Journal of Elementology ISSN 1644-2296

Bąk K., Gaj R., Budka A. 2016. *Distribution of zinc in maize fertilized with different doses of phosphorus and potassium.* J. Elem., 21(4): 989-999. DOI: 10.5601/jelem.2015.20.3.1095

ORIGINAL PAPERS

DISTRIBUTION OF ZINC IN MAIZE FERTILIZED WITH DIFFERENT DOSES OF PHOSPHORUS AND POTASSIUM

Krzysztof Bąk[1], Renata Gaj[2], Anna Budka[3]

[1]Poldanor SA, 77-320 Przechlewo
[2]Department of Agricultural Chemistry and Environmental Biogeochemistry
[3]Department of Mathematical and Statistical Methods
Poznan University of Life Sciences

Abstract

Evaluation of the nutritional status of zinc and other micronutrients in maize at the critical growth stages is an important diagnostic and prognostic factor that plays a substantial role in shaping its final yield. A hypothesis was verified that the application of different phosphorus and potassium fertilization doses affected the nutritional status of zinc in maize at the critical growth stages: leaf development (BBCH 17) and flowering (BBCH 65), as well as the zinc accumulation at the stage of ripening (BBCH 89, fully ripe). A single factor field study was conducted for 5 consecutive plant growing seasons (2007-2011). The results showed that mineral fertilization significantly increased zinc concentration in maize leaves at BBCH 17 and BBCH 65 growth stages. Regardless of the effects of the experimental factor, the Zn leaf content in maize at both critical growth stages was much below the standard value. Although the zinc concentration observed at the leaf development stage was low, no significant relationship was found between the zinc nutritional status in maize at that time and the subsequent grain yield. Stronger relationships between the zinc nutritional status in maize and grain yield were observed at the flowering stage. The total accumulation of zinc in maize was significantly differentiated by the experimental factor. The chemical form of phosphorus applied had no significant effect on Zn content in maize at the critical growth stages as well as on the accumulation of this nutrient in fully ripe plants. The ZnHI value obtained in the control treatment was 51.7%, whereas the values achieved in fertilizer treatments were higher and ranged from 52.9% (W100 PAPR – with partially acidulated phosphate rock) to 57.3% (W25 – 25% of K and P recommended rate). Correlation analysis on maize yield and zinc accumulation showed that yield volumes were determined most strongly by zinc accumulation in maize vegetative organs (especially husk leaves).

Keywords: critical growth stages, Zn accumulation, Zinc Harvest Index.

dr hab. Renata Gaj, Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznań University of Life Sciences, Wojska Polskiego str. 71F, 60-625 Poznań, Poland, email:grenata@up.poznan.pl

INTRODUCTION

Zinc is an essential micronutrient in human and animal diets. Raising the zinc concentration in crop plants has recently become one of the most important goals in view of the high consumption of zinc deficient cereal products (Cakmak et al. 1996, 2010). Deficiency of zinc has been observed in patients, especially in children, affected by several illnesses (Stain 2009, Cakmak 2008). According to the World Health Organization (WHO 2002), more than 2 billion people, mainly in Africa and Asia, suffer from zinc shortages in their everyday diet. Latest studies (Zhang et al. 2013, Hossain et al. 2008) have shown that the Zn content in maize grain can be enhanced either by soil application of Zn or by seed priming with this element. In most cases, the cause of zinc deficiency in plants is not the soil insufficiency but poor availability of this element (Kalayci et al. 1999). Zinc availability depends on many factors, such as soil reaction, density and moisture as well as organic matter content (Chang et al. 2007, Sadeghzadeh 2013). The zinc content in plants is differentiated and depends on plant species, variety and physiological characteristics (Cakmak et al. 1998, Oury et al. 2006). The accumulation of zinc in sensitive plants, such as maize, stimulates the uptake of nitrogen and its physiological activity (Potarzycki, Grzebisz 2009). On the other hand, plant nitrogen management is strongly associated with the carbohydrate management. Relationships among processes in plants induce such responses as an enhanced uptake of water and mineral nutrients, including zinc. Wrońska et al. (2007) showed that good nutrition of maize with zinc could increase nitrogen fertilization efficiency and consequently lower fertilization costs and nitrogen losses. In the last decades, Zn deficit in the soil-crop system has spread due to high yielding of selected maize varieties, increased purity of chemical fertilizers and progressively more intensive cropping systems (Fageria et al. 2002).

