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Article

Iodine Biofortification of Potato (*Solanum tuberosum* L.) Grown in Field

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Abstract: Despite wide prevention programmes, iodine deficiency remains a substantial problem in various populations around the world. Consumption of crop plants with increased iodine content may help supply additional amounts of that element in a daily diet. The aim of the work was to evaluate the efficiency of iodine biofortification of potato tubers. Soil application of KI and foliar application of KIO_3 in doses up to 2.0 kg I ha^{-1} were tested in a three-year field experiment. Biomass, yield as well as dry matter, iodine, starch, and soluble sugar content in potato tubers were analyzed. No negative effect of tested methods of iodine application on potato yield or dry matter content was observed. Both soil and foliar application of iodine allowed to obtain potato tubers with increased content of that element with no decrease of starch or sugar content. The highest efficiency of iodine biofortification was noted for foliar spraying with KIO_3 in a dose of 2.0 kg I ha^{-1}. The obtained level of iodine in 100 g of potatoes could be sufficient to cover up to 25% of Recommended Daily Allowance for that element. The findings of the study indicate that potatoes biofortified with iodine can become an additional source of I in a daily diet.

Keywords: iodine; potato; agronomic biofortification; starch; soil fertilization; foliar application

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1. Introduction

Iodine is a micronutrient crucial for the proper growth and development of human organisms. Despite wide programmes of the prevention of iodine deficiency diseases, the status of iodine nutrition in some populations still requires effective supplementation [1,2]. One of the most popular ways is the usage of iodized table salt. However, the efficiency of that approach can be hardened by major factors, including iodine loss during salt manufacturing and storage [3], thermal processing [4], as well as growing awareness of the need to reduce salt consumption due to related health hazards [5]. Over the years, it has been proposed that the consumption of crop plants with increased content of iodine in edible parts can improve its supply in a daily diet. The in-vivo studies have already confirmed the efficiency of that approach to increase iodine nutrition in human organisms [6].

For the last decades numerous studies have been conducted evaluating the possibility of increasing iodine content in selected parts of various crop plants; extensive reviews were presented by Medrano-Macias et al. [7] and Gonzali et al. [8]. The so-far obtained data indicate that the efficiency of iodine biofortification of crop plants depends on numerous factors such as plant type and species, growth conditions, method of iodine application, and chemical form of that chemical element. A great amount of the studies in the area has been focused on greenhouse cultivation of various plant species, including lettuce [9,10], pepper [11], spinach [12,13], and tomato [14–16]. Fewer works have studied the efficiency of iodine biofortification when crop plants, such as rice, wheat, corn [17], pea [18], carrot [19], or lettuce [20], were cultivated in field. The possibility of increasing iodine content in crops grown in field conditions is affected by various factors determining the availability of iodine to plants. Two main approaches can be taken into consideration, namely, soil fertilization and foliar application of iodine.

The main factors affecting the efficiency of soil fertilization with iodine compounds are iodine sorption and leaching within soil as well as plant preference towards particular iodine compound. Soil sorption of iodine depends on its chemical forms and is associated with its fixation with both organic (mainly humic and fulvic acids) and inorganic fractions (ferrous, aluminum, and copper complexes) of the soil [21]. Some amounts of iodine applied or present in the soil may also be released into the atmosphere due to biological or chemical processes leading to the formation of volatile I_2 or CH_3I [22–24]. It is estimated that only up to 10% of the total content of iodine in soil is present in the soil solution, therefore available for plants [24]. Some works indicate that iodates undergo stronger sorption with soil particles than iodide [25]. The applicability of foliar spraying for obtaining crop plants with increased content of iodine has been evaluated in a minority of works [18,26–28]. However, it has already been suggested as an efficient method for supplying various forms of that element during cultivation [20].

Potato is one of the most popular vegetables cultivated in various climatic conditions with the greatest producers including countries from Asia (China, India, Bangladesh and Turkey), Europe (Ukraine, Russian Federation, Poland), as well as United States of America [29]. It is a major source of carbohydrates (mainly starch), protein, vitamins, and micronutrients in a daily diet of over one billion people around the world [30]. As its popularity increases in some developing countries, it may be proposed as a convenient crop that may help counteract the deficiency of various micronutrients in the populations. Some reports indicate the possibility of obtaining potato yield with increased iodine content by fertigation in greenhouse cultivation [31] or applying iodine-enriched nutrient solution [32]. However, no long-term field studies on the efficiency of iodine biofortification of potato tubers have yet been conducted.

The aim of a three-year field study was to evaluate and compare the efficiency of iodine biofortification of potato by the soil and foliar application of iodine compounds. The study included the description of the influence of various biofortification approaches on yielding and major nutritional quality parameters of potato tubers in order to evaluate the potential applicability of tested methods for the production of biofortified crop.

