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PRELIMINARY EVALUATION OF THE INFLUENCE OF IODINE AND NITROGEN FERTILIZATION ON THE EFFECTIVENESS OF IODINE BIOFORTIFICATION AND MINERAL COMPOSITION OF CARROT STORAGE ROOTS

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Abstract

Biofortification of vegetables with iodine can become an alternative method to salt iodization of introducing this element to human diet. Iodine is not an essential nutrient for plants and its effect on plant growth and development has not yet been sufficiently examined. The aim of the study was to assess the influence of soil fertilization with iodine (in the form of I^- and IO_3^-) and nitrogen (applied as NO_3^- and NH_4^+) on the effectiveness of iodine biofortification as well as mineral composition of carrot storage roots. Carrot cv. Kazan F_1 was cultivated in a field experiment in 2008 and 2009. Different soil fertilization treatments with iodine as well as nitrogen were tested, including: 1 – control without N and I fertilization; 2 – KI fertilization without N application; 3 – KIO_3 fertilization without N application; 4 – KI + $Ca(NO_3)_2$ fertilization; 5 – KIO_3 + $Ca(NO_3)_2$ fertilization, 6 – KI + + $(NH_4)_2SO_4$ fertilization, 7 – KIO_3 + $(NH_4)_2SO_4$ fertilization. Iodine as KI and KIO_3 was applied pre-sowing in a dose of 2 kg I ha^{-1}. Nitrogen fertilization in the form of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ was performed pre-sowing and as top dressing with 100 kg N ha^{-1}. In carrot storage roots, the iodine content as well as P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb concentration were determined by the ICP-OES technique, while nitrogen – using Kjeldahl method. Better results of iodine enrichment in carrot were obtained

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after introducing this element in the form of KI, especially together with ammonium sulphate. Application of the IO_3^- form of iodine significantly improved nitrogen utilization from mineral fertilizers by carrot plants. In storage roots of carrots cultivated without N nutrition, iodine treatment (in both forms: KI and KIO_3) contributed to a significant increase in P, K and Ca content as well as a reduction in Fe accumulation. However, it had no influence on the concentration of Mg, S, Cu, Mn, Zn, Mo, Al and Pb in carrot storage roots. Application of KIO_3, in comparison to KI, resulted in a significant increase of the K, Fe and Zn content in carrot roots fertilized with $Ca(NO_3)_2$. In the case of $(NH_4)_2SO_4$ as a nitrogen source, KIO_3 contributed to significantly higher accumulation of P, K, Mg, S, Na, B, Cu, Fe, Mn, Al and Cd in carrot storage roots when compared to KI.

Key words: biofortification, iodine, nitrogen fertilization, mineral composition, carrot.