Among numerous factors affecting the zinc activity in plants, phosphorus plays a specific role (Mousavi 2011). The action of this nutrient has to be considered from two viewpoints, i.e. its influence on the soil and on the plant. Generally, with an increased phosphorus content in the soil or enlarged supply of P in fertilizers, the plants' uptake of zinc decreases more or less drastically, and often beyond a level which can be attributed to dilution effects caused by the plants' higher growth. Under natural conditions, considerable differentiation in the zinc content observed in soil is driven by natural, e.g. the parent rock, soil dust fallout, and anthropogenic factors, e.g. mineral fertilization, agricultural intensity (Amrani et al. 1999, Kaniuczak et al. 2009*a*,*b*). The amount of active Zn^{2+} in soil is controlled by phosphorus. Excessive phosphorus causes Zn regress towards inactive orthophosphoric precipitate and blocks zinc cation uptake by plants through the uptake of calcium cations along with orthophosphoric anions. The antagonistic action of phosphorus in the plant is a result of the binding of zinc by inorganic orthophosphates in the root apoplast and cell cytoplasm (Cakmak, Marschner 1987). Some symptoms seen as Zn deficiency in fact indicate an excess of inorganic phosphorus. Nevertheless, interactions between P uptake effciency and Zn uptake are largely unknown.

In the present study, it was assumed that different phosphorus and potassium fertilization doses influenced the Zn concentration and accumulation in maize. This hypothesis was verified in a single factor experiment with different doses of P and K fertilization at constant amounts of nitrogen and magnesium. The aim of the study was to evaluate the influence of different P and K fertilization doses on: (1) Zn concentration in maize at the critical growth stages, (2) accumulation and redistribution of zinc in plant parts at harvest and (3) Zn effect on grain yield.

MATERIAL AND METHODS

The study was carried out for 5 consecutive plant growing seasons (2007-2011). A closed field experiment on maize (variety *Veritis*) was established on a farm in the region Wielkopolska (52°02′ N 17°05′ E). The trial (single factor experiment) was part of a longitudinal study carried out since 2000, and established in a randomized complete block design with four replications for each treatment. Methodological details are described by Bąk, Gaj (2016). The experimental factor comprised different mineral fertilization doses of phosphorus and potassium. The recommended balanced fertilization for W100 treatment was designed based on the soil nutrient availability, the uptake rate of a specific nutrient and the expected yield. At constant N and Mg fertilization, further P and K doses were reduced to 25% and 50% of W100 treatment (W25 – 25% of K and P recommended dose as compared to optimally fertilized treatment; WP50 – 50% of P recommended dose; WK50 – 50% of K recommended dose).

Additionally, the control treatments with no potassium or phosphorus added (WKN and WPN, respectively) as well as the absolute control (no mineral fertilization) were tested. In W100 PAPR treatment, partially acidulated phosphate rock (PAPR) was applied as an alternate source of phosphorus applied as single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. sulfuric acid used up during a technological process run to obtain the product equalled 50% of the amount necessary for production of single superphosphate). During the trial, winter wheat was grown as a preceding crop. The experiment was set up on lessive soils on glacial tills (soil quality class IIIb in the Polish soil valuation system) with medium P and K availability. Phosphorus and potassium were applied in the autumn, at the doses corresponding to the experimental design. Assessments of the maize zinc content were carried out at the following maize growth stages: BBCH 17 (leaf development), BBCH 65 (flowering) and

BBCH 89 (ripening - fully ripe). At BBCH 17, the zinc content was assessed in leaves randomly collected from 10 maize plants growing on every experimental plot, at BBCH 65 – in the leaf below maize ear (earleaf), and at BBCH 89 – in the following maize parts: leaves, stems, ears, corn cobs (central core of an ear), husks and kernels (grain).