2. Materials and Methods

2.1. Plant Material, Cultivation and Treatments

Field cultivation of potato (*Solanum tuberosum* L.) cv. Irga was conducted in 2008, 2009, and 2011 in an Experimental Station of University of Agriculture located in Krakow-Mydlniki, Poland (50°07′910 N, 19°84′764 E). Each year potato was grown on a different site within a single soil complex maintaining the proper crop rotation. In 2010 studies were interrupted due to field flood after heavy rainfall. Characteristics of soil before potato cultivation in each year of the experiment are shown in Table 1. Each year, soil samples from 0 to 30 cm layers were collected in spring before the experiment outset. The eight individual samples were randomly collected from the area of the experimental field and mixed into a collective sample. Soil texture was analyzed using the Casagrande method. In the samples of soil mixed with water (1:2 *v/v*, soil: H_2O), pH and Eh were measured potentiometrically and EC was analyzed using a conductivity meter. The soil organic matter was determined by the Tiurin method. The soil sorption properties were as follows: cation exchange capacity (CEC) and base saturation ratio V(%) were determined using Kappen's method after measuring hydrolytic acidity (Ha) in 1 M

$(CH_3COOH)_2Ca$ with pH = 8.2 and sorption complex saturation with alkaline elements (S–sum of S_{Na} + S_K + S_{Ca} + S_{Mg}) after soil extraction by 1 M NH_4Cl. Cation exchange capacity was calculated as: CEC = Ha + S, while base saturation ratio as V(%) = (S × 100%)/CEC. Iodine content in the soil was analyzed using the ICP-OES spectrometer (Prodigy, Leeman Labs, New Hampshire, MA, USA).

Table 1. Soil characteristics before potato cultivation in each year of the experiment.

Soil Characteristics.	2008	2009	2011
Soil Type	**Silt Loam**	**Silt Loam**	**Silt Loam**
% sand	37	37	37
% silt	33	33	33
% clay	30	30	30
Base saturation V (%)	94.2	96.6	89.5
Cation exchange capacity ($cmol \cdot kg^{-1}$)	9.53	8.82	9.59
Organic matter content (%)	3.41	3.66	3.15
pH_{H2O}	6.99	7.19	6.85
EC ($mS \cdot cm^{-1}$)	0.13	0.10	0.10
Iodine ($mg \cdot dm^{-3}$ soil)	0.73	1.88	0.42

Diverse iodine soil fertilization (in the form of KI) and foliar nutrition (as KIO_3) were applied in the experiment including: 1–control (without soil fertilization and foliar nutrition with iodine); three treatments with pre-sowing soil fertilization with KI: 2–0.5 kg I ha^{-1}, 3–1.0 kg I ha^{-1}, and 4–2.0 kg I ha^{-1} as well as three treatments with four-time foliar application of KIO_3 in the following concentrations: 5–0.0005% (total dose: 0.02 kg I ha^{-1}), 6–0.005% (total dose: 0.2 kg I ha^{-1}), and 7–0.05% (total dose: 2.0 kg I ha^{-1}). Each foliar spraying was performed using approximately 1000 dm^3 of work solution per hectare. The experiment was arranged in a split-plot design with four replications of 13.5 m^2 plots. The total area of the experiment was 378 m^2. The applied experimental design with distinguishing three treatments of soil fertilization with KI and three treatments of foliar spraying with KIO_3 was based on own previous studies with field cultivation of lettuce and carrot [26,27].

Tubers of certified potato line ('Irga' cv.) of approximate diameter of: 35–40 mm (40–50 g) were used as planting material. One day before tuber planting into field, NPK mineral fertilizers (as ammonium nitrate, triple superpshosphate, potassium chloride) were introduced into soil in order to supplement the deficiency of nutrients to the level optimal for potato (in $kg \cdot ha^{-1}$): N-200 N, P-170, and K-160 based on the results of soil analysis [33]. The soil content of Mg and Ca was sufficient for potato cultivation therefore no additional supplementation of its level was required. At the same time, presowing soil fertilization with KI in tested doses was performed on plots from the treatments no. 2–4 (Table 2).

Table 2. Time schedule for the experiment.

Treatment	2008	2009	2011
Soil fertilization with KI (treatments no.2–4)	13.04	06.04	10.04
Potato planting	14.04	07.04	11.04
1st foliar application of KIO_3 (treatments no.5–7)/BBCH 25	05.06	05.06	06.06
2nd foliar application of KIO_3 (treatments no.5–7)/BBCH 45	18.06	18.06	17.06
3rd foliar application of KIO_3 (treatments no.5–7)/BBCH 55	27.06	30.06	28.06
4th foliar application of KIO_3 (treatments no.5–7)/BBCH 65	08.07	08.07	09.07
Potato harvest (BBCH 91)	28.07	15.07	7.07

Tubers were planted into the soil with spacing of 67.5 cm × 40 cm. During the cultivation foliar application of respective KIO_3 solutions were conducted on plants from treatments 5–7. Each year, foliar spraying was performed in the following growth stages of potato plants according to BBCH scale [34]: BBCH 25,45,55,65. Potato harvest (at BBCH 91 growth stage) was followed by yield assessment and collection of plant material for further analyses. For the evaluation of yield from each repetition potato tubers were collected from the middle part of each plot and weighed. Total yield, marketable yield (tubers of ≥3 cm diameter), and average weight of a single tuber in marketable yield were thus calculated.

2.2. Meteorological Data

Meteorological data for the period of potato cultivation in each year of the study is presented in Table 3 as ten-day values. Air temperature and relative humidity was registered in the Experimental Station with the use of HoBo®Pro Series data logger (Onset, Bourne, MA, USA). Information on total rainfall and the number of sunshine hours was retrieved from the Institute of Meteorology and Water Management–National Research Institute, Krakow branch, Poland.

Table 3. Meteorological data for the subsequent years of field cultivation of potato.