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

Abstrakt

Warzywa biofortyfikowane jodem mogą być alternatywnym, do jodowania soli, sposobem wprowadzenia tego pierwiastka do diety człowieka. Jod nie jest pierwiastkiem niezbędnym dla roślin. Jego oddziaływanie na rośliny nie zostało dostatecznie zdiagnozowane. Celem badań było określenie wpływu doglebowego nawożenia jodem (w formie I^- i IO_3^-) i azotem (w formie NO_3^- i NH_4^+) na efektywność biofortyfikacji jodem oraz na skład mineralny marchwi. Marchew odmiany Kazan F_1 uprawiano w doświadczeniu polowym w latach 2008-2009. W badaniach zastosowano zróżnicowane doglebowe nawożenie jodem (I w formie I^- lub IO_3^-) i azotem (N w formie NO_3^- lub NH_4^+): 1 – kontrola bez nawożenia N i I, 2 – nawożenie KI bez nawożenia N, 3 – nawożenie KIO_3 bez nawożenia N, 4 – nawożenie KI + $Ca(NO_3)_2$, 5 – nawożenie KIO_3 + $Ca(NO_3)_2$, 6 – nawożenie KI + $(NH_4)_2SO_4$, 7 – nawożenie KIO_3 + $(NH_4)_2SO_4$. Jod w formie KI i KIO_3 aplikowano przedsiewnie w dawce 2 kg I ha^{-1}, azot w formie $Ca(NO_3)_2$ i $(NH_4)_2SO_4$ – w dawce po 100 kg N ha^{-1} przedsiewnie i pogłównie. W marchwi oznaczono: zawartość jodu oraz P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd i Pb techniką ICP-OES; zawartość azotu metodą Kiejdahla. Lepsze efekty wzbogacania marchwi w jod uzyskano po zastosowaniu jodu w formie KI, zwłaszcza gdy stosowano ten związek w połączeniu z siarczanem amonu. Zastosowanie jodu w formie IO_3^- istotnie poprawiało efektywność wykorzystania azotu przez rośliny z zastosowanych nawozów mineralnych. W korzeniach spichrzowych roślin nienawożonych azotem zastosowanie jodu (w formie KI i KIO_3) powodowało istotne zwiększenie zawartości P, K, Ca oraz zmniejszenie zawartości Fe; natomiast nie miało wpływu na zawartość Mg, S, Cu, Mn, Zn, Mo, Al i Pb. Zastosowanie KIO_3, w porównaniu z KI, powodowało istotne zwiększenie zawartości K, Fe i Zn w marchwi nawożonej $Ca(NO_3)_2$. W przypadku nawożenia $(NH_4)_2SO_4$ aplikacja KIO_3, w porównaniu z KI, powodowała istotne zwiększenie zawartości P, K, Mg, S, Na, B, Cu, Fe, Mn, Al i Cd w marchwi.

Słowa kluczowe: biofortyfikacja, jod, nawożenie azotem, skład mineralny, marchew.

INTRODUCTION

In Poland and many other countries around the world, iodine content in human diet is currently raised through salt iodization. Excessive salt consumption, however, has recently led to increased incidences of cardiovascular diseases. For that reason, the Global Strategy on Diet, Physical Activity and Health for the years 2008-2013 has been proposed by WHO. This program includes significant reduction of salt intake and recommends searching for alternative ways of introducing iodine to human diet. The need for global development of effective methods to enrich our diet in this element results from numerous functions that iodine plays in a human organism. Moreover, 35.2% of the global population suffers from an inadequate iodine nutrition (WINGER et al. 2008).

Iodine biofortification of vegetables can be perceived as one of the alternative ways of introducing iodine into human diet. Biofortification is defined as such a process that increases the content of biogenic elements such as Fe, Zn, Ca, Mg, Cu, I or Se in edible parts of crop plants. As a result, the consumer's health is expected to improve. Increased accumulation of biogenic elements in plants can be achieved through application of agronomic, genetic or transgenic strategies (STRZETELSKI 2005,WHITE, BROADLEY 2005, 2009, YANG et al. 2007, ZHAO, MCGRATH 2009).

Iodine is not an essential nutrient for plant growth and development and its influence on plants has not yet been diagnosed (KABATA, MUKHERJEE 2007). In general, the research on iodine neglects problems in biofortification due to the interaction of iodine with physiological and biochemical processes occurring in plants, including mineral nutrition. Evaluation of these interrelations is crucial for developing optimal agrotechniques of plant biofortification with iodine.

At present, there are no norms for an acceptable level of iodine in vegetables. In the future, results of studies on iodine biofortification can help develop these standards in order to adequately balance the content of this element in human diet.

The aim of the study has been to determine the influence of soil fertilization with iodine (in the form of I^- and IO_3^-) and nitrogen (as NO_3^- and NH_4^+) on iodine biofortification efficiency and mineral composition of carrot storage roots.

