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ORIGINAL PAPER

CHANGES IN THE CONTENT OF SELENIUM IN AERIAL PARTS OF MAIZE VARIETIES, DEPENDING ON THE GROWING PERIOD AND SOIL TEXTURE*

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Abstract

The aim of the study was to evaluate changes in the selenium content in aerial parts of 32 maize varieties, different in the FAO number, as effected by the growing period and soil texture. The plant and soil samples were collected from demonstration plots of the Plant Breeding Institute Smolice Sp. z o.o. the IHAR group. Maize was grown on sandy loam and loamy sand with the natural selenium content (0.239 and 0.132 mg kg^{-1}soil, respectively). Plant samples were collected in four vegetative growth stages: the phase of the third leaf (BBCH 13), 7-9 leaf phase (BBCH 17-19), full flowering (BBCH 67), and full maturity – harvested product (BBCH 99). The content of Se in the aerial parts of maize was affected by both the agronomic category of soils and varietal properties. The highest content of selenium was found in young plants collected in the phase of the 3rd leaf (BBCH 13), decreasing afterwards, along with the plant growth. Approximately 87% of the tested varieties collected in BBCH 67 phase contained from 20.00 to 40.00 μg Se kg^{-1} DM in the aerial parts, whereas only 6% of them contained more than 40.00 μg Se kg^{-1} DM. The selenium content in maize grain ranged from 4.000 to 111.9 μg kg^{-1} DM, and the average content in grain collected from sandy loam was about twice as high as that determined in maize from loamy sand. Among all maize varieties, 41% had grains classified as selenium-deficient, 44% as having low Se content, and only 15% as having a medium amount of this microelement. The average selenium content in grain (31.50 μg kg^{-1} DM in BBCH 99 phase) and in the aerial parts (29.40 μg kg^{-1} DM in BBCH 67 phase) of maize grown in conditions where this element is naturally abundant can be considered as Se-deficient, insufficient to cover animals' needs for this element.

Keywords: selenium in maize, variety, biofortification, soil.

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INTRODUCTION

The fact that humans and animals need to function properly has been demonstrated by many researchers. One of the most important functions of this microelement is the antioxidant role in living organisms, achieved mainly by its presence in glutathione peroxidase (Rotruck et al. 1973) and its ability to reduce transformations of neoplastic cells (Sygit et al. 2018). Thus far, the presence of selenium has been found in more than 25 selenoproteins, and its low supplementation in the diet of humans and animals can lead to serious illnesses (Ebrahimi et al. 2019, Płaczek et al. 2019). Selenium deficiency in animal feed can lead to serious diseases, such as muscular dystrophy (NMD), white muscle disease, as well as the occurrence of clinical symptoms, such as the inhibition of growth, productivity and fertility (Mehdi, Dufrasne 2016).

There are several methods of supplementing selenium in animals' diets. However, due to the narrow range between its deficiency and toxic level, the content of this element in animal feed should be strictly controlled. The maximum selenium supplementation dose is 0.3 mg kg^{-1} DM (Sun et al. 2019), depending on a species, age and intended animal use. According to Khanal and Knight (2010), the optimum concentration of selenium in the dry matter of fodder intended for poultry is 0.150-0.200 mg kg^{-1}, for pigs 0.030-0.050 mg $kg^{-1}$and for cattle 0.100-0.180 mg kg^{-1}. Higher demand is demonstrated by dairy cows, heifers, piglets, weaners and sows (0.300-0.350 mg kg^{-1}) – Płaczek et al. (2019).

In addition to the proper selenium content in feed, the chemical form of this element given to animals is extremely important. Organic forms of selenium, such as selenomethionine (Se-Met) and selenocysteine (Se-Cys), are characterized by much higher bioavailability for human and animal organisms than its inorganic compounds (Suchý et al. 2014, Klusonova et al. 2015). Ruminants may be most vulnerable to selenium deficiency because mineral selenium compounds are reduced by bacteria to inassimilable forms due to the low pH in their rumen (Kruzhel et al. 2014, Żarczyńska et al. 2017). Therefore, feeding animals with fodder having an optimal content of this element seems to be the safest and most effective method.

In Poland, maize is one of the staple plant species grown for feed production, and it is an extremely valuable crop in this regard. Maize silage is a good ingredient in feeding mixtures administered to cattle, dairy cows and pigs. The selenium content in this plant species may be influenced by many factors, including the abundance and the form of this element in soil, the type and chemical properties of soil, climatic conditions, and the method of cultivation or processing of plants (Broadley et al. 2010, White 2016).