		Air Temperature (°C)			**Air Humidity (%)**			**Rainfall (mm)**			**Sunshine Hours (h)**		
Month	**Decade**	**2008**	**2009**	**2011**	**2008**	**2009**	**2011**	**2008**	**2009**	**2011**	**2008**	**2009**	**2011**
April	1	7.7	16.9	10.4	76.0	42.2	73.0	8.9	1.4	4.3	30.9	80.6	40.3
April	2	9.4	11.1	8.4	85.5	55.3	71.0	25.6	0.4	9.2	37.1	84.7	49.2
April	3	10.9	12.0	13.6	58.7	48.0	71.0	0.7	2.9	63.8	77.7	112.1	76.1
Total monthly		-	-	-	-	-	-	35.2	4.7	77.3	145.7	277.4	165.6
Average monthly		10.1	13.4	10.8	72.1	48.5	72.0	-	-	-	-	-	-
May	1	12.3	13.5	9.5	61.2	61.8	66.8	5.7	18.7	16.8	59.5	82.9	80.6
May	2	14.9	13.8	16.0	66.6	73.9	67.4	18.4	31.4	13.1	62.4	77.9	84.8
May	3	16.0	14.0	17.5	63.9	76.3	69.3	2.7	56.5	19.0	69.7	81.5	103.3
Total monthly		-	-	-	-	-	-	26.8	106.6	48.9	191.6	242.3	268.7
Average monthly		14.4	13.8	14.3	63.9	70.7	67.9	-	-	-	-	-	-
June	1	19.7	14.1	18.7	53.6	75.6	86.2	3.5	12.2	16.5	92.2	69.1	54.7
June	2	16.9	15.8	18.4	61.2	69.6	73.1	5.4	42.7	3.7	53.0	69.3	76.0
June	3	21.8	18.1	17.8	55.4	94.7	77.7	17.8	66.2	12.1	91.2	35.2	74.8
Total monthly		-	-	-	-	-	-	26.7	121.1	32.3	236.4	173.6	205.5
Average monthly		19.5	16.0	18.3	56.7	80.0	79.0	-	-	-	-	-	-
July	1	19.3	19.8	16.8	64.6	80.2	89.3	50.6	28.3	52.8	89.6	91.0	47.4
July	2	18.9	19.2	21.5	79.1	79.3	80.8	36.1	21.4	79.0	51.9	101.8	79.6
July	3	18.8	18.8	16.3	80.8	80.7	88.0	55.9	33.0	59.8	83.5	106.4	25.6
Total monthly		-	-	-	-	-	-	142.6	82.7	191.6	225.0	299.2	152.6
Average monthly		19.0	19.3	18.2	74.8	80.1	86.0	-	-	-	-	-	-

2.3. Plant Analysis

For the estimation of dry matter content, fresh tubers were dried at 105 °C. Iodine concentration in potato tubers was analyzed with the ICP-MS method (TQ ICP-MS spectrometer/ICP-MS triple quadrupole; ThermoFisher Scientific, Bremen, Germany). Fresh potatoes from each treatment were dried at 70 °C and ground in a lab mill (FRITSCH Pulverisette 14; FRITSCH GmbH, Weimar, Germany). An amount of 0.1 g of such-prepared sample was weighed out into a falcon tube; 10 mL of distilled water and 1 mL of 25% TMAH (tetramethylammonium hydroxide) were added. The samples were incubated at 90 °C for 3 h, cooled, and filled up to 30 mL with distilled water. Next, samples were centrifuged for 15 min at 4500 rpm, 5 °C [13–35]. To evaluate the accuracy of the analysis by ICP-MS, iodine content in certified spinach leaf reference material (CRM: NCS ZC73013) was additionally determined. The results obtained were as follows: 0.33 ± 0.08 mg I·kg^{-1} d. w. (n = 6) for the certified value of 0.36 ± 0.12 mg I·kg^{-1} d. w. Iodine uptake by potato tubers (g I·ha^{-1}) was calculated according to the following formula = [I content in potato tubers (mg I·kg^{-1} f.w.) × total yield (kg·ha^{-1})]/1000.

The coverage of RDA-I by 100 g of potato was calculated, taking as a reference the value of recommended daily allowance for iodine for men and women, i.e., 150 µg [36]. The following formula was applied: RDA-I % = [I content in potato tubers (µg I·100 g^{-1} f.w.) × 100%]/150 µg I. The content of starch was analyzed after acidic hydrolysis of tuber samples. The acidic hydrolysis was conducted with the use of 52% perchloric acid [37] and hydrolisates were analyzed for total soluble sugars by the anthrone method [38]. Independently from starch analysis, determination of total soluble sugars was also conducted in ethanolic extracts of fresh potato tubers by above-mentioned anthrone method [38].

2.4. Statistical Analysis

Obtained results were statistically verified by two-way analysis of variance with the use of STATISTICA PL 13.0 (Statsoft, Tulsa, OK, USA) at $p < 0.05$. Significance of differences between means resulting from F test was determined using Tukey test. To facilitate interpretation, significance of data presented in tables was marked using letter symbols.

3. Results

3.1. Potato Yield and Dry Matter Content

The statistical analysis of obtained results revealed no significant effect of applied treatments on total yield, percentage share of marketable yield, average weight of a single tuber and dry matter content of potato tubers (Tables 4 and 5). The interaction between the treatment and year of cultivation was significant only for the dry matter content. The value of that parameter was generally the lowest in 2008 as compared to other years of the study (Figure 1). In 2008 and 2011 no differences in dry matter content of potato tubers were noted between individual treatments. In 2009 a significant decrease of dry matter content, as compared to the control, was noted after foliar application of the highest dose of KIO_3 (2 kg I ha^{-1}).

Table 4. Summary of analysis of variance of yield and dry matter of potato tubers.