The value of zinc uptake was derived from the multiplication of the values obtained for: maize grain yield – data available in the paper by Bąk and Gaj (2016) x maize organ dry weight – data available from the authors of the present paper x Zn concentration in the maize parts examined. Zn Harvest Index was calculated based on the algorithm expressing the ratio of Zn accumulation in maize kernels (grain) and the total Zn accumulation in maize at the stage of physiological maturity.

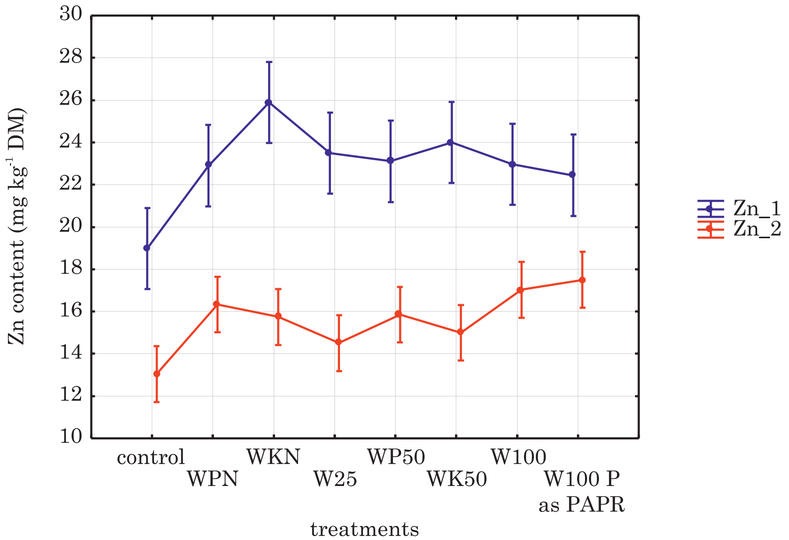
The plant material was dry mineralized at 550°C. The ash was mixed with 2 cm^3 of HNO_3 with distilled water (1:1) and then transferred to test tubes with distilled water added to 15 cm^3. The zinc concentration was assessed by atomic absorption spectroscopy (SpectraAA-250Plus Varian).

Statistical tests were performed using ANOVA for single factor experiments. Mean values of variables (Zn concentration in plant organs examined at different growth stages) were tested separately by means of ANOVA F-test ($\alpha = 0.05$). In order to determine homogenous groups ($\alpha = 0.05$), mean values of Zn concentrations with reference to the treatments examined were tested using the Tukey's test (multiple comparison procedure). Principal Component Analysis (PCA) allowed us to show regularities among maize grain yield, Zn concentration in plant organs and Zn uptake (in each treatment separately).

RESULTS AND DISCUSSION

Zinc concentrations in maize parts

The experimental factor significantly differentiated Zn concentrations in maize at all the growth stages examined as well in the plant organs analyzed (Figure 1, Table 1). Different P and K fertilization doses increased the Zn concentration in maize leaves at the stage of 7 unfolded leaves (BBCH 17), when compared to the control (Figure 1). Significant statistical differences were found not only with respect to the control treatment, but also between the treatments examined. The highest Zn concentration was observed in W100 treatment (optimally balanced with reference to nitrogen). The chemical form of phosphorus applied had no effect on shaping differences in leaf contents of Zn between the treatments. Regardless of the mineral fertilization level, in the early stage of maize growth, the zinc concentration in leaves ranged from 19 mg kg^{-1} to 24 mg kg^{-1}, i.e. it was considerably below the threshold level (55 mg kg^{-1} – 99 mg kg^{-1}). According to Zhang et al. (1991), plants containing less than 20 mg kg^{-1} of zinc in their tissues suffer



Vertical bars indicato 0.95 confidence levels, Zn 1 – Zn concentration in leaves at BBCH 17, Zn 2 – Zn concentration in leaves at BBCH 65

Fig. 1. Zinc concentration in maize leaves at the critical growth stages depending on differentiated P and K fertilization

Table 1

Effect of phosphorus and potassium fertilization on zinc concentrations in maize parts, mg kg^{-1} DM (BBCH 89 - fully ripe)

