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EFFECTS OF SELENIUM ON THE CONTENT OF ESSENTIAL MICRONUTRIENTS AND THEIR TRANSLOCATION IN GARDEN PEA*

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ABSTRACT

A laboratory study was conducted to evaluate the effects of selenium (Se) on the status of essential micronutrients in garden pea (*Pisum sativum* L.). The aim of the study was to verify whether Se affects the growth and essential micronutrient concentration, partitioning and translocation among individual plant parts of garden pea. Plants were grown under growth chamber conditions in Hoagland's nutrient solution No.1. Selenium was supplied to nutrient solution in the form of sodium selenite or sodium selenate, at concentrations of 10 and 20 $\mu\text{mol dm}^{-3}$, when plants were in the stage of the first pair of leaves. After 7 days, the fresh and dry matter of shoots, hypocotyls and roots as well the concentrations of Se and essential micronutrients (Fe, Zn, Mn, Mo, Cu and B) in individual plant parts were determined. Concentrations of Se and micronutrients were analysed with an inductively coupled plasma optical emission spectrometer (ICP-OES). Pea seedlings absorbed Se from the nutrient solution and accumulated it mainly in roots. More Se was accumulated in seedlings when it had been applied in the form of selenate than selenite. Se application at a higher concentration (20 $\mu\text{mol dm}^{-3}$) limited the increase of dry weight of shoots. Moreover, Se in both forms reduced the water content mainly in roots, wherein the effect of selenate was stronger and occurred also in aerial parts. Under the influence of Se, a decrease in the accumulation in pea seedlings and translocation to shoots of Fe, Zn, Mn, B and Cu was found. However, this was not observed in the case of Mo. The results suggest that the Se effect exerted on translocation of micronutrients was caused by dehydration associated with membrane damage of roots.

Keywords: selenate, selenite, boron, copper, iron, manganese, molybdenum, zinc, *Pisum sativum*.

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INTRODUCTION

Selenium (Se) is an essential component of human and animal cells, but it is not considered an essential element for higher plants, although at lower concentrations it can improve their biological functions and stimulate plant growth, whereas at higher concentrations it can exert toxic effects (HARTIKAINEN et al. 2000). Numerous reports have been published regarding the beneficial antioxidant effects of Se in stress caused by various factors (GUPTA, GUPTA 2017). The incorporation of Se instead of S into cysteine and methionine results in the synthesis of non-specific selenoproteins. Thus, Se phytotoxicity is attributed to the synthesis of malformed selenoproteins and the induction of oxidative stress as a result of a high concentration of this element (VAN HOEWYK 2013, GUPTA, GUPTA 2017). It has also been found that Se at higher concentrations can alter contents of essential nutrients in plants. However, there are differences in the results of various authors, which do not allow for generalizations (WU, HUANG 1992, ARVY et al. 1995, KOPSELL et al. 1995, PAZURKIEWICZ-KOCOT et al. 2003, FARGAŠOVÁ et al. 2006, HAWRYLAK-NOWAK 2008, SCHIAVON et al. 2013, HAWRYLAK-NOWAK et al. 2015, POLITYCKA et al. 2017). Discrepancies occur even when the results of experiments carried out in hydroponic cultures are compared, in which the composition of the nutrient solution is strictly defined and the conditions are controlled. DOMOKOS-SZABOLCSY et al. (2017) state in their review that although the interaction between Se and S is well documented, interactions between Se and other essential nutrients are not fully clarified and this issue should be further investigated. Therefore, the aim of this study was to examine the effect of selenate and selenite on micronutrient accumulation and translocation in garden pea (*Pisum sativum* L.) plants.

MATERIALS AND METHODS

Garden pea (*Pisum sativum* L.) cv. 'Akord' seeds were germinated for 4 days on Petri dishes lined with moist filter paper. Uniform, germinated seeds were then transferred to containers with 4 dm³ of aerated Hoagland's nutrient solution No. 1 and grown for the next 4 days. Se was added to the nutrient solution as sodium selenite (Na₂SeO₃ · 5H₂O) or sodium selenate (Na₂SeO₄) when the pea seedlings were in the stage of the first pair of leaves. The concentration of Se in the nutrient solution was 10 and 20 µmol dm⁻³. Control seedlings were grown in a nutrient solution without Se. The experiment was carried out in a controlled-environment growth chamber with the following conditions: under luminescent light with photon flux density 135 µmol m⁻² s⁻¹ (Philips lamps), a 14/10 day/night photoperiod, at 27/23°C day/night temperatures and relative humidity of about 60%. The experiment

was repeated 3 times in 3 replications, each replication involving 1 container with 35 pea seedlings. Seedlings were grown on Hoagland's solution No. 1 with selenium for 7 days and samples were collected when the plants were in the stage of the third pair of leaves.