Source of Variation	**Df**	**Total Yield (t·ha^{-1})**		**Marketable Yield (%)**		**Average Tuber Weight (g)**		**Dry Matter (%)**	
		***F* Value**	***p*-Value**	***F* Value**	***p*-Value**	***F* Value**	***p*-Value**	***F* Value**	***p*-Value**
T (treatment)	6	0.91	0.4955	0.04	0.8691	0.52	0.7891	2.20	0.0549
Y (year)	2	10.18	0.001	8.81	0.0004	29.85	<0.0001	159.37	<0.0001
T × Y	12	0.67	0.7753	0.61	0.8232	0.78	0.6635	3.21	0.0013

Table 5. Total and marketable yield, average tuber weight and dry matter content in potato tubers–means for three-years of the study; values ±standard error (n = 12).

	Treatment (T)	**Total Yield (t·ha^{-1})**	**Marketable Yield (%)**	**Average Tuber Weight (g)**	**Dry Matter (%)**
	Control	35.2 ± 1.82	76.1 ± 3.02	59.8 ± 3.12	18.1 ± 0.51
Soil	KI 0.5 kg I ha^{-1}	36.7 ± 1.88	75.6 ± 2.43	59.9 ± 4.09	17.8 ± 0.36
	KI 1.0 kg I ha^{-1}	36.0 ± 1.87	75.4 ± 2.86	61.9 ± 4.47	17.6 ± 0.50
	KI 2.0 kg I ha^{-1}	36.0 ± 1.57	76.9 ± 2.33	57.8 ± 2.84	17.8 ± 0.59
Foliar	KIO_3 0.02 kg I ha^{-1}	37.0 ± 1.73	78.6 ± 2.45	62.0 ± 3.60	17.9 ± 0.40
	KIO_3 0.2 kg I ha^{-1}	37.8 ± 1.47	78.7 ± 2.10	62.7 ± 3.69	17.8 ± 0.39
	KIO_3 2.0 kg I ha^{-1}	33.1 ± 1.55	75.2 ± 1.83	57.8 ± 3.27	17.2 ± 0.35

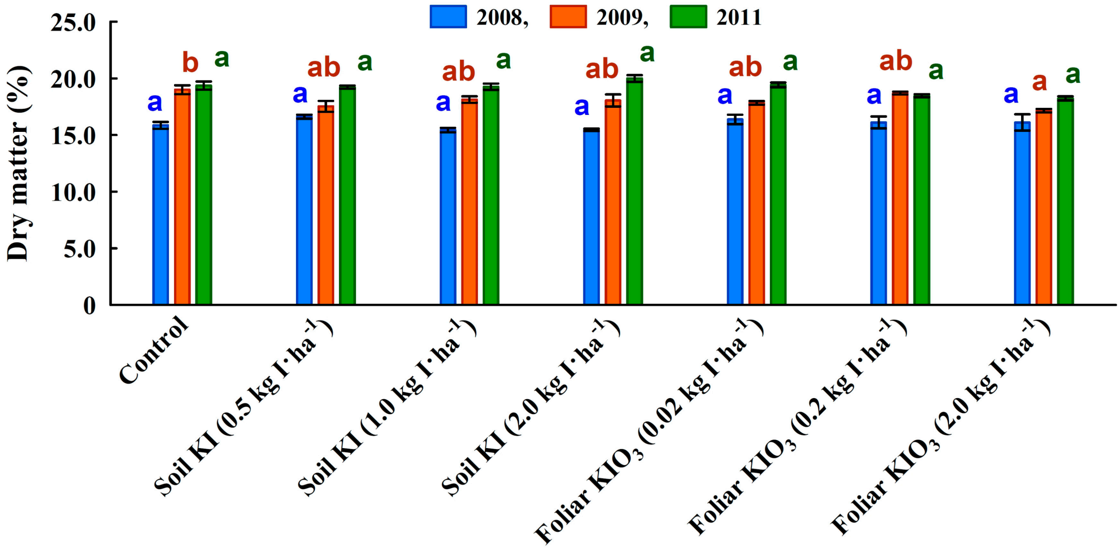

Figure 1. Dry matter content in potato tubers in individual years the study; values followed by the same letters within an individual year are not statistically different at $p < 0.05$, ($n = 4$).

3.2. Iodine Accumulation in Potato Tubers and Efficiency of Iodine Biofortification of Potato

The accumulation of iodine in potato tubers was significantly affected by the tested treatment (Tables 6 and 7). When KI was applied into the soil, a significant increase of iodine content in potato tubers was noted only for its highest dose, i.e., 2 kg I ha^{-1}. In the case of foliar spraying, improved iodine accumulation in potato tubers was noted when KIO_3 was applied in medium and high dose, i.e., 0.2, and 2.0 kg I ha^{-1}. The highest level of iodine in potato tubers was noted in the treatment with 2.0 kg I ha^{-1} as KIO_3 (1.5 mg kg^{-1} d.w.) and exceeded the control value (0.15 mg kg^{-1} d.w.) by approximately 10 times. The applicability of the tested methods of iodine enrichment was further substantiated by the values of iodine uptake calculated for the yield of potato tubers. Also in that case, foliar application of KIO_3 was found to be the most effective in increasing iodine content in the potato yield with the average value of 8.92 g I ha^{-1}. It needs to be underlined that the accumulation of iodine was also affected by the year of cultivation. Particularly low values of iodine content (Figure 2) and iodine uptake by potato tubers were noted in 2008 (Figure 3).