Treatments	Grain	Leaves	Husk leaves	Stem	Cob core
Control	15.33*abc**	6.040*ab*	7.242*a*	15.06*bc*	28.04*a*
WPN	15.48*ab*	6.016*ab*	6.879*a*	16.08*abc*	18.06*bc*
WKN	13.61*cd*	5.026*b*	5.278*a*	14.46*bc*	17.11*c*
W25	15.62*a*	6.454*a*	5.860*a*	17.34*ab*	17.51*bc*
WP50	13.30*d*	5.521*ab*	5.076*a*	14.10*c*	18.09*bc*
WK50	14.90*abcd*	5.806*ab*	6.245*a*	16.41*abc*	18.54*bc*
W100	14.49*abcd*	5.380*ab*	5.995*a*	19.14*a*	18.64*bc*
W100 P as PAPR	13.74*bcd*	5.626*ab*	6.426*a*	14.51*bc*	22.89*ab*

* Means with the same letter are not significantly different; $\alpha = 0.05$ (the Tukey's test).

from zinc deficit. A low concentration of zinc in a plant can be a result of an increased phosphorus uptake. On the other hand, high Zn contents decrease P uptake (Mousavi 2011). Kizilgoz and Sakin (2010) state that P/Zn ratios observed in the plant are useful in an assessment of the P and Zn status. In young leaves, P/Zn ratios ranging from 106 to 151 are considered as adequate for a plant's optimal growth, and those above 231 indicate Zn deficiency. In the present study, regardless of the treatment applied, P/Zn ratios ranged from 91.34 to 122.90. While there can be several chemical zinc compounds in the soil, plants are able to absorb only zinc ions. Other chemical compounds can affect the process of zinc uptake from the soil into the plant as well as zinc accumulation in plant tissues. Apart from various soil features that affect zinc uptake by plants, the chemical form of this nutrient occurring in the soil plays an important role in the process (Spiak 1996). Although the zinc concentration in maize leaves observed in this study was low, no significant relationship was found between maize Zn nutritional status and the grain yield obtained. The correlation analysis on the zinc concentration in maize leaves at the early growth stage and the yield of maize grain showed a significant relationship only in W100 PAPR treatment (with partially acidulated phosphate rock as the alternate phosphorus source).

Different mineral fertilization regimes supplying phosphorus and potassium significantly differentiated Zn concentrations in maize plants at the flowering stage (BBCH 65) – Figure 1. The leaf Zn concentration increased as a result of fertilization, although it was lower than at BBCH17 stage. Significant differences were observed among fertilized treatments and when compared to the control. Reduction of a potassium dose to 50% of W100 dose (treatment WK 50) or elimination of this nutrient (treatment WKN) resulted in a greater decrease of the Zn leaf concentration than in the analogous treatment with phosphorus (WPN). Regardless of the treatment tested, the Zn concentration in the leaf below the ear (earleaf) was much lower than the norm (19-75 mg kg^{-1}) determined by Schulte and Kelling (2000). An evaluation of the nutritional status of zinc and other nutrients at the maize flowering stage is of great importance since this stage comprises one of the key growth phases of maize that have a significant influence on the final yield. At the flowering stage, zinc increases the vitality of pollen grains, and therefore it advances the development of more kernels (Westage et al. 2003). In contrast to BBCH 17, a stronger relationship was observed between the final yield and zinc nutritional status at the maize flowering stage (BBCH 65). Significant correlations were found in the following treatments: WPN (0.769), WKN (0.616) and WK50 (0.666). Another factor that affected the Zn concentration in maize at the flowering stage was the unfavourable weather, especially before flowering in 2008 and 2009. The rainfalls in 2008 and 2009 were 65% and 16%, respectively, of the long-term precipitation data. Water deficiency resulted in lower values obtained for the Zn leaf concentration. This could have been caused by the limited root growth in the soil or else by a depressed activity of microorganism activity and decreased release of zinc from organic matter (Alam et al. 2010). According to Subedi and Ma (2005) as well as Grzebisz at al. (2008), an intensive uptake of the majority of mineral nutrients, including zinc, occurs in the period prior to flowering. Water stress inhibits the transfer of zinc (mainly through diffusion) from the soil toward the root surface (Cakmak et al. 1996, Hong and Ji-yun 2007).