MATERIAL AND METHODS

In 2008-2009, a field experiment was conducted in Kraków (Poland), on carrot cv. Kazan F_1 grown in crop rotation on uniform soil complex. The carrot was cultivated on silt loam soil (35% sand, 28% silt and 37% clay) with the content of organic matter 2.84%-3.41% in the 0-30 cm soil layer and the following concentrations of the available forms of nutrients soluble in 0.03 M acetic acid: 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 in 1 dm^{-3} of soil (in 2008 and 2009, respectively). In the subsequent years, the soil

$pH_{(H_2O)}$ was 6.98-7.10 while the general concentration of salt in soil (EC) was 0.12-0.11 mS cm^{-1}. The carrot was grown on ridges, 40 cm wide and 30 cm high, where seeds were sown in one row at a rate of 37 seeds m^{-1} (approximately 550 000 seeds per 1 hectare). Seed sowing was performed on 24 April in both years of the study.

Several variants of soil fertilization with iodine (in the form of I^- or IO_3) and nitrogen (as NO_3^- or NH_4^+) were applied in the experiment: 1 – control without N and I fertilization; 2 – KI application without N fertilization; 3 – KIO_3 application without N fertilization; 4 – KI + $Ca(NO_3)_2$ fertilization; 5 – KIO_3 + $Ca(NO_3)_2$ fertilization; 6 – KI + $(NH_4)_2SO_4$ fertilization; 7 – KIO_3 + $(NH_4)_2SO_4$ fertilization. Iodine (in both forms) was applied pre-sowing in a dose of 2 kg I ha^{-1}. The iodine dose used in the experiment was chosen on the basis of our previous studies (Smoleń et. al. 2009b, Strzetelski et. al. 2010) as well as the results obtained by other authors (Borst Pauwels 1961, Smith, Middleton 1982, Altmok et al. 2003).

Nitrogen in the forms of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ was introduced pre-sowing and as top dressing, each dose of 100 kg N ha^{-1}. The pre-sowing nitrogen fertilization (and iodine application) was conducted immediately before the ridge formation, whereas the top dressing – at canopy closure. The experiment was arranged in a split-plot design. Each experimental treatment was randomized in four replications on 2.7 m × 5 m (13.5 m^2) plots. The total area used for the experiment was 378 m^2.

The carrot was harvested on 30 and 23 September (in 2008 and 2009, respectively). During harvest, about 5 kg of carrot storage roots were taken in four replications (from each plot) for further analyses alongside soil samples from three layers (0-30 cm, 30-60 cm and 60-90 cm), which were collected using a soil drill.

In carrot storage roots, iodine content was assessed after sample incubation with 25% TMAH according to the standard project prEN 15111-R2-P5--F01, while N-total was determined using Kjeldahl method (Persson, Wennerholm 1999). The concentration of P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb was determined after 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 extraction with 0.03 M acetic acid (Nowosielski 1988). The content of B, Cu, Fe, Mn, Zn, Mo, Al, Cd and Pb was assayed after soil extraction with 1 M HCl (Gorlach 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. The concentration of nitrogen forms in soil samples (N-NH_4, N-NO_3) was determined with 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 at the significance level $P < 0.05$. Significance of changes was assessed with the use of variance analysis. For significant changes, homogenous groups were distinguished on the basis of Duncan test.