The fresh and dry mass values of pea shoots, hypocotyls and roots were taken as growth criteria. Results are means of about 300 seedlings. The content of water in shoots and roots was calculated on the basis of fresh and dry mass.

Air-dried 0.5 g samples of pea shoots, hypocotyls and roots were digested at 200°C (15 min of warming plus 20 min of maintaining the set temperature) in 10 cm³ of 65% super pure HNO₃ using the microwave system CEM MARS-5 Xpress. Samples were then replenished with double-distilled water to the final volume of 25 cm³. The analyses of Se, Fe, Zn, Mn, Mo, Cu and B in pea samples were conducted using an inductively coupled plasma optical emission Prodigy spectrometer (ICP-OES Teledyne Leeman Labs USA).

Moreover, the total micronutrient content in shoot, hypocotyl and root was obtained by multiplying the micronutrient content in a plant part by its dry matter, while the translocation index (TI) for relative nutrient transport to the shoot was calculated by dividing the shoot micronutrient content by the total plant micronutrient content and expressed as the percentage of control (RENGEL, GRAHAM 1996).

The results were subjected to statistical analysis using analyses of variance and the significance of differences between the means was estimated by the Duncan's test.

RESULTS AND DISCUSSION

The Se content in pea seedlings significantly increased following an application of this element in either form, and was higher at the higher Se concentration in the nutrient solution (Table 1). In seedlings grown in a nutrient solution with the addition of selenate, on average the content of Se was 3.2-fold higher than in seedlings grown in a solution with selenite. Similar results were obtained in both soil and hydroponic experiments for different plant species (CARTES et al. 2005, ZHAO et al. 2005, GAROUSI et al. 2016, MOLNÁROVÁ, FARGAŠOVÁ 2016). The Se treatment of pea seedlings resulted in significant differences in the distribution of Se between individual plant parts. Regardless of the form, a higher Se concentration was found in the roots than in the shoots. It is believed that selenate taken up by plant roots is quickly transported through the xylem to shoots (LI et al. 2008, KOSTOPOULOU et al. 2010). However, other results obtained by some authors suggest that the distribution of Se applied in the form of selenite or selenate in individual plant parts is dependent on plant species (ARVY 1993, HAWRYLAK-NOWAK 2013,

Table 1

Selenium content in plant parts of garden pea supplied with selenium in forms of sodium selenite and sodium selenate

Plant part	Se content ($\mu\text{g kg}^{-1}$ DW)				
	control	selenite		selenate	
		10 $\mu\text{mol dm}^{-3}$	20 $\mu\text{mol dm}^{-3}$	10 $\mu\text{mol dm}^{-3}$	20 $\mu\text{mol dm}^{-3}$
Shoot	0.551 a^*	6.021 b	19.50 c	203.4 d	787.3 e
Hypocotyl	2.614 a	19.31 b	40.98 d	31.58 c	96.24 e
Root	4.102 a	307.9 b	382.5 c	708.5 d	1755.5 e

* Means from the individual rows of the table not followed by the same letter are significantly different at $\alpha \leq 0.05$.

HAWRYLAK-NOWAK et al. 2015, GAROUSI et al. 2016, MOLNÁROVÁ, FARGAŠOVÁ 2016). There is no information in the literature on the accumulation of Se in the hypocotyl. Our study showed that the Se content in hypocotyls of pea seedlings treated with selenite was lower than in roots, but higher than in shoots, while a lower Se content was found in hypocotyls of seedlings treated with selenate compared to shoots and roots.