At BBCH 89 (fully ripe), the experimental factor significantly differentiated Zn concentrations in the maize organs examined (Table 1). The tested fertilization had no significant effect only in the case of husk leaves. The zinc concentrations decreased as follows: cob core > grain> stem > husk leaves > leaves. This order indirectly indicates zinc mobility in maize organs during the plant growing season. When compared to other plant parts, a higher zinc concentration in the vegetative parts of maize cobs reflects the temporary status of zinc, before reaching the final storage organ, i.e. grain. POTARZYCKI (2010) points out that the cob core can be considered as an important buffer storage organ in view of relatively low zinc amounts observed in grain and those accumulated in the cob core. The highest zinc content in maize kernels (15.48 mg kg^{-1}) was observed in the W 25 (Table 1), whereas two- and three -fold lower Zn concentrations were found in maize leaves and husks. KUTMAN et al. (2011) found that extreme Zn deficiency enhanced the content of phosphorus and its transport toward grains.

Zinc uptake

The total accumulation of zinc in maize was significantly differentiated by the experimental factor (Figure 2). Maize plants cultivated in plots with

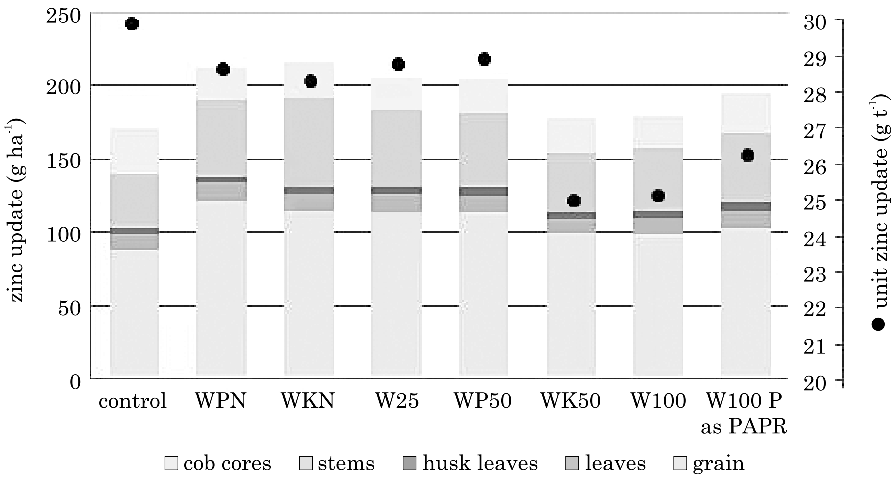


Fig. 2 Effect of phosphorus and potassium fertilization on zinc accumulation in maize parts (BBCH 89 – fully ripe)

no potassium fertilization for 10 years accumulated considerably less zinc when compared to the treatment with no phosphorus added for 10 years. This result confirms general findings on mutual relationships between P and Zn. Numerous studies have been conducted on zinc and phosphorus interactions, all confirming that the lack of balance between zinc and phosphorus in the plant due to excessive accumulation of phosphorus leads to the deficiency of zinc (DAS et al. 2005, SALIMPOUR et al. 2010). As indicated by literature, phosphorus is an essential element negatively affecting the zinc uptake by plants because the soil content of zinc declines at higher soil content of phosphorus. Yang et al. (2011) report that excess phosphorus in the soil environment acts antagonistically toward Zn, and therefore the Zn uptake by roots decreases. Furthermore, Zhao et al. (1998) showed Zn deficiency in cereal grains under the conditions of increasing phosphorus fertilization. In the present study, zinc accumulation in the treatment with PAPR as a source of phosphorus was not significantly different from the W100 treatment. A decreasing trend was just observed due to the PAPR application.

An important component of the evaluation of nutrient accumulation in final yield of maize is an assessment of nutrient distribution in plant organs, with particular attention paid to the relative share of a given nutrient observed in harvested grain. Zinc Harvest Index (ZnHI) defines the relative share of grain-accumulated nutrients in the total plant accumulation. In the present study, among the maize organs analyzed, the highest Zn accumulation was observed in kernels, then in the stem and in the remaining vegetative plant parts examined (Figure 2). The ZnHI value obtained in the control treatment was 51.7%, whereas the values obtained in fertilized treatments were higher and ranged from 52.9% (W100 PAPR) to 57.3% (W25).

