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PRELIMINARY EVALUATION OF THE INFLUENCE OF SOIL FERTILIZATION AND FOLIAR NUTRITION WITH IODINE ON THE EFFECTIVENESS OF IODINE BIOFORTIFICATION AND MINERAL COMPOSITION OF CARROT*

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Abstract

Vegetables enriched with iodine can become an alternative to iodized salt as a way of introducing this element to human diet. Iodine is not a nutritional element for plants. Its influence on biochemical and physiological processes occurring in plants, including mineral nutrition, has not yet been diagnosed. In the available literature, no information can be found on the comparison of iodine biofortification efficiency of carrot storage roots through soil fertilization and foliar nutrition. The aim of this study was to assess the influence of pre-sowing soil fertilization with iodine (in the form of KI) and foliar application of this element (as KIO_3) on the biofortification effectiveness and mineral composition of carrot storage roots. Carrot cv. Kazan F_1 was cultivated in a field experiment in 2008 and 2009. The experiment comprised different variants of soil and foliar application of iodine: control (without soil or foliar application of iodine), combinations with pre-sowing soil fertilization with iodine in the dose of 0.5, 1.0 and 2.0 kg I ha^{-1} as well as foliar nutrition with iodine in the concentration of: 0.0005%, 0.005% and 0.05% repeated four times. In total, using 1,000 dm^3 of work solution per 1 ha, the following amounts of iodine were applied to plants in the latter variant: 0.02, 0.2 and 2.0 kg I ha^{-1}, respectively. In carrot storage roots, iodi-

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ne as well as P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb were analyzed with the ICP-OES technique, whereas nitrogen was determined with Kiejdahl's method. In all the tested combinations, significant increase in iodine concentration in carrot was observed versus the control (2.1 mg I kg^{-1} d.w). Storage roots of carrot treated with the highest doses of iodine (through soil and foliar application) contained comparable amounts of this element: 10.2 and 8.6 mg I kg^{-1} d.w., respectively, which were also the highest quantities relative to the control and the other treatments. Soil fertilization in the dose of 1.0 and 2.0 kg I ha^{-1} as well as foliar nutrition with 0.0005%, and 0.05% solution of iodine contributed to an increased content of nitrogen in carrot roots. Soil and foliar application of iodine, in relation to the control, resulted in a higher content of Mg, Fe, Al and K as well as a lower S concentration in carrot, except K and S in the combination with soil fertilization of 0.5 kg I ha^{-1}. Diversified influence of the iodine dose, form and application method was observed in reference to concentrations of: P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb in carrot storage roots. Iodine treatments included in the research had no significant influence on the Mo content in carrot.

Key words: biofortification, iodine, foliar nutrition, mineral composition, carrot.

WSTĘPNA OCENA WPŁYWU NAWOŻENIA I DOKARMIANIA DOLISTNEGO JODEM NA EFEKTYWNOŚĆ BIOFORTYFIKACJI MARCHWI W JOD ORAZ JEJ SKŁAD MINERALNY

