upward trend with increasing concentrations of the nutrient (Table 3). These results agree with those of Kiferle et al. (2013), who reported that the

Table 1. Nutrient solution used for tomato cultivation.

	mg L^{-1}								
Cultivation stage (DAT)	**N-NO_3**	**P**	**K**	**Ca**	**Mg**	**Zn**	**Fe**	**Mn**	**B**
Planting-flowering (0-47)	60	101	65	48	6	0.5	1	0.3	0.3
Flowering-start of harvest (47-65)	142	96	154	114	15	0.6	1	0.3	0.3
Harvest (65-198)	165	67	198	110	23	0.9	2	0.4	0.4

DAT: days after transplanting.

Table 2. Effect of foliar applications of iodine (KI) on commercial parameters and yield of tomato fruits produced under shade netting.

KI (μM L-1)	Diameter (mm) Polar	Diameter (mm) Equatorial	Firmness (N)	Soluble solids (°Brix)	Fruit weight (g)	Performance (g/plant)
0	51.24 ± 1.338b*	36.65 ± 1.281bc	4.04 ± 0.406a	6.12 ± 0.340ab	41.37 ± 4.204b	1489.32 ± 151.33a
5	53.63 ± 3.626a	34.66 ± 1.700c	3.97 ± 592a	6.48 ± 0.123a	44.09 ± 4.946ab	1519.52 ± 149.58a
10	57.79 ± 1.487a	38.52 ± 1.082ab	3.93 ± 0.608a	5.97 ± 0.577ab	44.86 ± 2.356a	1570.38 ± 82.47a
15	57.25 ± 2.801a	39.38 ± 1.156c	4.19 ± 0.277a	6.01 ± 0.190ab	50.06 ± 3.069a	1581.60 ± 90.67a
20	58.27 ± 2.794a	41.12 ± 2.129ab	4.20 ± 0.460a	5.86 ± 0.617b	51.91 ± 3.143a	1599.80 ± 124.08a

* Means with the same letter within the same column do not differ statistically (Tukey; P≥0.05). Performance was considered only four cuts.

Table 3. Effect of foliar applications of iodine (KI) on nutraceutical parameters of tomato fruits produced under shade netting.

Iodine (μM L-1)	Antioxidant capacity (meq. Trolox 100 mg-1 Fresh Weight)	Phenolic capacity (mg 100 g fresh weight)	Flavonoids (mg 100 g fresh weight)	Lycopene (mg 100 g fresh weight)
0	87.87 ± 2.10d	176.79 ± 1.67e	127.240 ± 1.60d	29.75 ± 1.35a
5	94.81 ± 1.27c	185.85 ± 1.60d	133.877 ± 3.25c	25.88 ± 0.46bc
10	109.22 ± 1.85b	196.94 ± 1.54c	169.543 ± 1.70b	26.05 ± 0.14b
15	110.46 ± 0.61b	205.12 ± 2.06b	188.377 ± 1.36a	25.61 ± 0.56bc
20	116.00 ± 2.17a	219.54 ± 0.87a	193.797 ± 1.66a	24.03 ± 0.21c

* Means with the same letter within the same column do not differ statistically (Tukey; *P*≥0.05).

highest total antioxidant capacity accumulated in tomato fruits was obtained in fruits with the highest accumulation of iodine.

For total phenolic content (TFC), all the treatments with iodine recorded higher levels than the control; the dose of 20 μM L^{-1} of iodine recorded the highest TFC of 219.547 mg 100 g^{-1}, surpassing the control treatment by 24.18%, whereas the treatments with 5 μM L^{-1}, 10 μM L^{-1}, and 15 μM L^{-1} of iodine were 18.2%, 11.47%, and 7.02% higher than the control, respectively. This coincides with the findings of Lima et al. (2023) and Blasco et. al (2011), who reported a positive increase in TFC as the dose of iodine increased in tomato and lettuce leaves, with the highest values being obtained at doses greater than 100 μM. Conversely, Medrano-Macías et al. (2016) found no differences in phenolic compounds in tomato fruits treated with foliar applications of iodine of 1 μM and 100 μM applied daily and biweekly.

In terms of flavonoids, the treatments with 15 and 20 μM L^{-1} of iodine presented values of 188.377 and 193.797 mg 100 g^{-1}, respectively. Both treatments surpassed the control by 48.04 and 52.30%, respectively. The treatment with the lowest iodine dose (5 μM L^{-1}) showed an increase in flavonoid content of 5.21% with respect to the control, while the treatment with the highest dose (20 μM L^{-1}) increased flavonoid levels by 44.75% with respect to the former treatment. Similarly, Andrade-Sifuentes et al. (2024) reported that concentrations of 15 and 20 μM of iodine applied to melon provide greater accumulation of flavonoids.