According to many researches, the low content of selenium in the soil, as well as its low availability for plants, may lead to the production of feed with insufficient content of this micronutrient for animal nutrition, which in the long term may also be a problem for human health. This problem has also been indicated in Poland (Dębski 1992, Tomza-Marciniak et al. 2010, Korol et al. 2013, Nowakowska et al. 2015). To increase the level of consumption of this element, many countries have attempted in recent years to biofortify various plant species, such as potato (Hlusek et al. 2005), wheat (Tucker et al. 2010, Ducsay et al. 2016), maize (Chilimba et al. 2012), or oilseed rape (Ebrahimi et al. 2015) with this element.

The aim of the study was to evaluate changes in the selenium content in grain and aerial parts of 32 maize varieties, depending on the growing period and the soil texture.

MATERIAL AND METHODS

The plant and soil samples were collected from the demonstration plots of the Plant Breeding Institute Smolice Sp. z o.o. the IHAR group, in 2009. The annual rainfall in this region was 667.9 mm (average 55.66mm per month), and the rainfall for the study period (April-September) was 420.1 mm. The average annual temp. was 9.05°C (15.85°C for the growing period). Maize was grown on Luvisol (WRB classification) soils: sandy loam (pH KCl=6.0) and loamy sand (pH KCl=6.0). Two composite soil samples consisting of 15 individual samples were collected from the layer 0-20 cm for each soil type. The material was dried, sift through a 2 mm sieve and ground in an agate mortar. Soil samples were prepared for the determination of selenium according to the method given by Beach (1992), and by the AAS method in combination with the generation of hydrides on a Spectra 220 FS Varian apparatus with a VGA-76 adapter (Varian Australia Pty Ltd, 1997). The natural total selenium content in soil was assessed to be at 0.239 μg kg^{-1} (sandy loam) and 0.132 mg kg^{-1} (loamy sand), and the form of this element soluble in DTPA was in amounts of 14.30 μg kg^{-1} and 6.300 μg kg^{-1}, respectively. Comparably high total content of selenium in sandy loam was demonstrated by Skoczyliński and Patorczyk-Pytlik (2006). The same amount of mineral fertilization was applied to both soils before plant sowing: 120 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1}.

The selenium content was evaluated in the aerial parts (stems, leaves) and grains of 32 maize (*Zea mays* L.) varieties differing in the FAO number: FAO < 230: (Wilga, Cedr, Wiarus, Jawor, Smolitop), FAO 230-240: (Reduta, Glejt, Piorun, Smok, Smh 220, Dumka, Tur, Bielik, Bejm, Smolik, Rataj, Malibu, Maksym, Opoka), FAO > 240: (Lober, Narew, Kresowiak, Fmb10, Juhas, San, Vitras, Popis, Smh27008, Blask, Bosman, Wigo, Kozak). One sample consisted of 4 plants randomly collected from four rows. The maize was harvested in four plant growth stages: the phase of the third leaf (BBCH 13), 7-9 leaf phase (BBCH 17-19), full flowering (BBCH 67) and full maturity – harvested product (BBCH 99). In the first three development phases, the selenium content was examined in the aerial parts of whole plants, while in the last phase (BBCH 99), its content was only measured in the maize grain.

The plant material was digested according to the method specified in the Annex… (2003). The selenium content in plants and soils was determined by the AAS method in combination with the generation of hydrides on a Spectra 220 FS Varian apparatus with a VGA-76 adapter (Varian Australia Pty Ltd, 1997). All the measurements were performed twice for each sample, and the results shown in this study are their mean values. The mineralization and measurement conditions were optimized by determining the repeatability and recovery from certified plant material INCTTL-1. Statistical analysis was performed using the Statistica 8.0 and Microsoft Office Excel 2010 programs.