RESULTS AND DISCUSSION

In comparison to the control, significantly increased iodine content in carrot storage roots was observed in all combinations with iodine fertilization in the form of KI (Table 1). The highest amount of this element was detected in roots of plants fertilized with KI and $(NH_4)_2SO_4$ (combination 6). A slightly lower but still comparable level of iodine in carrot roots was found after fertilization with KI only (combination no.2) as well as KI together with calcium nitrate (combination no.4). It was revealed that soil application of KIO_3 (along with nitrogen fertilizers) resulted in just a slight build-up of iodine in carrot storage roots. In storage roots of plants treated with KIO_3, a tendency for increasing iodine concentration (in comparison to the control) was observed but no statistical significance was noted. It should be mentioned that in all the tested combinations, iodine content in the 0-90 cm soil layer remained at a comparable level (Table 2). In our previous studies with pot cultivation of carrot (SMOLEŃ et al. 2009a) conducted in an analogous experiment design with iodine and nitrogen fertilization (on soil characterized by similar physicochemical properties), iodine applied as KI and KIO_3 did not contribute to biofortification of carrot storage roots and leaves with this element. Exceptionally, increased concentration of iodine was found only in leaves of carrot treated with KIO_3 (without N) as well as $Ca(NO_3)_2$+KI. It should be underlined, however, that in that pot experiment iodine concentration in carrot was assayed after incubation of root and leaf samples in 2% acetic acid, not 25% solution of TMAH as in the present work. Thus, the analytical procedure applied for iodine determination (apart from different cultivation conditions) could be responsible for obtaining different results in reference to the effect of I and N fertilization on iodine biofortification of carrot.

Iodine application regarded together with differential nitrogen fertilization significantly affected the content of: N, P, K, Mg, Ca, S, Na, B, Cu, Fe, Mn, Zn, Al, Cd and Pb in carrot (Table 1). However, the iodine and nitrogen treatments tested in the experiment did not influence Mo concentration in carrot storage roots.

In the aforementioned pot cultivation of carrot (SMOLEŃ 2009, SMOLEŃ et al. 2009a), application of iodine in the form of KIO_3 (in reference to KI),

Table 1

Mineral composition and the effectiveness of iodine biofortification of carrot storage roots depending on nitrogen and iodine fertilization – means from 2008-2009

Combinations	Content of iodine (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 (without N and I)	2.0 *a*	1.42 *a*	0.350 *ab*	2.30 *b*	0.113 *a*	0.318 *ab*	0.13 *a*	0.76 *d*
2. KI (without N)	4.3 *cd*	1.46 *b*	0.380 *c*	2.46 *d*	0.111 *a*	0.345 *bc*	0.13 *a*	0.76 *d*
3. KIO_3 (without N)	2.6 *ab*	1.40 *a*	0.364 *bc*	2.38 *c*	0.112 *a*	0.348 *c*	0.13 *a*	0.81 *e*
4. $Ca(NO_3)_2$+KI	3.8 *bcd*	1.77 *c*	0.367 *bc*	2.45 *d*	0.128 *b*	0.337 *abc*	0.13 *a*	0.73 *c*
5. $Ca(NO_3)_2$+KIO_3	3.4 *abc*	2.00 *d*	0.377 *bc*	2.50 *e*	0.132 *bc*	0.351 *c*	0.14 *a*	0.72 *c*
6. $(NH_4)_2$SO4+KI	5.0 *d*	1.75 *c*	0.327 *a*	2.23 *a*	0.116 *a*	0.313 *a*	0.14 *a*	0.69 *a*
7. $(NH_4)_2SO_4$+KIO_3	3.1 *abc*	1.99 *d*	0.381 *c*	2.55 *f*	0.135 *c*	0.339 *abc*	0.15 *b*	0.70 *b*
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 (without N and I)	24.5 *c*	4.8 *a*	47.2 *c*	6.3 *ab*	24.3 *a*	0.315	44.0 *c*	1.15 *a*	0.273 *c*
2. KI (without N)	23.9 *b*	4.9 *ab*	39.5 *ab*	6.0 *a*	25.9 *a*	0.373	40.7 *bc*	1.27 *b*	0.226 *bc*
3. KIO_3 (without N)	24.2 *bc*	4.6 *a*	40.8 *ab*	6.3 *ab*	24.4 *a*	0.325	43.8 *c*	1.16 *a*	0.161 *abc*
4. $Ca(NO_3)_2$+KI	24.2 *bc*	5.3 *bc*	40.1 *ab*	6.4 *bc*	29.9 *b*	0.360	28.0 *b*	1.25 *ab*	0.230 *bc*
5. $Ca(NO_3)_2$+KIO_3	24.1 *bc*	5.6 *c*	41.8 *c*	6.6 *c*	33.2 *c*	0.385	39.8 *bc*	1.34 *b*	0.230 *bc*
6. $(NH_4)_2SO_4$+KI	23.0 *a*	5.2 *b*	33.5 *a*	11.5 *d*	30.9 *bc*	0.282	27.4 *a*	1.50 *c*	0.086 *a*
7. $(NH_4)_2SO_4$+KIO_3	25.1 *d*	6.1 *d*	42.5 *c*	16.2 *e*	37.7 *d*	0.321	38.3 *b*	1.68 *d*	0.106 *ab*
Test *F*	*	*	*	*	*	n.s.	*	*	*