Growth parameters are most commonly used as indices of phytotoxicity caused by various stress factors. Plant growth responses are closely related to the content of Se in plant tissues. Se excess reduces plant mass (MROZCEK-ZDYRSKA, WÓJCIK 2012, HAWRYLAK-NOWAK 2008, 2013, HAWRYLAK-NOWAK et al. 2015, MOLNÁROVÁ, FARGAŠOVÁ 2016). In our experiment, significant reduction of fresh weight under the influence of Se was observed in shoots and roots of pea seedlings but not in hypocotyls (Table 2). Compared to the control, stronger inhibition of the shoot growth was induced by selenate (on average by 39.52%) than by selenite (22.39%), while the root growth was inhibited respectively by 45.46% and 27.28%. Significant reduction of dry weight, by 19.36% on average, was found only in shoots treated with 20 $\mu\text{mol dm}^{-3}$ Se in either form. The calculated water content clearly indicated that dehydration occurred in the roots under the influence of Se in both forms, as well as in the shoots treated with selenate. Similar results were obtained for bean, pea, white mustard, tobacco and yellow sweet clover (KOSTOPOULOU et al. 2010, AGGARWAL et al. 2011, HEGEDÚSOVÁ et al. 2012, MOLNÁROVÁ, FARGAŠOVÁ 2016).

The phytotoxicity of selenite and selenate has been widely reported (VAN HOEWYK 2013, GUPTA, GUPTA 2017). It depends on an Se concentration and the sensitivity of plants, which is different for various species (DHILLON, DHILLON 2009, KAUR et al. 2014). Most plants are more sensitive to selenite than to selenate (VAN HOEWYK 2013). Pea seedlings showed more sensitivity to selenate than to selenite, as expressed by the inhibition of fresh weight, probably because of greater accumulation of Se supplied in the selenate form and stronger dehydration in roots. Different stress factors cause damage to plasma membranes, resulting in cell dehydration. Such a relationship was observed in common bean under the influence of Se in the form of selenite at

Table 2

Fresh and dry weight and water content of plant parts of garden pea supplied with selenium in forms of sodium selenite and sodium selenate

Plant part	Treatment				
	control	selenite		selenate	
		10 $\mu\text{mol dm}^{-3}$	20 $\mu\text{mol dm}^{-3}$	10 $\mu\text{mol dm}^{-3}$	20 $\mu\text{mol dm}^{-3}$
FW (g plant ⁻¹)					
Shoot	1.050d*	0.830c	0.800c	0.740b	0.530a
Hypocotyl	0.059a	0.055a	0.062a	0.058a	0.060a
Root	0.660c	0.550bc	0.410b	0.460b	0.300a
DW (g plant ⁻¹)					
Shoot	0.124b	0.103ab	0.093a	0.118b	0.097a
Hypocotyl	0.006a	0.006a	0.006a	0.006a	0.005a
Root	0.042a	0.043a	0.044a	0.044a	0.042a
WC (g water g ⁻¹ DW)					
Shoot	7.468c	7.058c	7.602c	5.271b	4.464a
Hypocotyl	8.833bc	8.167a	9.333c	8.660ab	11.00d
Root	14.71d	11.79c	8.318b	9.454b	6.142a

* Means from the individual rows of the table not followed by the same letter are significantly different at $\alpha \leq 0.05$.

a toxic concentration (AGGARWAL et al. 2011). Many studies showed that Se applied in forms of selenite and selenate at higher concentrations increased lipid peroxidation, which caused damage of plasma membranes (HARTIKAINEN et al. 2000, MORA et al. 2008, MROCZEK-ZDYRSKA, WÓJCIK 2012). MORA et al. (2008) reported that Se applied in the form of selenite caused an increase of lipid peroxidation in white clover shoots when its content was above 200 $\mu\text{g Se kg}^{-1}$ dry weight. MROCZEK-ZDYRSKA and WÓJCIK (2012) observed enhanced lipid peroxidation and plasma membrane damage in the roots of faba bean grown in Hoagland's nutrient solution with 6 $\mu\text{mol dm}^{-3}$ Se in the selenite form. The effect of Se on the uptake of micronutrients could be the result of such changes in garden pea.

Analysis of micronutrients showed that Se affected their content in pea seedlings (Table 3). The content of Fe, Zn, Mn and B in shoots of Se-treated seedlings, regardless of the Se concentration and form, was significantly lower compared to the control. In contrast, the content of Cu in seedlings treated with 20 $\mu\text{mol dm}^{-3}$ Se in both forms and the content of Mo treated with selenate at both concentrations were significantly higher (on average Cu by 15.95% and Mo by 11.65%) than the control. In hypocotyls, all Se treatments caused a significant increase in the content of Fe (by 32.59% on average), Zn (by 50.39%) and Cu (by 115.35% compared to control). While an average decrease in the Mn content by 25.03% was observed in hypocotyls treated

Table 3

Content of micronutrients in plant parts of garden pea supplied with selenium in forms of sodium selenite and sodium selenate