Differentiated fertilization with phosphorus and potassium had no significant effect on the rate of specific nutrient uptake (Figure 2). The value of the Zn uptake rate in fully ripe maize specifies the quantity of this nutrient in yield (here: grain). The effects of different doses of phosphorus and potassium on the rate of Zn uptake were reflected in a tendency of the values of this parameter being lower than in the control.

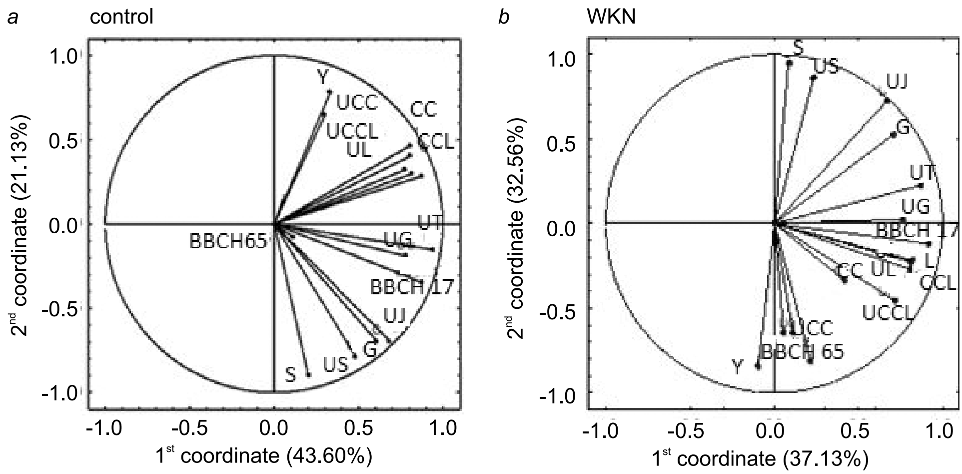


Fig. 3 Two-dimensional space image of variable Zn concentration and accumulation as well as maize grain yield: Y – yield, Zn 1 – Zn concentration in leaves at BBCH 17, Zn 2 – Zn concentration in leaves at BBCH 65, G – Zn concentration in grain at BBCH 89, L – Zn concentration in leaves at BBCH 89, CCL – Zn concentration in husks at BBCH 89, S – Zn concentration in steam at BBCH 89, CC – Zn concentration in corn cob at BBCH 89, UG – Zn accumulation in grain, UL – Zn accumulation in leaves, UCCL – Zn accumulation in husks at BBCH 89, US – Zn accumulation in stem at BBCH 89, UCC – Zn accumulation in corn cob at BBCH 89, UT – total Zn accumulation in corn cob at BBCH 89, UJ – unit Zn uptake

Relationships (correlations) between maize grain yield and the total Zn accumulation, as well as Zn uptake by the plant organs examined at BBCH 89 were tested using Principal Component Analysis (PCA). Regardless of the impact of the experimental factor, the analysis of correlation with regard to relations between maize grain yield and Zn accumulation in fully ripe plants showed that the yield mostly depended on the Zn accumulation in vegetative parts (especially husks) of maize. Significant relationships between maize yield and Zn accumulation in husk leaves were found in the majority of the treatments (e.g. the control, Figure 3*a*), except the WKN treatment, which showed a weak correlation (Figure 3*b*).

CONCLUSIONS

1. When compared to the control, differentiated mineral fertilization with phosphorus and potassium significantly increased the zinc content in organs of maize at all the growth stages analyzed.

2. Regardless of P and K fertilization doses, zinc concentrations in maize leaves at the critical growth stages (BBCH 17 and BBCH 65) were lower than the threshold values.

3. The assessment of zinc in maize leaves at the flowering stage (BBCH 65) was more useful for yield prognosis than an analogous assessment carried out on maize at growth stage BBCH 17.