Table 6. Summary of analysis of variance of iodine content and uptake as well as the content of starch and soluble sugars in potato tubers.

Variable	Df	Iodine (mg·kg^{-1} d.w.)		Iodine Uptake (g I·ha^{-1})		Starch (g 100 g^{-1} f.w.)		Soluble Sugars (mg·100 g^{-1} f.w.)	
		F Value	*p*-Value	*F* Value	*p*-Value	*F* Value	*p*-Value	*F* Value	*p*-Value
T (treatment)	6	488.57	<0.0001	449.76	<0.0001	4.88	0.0004	11.56	<0.0001
Y (year)	2	161.79	<0.0001	263.4	<0.0001	22.00	<0.0001	1287.94	<0.0001
T × Y	12	22.38	<0.0001	22.99	<0.0001	3.56	0.0005	19.23	<0.0001

Table 7. Iodine content, iodine uptake by yield of tubers and the content of starch and soluble sugars in potato tubers, means for three years of the study; values ± standard error; values followed by the same letters are not statistically different at $p < 0.05$, ($n = 12$).

Treatment		**Iodine (mg I·kg^{-1} d.w.)**	**Iodine Uptake (g I·ha^{-1})**	**Starch (g·100 g^{-1} f.w.)**	**Soluble Sugars (mg·100 g^{-1} f.w.)**
Control		0.15 ± 0.021 a	1.00 ± 0.159 a	12.6 ± 0.39 ab	602.6 ± 52.05 abc
Soil	KI 0.5 kg I ha^{-1}	0.20 ± 0.029 ab	1.40 ± 0.233 a	12.7 ± 0.34 ab	636.0 ± 63.89 cd
	KI 1.0 kg I ha^{-1}	0.22 ± 0.032 ab	1.55 ± 0.259 ab	11.7 ± 0.41 a	653.4 ± 60.54 d
	KI 2.0 kg I ha^{-1}	0.29 ± 0.036 b	1.99 ± 0.285 b	13.0 ± 0.44 b	614.1 ± 56.56 bcd
Foliar	KIO_3 0.02 kg I ha^{-1}	0.19 ± 0.030 a	1.37 ± 0.239 a	13.8 ± 0.57 b	579.1 ± 56.60 ab
	KIO_3 0.2 kg I ha^{-1}	0.40 ± 0.052 c	2.84 ± 0.410 c	13.1 ± 0.31 b	594.7 ± 54.05 ab
	KIO_3 2.0 kg I ha^{-1}	1.55 ± 0.153 d	8.92 ± 0.957 d	12.7 ± 0.31 ab	564.1 ± 46.47 a

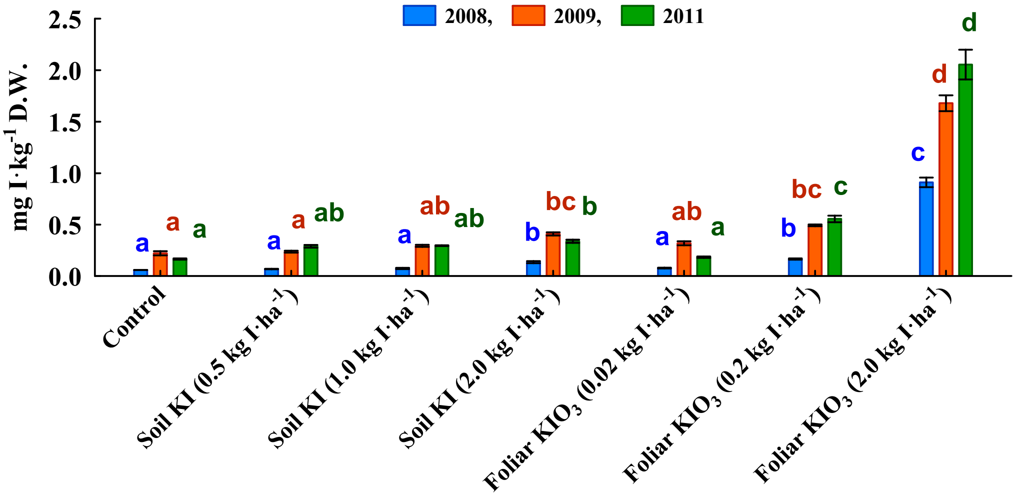

Figure 2. Iodine content in potato tubers in individual years the study; values followed by the same letters within an individual year are not statistically different at $p < 0.05$, ($n = 4$).