Treatment	Fe	Zn	Mn	B	Cu	Mo
	(mg kg ⁻¹ DW)					
Shoot						
Control	109.2c	95.62b	39.52c	24.60b	8.090b	1.081a
10 µmol dm ⁻³ selenite	83.67b	75.15a	26.23a	20.06a	6.410a	1.128a
20 µmol dm ⁻³ selenite	73.07a	67.13a	24.07a	21.37a	9.084c	0.999a
10 µmol dm ⁻³ selenate	78.92ab	76.72a	33.41b	21.69a	8.033b	1.230b
20 µmol dm ⁻³ selenate	64.65a	67.33a	32.46b	21.55a	9.677c	1.292b
Hypocotyl						
Control	142.9a	60.96a	36.92b	11.85b	22.55a	2.440b
10 µmol dm ⁻³ selenite	178.1b	107.6d	37.04b	9.933a	29.52b	1.105a
20 µmol dm ⁻³ selenite	201.1c	66.36b	26.29a	10.07a	49.63c	1.017a
10 µmol dm ⁻³ selenate	198.9c	86.25c	34.57b	11.35b	50.80c	2.258b
20 µmol dm ⁻³ selenate	179.8b	106.5d	29.07a	12.46b	64.30d	2.388b
Root						
Control	140.3a	98.03b	19.27c	4.535a	10.98a	2.030b
10 µmol dm ⁻³ selenite	144.2a	111.2c	16.96b	5.521b	13.89b	1.615a
20 µmol dm ⁻³ selenite	147.4a	72.42a	14.68a	4.046a	20.69c	1.917b
10 µmol dm ⁻³ selenate	149.1a	104.6bc	19.43c	5.232b	18.14c	1.892b
20 µmol dm ⁻³ selenate	138.4a	82.96a	14.33a	7.092c	24.35d	2.064b

* Means for the individual plant parts within one column not followed by the same letter are significantly different at $\alpha \leq 0.05$.

with 20 µmol dm⁻³ Se in both forms, the content of B decreased by 15.60% and Mo fell down by 51.51% in plants treated with selenite at both concentrations. In roots, the following increased: the Cu content in all Se treatments by 75.48% on average compared to control, the B content in all treatments (by 31.16% on average) except 20 µmol dm⁻³ selenite, and the Zn content only in the treatment with 10 µmol dm⁻³ selenite (by 13.43%). In contrast, a decrease of the Zn content was observed in roots treated with 20 µmol dm⁻³ Se in both forms (on average 20.75% compared to control), of Mn in all treatments (on average 15.15% compared to control) except at 10 µmol dm⁻³ selenate treatment, and of Mo in roots treated with 10 µmol dm⁻³ selenite (20.44% compared to control). SCHIAVON et al. (2013) observed a significant decrease of Mo, Mn, Fe and Cu in tomato roots at 5 and 10 µmol dm⁻³ selenate. These changes in the content of micronutrients could affect the enzymatic antioxidant system. Fe, Zn, Cu and Mn are components or co-factors of antioxidant enzymes such as superoxide dismutases or ascorbate

peroxidase and the activity of these enzymes is positively correlated with the content of these micronutrients (CAKMAK 2000, ALSCHER et al. 2002, BLOKHINA et al. 2003, CARTES et al. 2005, POLITYCKA et al. 2017).

Ions are not distributed evenly in the whole plant and there are great differences in their mobility in plants. Because of Casparian strips in the endodermis of the root, which are a barrier blocking radial movement of ions in the cell wall, ions must move at least part of the way through the symplast. Mineral compounds loaded into the xylem remain for the most part in the form of simple ions and are carried in the transpiration stream to the shoot. From the apoplast or from the xylem, ions may be absorbed into the symplast, where selection of ions takes place.

Calculated total accumulation of micronutrients in whole pea seedling showed that under the influence of Se their uptake from the nutrient solution decreased and was clearly dependent on an Se concentration (Table 4). The uptake of mineral nutrients is closely associated with the uptake of water by plant roots. Therefore lower water content observed in the roots of pea

Table 4

Total content of micronutrients in plant parts of garden pea supplied with selenium in forms of sodium selenite and sodium selenate