4. Notwithstanding the effect of the experimental factor, maize grain yield was determined mostly by zinc accumulation in vegetative organs (especially in husk leaves).

5. The chemical form of phosphorus applied had no significant effect on the Zn content in maize at the critical growth stages or on the Zn accumulation in fully ripe plants.

REFERENCES

Alam M.N., Abedin M.J., Azad Mak 2010. *Effect of micronutrients on growth and yield of onion under calcareous soil environment*. Int. Res. J. Plant Sci., 1(3): 056-061.

Amarani M., Westfall D.G., Peterson G.A. 1999. *Influence of water solubility of granular zinc fertilizers on plant uptake and growth*. J. Plant Nutr., 22(2): 1815-1827.

Bąk K., Gaj R. 2016. *The effect of differentiated phosphorus and potassium fertilization on maize grain yield and plant nutritional status at the critical growth stage*. J. Elem., 21(2): 337-348. DOI: 10.5601/jelem.2015.20.3.996

Cakmak I. 2008. *Enrichment of cereal grains with zinc: Agronomic or genetic bifortification?* Plant Soil, 302: 165-172.

Cakmak I., Torun B., Ernoglu B., Ozturk L., Marschner H., Kalayci M., Ekiz H. 1998. *Morphological and physiological differences in cerals in response to zinc deficiency*. Ephytica, 100: 349-357.

Cakmak I., Marschner H. 1987. *Mechanism of phosphorus induced zinc deficiency in cotton.* III. *Changes in physiological availability of zinc in plants*. Physiol. Plant., 70: 13-20.

Cakmak I., Pfeiffer W.H., McClafferty B. 2010. *Biofortification of durum wheat with zinc and iron*. Cereal Chem., 87: 10-20.

Cakmak I., Yilmaz A., Kalayci M., Ekiz H., Torun B., Erenoglu B., Braun H.J. 1996. *Zinc deficiency as a critical problem in wheat production in Central Anatolia.* Plant Soil, 18: 165-172.

Chang W.Y., Lu B.Y., Yun J.J., Ping Y., Zheng X.S., Xin L.G., Wei S., Chun Z. 2007. *Sufficiency and deficiency indices of soil available zinc for rice in the alluvial soil of the coastal Yellow Sea*. Rice Sci., 14(3): 223-228.

Das K., Dang R., Shivananda T.N., Sur P. 2005. *Interaction between phosphorus and zinc on the biomass yield attributes of the medical plant stevia (Stevia rebaudiana).* Sci. World J, 5: 390-395.

Fageria N.K, Baligar C, Clark R.B. 2002. *Micronutrients in crop production*. Adv. Agron., 77: 185-268.

Grzebisz W., Wrońska M., Diatta J.B., Szczepaniak W. 2008. *Effect of zinc foliar application at early stage of maize growth on the patterns of nutrients and dry matter accumulation by the caopy.* Part II. *Nitrogen uptake and dry matter accumulation patterns.* J. Elem., 13(1): 29-39.

Hong W., Ji-yun J. 2007. *Effects of zinc deficiency and drought on plant growth and metabolism of reactive oxygen species in maize (Zea mays* L.*).* Agr. Sci. China, 6(8): 988-995.

Hossain M.A., Jahiruddin M., Islam M.R., Mian M.H. 2008. *The requirement of zinc for improvement of crop yield and mineral nutrition in the maize-mungbean-rice system*. Plant Soil, 306: 13-22.

Kalayci M., Torun B., Eker S., Aydin M., Ozturk L., Cakmak I. 1999. *Grain yield, zinc efficiency and zinc concentration of wheat cultivars grown in a zinc-deficient calcareous soil in field and greenhouse.* Field Crops Res., 63: 87-98.