RESULTS AND DISCUSSION

The dynamics of selenium uptake by aerial parts of maize

According to Sali et al. (2018), maize (*Z. mays* L.) belongs to the world's most widely grown cereals, yet little consideration has been given in the literature to its ability to accumulate selenium and its effect on physiological parameters. The content of selenium in the aerial parts of maize collected from plots of the Institute of Plant Breeding in Smolice was significantly varied and depended on varietal properties, development phase and the agronomic category of soil (Figures 1, 2). Selenium accumulation in plants may be affected by the soil Se concentration, soil properties, or the chemical form of Se, and it may vary in relation to a plant species (Puccinelli et al. 2017). This study indicates that differences in the ability to accumulate this element may occur also among maize varieties. The calculated coefficient of variation (V) for 32 varieties grown on soils of both agricultural suitability complexes was 34% (BBCH 13), 30% (BBCH 17-19) and 33% (BBCH 67) – Table 1. Less variation in the Se content was noted in plants cultivated on loamy sand than on sandy loam. According to White (2018), the ratio of the selenium content in plants' aerial parts to the selenium content in the soil they grow on varies significantly. This variation may be dependent on differences in relative Se-phytoavailability, interactions between selenium and other minerals, on their uptake and metabolism in plants, on the age of the plants sampled, and on genetic variation in Se accumulation among individuals of a plant species (White 2018).

In this study, the highest selenium content was found in young plants collected in the phase of the 3rd leaf (BBCH 13). The concentration of this microelement decreased as the plant grew older, which is connected with the dilution effect due to intensive mass increase (Figures 1, 2, Table 1). In the phase of the 9-leaf (BBCH 17-19), this content was 32% (sandy loam)