Treatment	Fe	Zn	Mn	B	Cu	Mo
	total content in plant part (mg plant ⁻¹)					
Shoot						
Control	13.54c	11.87d	4.900d	3.050c	1.003c	0.134c
10 µmol dm ⁻³ selenite	8.618b	7.740b	2.702ab	2.066a	0.660a	0.116b
20 µmol dm ⁻³ selenite	6.795a	6.243a	2.238a	1.987a	0.845b	0.093a
10 µmol dm ⁻³ selenate	9.312b	9.053c	3.942c	2.559b	0.948c	0.145c
20 µmol dm ⁻³ selenate	6.271a	6.531a	3.149b	2.090a	0.939bc	0.125b
Hypocotyl						
Control	0.857a	0.366a	0.221b	0.071b	0.135a	0.015c
10 µmol dm ⁻³ selenite	1.069b	0.646d	0.260c	0.060a	0.177b	0.007a
20 µmol dm ⁻³ selenite	1.207c	0.398b	0.158a	0.060a	0.298c	0.006a
10 µmol dm ⁻³ selenate	1.193c	0.518c	0.207b	0.068b	0.305c	0.013b
20 µmol dm ⁻³ selenate	0.899a	0.532c	0.145a	0.062a	0.321c	0.012b
Root						
Control	5.893a	4.117b	0.809c	0.190a	0.461a	0.085b
10 µmol dm ⁻³ selenite	6.201b	4.782c	0.729b	0.237b	0.597b	0.069a
20 µmol dm ⁻³ selenite	6.486b	3.186a	0.646a	0.178a	0.910d	0.084b
10 µmol dm ⁻³ selenate	6.560b	4.602b	0.855c	0.230b	0.798c	0.083b
20 µmol dm ⁻³ selenate	5.813a	3.484a	0.602a	0.298c	1.023e	0.087b

* Means for the individual plant parts within one column of the table not followed by the same letter are significantly different at $\alpha \leq 0.05$.

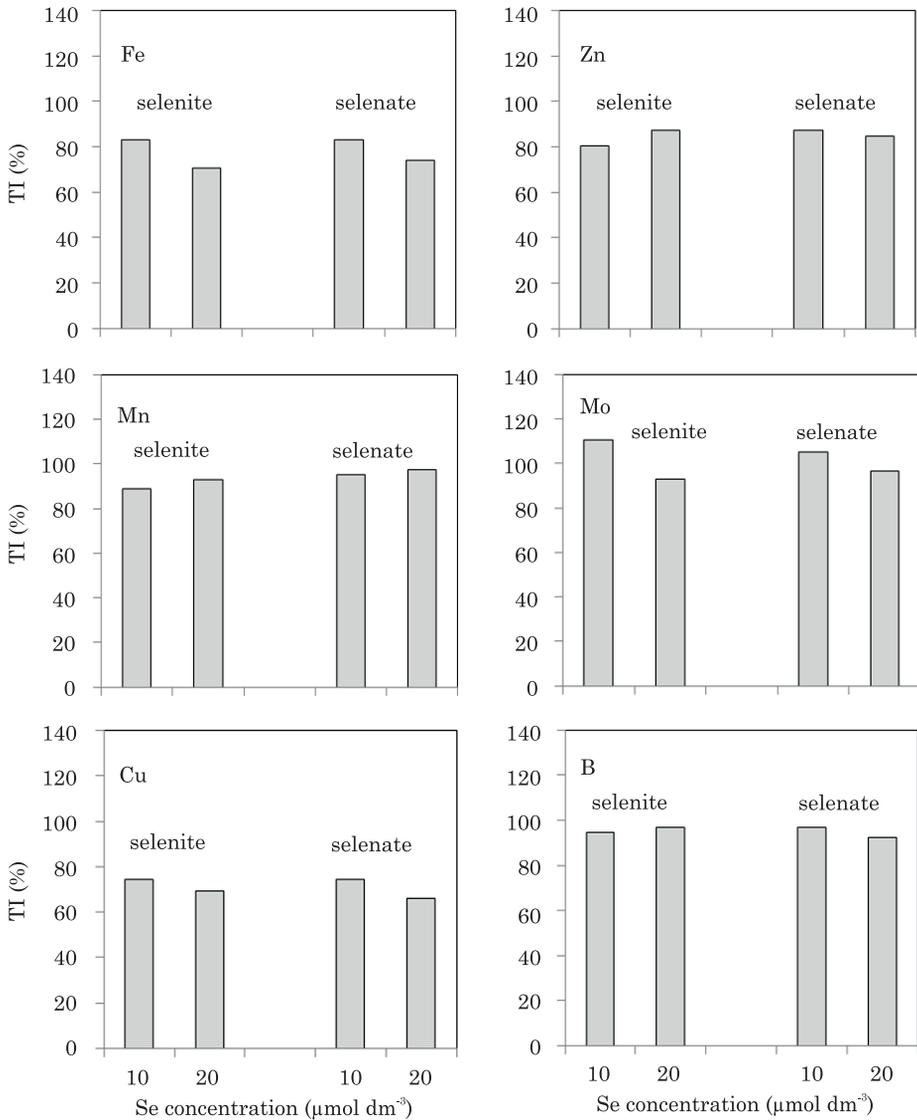


Fig. 1. Translocation index (TI) of micronutrients in garden pea supplied with selenium in forms of sodium selenite and sodium selenate