Means followed by the same letters are not significantly different for $P < 0.05$.
* means are significantly different, n.s. – not significant, ** results for Mo from 2009 only

Table 2

Results of chemical analysis of soil after carrot cultivation – means for the 0-90 cm soil layer from 2008-2009

Combinations	pH_{H_2O}	(mg dm^{-3} soil)								
		I	N-NH_4	N-NO_3	P	K	Mg	Ca	S	Na
1. Control (without N and I)	7.23 *de*	1.15	0.3 *a*	1.3 *a*	16.2	23.2 *a*	75.3	998.5 *a*	7.8 *a*	4.5 *a*
2. KI (without N)	7.27 *e*	1.09	0.8 *a*	3.1 *b*	15.3	34.9 *d*	84.4	1111.5 *bc*	7.6 *a*	5.7 *bc*
3. KIO_3 (without N)	7.19 *de*	1.14	1.0 *a*	2.7 *b*	14.6	29.3 *b*	86.2	1104.5 *bc*	7.6 *a*	6.4 *c*
4. $Ca(NO_3)_2$+KI	7.14 *cd*	1.45	0.5 *a*	7.7 *c*	16.0	26.7 *ab*	82.8	1053.3 *abc*	5.9 *a*	4.7 *ab*
5. $Ca(NO_3)_2$+KIO_3	7.06 *bc*	0.52	3.0 *b*	16.0 *d*	13.9	30.8 *bc*	79.9	1008.2 *ab*	7.7 *a*	6.2 *c*
6. $(NH_4)_2$SO4+KI	7.01 *b*	0.90	0.7 *a*	8.4 *c*	16.4	35.8 *d*	89.6	1149.2 *c*	32.6 *b*	4.6 *a*
7. $(NH_4)_2SO_4$+KIO_3	6.64 *a*	0.72	7.7 *c*	18.9 *e*	13.3	35.5 *d*	86.6	1083.2 *abc*	84.8 *c*	6.4 *c*
Test *F*	*	n.s.	*	*	n.s.	*	n.s.	*	*	*
(mg kg^{-1} soil)										
	B	Cu	Fe	Mn	Zn	Mo	Al	Cd	Pb	
1. Control (without N and I)	1.3	6.63 *bc*	2073.6 *d*	239.8 *de*	38.9 *a*	1.33 *d*	1453.4 d	0.735 *ab*	39.1 *b*	
2. KI (without N)	1.3	5.99 *ab*	1920.1 *ab*	240.6 *de*	49.3 *b*	1.18 *ab*	1384.6 *a*	0.743 *abc*	74.7 *c*	
3. KIO_3 (without N)	1.9	6.82 *c*	1996.3 *c*	229.7 *b*	38.8 *a*	1.16 *a*	1406.1 *ab*	0.736 *ab*	21.7 *a*	
4. $Ca(NO_3)_2$+KI	1.2	7.09 *c*	1882.8 *a*	236.3 *c*	39.2 *a*	1.19 *abc*	1403.6 *ab*	0.729 *b*	63.4 *c*	
5. $Ca(NO_3)_2$+KIO_3	1.2	5.96 *ab*	1935.6 *b*	221.7 *a*	39.0 *a*	1.22 *bc*	1422.5 *bc*	0.727 *a*	20.9 *a*	
6. $(NH_4)_2SO_4$+KI	1.2	5.63 *a*	2035.5 *cd*	245.8 *e*	40.4 *a*	1.22 *c*	1436.3 *cd*	0.752 *bc*	21.8 *a*	
7. $(NH_4)_2SO_4$+KIO_3	1.0	6.40 *bc*	2150.1 *f*	262.1 *f*	38.9 *a*	1.38 *f*	1509.2 *f*	0.758 *c*	119.3 *d*	
Test *F*	n.s.	*	*	*	*	*	*	*	*	