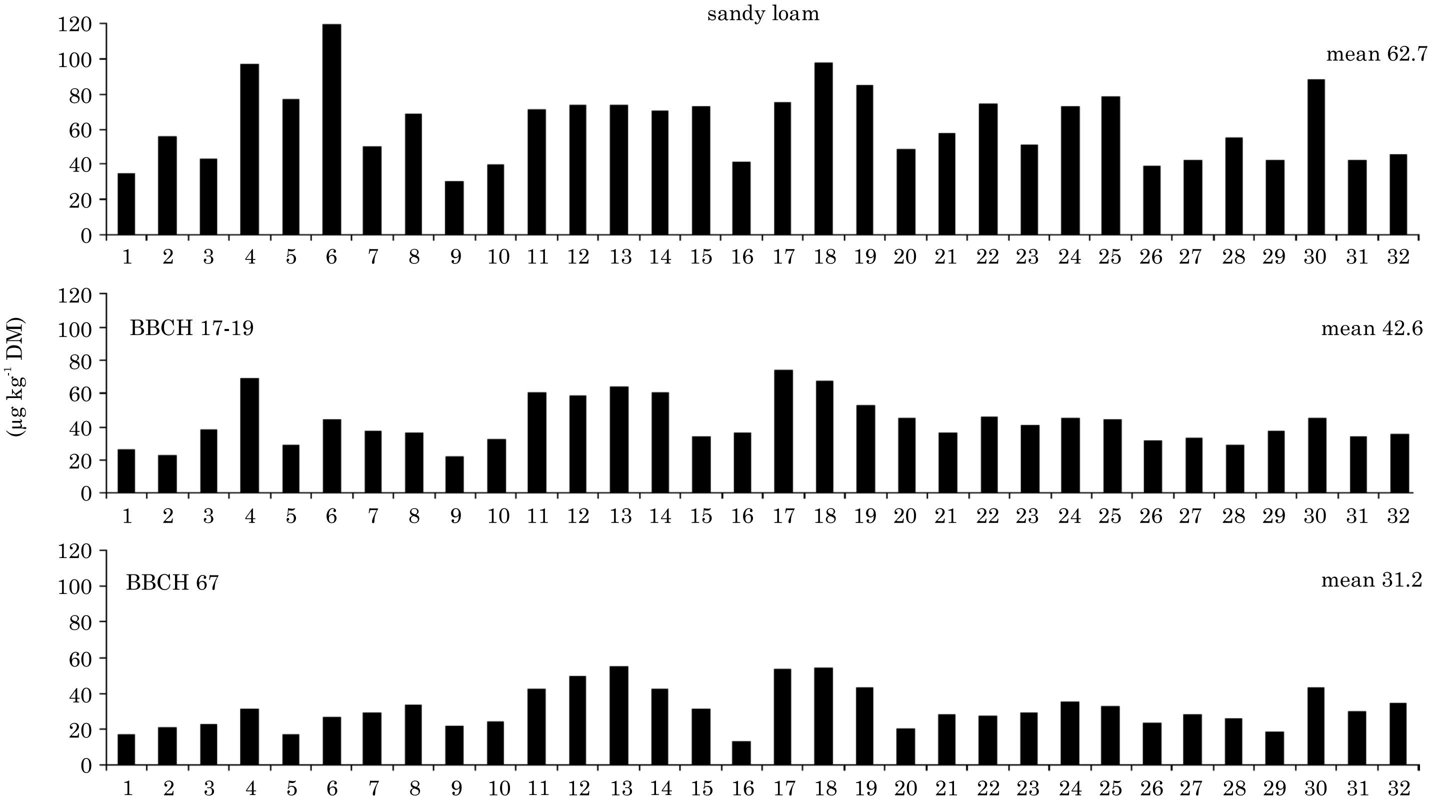

Fig. 1. Selenium content (μg kg^{-1} DM) in aerial parts of 32 maize varieties (*Zea mays* L.) collected from sandy loam: 1 – Wilga, 2 – Cedr, 3 – Wiarus, 4 – Jawor, 5 – Smolitop, 6 – Reduta, 7 – Glejt, 8 – Piorun, 9 – Smok, 10 – Smh 220, 11 – Dumka, 12 – Tur, 13 – Bielik, 14 – Bejm, 15 – Smolik, 16 – Rataj, 17 – Malibu, 18 – Maksym, 19 – Opoka, 20 – Lober, 21 – Narew, 22 – Kresowiak, 23 – Fmb10, 24 – Juhas, 25 – San, 26 – Vitras, 27 – Popis, 28 – Smh27008, 29 – Blask, 30 – Bosman, 31 – Wigo, 32 – Kozak