seedlings (Table 2) was probably the reason for the lower uptake and transport of ions, while distribution of micronutrients among individual plant parts varied and depended on the type of micronutrient. A decrease in the accumulation of all micronutrient in the shoots of pea seedlings was observed, except Mo in the selenite treatment, while the content of Fe, Zn, Cu decreased in hypocotyls and roots, although there were exceptions of higher Se concentrations. This was probably due to the closure of stomata and the

suppression of the transpiration stream. Dehydration of roots could have generated an ABA signal that was transmitted to the shoots, leading to the closure of stomata in leaves. Such a consequence was observed by JIANG et al. (2015) in tobacco plants, in which a high Se content in roots (but not in leaves) resulted in the closure of the stomatal apparatus and a decrease of the photosynthetic rate. Therefore, the growth inhibition of pea seedlings under an Se treatment may be the result of impaired photosynthesis and inhibition of the dry matter increase observed at the higher concentration of Se.

The suggestion that stomatal closure occurs under the influence of Se, could explain the reduced translocation of all micronutrients, except Mo (Figure 1), and the accumulation of Se applied as selenite in roots (Table 1). In the case of Mo, under the influence of Se at the lower concentration, particularly in the form of selenite, the translocation of this nutrient to shoots was stimulated. It has been shown that Fe, Mn, Cu, Zn and B ions absorbed by the roots are distributed in the plant through the xylem by the transpiration stream (SAVIC et al. 2012, ÁLVAREZ-FERNÁNDEZ et al. 2014). There is a large gap in understanding the long-distance transport of Mo in plants. Early studies of KANNAN and RAMANI (1978) using ^{99}Mo -labelled and metabolic inhibitor proved that molybdate translocation in plants is an active process. The difference between the translocation of Mo and the other micronutrients confirms the suggestion that the closure of stomata occurred due to the dehydration caused by Se treatment. The negative effect exerted on the translocation of micronutrients to shoots was probably caused by dehydration associated with some membrane damage of roots. However, further investigations are needed to substantiate this hypothesis.

CONCLUSIONS

1. Pea seedlings absorbed Se from the nutrient solution and accumulated it mainly in roots. More Se was accumulated in seedlings when it was applied in the form of selenate than selenite.

2. Se application at a higher concentration ($20 \mu\text{mol dm}^{-3}$) limited the increase of dry weight of shoots. Moreover, Se in both forms reduced the water content mainly in roots, wherein the effect of selenate was stronger and also occurred also in shoots.

3. Under the influence of Se, a decrease in the accumulation and translocation to shoots of Fe, Zn, Mn, B and Cu in pea seedlings was found. However, it was not observed in the case of Mo.