Abstrakt

Warzywa wzbogacane w jod mogą stać się alternatywną, do jodowania soli kuchennej, drogą wprowadzania jodu do diety człowieka. Jod nie jest składnikiem pokarmowym roślin. Jego oddziaływanie na procesy biochemiczne i fizjologiczne roślin, w tym na funkcjonowanie gospodarki mineralnej, nie zostało zdiagnozowane. W dostępnej literaturze brak jest informacji na temat porównania efektywności biofortyfikacji korzeni spichrzowych marchwi w jod poprzez nawożenie doglebowe i dolistną aplikację tego pierwiastka. Celem badań było określenie wpływu doglebowego przedsiewnego nawożenia jodem (w formie KI) i dolistnej aplikacji tego pierwiastka (w formie KIO_3) na efektywność biofortyfikacji w jod oraz skład mineralny korzeni spichrzowych marchwi. Marchew odmiany Kazan F_1 uprawiano w latach 2008-2009 w doświadczeniu polowym. W badaniach uwzględniono kombinacje ze zróżnicowanym nawożeniem doglebowym i dokarmianiem dolistnym jodem. Wyróżniono kontrolę (nienawożoną i niedokarmianą dolistnie jodem), kombinacje z przedsiewnym nawożeniem doglebowym jodem w dawkach: 0,5, 1,0 i 2,0 kg I ha^{-1} oraz 4-krotne dolistne dokarmianie roślin jodem w stężeniach 0,0005%, 0,005% i 0,05% – sumarycznie po zastosowaniu 1000 dm^3 cieczy roboczej ha^{-1} zaaplikowano roślinom odpowiednio: 0,02, 0,2 i 2,0 kg I ha^{-1}. W korzeniach spichrzowych marchwi oznaczono: zawartość jodu oraz P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd i Pb techniką ICP-OES, a także zawartość azotu metodą Kiejdahla. We wszystkich badanych kombinacjach stwierdzono istotne zwiększenie zawartości jodu w marchwi w porównaniu z kontrolą (2,1 mg I kg^{-1} s.m.). Korzenie marchwi traktowanej najwyższymi dawkami jodu (doglebowo i dolistnie) zawierały porównywalną, najwyższą zawartość jodu – odpowiednio 10,2 i 8,6 mg I kg^{-1} s.m. W odniesieniu do kontroli nawożenie doglebowe w dawkach 1 i 2 kg I ha^{-1} oraz dokarmianie dolistne 0,0005%, i 0,05% wpłynęło na zwiększenie zawartości azotu w marchwi. Dolistna i doglebowa aplikacja jodu, w porównaniu z kontrolą, wpłynęła na zwiększenie zawartości Mg, Fe i Al, a także K oraz obniżenie zawartości S w marchwi – oprócz K i S w kombinacji z nawożeniem 0,5 kg I ha^{-1}. Stwierdzono zróżnicowane oddziaływanie dawki, formy i sposobu aplikacji jodu na zawartość P, Ca, Na, B, Cu, Mn, Zn, Cd i Pb w marchwi. Zastosowane zabiegi aplikacji jodu nie miały wpływu na zawartość Mo w marchwi.

Słowa kluczowe: biofortyfikacja, jod, dokarmianie dolistne, skład mineralny.

INTRODUCTION

Plant biofortification with iodine (or other biogenic elements) is defined as such an increase in the concentration of the element in edible parts of plant that efficiently improves the consumer's health (WHITE, BROADLEY 2005, 2009, YANG et al. 2007, ZHAO, MCGRATH 2009).

In Poland and in many other countries, the build-up of iodine content in human diet is achieved through salt iodization. It is an effective way of introducing iodine to people's diet in order to reduce health problems resulting from its deficiency. On the other hand, salt consumption in many countries is far too excessive and has led to greatly increased incidences of cardiovascular diseases. For that reason, WHO has developed the Global Strategy on Diet, Physical Activity and Health for the years 2008-2013. One of the main goals of this programme is to reduce salt intake while seeking alternative methods of introducing iodine to human diet. The need for a global development of an effective way of increasing iodine intake results from numerous functions that iodine plays in the human organism. Moreover, it should be mentioned that 35.2% of the global population has inadequate iodine nutrition (WINGER et al. 2008).

Plant roots preferably take up the iodide (I^-) rather than iodate (IO_3^-) form of iodine (SMITH et al. 1999). In higher doses, however, iodates are less toxic to plants when compared to the reduced form of this element – in particular via foliar application of iodine. With respect to the effectiveness of plant biofortification, it is higher for foliar nutrition with this element rather than with soil fertilization (ALTMOK et al. 2003, STRZETELSKI et al. 2010), especially when long-term drought occurs during plant cultivation that favors strong iodine binding by the soil sorption complex (DAI et al. 2004).

In the last few years, many studies have been carried out on iodine biofortification of numerous plant species such as cabbage (WENG et al. 2008), lettuce (BAI et al. 2007, BLASCO et al. 2008), tomato and spinach (GONDA et al. 2007), alfalfa (ALTMOK et al. 2003), pakchoi, celery, pepper and radish (HONG et al. 2008) as well as radish (STRZETELSKI et al. 2010). The scope of the mentioned research has included the assessment of the effectiveness of plant fortification with iodine depending on the dose, form and source type of the element – technical salts and organic matter rich in iodine (application of marine algae). The cited papers, however, contain no information on a documented effect of iodine on mineral nutrition of plants. Likewise, no data can be also found in the available literature on the comparison between the effectiveness of iodine biofortification of carrot achieved through soil fertilization and foliar nutrition.