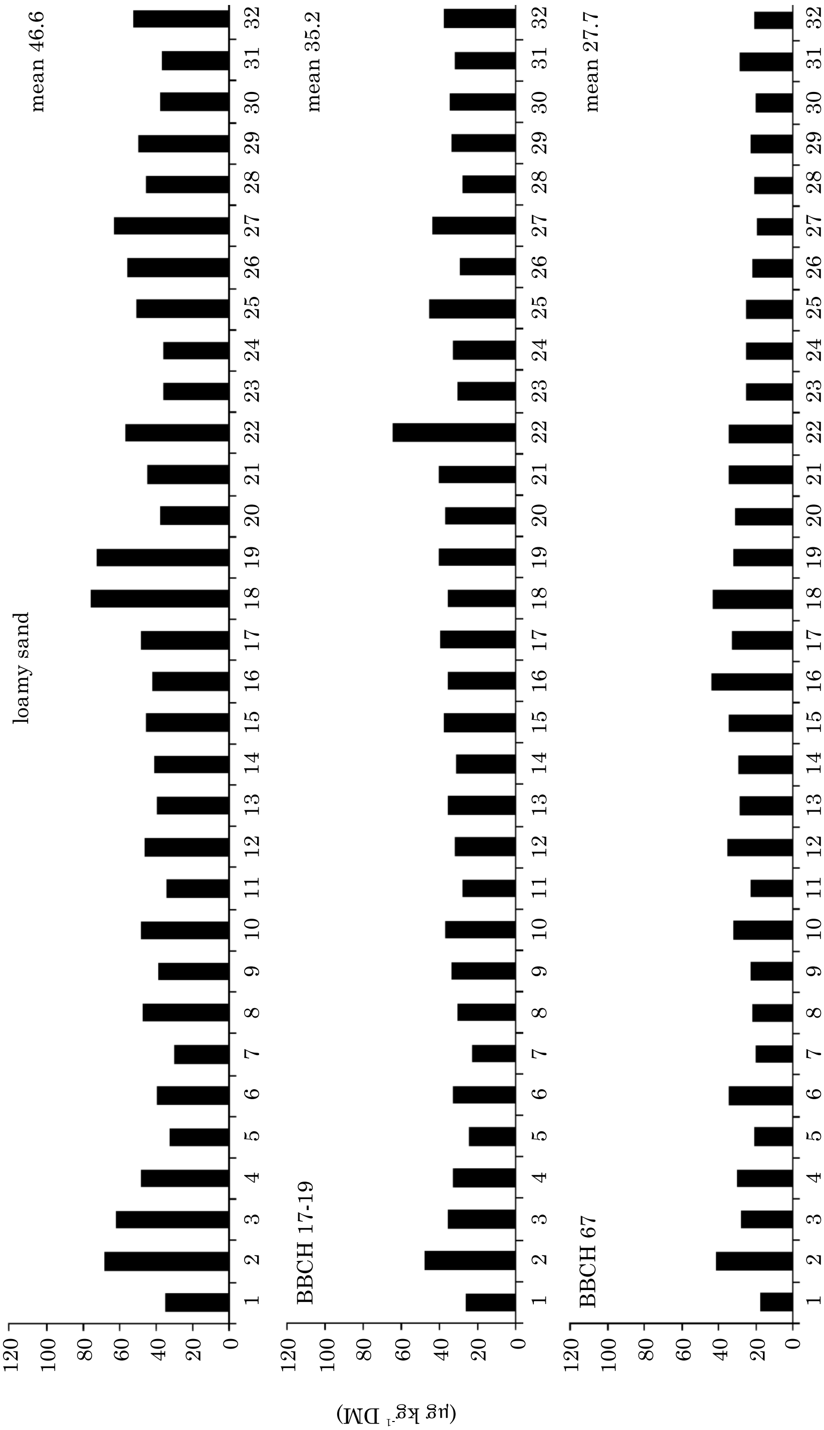

Fig. 2. Selenium content (µg kg^{-1} DM) in aerial parts of 32 maize varieties (*Zea mays* L.) collected from loamy sand (explanations Fig. 1)

Table 1

Statistical analysis of selenium content (μg kg^{-1} DM) in aerial parts of 32 maize varieties harvested from sandy loam (SL) and loamy sand (LS) and mean for soils (M)

Specification	BBCH 13			BBCH 17-19			BBCH 67		
	SL	LS	M	SL	LS	M	SL	LS	M
Mean	62.7	46.6	54.6	42.6	35.2	38.9	31.2	27.7	29.5
SD	21.3	11.6	18.8	14.0	7.8	11.8	11.5	7.2	9.7
V (%)	34.0	25.0	34.0	33.0	22.0	30.0	37.0	26.0	33.0
$LSD_{0.05}$	7.4	4.0	4.6	4.8	2.7	2.9	4.0	2.5	2.4
Min	30.0	29.5	29.5	21.9	23.1	21.9	12.5	17.0	12.5
Max	119.4	75.5	119.4	74.3	64.4	74.3	53.0	43.2	53.0

Table 2

Statistical analysis of selenium content (μg kg^{-1} DM) in maize grain (Zea mays L.) harvested at the BBCH 99 stage (harvested product)

Specification	Sandy loam	Loamy sand	Mean
Mean	42.4	20.6	31.5
SD	20.8	9.8	19.5
V (%)	49	48	62
$LSD_{0.05}$	7.2	3.4	4.8
Min	11.6	4.0	4.0
Max	111.9	47.0	111.9

and 24% (loamy sand) lower than determined in plants harvested in the earlier phase. Similar relationships were found for oilseed rape after soil fertilization with inorganic selenium (Ebrahimi et al. 2015). The authors stated that during the early stages of plant growth, reduction in the Se concentration in roots may be caused by the translocation of absorbed selenium to other parts of plants (stems, leaves), in addition to the effect of dilution caused by the increasing biomass. At a later stage, during the reproductive phase, the selenium concentration in leaves, stems and roots may decrease in favour of increasing its content in plant seeds (Ebrahimi et al. 2015).

The influence of the agronomic category of soil on the selenium content in plants was visible above all in earlier development phases. It was found that in the phase of the 3rd leaf, the content of this microelement in maize varieties cultivated on sandy loam was 26% higher than that determined in plants harvested from loamy sand. In the next stage (BBCH 17-19), this difference diminished to 17%, and in BBCH 67, the average content of selenium in plants collected from both soils was similar.

The selenium bioavailability for plants is not only related to its total concentration in soils. The soil pH and the redox potential values may condition the chemical form in which selenium occurs (Lyons et al. 2007). Plants are able to uptake this element in the pH range of 6-8 due to a decline in the sorption strength of Se (IV) and the potential oxidation of Se(IV) to Se (VI) at a higher pH (Chilimba et al. 2012).