REFERENCES

- AGGARWAL M., SHARMA S., KAUR N., PATHANIA D., BHANDARI K., KAUSHAL N., KAUR R., SINGH K., STRIVASTAVA A., NAYYAR H. 2011. *Exogenous proline application reduces phytotoxic effects of selenium by minimising oxidative stress and improves growth in bean (Phaseolus vulgaris L.) seedlings*. Biol. Trace Elem. Res., 140: 354-367. DOI: 10.1007/s12011-010-8699-9
- ALSCHER R.G., ERTURK N., HEATH L.S. 2002. *Role of superoxide dismutases (SODs) in controlling oxidative stress in plants*. J. Environ. Bot., 53(372): 1331-1341. <https://doi.org/10.1093/jexbot53.372.1331>
- ÁLVAREZ-FERNÁNDEZ A., DÍAZ-BENITO P., ABADÍA A., LÓPEZ-MILLÁNAND A.-F., ABADÍA J. 2014. *Metal species involved in long distance metal transport in plants*. Front. Plant Sci., 5: 106. DOI: 10.3389/fpls.2014.00105
- ARVY M.P. 1993. *Selenate and selenite uptake and translocation in bean plants (Phaseolus vulgaris)*. J. Exp. Bot. 44: 1083-1087. <https://doi.org/10.1093/jxb/44.6.1083>
- ARVY M.P., THIERSAULT M., DOIREAU P. 1995. *Relationships between selenium, micronutrients, carbohydrates, and alkaloid accumulation in Catharanthus roseus cells*. J. Plant Nutr., 18: 1535-1546. <https://doi.org/10.1080/01904169509365002>
- BLOKHINA O., VIROLAINEN E., FAGERSTEDT K.V. 2003. *Antioxidants, oxidative damage and oxygen deprivation stress: a review*. Ann. Bot., 91(2): 179-194. <https://doi.org/10.1093/aob/mcf118>
- CAKMAK I. 2000. *Possible roles of zinc in protecting plant cells from damage by reactive oxygen species*. New Phytol., 146: 185-205. DOI: 10.1046/j.1469-8137.2000.00630.x
- CARTES P., GIANFERA L., MORA M.L. 2005. *Uptake of selenium and its antioxidant activity in ryegrass when applied a selenate and selenite forms*. Plant Soil, 276: 359-367. DOI: 10.1007/s11104-005-5691-9
- DHILLON K.S., DHILLON S.K. 2009. *Accumulation and distribution of selenium in some vegetable crops grown in selenate-Se treated clay loam soil*. Front Agric China, 3: 366-373. DOI: 10.1007/s11703-009-0070-6
- DOMOKOS-SZABOLCSY É., ALSHAAL T., NEVIEN E., NEAMA A., DOS REIS A.R., EL-RAMADY H. 2017. *The interactions between selenium, nutrients and heavy metals in higher plants under abiotic stresses*. Env. Biodiv. Soil Security, 1: 4-31. DOI: 10.21608/jenvbs.2017.951.1001
- FARGAŠOVÁ A., PASTIEROVÁ J., SVETKOVÁ K. 2006. *Effect of Se-metal pair combinations (Cd, Zn, Cu, Pb) on photosynthetic pigments production and metal accumulation in Synapis alba L. seedlings*. Plant Soil Environ., 52: 8-15. <http://www.iaei.cz/library-of-antonin-svehla/>
- GAROUSI F., VERES S., KOVÁCS B. 2016. *Comparison of selenium toxicity in sunflower and maize seedlings grown in hydroponic cultures*. Bull. Environ. Contam. Toxicol., 97: 709-713. DOI: 10.1007/s00128-016-1912-6
- GUPTA M., GUPTA S. 2017. *An overview of plant uptake, metabolism, and toxicity in plants*. Front. Plant Sci., 7: 2074. DOI: 10.3389/fpls.2016.02074
- HARTIKAINEN H., XUE H., PIIRONEN V. (2000). *Selenium as an antioxidant*. Plant Soil, 225: 193-200. <http://link.springer.com/content/pdf/10.1023/FA%3A1026512921026.pdf>
- HAWRYLAK-NOWAK B. 2008. *Effect of selenium on selected macronutrients in maize plants*. J. Elem., 13: 513-519. <http://www.uwm.edu.pl/jold/index.1342008.pdf>
- HAWRYLAK-NOWAK B. 2013. *Comparative effects of selenite and selenate on growth and selenium accumulation in lettuce plants under hydroponic conditions*. Plant Growth Regul., 70: 149-157. DOI: 10.1007/s10725-013-9788-5
- HAWRYLAK-NOWAK B., MATRASZEK R., POGORZELEC M. 2015. *The dual effects of two inorganic selenium forms on the growth, selected physiological parameters and macronutrients accumulation in cucumber plants*. Acta Physiol. Plant., 37: 41. DOI: 10.1007/s11738-015-1788-9
- HEGEDŰOVÁ A., JAKABOVÁ S., HEGEDŰS O., VALŠIKOVÁ M., UHER A. 2012. *Testing of selenium inhibition effect on selected characteristics of garden pea*. Eur. Chem. Bull., 1: 520-523. DOI: 10.17628/ECB.2012.1.520