The aim of the study was to determine the influence of pre-sowing soil fertilization with iodine (in the form of KI) and foliar application of this element (as KIO_3) on the effectiveness of iodine biofortification and mineral composition of carrot storage roots.

MATERIAL AND METHODS

In 2008-2009, a field experiment was conducted in Kraków, Poland, involving cv. Kazan F_1 carrot cultivation in crop rotation system on uniform soil complex. Carrot was cultivated on silt loam soil (35% sand, 28% silt and 37% clay) with the content of organic matter in the 0-30 cm soil layer: 2.84%-3.41% (in 2008 and 2009, respectively) and the following concentrations of the available nutrient forms soluble in 0.03 M acetic acid (in 2008 and 2009, respectively): N (NO_3-N+NH_4-N) – 8.1-3.8 mg, P – 51.4-45.0 mg, K – 111.8-185.4 mg, Mg – 115.6-107.4 mg and Ca – 1255.8-837.9 mg dm^{-3} soil. In 2008 and 2009, soil $pH_{(H2O)}$ was 6.98-7.10, while the total concentration of salt in soil (EC) was 0.12-0.11 mS cm^{-1}, respectively. Carrot was grown on ridges, 40 cm wide and 30 cm high, where seeds were sown at a rate of 37 seeds m^{-1} in a row (approximately 550,000 seeds per 1 hectare). Seed sowing was performed on 24 April in both years of the study. Nitrogen as ammonium nitrate was applied in a dose of 100 kg N ha^{-1} pre-sowing and as top dressing. Pre-sowing nitrogen fertilization (and iodide application) was conducted immediately before ridge formation, whereas top dressing was performed at canopy closure.

Different iodine soil fertilization (as KI) and foliar nutrition (in the form of KIO_3) treatments were applied in the experiment, including: 1 – control (without soil fertilization and foliar nutrition with iodine); combinations with soil pre-sowing fertilization of iodine in the dose of 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 combinations with foliar application of iodine, repeated four times, in the following concentrations: 5 – 0.0005% (total – 0.02 kg I ha^{-1}), 6 – 0.005% (0.2 kg I ha^{-1}) and 7 – 0.05% (2.0 kg I ha^{-1}). Foliar nutrition was performed using 1,000 dm^3 of work solution per hectare on the following dates: 1^{st} – 8 and 10 July, 2^{nd} – 22 and 28 July, 3^{rd} – 4 and 19 August, 4^{th} – 18 August and 7 September (in 2008 and 2009, respectively).

The experiment was arranged in a split-plot design with four replications. Each experimental treatment was randomized in four repetitions on 2.7 m × 5 m (13.5 m^2) plots. The total area under experiment was 378 m^2.

Carrot was harvested on 30 September 2008 and 23 September 2009. During harvest, about samples consisting of 5 kg of carrot storage roots were taken in four replications (from each plot) for further analyses. Additionally, soil samples were collected from the 0-30 cm layer with a soil drill.

In carrot storage roots, the content of iodine was assessed after incubation with 25% TMAH according to the standard protocol prEN 15111- R2-P5--F01 and the amount of N-total was determined with Kjeldahl's method (PERSSON, WENNERHOLM 1999). Concentration of P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb were determined after sample mineralization in 65% super pure HNO_3 (Merck no 100443.2500) in a CEM MARS-5 Xpress microwave oven (PASŁAWSKI, MIGASZEWSKI 2006).

In soil samples, pH was determined with a potentiometer and concentrations of I, N-NH_4, N-NO_3, P, K, Mg, Ca, S and Na were determined after soil extraction in 0.03 M acetic acid (NOWOSIELSKI 1988). The content B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb was assayed after extraction with 1 M HCl (GORACH et al. 1999).

Iodine as well as P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb in carrot and soil samples were determined with the ICP-OES technique using a Prodigy Teledyne Leeman Labs USA spectrometer. Concentrations of nitrogen forms in soil samples (N-NH_4, N-NO_3) were determined by the FIA technique [PN-EN ISO 13395: 2001; PN-EN ISO 11732:2005 (U)].