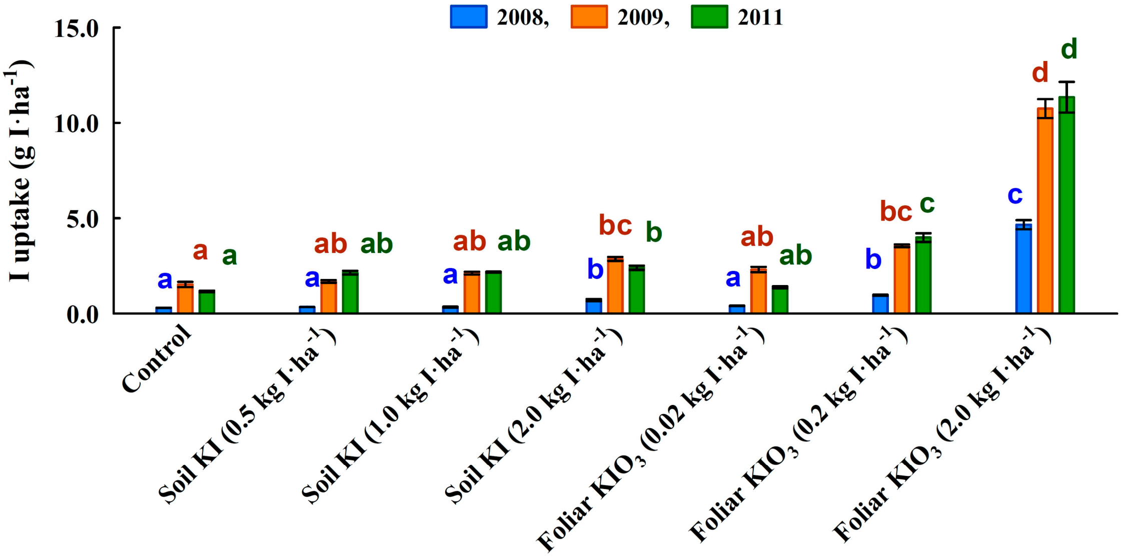

Figure 3. Iodine uptake by potato yield in individual years the study; values followed by the same letters within an individual year are not statistically different at $p < 0.05$, ($n = 4$).

In order to assess the efficiency of iodine biofortification of potato tubers with respect to the prevention of iodine deficiency, the percentage coverage of recommended daily allowance for iodine by the consumptions of potatoes was calculated. For the calculation, an average portion of 100 g of potatoes and the recommended daily allowance on the level of 150 µg I [36] were taken. It has been shown that 100 g of iodine-enriched potatoes could supply up to almost 25% of daily requirement for that micronutrient, depending on the cultivation year (up to almost 18 % on average). However, such high value was noted only for potato tubers from the treatment with foliar spraying with 2.0 kg I ha^{-1} as KIO_3. In any other treatment the percentage coverage of iodine demands in a daily diet was below 7% (Table 8).

Table 8. Percentage coverage of Recommended Daily Allowance for iodine (% RDA-I) by 100 g of fresh potato tubers in individual years of the study.

	Treatment	2008		2009		2011		Average RDA-I (%)
		Iodine (mg I kg^{-1} f.w.)	RDA-I (%)	Iodine (mg I kg^{-1} f.w.)	RDA-I (%)	Iodine (mg I kg^{-1} f.w.)	RDA-I (%)	
	Control	0.009	0.62	0.042	2.77	0.032	2.13	1.84
Soil	KI 0.5 kg I ha^{-1}	0.011	0.76	0.042	2.81	0.056	3.71	2.43
	KI 1.0 kg I ha^{-1}	0.011	0.76	0.053	3.56	0.057	3.80	2.71
	KI 2.0 kg I ha^{-1}	0.021	1.39	0.074	4.94	0.068	4.51	3.61
Foliar	KIO_3 0.02 kg I ha^{-1}	0.013	0.85	0.057	3.78	0.036	2.38	2.34
	KIO_3 0.2 kg I ha^{-1}	0.027	1.78	0.092	6.15	0.103	6.84	4.92
	KIO_3 2.0 kg I ha^{-1}	0.147	9.78	0.288	19.2	0.375	24.97	17.98

3.3. The Content of Starch and Soluble Sugars in Potato Tubers

Determination of the effect of applied iodine treatments on the nutritional quality of potato tubers included the accumulation of starch and soluble sugars. Even though statistical analysis revealed some variation between the tested treatments with respect to starch accumulation in potato tubers (Tables 6 and 7) in neither case that level differed from the control value (12.6 g 100 g f.w.). Only in 2011 an increased level of starch was noted after foliar spraying with the lowest dose of KIO_3 (0.02 kg I ha^{-1}). In other years of the study no differences between tested treatments were observed (Figure 4).

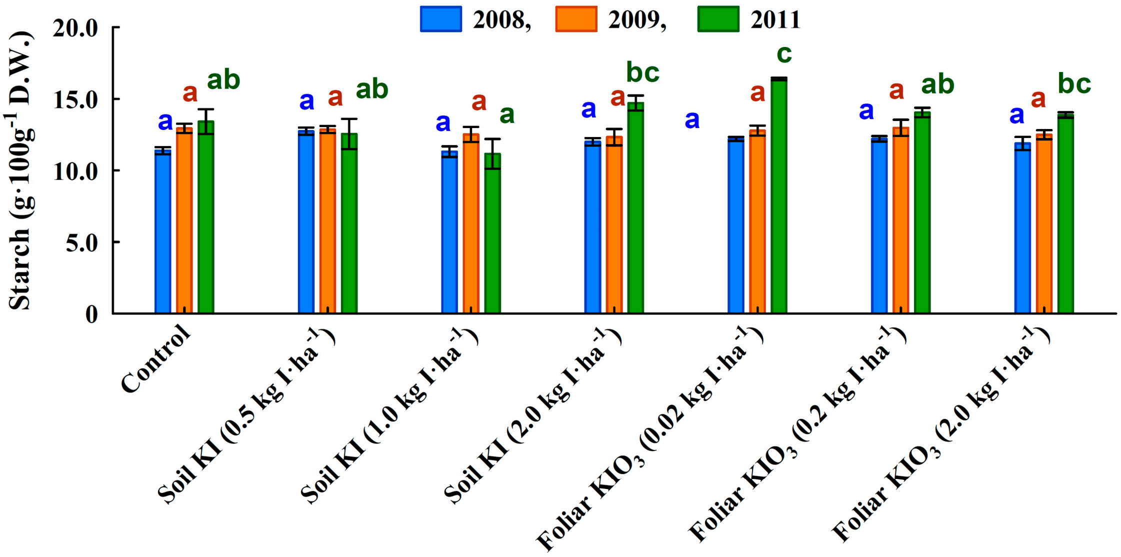

Figure 4. Content of starch in potato tubers in individual years the study; values followed by the same letters within an individual year are not statistically different at $p < 0.05$, ($n = 4$).