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

both with and without N nutrition, resulted in a higher content of N-total in storage roots but had no influence on the level of this element in leaves. In the present work, soil application of KI without nitrogen, in comparison to the control and KIO_3, contributed to a higher content of N-total in carrot (Table 1). In the case of plants fertilized with nitrogen (both as calcium nitrate and ammonium sulphate), soil application of KIO_3 (when compared to KI) significantly increased the level of N-total in carrot storage roots. The effects shown above could have been related to a higher concentration of mineral nitrogen in soil from these combinations (Table 2). The results indicate that the IO_3^- form of iodine most affected the ammonium nitrogen stabilization in soil, possibly by depressing nitrification processes – in combination with the ammonium sulphate application. Notably, the concentration of N-NO_3 in soil fertilized with $Ca(NO_3)_2$ + KIO_3 was only slightly lower when compared to the application of $(NH_4)_2SO_4$ + KIO_3. Moreover, the level of this N form in soil in the above combinations was distinctively higher when compared to KI fertilization along with the both tested nitrogen fertilizers. Iodine in the form of IO_3^- may have limited total denitrification of NO_3^- to N_2. It is worth mentioning that trace amounts of mineral nitrogen were found in soil after carrot cultivation in pots (SMOLEŃ et al. 2009a). In the available literature, no information can be on the influence of iodine (in I^- or IO_3^- form) on the conversion of mineral nitrogen in the soil environment.Therefore, it is difficult to compare our results with those reported by other authors.

In storage roots of plants grown without N, iodine application (in both forms: KI and KIO_3) led to a significant increase in the P, K and Ca content as well as a reduction in the Fe concentration. It had no influence, however, on the accumulation of Mg, S, Cu, Mn, Zn, Mo, Al and Pb in carrot (Table 1). Changes in the K, Ca and Fe concentration in carrot observed in our trials were clearly attributable to the influence of KI and KIO_3, such as an elevated content of easily soluble forms of K and Ca, as well a reduced level of Fe in soil (Table 2). It should be added that in the study conducted by SMOLEŃ (2009), fertilization with KIO_3 but without N led to higher accumulation of Al and Li as well as a reduced Cu content in carrot while the application of KI depressed the level of B, Fe, Ti and V in storage roots.

Interesting results were found with reference to iodine influence (in KI and KIO_3 forms) on mineral composition of carrot roots in dependence on the type of nitrogen fertilizer (Table 1). A significant increase in K, Fe and Zn concentration in carrot was noted after using $Ca(NO_3)_2$ + KIO_3 rather than $Ca(NO_3)_2$ + KI. In case of K and Fe, obtained results might have been related to higher level of easily soluble forms of these elements in soil (Table 2). In respect to plants fertilized with calcium nitrate, type of used iodine forms had no significant effect (when comparing KI and KIO_3) on the content of: P, Mg, Ca, S, Na, B, Cu, Mn, Mo, Al, Cd and Pb in carrot storage roots.