The results were statistically verified using the ANOVA module of Statistica 9.0 PL programme for significance level $P<0.05$. Significance of changes was assessed with the use of variance analysis. When significant changes appeared, homogenous groups were determined with Duncan's test.

RESULTS AND DISCUSSION

Carrot storage roots from all the tested combinations with iodine soil and foliar treatments contained significantly higher amounts of this element than control plants (Table 1). When lower iodine doses through soil fertilization (0.5 and 1.0 kg I ha^{-1}), carrot roots accumulated slightly more iodine than after foliar application of iodine in the total dose of 0.02 and 0.2 kg I ha^{-1}. On the other hand, carrot treated with the highest doses of iodine (both soil and foliar application of 2.0 kg I ha^{-1}) contained comparable concentrations of this element, i.e.10.2 and 8.6 mg I kg^{-1} d.w., respectively, which were also the highest quantities determined It is worth mentioning that the soil carrot harvest, in all the treatments, contained a comparable content of iodine soluble in 0.03 M acetic acid (Table 2). This observation indirectly indicates that iodine introduced to soil was either taken by cultivated plants or strongly sorbed by organic matter (thiol groups and polyphenols) or hydrous oxides of Fe and Al (WHITEHEAD 1984, MURAMATSU et al. 1996, YAMAGUCHI et al. 2005). Iodine desorption in soil is most profound under anaerobic conditions with the negative redox potential (Eh) resulting mainly from excessive humidity of soil (MURAMATSU et al. 1996). For that reason, in cultivated soils (mostly characterized by aerobic conditions and the positive redox potential), iodine desorption as well its uptake by plants can be inhibited. This assumption can be an additional explanation for the fact that despite applying smaller doses of iodine in foliar nutrition (combinations 5 and 6) iodine concentration in carrot was only slightly lower comparing to soil fertilization in combinations 2 and 3.

In comparison to the control, soil fertilization with 1.0 and 2.0 kg I ha^{-1} as well as foliar application of 0.02 and 2 kg I ha^{-1} contributed to increased

Table 1

Mineral composition and the effectiveness of iodine biofortification of carrot depending on soil fertilisation and foliar application of iodine - means from 2008-2009

Combinations**	Iodine content (mg I kg^{-1} d.w.)	Content of macroelements in % d.w. of carrot storage roots						
		N	P	K	Mg	Ca	S	Na
1. Control	2.1 *a*	1.75 *ab*	0.368 *b*	2.32 *b*	0.115 *a*	0.349 *bc*	0.132 *a*	0.72 *c*
2. Fertilization 0.5 kg I ha^{-1}	6.2 *bc*	1.70 *a*	0.355 *a*	2.29 *a*	0.123 *c*	0.342 *ab*	0.130 *a*	0.70 *b*
3. Fertilization 1.0 kg I ha^{-1}	9.9 *d*	1.83 *c*	0.408 *d*	2.69 *e*	0.126 *d*	0.338 *a*	0.142 *cd*	0.64 *a*
4. Fertilization 2.0 kg I ha^{-1}	10.2 *d*	1.85 *cd*	0.381 *c*	2.38 *c*	0.127 *d*	0.363 *d*	0.145 *d*	0.80 *e*
5. Foliar application 0.02 kg I ha^{-1}	4.8 *b*	1.85 *cd*	0.427 *f*	2.67 *e*	0.122 *bc*	0.377 *e*	0.151 *e*	0.78 *d*
6. Foliar application 0.2 kg I ha^{-1}	6.4 *bc*	1.77 *b*	0.366 *ab*	2.45 *d*	0.119 *b*	0.337 *a*	0.138 *b*	0.64 *a*
7. Foliar application 2.0 kg I ha^{-1}	8.6 *cd*	1.89 *d*	0.406 *d*	2.36 *c*	0.127 *d*	0.355 *c*	0.141 *bc*	0.82 *f*
Test *F*	*	*	*	*	*	*	*	*

Content of microelements, Al, Cd and Pb in mg kg^{-1} d.w. of carrot storage roots