In the third leaf phase, the highest selenium content among maize varieties cultivated on sandy loam was observed in Reduta (119.0 μg kg^{-1} DM). In four of the varieties tested (Jawor, Maksym, Opoka, Bosman), the Se content ranged from 80.00 to 100.0 μg kg^{-1} DM The largest group was composed of the varieties which accumulated from 60.00 to 80.00 μg kg^{-1} DM. Se in their tissues. In the maize varieties Wilga, Smok, Smh 220 and Vitras, the selenium content was very low, below 40.00 μg kg^{-1} DM – Figure 1.

In the 7-9th leaf stage, the varieties Jawor, Dumka, Bielik, Bejm, Maksym and Malibu accumulated significantly more selenium in the aerial parts (above 60.00 μg kg^{-1} DM) than the other varieties. Five varieties (Wilga, Cedr, Smolitop, Smok, Smh27008) were characterized by a very low content of this element (less than 30.00 μg kg^{-1} DM Se) (Figure 1).

During the next 43 days of growth (BBCH 67), the selenium content in the dry mass of tested plants decreased by 27% compared to the previous stage (BBCH 17-19). The decrease depended on the varietal properties of the cultivated maize. The smallest decline in the amount of selenium was recorded in Piorun, Smok, Smolik, Smh27008, Bosman and Kozak (a decrease by 2-7%), while the largest reduction in Se concentration in plants was observed in Jawor, Rataj and Blask (a decrease by 51-67%) – Figure 1, Table 1.

In over 62% of maize varieties harvested from sandy loam in phase BBCH 67, the selenium content was from 20.00 to 40.00 μg kg^{-1} DM. Only three varieties (Bielik, Malibu and Maksym) contained more than 50.00 μg kg^{-1} DM of this microelement. The varieties with the lowest Se content in this phase (containing less than 20.00 μg kg^{-1} DM) were Rataj, Wilga, Blask and Smolitop (Figure 1).

The average content of Se in maize cultivated on loamy sand was lower than that determined in maize grown on sandy loam (Table 2), but an inverse relationship occurred in the case of 7 varieties harvested in the third leaf phase, and in 17 cases from the next stages (Figure 2, Table 1). In the phase of the 3rd leaf, the highest content of this element (above 70.00 μg kg^{-1} DM) was determined in the varieties Maksym and Opoka, and the lowest was in Glejt (29.50 μg kg^{-1} DM). Nearly 40% of the 32 analyzed varieties accumulated this micronutrient in amounts ranging from 20.00-40.00 μg kg^{-1} DM (Wilga, Smolitop, Reduta, Smok, Dumka, Bielik, Lober, Fmb10, Juhas, Bosman, Wigo, Glejt), while in 11 maize varieties, the selenium content was found to be at the level of 40.00-50.00 μg kg^{-1} DM.

In the 7-9th leaf stage, the highest content of this element was observed in Kresowiak (60.00 μg kg^{-1} DM), while the lowest was found in Glejt and Wilga (23.00 μg kg^{-1} DM). In full flowering (BBCH 67), Rataj and Cedr contained the highest amount of this element (above 40.00 μg kg^{-1} DM), and the variety with its lower concentration turned out to be Wilga (16.00 μg kg^{-1} DM) – Figure 2.

Having analyzed the selenium content of maize harvested in BBCH 67 phase from loamy sand, it can be concluded that 87% of the tested varieties contained from 20.00 to 40.00 μg kg^{-1} DM of this element, whereas only 6% contained more than 40.00 μg kg^{-1} DM – Figure 2.

These results indicate that even in the conditions of maize cultivation on soil with a selenium content at the level of 0.239 mg kg^{-1}, the content of this microelement will depend on the ability of a maize variety to accumulate this element. However, out of all 32 varieties grown on soil with varied texture, only one collected in the BBCH 13 phase (Reduta) contained the optimal amount of selenium for production of feed for cattle. In this phase, however, plants are not harvested for fodder purposes. None of the 32 maize varieties tested that were cultivated on soils with a natural content of selenium and harvested in the full flowering phase would cover animals' daily need for this microelement.

The content of selenium in maize grain

The selenium content in grain of maize grown on soil with natural abundance of this element has not been examined in Poland before. Based on the results reported by Korol et al. (2013), it was confirmed that feed mixes produced in Poland for animals such as poultry, swine and dairy cows contained insufficient amounts of this microelement.