Regarding lycopene, the treatment with the highest content of this compound was the control. On the contrary, iodine applications resulted in a 20% decrease in lycopene levels. This agrees with Fuentes et al. (2022), who found a decrease in lycopene content with the application of 100 μM iodate. However, Smoleń et al. (2015) found that applying 7.88 μM of potassium iodide and iodate had no influence on the concentration of lycopene in tomato fruits. Likewise, Islam et al. (2018) studied cherry tomatoes with iron, iodine and selenium treatments, reporting no significant differences in lycopene content.

The effect of iodine on nutraceutical quality is due to the fact that iodine could have interfered with the metabolism of primary compounds within the fruit (Cezar et al., 2024); probably to the stress caused by it. The foliar application at the highest dose of iodine (20 μM L^{-1}) increased the synthesis of bioactive compounds to combat oxygen-reactive species as a survival mechanism (Andrade-Sifuentes et al., 2024). Halka et al. (2020) found a relationship between the increase in iodine doses (in a range of 10 to 50 μM L^{-1}) and the increase in the synthesis and accumulation of secondary metabolites as a response mechanism to oxidative stress in tomato fruit. Lycopene is part of the secondary metabolites that can affect coloration, nutritional value, shelf life and functional potential of tomato fruit (Lima et al., 2023). The lycopene content obtained in this research was reduced with doses of up to 20 μM L^{-1} of KI, probably due to the lack of stimulation in the production of secondary metabolites such as lycopene, since tomato begins to present symptoms of phytotoxicity at concentrations of more than 20mM KI (Landini et al., 2011).

Regarding the concentrations of micronutrients in the leaf tissue, there were significant differences in copper (Cu), iron (Fe), manganese (Mn) and nickel (Ni), while zinc (Zn) did not show significant differences between the different doses of iodine applied (Table 4). In general, with the application of 20 μM L^{-1} of iodine, the contents of Cu, Fe, Mn and Ni were 55% higher than the control treatment. These results suggest that the application of iodine can increase the content of microelements in tomato leaf tissue. The contents of Cu and Fe increased with the application of 100 μM in tomato (Fuentes et al., 2022) and 80 μM of IO_3^- in lettuce plants (Blasco et al. 2012). In addition, synergisms were reported between Mn and Cu ions in cactus cultivation (García Osuna et al. 2014), and between KI and Fe in lettuce (Blasco et al., 2012).

Regarding Mn, the highest value of 52% was obtained with the dose of 20 μM L^{-1} of KI compared to the control, which coincides with Lara-Izaguirre et al. (2023), who found that the concentration of Mn in eggplant fruits increased by up to 34% with the application of 90 μM of KI to the plants, compared to the control. However, in tomato plants, doses of up to 0.5 mg L^{-1} did not result in differences (Dobosy et al., 2020), and thus more research is required to further understand the relationship between Mn and iodine. Iodine is applied at different concentrations and applications vary depending on plant species.

Ni concentration was higher at the dose of 20 μM L^{-1} of KI. Ni is an essential micronutrient for plant development and plays a key role in regulating the expression of hydrogenase synthesis (Dixon et al., 1975). Insufficient Ni and low urease activity may disrupt nitrogen metabolism, leading to excessive urea accumulation in the shoots, negatively affecting plant development and yield (Brown et al., 1987).

Zn concentration did not increase with the applied iodine doses. Similar results were reported when using iodine doses of 80 μM L^{-1} in lettuce (Blasco et al., 2012) and 0.5 mg L^{-1} in potato (Dobosy et al., 2020).

With respect to the recommended amounts of Cu (900 μg day^{-1}), Fe (18 mg day^{-1}), Mn (2.3 mg day^{-1}) and Ni (1 mg day^{-1}) for human consumption, values were higher than those observed with the different treatments.

Regarding the concentration of iodine in the fruits, the analysis of variance showed significant statistical differences (P≤0.05) due to the effect of the applied doses. The treatment with 20 μM L^{-1} of iodine recorded the highest concentration of 29.18 mg kg^{-1} fresh weight iodine. As observed in Fig. 1, iodine content in the fruits increased as concentration increased.

Lawson et al. (2015) compared the amount of

Table 4. Effect of foliar applications of iodine (KI) on micronutrients in the plant tissue of tomato plants.