	B	Cu	Fe	Mn	Zn	Mo***	Al	Cd	Pb
1. Control	24.9 *a*	6.6 *b*	34.1 *a*	7.8 *c*	35.8 *ab*	0.147	22.8 *a*	1.41 *bc*	0.10 *a*
2. Fertilization 0.5 kg I ha^{-1}	25.5 *b*	5.6 *a*	42.7 *b*	7.4 *a*	34.3 *a*	0.158	32.2 *b*	1.33 *a*	0.24 *ab*
3. Fertilization 1.0 kg I ha^{-1}	24.8 *a*	6.1 *ab*	49.6 *d*	7.3 *a*	37.8 *cd*	0.178	43.3 *e*	1.45 *c*	0.27 *b*
4. Fertilization 2.0 kg I ha^{-1}	25.6 *b*	5.6 *a*	56.8 *e*	7.6 *b*	36.9 *bc*	0.176	51.3 *f*	1.39 *b*	0.27 *b*
5. Foliar application 0.02 kg I ha^{-1}	27.2 *d*	7.5 *c*	49.5 *d*	8.7 *f*	38.3 *cd*	0.193	42.4 *de*	1.58 *d*	0.24 *ab*
6. Foliar application 0.2 kg I ha^{-1}	24.9 *a*	5.8 *a*	44.0 *b*	8.2 *e*	35.2 *ab*	0.151	36.3 *c*	1.34 *a*	0.11 *a*
7. Foliar application 2.0 kg I ha^{-1}	26.1 *c*	6.1 *ab*	47.3 *c*	8.1 *d*	39.3 *d*	0.126	40.0 *d*	1.45 *c*	0.21 *ab*
Test *F*	*	*	*	*	*	n.s.	*	*	*

Means followed by the same letters are not significantly different at $P<0.05$,
*means are significantly different,
**in combinations nos: 5-7, the total dose of iodine applied in four foliar nutrition treatments was given,
***results for Mo only from the year 2009.

Table 2

Results of chemical analysis of soil after carrot cultivation (means from 2008-2009 for the 0-30 cm soil layer)

Combinations	pH_{H_2O}	(mg dm^{-3} soil)								
		I	$N\text{-}NH_4$	$N\text{-}NO_3$	P	K	Mg	Ca	S	Na
1. Control	6.91 *c*	2.6	0.25	5.6 *d*	31.4 *bc*	48.3 *b*	108.7	1052.1	5.3 *c*	4.4
2. Fertilization 0.5 kg I ha^{-1}	6.76 *a*	2.2	0.25	3.6 *bc*	25.0 *a*	38.8 *a*	101.8	918.3	4.3 *ab*	3.1
3. Fertilization 1.0 kg I ha^{-1}	7.03 *e*	3.1	0.25	3.0 *ab*	34.3 *c*	66.7 *e*	109.2	1039.2	3.8 *a*	3.5
4. Fertilization 2.0 kg I ha^{-1}	6.96 *d*	3.6	0.34	1.9 *a*	32.8 *bc*	64.1 *de*	101.9	974.6	3.6 *a*	3.5
5. Foliar application 0.02 kg I ha^{-1}	6.91 *c*	3.2	0.29	5.5 *d*	30.9 *bc*	57.4 *c*	104.2	982.7	5.0 *bc*	4.7
6. Foliar application 0.2 kg I ha^{-1}	6.95 *d*	2.6	0.33	4.5 *cd*	30.2 *b*	58.6 *cd*	106.9	992.9	4.6 *bc*	3.7
7. Foliar application 2.0 kg I ha^{-1}	6.87 *b*	3.8	0.45	5.5 *d*	26.3 *a*	44.1 *ab*	104.9	963.1	7.2 *d*	3.9
Test *F*	*	n.s.	-	*	*	*	-	-	*	-