- JIANG C., ZU C., SHEN J., SHAO F., LI T. 2015. *Effects of selenium on the growth and photosynthetic characteristics of flue-cured tobacco (Nicotiana tabacum L.)*. Acta Soc. Bot. Pol., 84(1): 71-77. DOI: 10.5586/asbp.2015.006
- KANNAN S., RAMANI S. 1978. *Studies on molybdenum absorption and transport in bean and rice*. Plant Physiol., 62: 179-181. www.plantphysiol.org/content/plantphysiol/62/2/179
- KAUR N., SHARMA S., KAUR S., NAYYAR H. 2014. *Selenium in agriculture: a nutrient or contaminant for crops?* Arch. Agr. Soil Sci., 60(12): 1593-1624. https://doi.org/ 10.1080/03650340.2014.918258
- KOPSELL D.A., RANDLE W.M., MILLS H.A. 2000. *Nutrient accumulation in leaf tissue of rapid-cycling Brassica oleracea responds to increasing sodium selenate concentrations*. J. Plant Nutr., 23: 927-935. https://doi.org/10.1080/01904160009382071
- KOSTOPOULOU P., BARBAYIANNIS N., NOITSAKIS B. 2010. *Water relations of yellow sweetclover under the synergy of drought and selenium addition*. Plant Soil, 330: 65-71. DOI: 10.1007/s11104-009-0176-x
- LI H.F., MCGRATH S.P., ZHAO F.J. 2008. *Selenium uptake translocation and speciation in wheat supplied with selenite and selenate*. New Phytol., 178: 92-102. DOI: 10.1111/j.1469-8137.2007.02343.x
- MOLNÁROVÁ M., FARGAŠOVÁ A. 2016. *Se(IV), Se(VI), Cu and Zn phytotoxicity in correlation to their accumulation in Sinapsis alba L. seedlings*. Plant Root, 10: 11-20. DOI: 10.3117/plantroot.10.11
- MORA M.L., PINILLA L., ROSAS A., CARTES P. 2008. *Selenium uptake and its influence on the anti-oxidative system of white clover as affected by lime and phosphorus fertilization*. Plant Soil, 303: 139-149. DOI: 10.1007/s11104-007-9494-z
- MROCZEK-ZDYRSKA M., WÓJCIK M. 2012. *The influence of selenium on root growth and oxidative stress induced by lead in Vicia faba L. minor plants*. Biol. Trace Elem. Res., 147: 320-328. DOI: 10.1007/s12011-011-9292-6
- PAZURKIEWICK-KOCOT K., KITA A., PIETRUSZKA M. 2008. *Effect of selenium on magnesium, iron, manganese, copper, and zinc accumulation in corn treated by indole-3-acetic acid*. Commun. Soil Sci. Plant Anal., 39(15-16): 2303-2318. https://doi.org/10.1080/ 00103620802292343
- POLITYCKA B., SMOLEŃ S., GOLCZ A., ŁUKASZEWICZ S. 2017. *Effects of selenium on contents of selected micronutrients and activities of antioxidant enzymes in cucumber roots expose to p-coumaric acid*. Allelopathy J., 41(2): 101-112. http://www.allelopathyjournal.org/ 10.26651/2017-41-1-1087
- RENGEL A., GRAHAM R.D. 1996. *Uptake of zinc from chelate-buffered nutrient solutions by wheat genotypes differing in zinc efficiency*. J. Exp. Bot., 47(295): 217-226. https:// academic.oup.com/jxb/article-abstract/47/2/217/457838
- SAVIC J., ROMHELD V., NIKOLIC M. 2012. *Oilseed rape (Brassica napus L.) genotypic variation in response to boron deficiency*. Turk. J. Agric. For., 36: 408-414. DOI: 10.3906/tar-1109-43
- SCHIAVON M., DALL'ACQUA S., MIETTO A., PILON-SMITS E.A.H., SAMBO P., MASI A., MALAGOLI M. 2013. *Selenium fertilization alters the chemical composition and antioxidant constituents of tomato (Solanum lycopersicon L.)*. J. Agric. Food Chem., 61: 10542-10554. dx.doi.org/10.1021/jf4031822
- VAN HOEWYK D. 2013. *A tale of two toxicities: malformed selenoproteins and oxidative stress both contribute to selenium stress in plants*. Ann. Bot., 112: 965-972. DOI: 10.1093/aob/mct163
- WU L., HUANG Z. 1992. *Selenium assimilation and nutrient element uptake in white clover and tall fescue under the influence of sulphate concentration and selenium tolerance of the plants*. J. Exp. Bot., 43: 549-555. https://doi.org/10.1093/jxb/43.4.549
- ZHAO C., REN J., XUE C., LIN E. 2005. *Study on the relationship between soil selenium and plant selenium uptake*. Plant Soil, 277: 197-206. DOI: 10.1007/s11104-00507011-9