Iodine (μM L^{-1})	Cu	Fe	Mn	Ni	Zn
	mg kg^{-1}				
0	510.910 c ± 9.42c	133.245 ± 4.510c	179.463 ± 19.85b	3.60 ± 0.25abc	28.895 ± 5.54a
5	616.110 b ± 8.55b	182.465 ± 0.145b	250.130 ± 0.76a	2.972 ± 0.14bc	32.030 ± 0.04a
10	581.810 b ± 44.75b	108.530 ± 1.215e	168.135 ± 7.03b	1.970 ± 0.40c	35.707 ± 2.017a
15	330.250 d ± 2.98d	125.030 ± 1.28d	160.518 ± 3.16b	4.570 ± 1.14ab	34.448 ± 1.87a
20	814.440 a ± 8.55a	209.658 ± 2.42a	273.910 ± 3.60a	5.097 ± 1.04a	29.680 ± 2.59a

Fe= iron; Zn=zinc; Mn= manganese; Ni= nickel; MSD = minimum significant difference; MDE = mean square error; CV= coefficient of variation. *Values followed with the same letter are not statistically different (Tukey; P≤0.05).

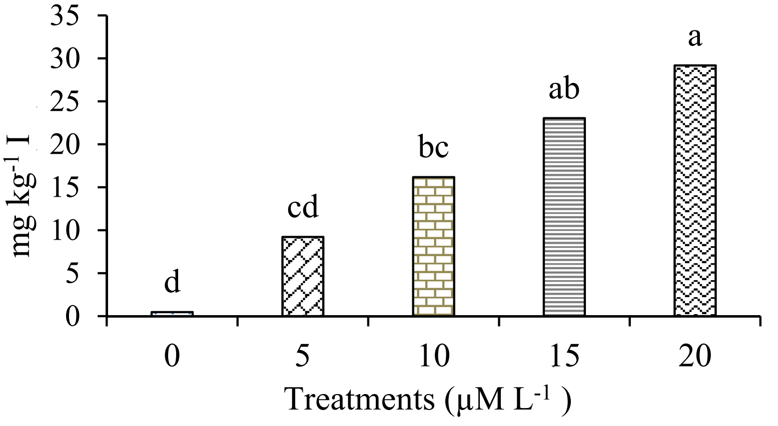

Fig. 1. Iodine concentration in tomato fruits produced under shade netting. Bars with different letters are statistically different (Tukey; P ≤ 0.05).

iodine accumulated through soil fertilization and foliar spraying in lettuce and cabbage, finding a greater accumulation through the foliar application of 0.5 kg I ha^{-1} in lettuce, but not in cabbage, which was probably attributed to the way this element was transported. Similarly, Smoleń et al. (2012) found positive results in the accumulation and biofortification of lettuce plants with the foliar application of KIO_3 at a concentration of 2 kg I ha^{-1}. In addition, Smoleń et al. (2018) found favorable results in the accumulation of iodine in potatoes, pointing out that iodine content was several times lower in the control plants compared to those treated with iodine. In tomato fruits, Kiferle et al. (2013) reported iodine concentrations in the range of 0.3 and 4.5 mg L kg^{-1} fresh base (BF) in treatments with 1 to 5 mM KI, respectively; and concentrations of 0.2 to 1.9 mg I kg^{-1} BF in treatments with 0.5 to 2 Mm KIO_3.

The principal source of iodine for humans is food and is a critical constituent of thyroid hormones T4 and T3, representing 65% and 59% of the molecular weight of these hormones, respectively (Triggiani et al., 2009). Therefore, as vegetables do not provide an adequate dietary iodine intake (150 µg), biofortification can be a good strategy to prevent or reduce iodine deficiency.

A low concentration of iodine (up to 20 µM) can indirectly affect plant resistance by promoting the synthesis of multiple compounds, both enzymatic and non-enzymatic, which are involved in the plant's defense mechanisms against environmental stressors (Kiferle et al., 2021). Concentrations higher than 50 µM of iodine may accelerate tissue oxidation and the senescence process in plants, in turn affecting plant growth (Incrocci et al., 2019).

CONCLUSIONS

The biofortification of tomato with the application of potassium iodide (KI) did not alter the commercial quality of the fruits, since they maintained fruit size, firmness and weight, nor affected the development of the plant. Regarding nutritional compounds, a small reduction in sugar content was observed with respect to the control. The foliar application of 20 µM L^{-1} KI can be part of the productive management of tomato, because it increases the antioxidant capacity and contents of phenols and flavonoids of tomato fruits. The results are encouraging as they show that tomato fortification with potassium iodide results in a significant increase in iodine concentration in the fruits, and thus it could be an effective strategy to reduce or prevent health problems related to iodine deficiency.

ACKNOWLEDGMENTS

The authors thank DESUS S.A. (Argentina) and GENOSA I+D (Spain) for the donation of chia meal and hydroxytyrosol, respectively.

Author Contributions

The authors declare active participation in the bibliographic review by Tomás Juan and Pablo Preciado; in the development of the methodology: Erika Lagunes Cirilo Vázquez; in the discussion of the results: Tomás Juan Álvaro Cervantes and María Gabriela Cervantes; in review and approval of the final version of the article: Manuel Fortis-Hernández and Edgar O. Rueda-Puente.

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