	(mg kg^{-1} soil)								
	B	Cu	Fe	Mn	Zn	Mo	Al	Cd	Pb
1. Control	1.94 *b*	5.5 *b*	2003.7	283.8 *abc*	52.5 *a*	1.02 *cd*	1280.0 *b*	1.023 *ab*	30.4 *a*
2. Fertilization 0.5 kg I ha^{-1}	1.80 a	5.3 *a*	1989.9	286.7 *bc*	53.3 *ab*	0.97 *abc*	1247.7 *ab*	1.040 *bc*	31.3 *abc*
3. Fertilization 1.0 kg I ha^{-1}	1.87 *ab*	5.4 *ab*	1997.2	288.0 *c*	53.7 *b*	0.92 *a*	1227.1 *a*	1.047 *bc*	31.7 *bc*
4. Fertilization 2.0 kg I ha^{-1}	1.84 *ab*	5.4 *ab*	1997.8	275.6 *a*	55.3 *d*	0.96 *ab*	1251.8 *ab*	1.048 *c*	31.8 *c*
5. Foliar application 0.02 kg I ha^{-1}	1.85 *ab*	5.5 *b*	2037.2	281.8 *abc*	54.0 *bc*	0.99 *bcd*	1273.7 *b*	1.044 *bc*	31.2 *abc*
6. Foliar application 0.2 kg I ha^{-1}	1.79 *a*	5.5 *b*	2028.3	275.9 *abc*	54.9 *cd*	0.97 *abc*	1265.4 *ab*	1.045 *bc*	31.7 *bc*
7. Foliar application 2.0 kg I ha^{-1}	1.79 *a*	5.4 *ab*	2028.1	278.8 *ab*	52.5 *a*	1.03 *d*	1288.2 *b*	1.014 *a*	30.8 *ab*
Test *F*	*	*	-	*	*	*	*	*	*

Means followed by the same letters are not significantly different at $P<0.05$,
* means are significantly different,
n.s. – not significant.

content of N-total in carrot (Table 1). Positive effect of soil iodine fertilization on N-total concentration in carrot storage roots (enhancement of nitrogen utilization from mineral fertilizers) is confirmed by our previous results obtained from pot (SMOLEŃ et al. 2009) and field cultivation of carrot (SMOLEŃ et al. 2010). It should be mentioned that in the present study soil analyses after carrot harvest demonstrated a relatively low content of mineral nitrogen: $N\text{-}NH_4$ and $N\text{-}NO_3$ (Table 2). In the case of $N\text{-}NO_3$, significant changes in the amount of this nitrogen form observed in soil did not correlate with its content in carrot storage roots.

The tested factors (soil fertilization and foliar application of iodine) had significant influence on the content of P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Al, Cd and Pb (Table 1) in carrot roots. Accumulation of Mo in carrot roots from all the tested combinations remained on a comparable level. Significant differentiation was revealed between the tested combination in respect of pH as well concentrations of P, K, S, B, Cu, Mn, Zn, Mo, Al, Cd and Pb in soil after carrot cultivation (Table 2).

In comparison to the control, foliar and soil application of iodine resulted in increased concentrations of Mg, Fe and Al as well as K and S, except K and S in carrot fertilized with 0.5 kg I ha^{-1} (Table 1). The changes in K concentration in carrot were reflected by the changeable level of this element in soil (Table 2). When compared to the control, higher accumulation of Al in carrot roots, caused by soil application of iodine, was related to enhanced uptake of this element from soil. This observation is supported by the reduced content of Al in soil samples from these combinations. Changes in the Mg and Fe concentration in carrot cannot be explained on the basis of the results of soil analyses, as the levels of these elements in soil samples from all the tested combinations were comparable.

In the case of P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb, the iodine dose, form and method of application produced varied effects on the accumulation of these elements in carrot storage roots (Table 1).

Taking into consideration soil fertilization alone, application of higher doses of iodine (1.0 and 2.0 kg I ha^{-1}) led to increased concentrations of P, Zn Cd and Pb in carrot in comparison to the control (Table 1). A significant build-up in Ca, Na and Mn concentration in carrot roots fertilized with 2.0 kg I ha^{-1} (combination no 4) as well as a reduction in the accumulation of these elements in carrot fertilized with 0.5 and 1.0 kg I ha^{-1} were observed. In all the combination with soil iodine application, a lower concentration of Cu was found when compared to the control. As regards boron, a significant increase of its accumulation in carrot was observed when fertilized with iodine in the doses of 0.5 and 2.0 kg I ha^{-1}. Among all the elements (P, Ca, Na, B, Cu, Mn, Zn, Cd, Pb), correlation consisting of an increased concentration in carrot (Table 1) and soil (Table 2) as a result of iodine fertilization was observed only for Zn, Cd and Pb. Lower accumulation of copper in carrot roots (Table 1) could be related to its reduced content in soil (Table 2).