Slightly adverse observations were noted for the content of soluble sugars in potato tubers (Tables 6 and 7). Foliar application of three tested doses of KIO_3 (0.02, 0.2 and 2 kg I ha^{-1}) had no effect on the average sugar accumulation in potato tubers as compared to the control. In the case of soil fertilization with KI, only the application of 1.0 kg I ha^{-1} dose significantly increased sugar accumulation in potatoes. However, a significant differentiation in the content of soluble sugars was noted between the three years of the study (Figure 5). The lowest values of sugar accumulation in potato tubers were generally noted in 2008 with no significant differentiation between tested treatments. Similarly, in 2011 no changes in sugar content were noted after soil or foliar application of iodine compounds. In 2009, the lowest dose of KIO_3 caused a significant decrease of sugar content in tubers, while all doses of KI applied into the soil increased sugar accumulation in potatoes.

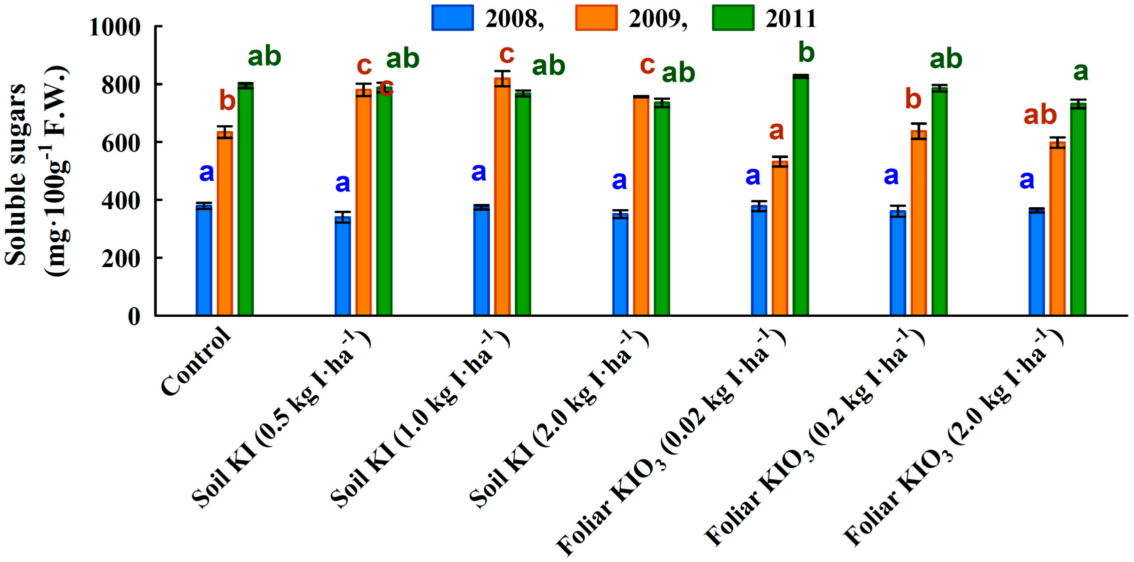

Figure 5. Content of soluble sugars in potato tubers in individual years the study; values followed by the same letters within an individual year are not statistically different at $p < 0.05$, ($n = 4$).

4. Discussion

The role of iodine in plants has not been widely studied until the current decade. The recent findings have allowed to suggest its potential beneficial role for plant growth and selected physiological processes [8–39]. Due to a substantial intensification of the research on iodine in plants it has been revealed that, when applied in properly adjusted doses, iodine compounds are tolerated by plants without decreasing its growth and yielding. However, the effect strongly depends on the cultivated species, method of cultivation as well as iodine application as thoroughly reviewed by Medrano-Macias et al. [7]. As far as potato cultivation in field is concerned, little information is available in the literature. In the field studies conducted by Mao et al. [40] soil application of KIO_3 in a dose of 0.59 kg I ha^{-1} significantly reduced the tuber yield of potato. Similar observations were noted for potato plants grown in pot experiment and irrigated with iodide and iodate solutions of various concentrations with more detrimental effect exerted by iodide [31]. On the other hand, the introduction of iodate in a concentration of 5 mg of I dm^{-3} had no effect on the tuber yield of potato plants cultivated in hydroponic conditions [32]. The present three-year study reveals that soil application of KI and foliar application of KIO_3 in doses up to 2.0 kg I ha^{-1} did not cause any significant drop in potato yield parameters (evaluated as total yield, percentage share of marketable yield, average weight of a tuber, as well as its dry matter content). That indicates no harmful effect exerted by the tested agronomic approaches on potato plants.