Soil application of KIO_3 (in comparison to KI) to plants fertilized with ammonium sulphate contributed to an increased concentration of P, K, Mg, S, Na, B, Cu, Fe, Mn, Zn, Al and Cd in carrot (Table 1). Among these elements, a significantly higher level of easily soluble forms of S, Na, Cu, Fe, Mn and Al was found in soil after cultivation of carrot fertilized with $(NH_4)_2SO_4$ + KIO_3 (when compared to $(NH_4)_2SO_4$ + KI), which could have directly affected its content in carrot roots. The concentrations of P, K, Mg, B, Zn and Cd in soil from these both combinations remained comparable.

The results of our experiment allow us to assume that an increased content of P, K, Mg, B, Zn and Cd in carrot fertilized with $(NH_4)_2SO_4$ + + KIO_3 could have been caused by the synergistic interaction of the IO_3^- form of iodine and SO_4^{2-} ions, affecting the uptake of these elements by plants. Furthermore, nitrogen fertilization in either form (calcium nitrate, ammonium sulphate) and application of iodate could have stimulated the uptake of zinc from soil. With these results, it is impossible to objectively claim whether higher accumulation of Zn in carrot was related to some synergism between IO_3^- and NO_3^-/SO_4^{2-} or with cations (Ca^{2+}, NH_4^+) introduced to soil with mineral fertilizers. Nonetheless, it is noteworthy that in the earlier pot experiment with carrot (Smoleń 2009) no significant effect of KI and KIO_3 application (with different N fertilization) on the Zn content in carrot was found. In the above study, nitrogen application, both in the $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ forms, modified the influence of iodine on the uptake and accumulation of Ca, K, Mg, Na, P and S (Smoleń et al. 2009a) as well as Al, B, Cd, Cr, Cu, Fe, Li, Ti and V (Smoleń 2009) in comparison to the combinations without N fertilization.

In the present study, contrary results were obtained with respect to the effect of iodine application as KI and KIO_3 (with different nitrogen fertilization) on mineral composition of storage roots in comparison to our previous experiments with pot cultivation of carrot (Smoleń 2009, Smoleń et al. 2009a). This inconsistency could be related to the different methods of carrot cultivation, particularly resulting from the limited capacity of growth by carrot roots in the pot experiment.

CONCLUSIONS

1. In comparison to the control, a significant increase in the iodine content in carrot storage roots was found in all the combinations with iodine application in the form of KI.

2. The best effects of iodine biofortification of carrot was obtained through iodine application in the form of KI, particularly together with N fertilization with ammonium sulphate.

3. Iodine application as KIO_3 (when compared to KI) significantly improved nitrogen utilization from mineral fertilizers by carrot plants.

4. The influence of the iodine form on the N-total content in carrot roots was varied, depending on whether cultivation was carried out without N fertilization or using ammonium sulphate and calcium nitrate.

5. In the combinations without N nutrition, iodine application (both as KI and KIO_3) contributed to a significant increase in the P, K and Ca content and a reduction in the Fe concentration but had no effect on the Mg, S, Cu, Mn, Zn, Mo, Al and Pb accumulation in carrot storage roots.

6. KIO_3 application, when compared to KI, to plants fertilized with ammonium sulphate increased the concentration of: N, P, K, Mg, S, Na, B, Cu, Fe, Mn, Zn, Al and Cd in carrot. In the case of fertilization with calcium nitrate, KIO_3 treatment led to higher levels of N, K, Fe and Zn in carrot storage roots than application of KI.

7. In the combinations without N fertilization, changes in the carrot content of K, Ca and Fe were related to the influence of iodine on the availability of easily soluble forms of these elements in soil. In the case of $Ca(NO_3)_2$ application, it caused accumulation of K and Fe. When $(NH_4)_2SO_4$ was used, the concentrations of S, Na, Cu, Fe, Mn and Al in carrot roots were all affected by some interaction of iodine with these elements in soil.

8. Iodine application in the form of KI and KIO_3 together with N fertilization had a variable influence on soil pH as well as the content of $N\text{-}NH_4$, $N\text{-}NO_3$, K, S, Na, Cu, Fe, Mn, Mo, Al, Cd and Pb in soil after carrot cultivation.

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