The influence of foliar iodine nutrition with (combinations nos 5-7) on the content of P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb in carrot storage roots was also interesting to trace (Table 1). It should be highlighted that, depending on the dose of iodine sprayed over leaves, the treatment produced different effects on the above elements was found, i.e. significant increase, reduction or no effect of iodine on the accumulation of P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb in carrot. After foliar application of the lowest concentration of iodine (0.02 kg I ha^{-1}), storage roots of carrot plants contained the highest levels of P, Ca, B, Cu, Mn and Cd, even when compared to the control. Noteworthy is the fact that alongside increased concentrations of the applied iodine, reduced Mn accumulation was observed. Notwithstanding, in all the tested combinations with iodine foliar nutrition, Mn content exceeded values obtained for the control. It should be mentioned that the differentiation of the carrot concentration of P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb was not reflected by the content of these elements in soil (Table 2).

In the context of the above results, it was interesting to notice that the foliar application of iodine in the lowest concentration (combination no 5) contributed to significantly enhanced uptake of N, P, Ca, Na, B, Cu, Zn and Cd by carrot storage roots. This observation can indirectly bring explanation for yet unsupported positive influence of low concentration of iodine on improved plant growth and yielding (Kabata and Mukherjee 2007). Nevertheless, in the present study no significant impact of iodine applied to leaves or soil was found in reference to the yield of carrot storage roots or leaves – detailed data not shown.

To sum up, it can be stated that the influence of iodine on mineral nutrition of carrot plants is ambiguous. To much extent it can depend on agronomic conditions of cultivation, including the applied nitrogen fertilization (Smoleń 2009, Smoleń et al. 2009, 2010). In studies with pot carrot cultivation, nitrogen fertilization both in the form of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$, in comparison to the control, contributed to a different iodine influence (in the form of KI and KIO_3) on the uptake and accumulation of Ca, K, Mg, Na, P and S (Smoleń et al. 2009) as well as Al, B, Cd, Cr, Cu, Fe, Li, Ti and V (Smoleń 2009) in carrot storage roots. In the field experiments conducted by Smoleń et al. (2010), iodine nutrition (both as KI and KIO_3) of plants not fertilized with nitrogen resulted in a significant increase of P, K, Ca content and a reduction in Fe concentration but had no effect on Mg, S, Cu, Mn, Zn, Mo, Al and Pb accumulation in carrot roots. However, KIO_3 application (in comparison to KI) to plants fertilized with ammonium sulphate led to higher concentrations of N, P, K, Mg, S, Na, B, Cu, Fe, Mn, Zn, Al and Cd in carrot. As far as the fertilization with calcium nitrate is concerned, soil application of KIO_3 contributed to increased accumulation of N, K, Fe and Zn in carrot storage roots when compared to a KI treatment.

CONCLUSIONS

1. Foliar nutrition of carrot with iodine in the dose of 2.0 kg I ha^{-1} (as KIO_3) allowed us to obtain a comparable effect of iodine biofortification of carrot storage roots in comparison to soil fertilization with this element in the same dose but applied in the KI form.

2. An increase in the N-total content in carrot was observed as a result of soil fertilization in the dose of 1.0 and 2.0 kg I ha^{-1} as well as foliar nutrition of iodine in the concentration of 0.02 and 2.0 kg I ha^{-1}).

3. The research revealed a synergistic effect of iodine applied both to soil and to leaves on the uptake of N, K, Mg, S, Fe and Al by carrot storage roots.

4. In the case of P, Ca, Na, B, Cu, Mn, Zn, Cd and Pb, different effects of the iodine dose, form and application method were observed in reference to the concentrations of these elements in carrot roots.

5. Soil fertilization with iodine resulted in an increased uptake of P, Zn Cd and Pb (synergistic effect) as well as a reduced uptake of Cu (antagonism) by carrot storage roots.

6. Foliar application of the lowest concentration of iodine (0.02 kg I ha^{-1}) contributed to significantly higher accumulation of P, Ca, Na, B, Cu, Zn and Cd in carrot storage roots.

7. A significant effect of the tested factors was found in reference to the changes of soil pH as well as the content of $N\text{-}NO_3$, P, K, S, B, Cu, Mn, Z, Mo, Al, Cd and Pb in soil after carrot cultivation.

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