Kaniuczak J., Hajduk E., Właśniewski S. 2009*a*. *The influence of liming and mineral fertilization on manganease and zinc content in potato tubers and green mass of pasture sunflower cultivated in loessial soil*. Zesz. Probl. Post. Nauk Rol., 541: 199-206. (in Polish)

Kaniuczak J., Właśniewski S., Hajduk E., Nazarkiwicz M. 2009*b*. *The influence of liming and mineral fertilization on manganease and zinc content in grain of winter wheat and spring barley cultivated in lessal soil*. Zesz. Probl. Post.Nauk Rol., 541: 207-215. (in Polish)

Kizilgoz I., Sakin E. 2010. *The effects of increased phosphorus application on shoot dry matter, shoot P and Zn concentrations in wheat (Triticum durum* L.*) and maize (Zea mays* L.*) grown in calacereous soil*. Afr. J. Biotechnol., V 9(36): 5893-5896.

Kutman U.B., Yildiz B., Cakmak I. 2011. *Improved nitrogen status enhances zinc and iron concentrations both in the whole grain and endosperm fraction of wheat.* J. Cereal Sci., 53: 118-125.

Mousavi D.R. 2011. *Zinc in crop production and interaction with phosphorus*. Aust. J. Basic Applied Sci., 5(9): 1503-1509.

Oury F.X., Leenhardt F., Rémésy C., Chanliaud E., Duperrier B., Balfourier F., Charmet G. 2006. *Genetic variability and stability of grain magnesium, zinc and iron concentrations in bread wheat*. Eur. J. Agron., 25: 177-185.

Potarzycki J. 2010. *The impact of fertilization systems on zinc management by grain* maize. Fertilizers and Fertilization, 39: 78-89.

Potarzycki J., Grzebisz W. 2009. *Effect of zinc foliar application on grain yield of maize and its yielding components*. Plant Soil Environ., 55(2): 519-527.

Sadeghzadeh B. 2013. *A review of zinc nutrition and plant breeding.* .J. Soil Sci. Plant Nutr., 13 (4): 905-927

Salimpour S., Khavazi H., Nadian H., Besharati H., Miransari M. 2010. *Enhancing phosphorus availability to canola (Brassica napus* L.*) using P solubilizing and sulfur oxidizing bacteria*. Aust. J. Crop Sci., 4(5): 330-334.

Schulte E., Kelling K. 2000. *Plant analysis: A diagnostic tool.* University of Wisconsin-Madison. Available online at: www.ces.pardue.edu/extmedia/NCH/NCH-46.html

Spiak Z. 1996. *Effect of the chemical form of zinc on their uptake by plants*. Zesz. Probl. Post. Nauk Rol., 434:997-1003. (in Polish)

Stain A.J. 2009. *Global impacts of human mineral nutrition*. Plant Soil, 335: 133-154.

Subedi K., Ma B. 2005. *Nitrogen uptake and partitioning in stay-green and leafy maize hybrids*. Crop Sci., 45: 740-747.

Westage M., Lizaso J., Batchelor W. 2003. *Quantitative relationships between pollen shed density and grain yield of maize*. Crop Sci., 43: 934-942.

WHO 2002. *World Health Report. Reducing risks promoting healthy life*. http://www.who.int/whr/2002/en/whr02.en.pdf (retrived 13.07.2010)

Wrońska M., Grzebisz W., Potarzycki J., Gaj R. 2007. *Maize response to nitrogen and zinc fertilization. Part II. Accumulation of nutrients at maturity*. Fragm. Agron., 24, 2(94): 400-407. (in Polish)

Yang X.W., Tian X.H., Lu X.C., Cao Y.X., Chen Z.H. 2011. *Impacts of phosphorus and zinc levels on phosphorus and zinc nutrition and phytic acid concentration in wheat (Triticum aestivum* L.*)*. J. Sci. Food Agric., 91: 2322-2328.

Zhang F., Romheld V., Marschner H. 1991. *Release of zinc mobilizing root exudates in different plant species as affected by zinc nutrition status*. J. Plant Nutr., 14: 675-686.

Zhang Y., Pang L., Yan P., Liu D., Zhang W., Yost R., Zhang F., Zou Ch. 2013. *Zinc fertilizer placement affects zinc content in maize plant*. Plant Soil, 372: 81-92.

Zhao F.J., Shen Z.G., McGrathh S.P. 1998. *Solubility of zinc and interactions between zinc and phosphorus in the hyperaccumulator Thlaspi caerulescens*. Plant Cell Environ., 21: 108-114.