This research showed that the selenium content in maize grain varied considerably, ranging from 4.000 to 111.9 μg kg^{-1} DM (Figure 3, Table 2). The average selenium content in maize grain harvested from sandy loam was higher (42.40 μg kg^{-1}) than that determined in plants harvested from loamy sand (20.60 μg kg^{-1}). According to Wang et al. (2013), the average selenium content in 543 maize grain samples in China was 19.40 μg kg^{-1}, and this concentration was classified as Se-deficient. An analysis of the selenium content in maize grain cultivated in South Africa made by Courtman et al. (2012) showed that 94% samples contained less than 50.00 μg kg^{-1} DM, and could therefore be classified as conducive to Se deficiency in animal and human nutrition.

In our experiment, the selenium content in maize harvested from sandy loam ranged from 11.60 to 111.9 μg kg^{-1} DM, with the average being 42.40 μg kg^{-1} DM. The grain of 9 varieties (Wilga, Smh220, Lober, Popis, Smh27008, Blask, Bosman, Wigo and Kozak) had very low ability to accumulate selenium (less than 30.00 μg kg^{-1} DM). 53% of the tested varieties contained Se from 30.00 to 50.00 μg kg^{-1} DM. However, only 6 varieties (Dumka, Bejm, Tur, Bielik, Opoka and Maksym) accumulated more than 50.00 μg kg^{-1} DM.

The average selenium content in the grain of 32 maize varieties grown on loamy sand was 20.60 μg kg^{-1} DM, fluctuating from 4.000 to 47.00 μg kg^{-1} DM.

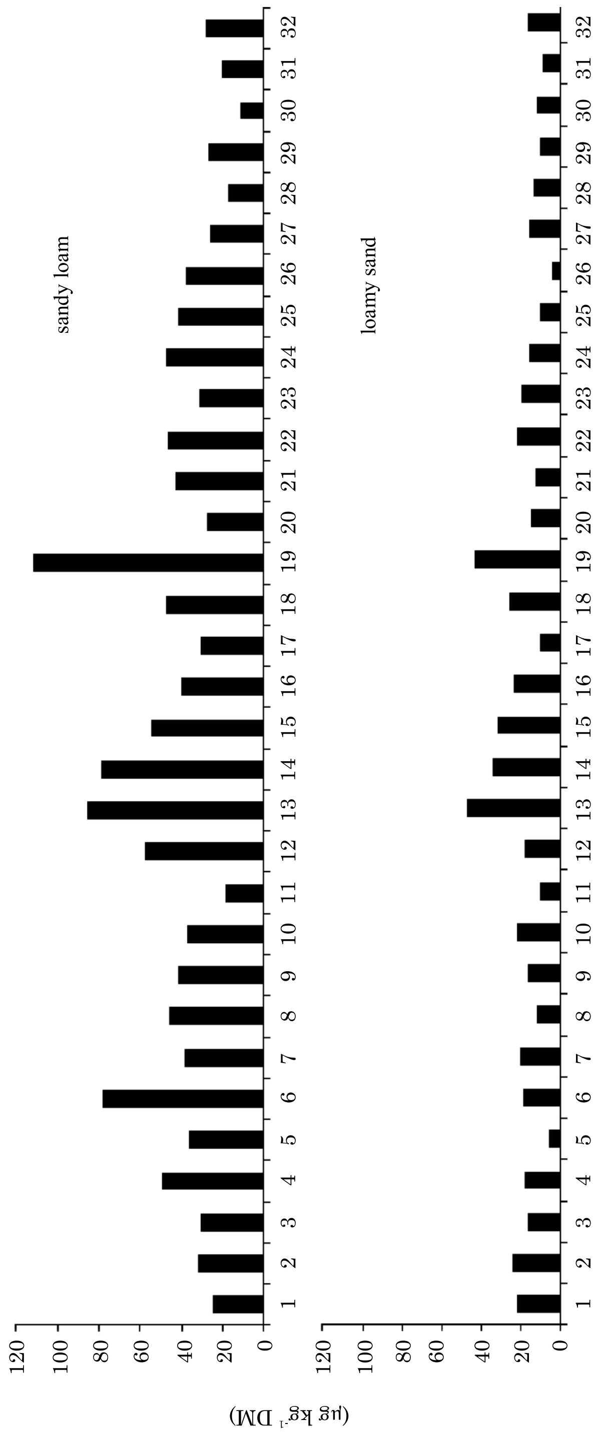

Fig. 3. Selenium content (µg kg^{-1} DM) in maize grain (*Zea mays* L.) harvested at BBCH 99 stage (harvested product) – explanation Fig. 1

The highest content of this element was noted by Tur and Maksym (> 40.00 μg kg^{-1} DM), then by Bielik and Bejm (> 30.00 μg kg^{-1} DM). 72% of all varieties tested contained less than 20.00 μg Se kg^{-1} DM, including three (Wigo, Vitras and Smolitop) with less than 10.00 μg Se kg^{-1} DM (Figure 3, Table 2).