The present study has shown higher efficiency of iodine biofortification of potato tubers after foliar spraying with KIO_3 than soil application with KI. This may be due to numerous factors. When iodine is applied into the soil environment, it undergoes fast and strong sorption, as it is easily bound with soil organic matter, mainly through aromatic rings of humic and fulvic acids [41]. Additionally iodine may interact with inorganic fraction of the soil including Fe/Al, Cu/Al and Cu/Cr hydroxides as well as Cu(I)-sulphides and Cu(I)-Fe(III) complexes [42–44]. The process of iodine desorption is low and dependent on numerous factors including soil pH, Eh, and microbial activity [41–45]. The described processes substantially limit the availability of that element for the roots of cultivated plants. Comparative studies have revealed that in soil environment iodide ions are characterized by higher bioavailability for plants than iodate [9–46]. Studies conducted by Hong et al. [25] on three types of soil clearly shown stronger soil sorption of iodate and its lower desorption from these analyzed soils as compared to iodide ions. Furthermore, the difference in iodide and iodate bioavailability was verified by vegetation experiment confirming that exogenous iodate remained in the cultivated soil in a greater amount than iodide [25]. An additional factor that should be considered is that the plant uptake of iodate is preceded by the process of its chemical reduction by respective iodate or nitrate reductases [47] or driven by microbial activity [48].

Foliar application of mineral elements has been proposed as one of the most cost-effective and efficient method of agronomic biofortification of crop plants. The studies on the possibility of improving Zn content in rice conducted within the framework of the HarvestPlus programme showed a higher effect of seed enrichment after spraying of plants as compared to soil application of that element [49]. The efficiency of foliar application of Fe, Zn, and Se for increasing grain content of these micronutrients was also confirmed for rice [50]. Foliar spraying with multi-element cocktail containing Se, Zn, and I has substantially increased the content of these elements in the grains of various wheat cultivars grown in various locations [51]. Foliar spraying of plants with iodine solutions has been less frequently tested in terms of its applicability for iodine biofortification of plants. However, it has been shown to provide beneficial effects even as compared to the introduction of iodine solution the root zone, particularly for leafy vegetables such as lettuce [16–26,52] and alfalfa [28]. Its applicability for increasing iodine content has already been demonstrated for plum, nectarine, and tomato fruits [31], carrot roots [53], and kohlrabi tubers [54]. What is more, foliar spraying with KIO_3 has been proposed as recommended approach to iodine biofortification of cereals [17]. The results of the present study revealed that foliar application of KIO_3 turned out more efficient in iodine accumulation in potato tubers as compared to soil application of KI when introduced in the same final iodine dose. In the studies conducted by Caffagni et al. [31] foliar application of KI was less efficient in terms of iodine biofortification of potato tubers as compared to soil application of KI. However, in that study the highest iodine dose applied foliarly was eight times lower than a dose used for soil fertilization. In the work by Lawson et al. [52], foliar application of iodine proved less efficient in increasing iodine content in kohlrabi stem tuber as compared to soil application of respective iodine compounds (KI, KIO_3). In that case, the significant factor that may have affected the results could include the morphology of kohlrabi leaves that are characterized by a dense cuticle layer. The presence of such a hydrophobic barrier may have significantly decreased the level of iodine absorption into deeper layers of leaves [52]. In plants, iodine is transported mainly through xylem [46] therefore its distribution into the tubers, roots, or fruits is hardened. However, there is growing evidence of phloem mobility of that element [16,17]. The results obtained in the present studies, indicating greater efficiency of iodine biofortification of potato through foliar spraying, provide the additional evidence of substantial level of phloem transport of iodine.

Calculations of the average coverage of daily requirements for iodine by the consumption of 100 g of iodine-enriched potatoes substantiate its potential applicability as additional iodine sources in the human diet. It needs to be taken into account that iodine-biofortified vegetables, potato included, are not aimed to be the sole source of that element in the human diet. Therefore, it is even more desirable not to obtain particularly high values of RDA-I coverage in order to avoid the risk of excessive intake of that element. In the studies on iodine biofortification of tomato approximately 36.5% of RDA-I was covered by 100 g of tomato fruits biofortified with KIO_3 [14]. Studies on foliar application of various forms of I during kohlrabi cultivation led to an increase in iodine content in tubers, allowing approximately 1.5% of RDA-I to be provided by a 100 g portion [52].

The concentration of starch and soluble sugars in potato tubers is a key parameter regarding its consumption and processing quality. The present study showed that the application of iodine through soil or foliar spraying had relatively small effect on the sugar concentration in potato tubers and the main factor affecting the obtained variation were the weather conditions in individual years of the study. The findings described by various authors do not allow to clearly indicate the influence of exogenous iodine on sugar accumulation in crop plants. Similar observations as those from the present study were found by Smoleń et al. [27] with field cultivation of carrot. The studies by Kiferle et al. [15] showed only a small reduction of soluble sugar content in tomato fruits grown in the presence of iodine in the nutrient solution. On the other hand, iodine applied in low-to moderate doses may contribute to a significant increase in sugar accumulation in pepper [11] and strawberry fruits [55]. No effect of soil or foliar application of various forms of iodine was noted with respect to the content of soluble sugars in radish [56].

5. Conclusions

The current work evaluates the possibility of applying various agronomic approaches to iodine biofortification of potato cultivated in field conditions. Based on the obtained results, it can be stated that both soil application of KI as well as foliar application of KIO_3 in total doses up to 2.0 kg I ha^{-1} can be safely used during potato cultivation as no reduction of growth or yield was noted. Four-times foliar application of KIO_3 in a total dose of 2.0 kg I ha^{-1} turned out to be the most efficient in increasing iodine accumulation in potato tubers in all years of the cultivation without any substantial changes in starch or soluble sugar content. Despite observed year-dependency, tubers from that treatment contained enough iodine to cover up to almost 25% of Recommended Daily Allowance for that element. The findings of the work may be of great importance for the recognition of potato crop as an excellent target for the agronomic iodine biofortification and its suitability as an additional iodine source in a daily diet.

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