The study shows that the highest average selenium content in maize grain from both soils was found in the varieties Maksym (77.60 μg kg^{-1} DM), Tur (66.20 μg kg^{-1} DM) and Bielik (56.20 μg kg^{-1} DM). The grain of only one variety (Maksym) cultivated on sandy loam contained an optimum Se amount, which would cover animals' needs for this microelement.

According to the values provided by Tan, cited by HAWKESFORD and ZHAO (2007), the Se grain content of less than 25.00 μg kg^{-1} DM should be considered as deficient, 25.00-40.00 μg kg^{-1} DM as low, 40.00-1000 μg kg^{-1} DM as medium to high, while the content exceeding 1000 μg kg^{-1} DM would be too excessive. According to this classification, among all the tested maize varieties, 41% had grains classified as selenium-deficient, 44% produced grains low Se content, and only 15% yielded grains with a medium amount of this microelement.

Figure 4 shows the impact of the FAO number and the agronomic category of soil on the accumulation of selenium in maize grain. The highest average Se content was observed in varieties with FAO 230-240 collected from sandy loam and with FAO <240 from loamy sand.

The lowest concentration of selenium in grain was found in maize with FAO >240 harvested from loamy sand. Based on the average content of Se in maize grains with different FAO numbers, the varieties can be arranged in descending order: FAO 230-240 > FAO to 230 > FAO above 240.

The content of selenium in aerial parts of maize can be insufficient for animal nutrition because maize is grown on light soil (loamy sand) with a low concentration of this microelement. According to GUPTA and GUPTA (2002), the content of selenium in soils at a level above 0.6 mg kg^{-1} ensures the production of fodder that may cover animals' needs for this element.

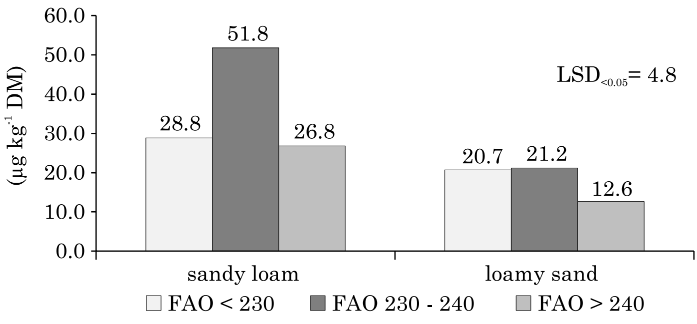

Fig. 4. Selenium content (μg kg^{-1} DM) in maize grain (*Zea mays* L.) depending on the FAO number

As stated by Tan (Hawkesford, Zhao 2007), the Se content in soils below 0.125 mg kg^{-1} should be considered as deficient, 0.125-0.175 mg kg^{-1} as marginal, 0.175-3.000 mg kg^{-1} as medium-high, and above 3.000 mg kg^{-1} as excessive. Based on this classification, it can be concluded that the maize in this study was grown on soil with marginal (loamy sand) and medium-high content of selenium.

CONCLUSIONS

The content of Se in aerial parts of maize was affected by both the agronomic category of soils and varietal properties. The average selenium content in grain (31.50 μg kg^{-1} DM) and aerial parts (29.40 μg kg^{-1} DM in BBCH 67 phase) of maize grown in conditions of natural abundance of this element can be considered as Se-deficient, insufficient to cover animals' needs. The results obtained here confirm that biofortification of plants intended for feeding animals in Poland is necessary. However, this study is based on a relatively limited number of plant samples. The selenium content in plants is mainly influenced by the availability of this element from soil. In our study, the average amount of Se in maize grain harvested from loamy sand was about twice as high as that determined in plants grown on sandy loam. Any attempts to introduce this element in a basic plant fertilization plan should be preceded by detailed research on the content and availability of selenium for plants. Future research should concentrate on other factors, including rainfall, soil management, crop yield and also species and variety diversity of plants in their ability to accumulate selenium from soil.

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