Journal of Elementology ISSN 1644-2296

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

EFFECT OF DIFFERENTIATED PHOSPHORUS AND POTASSIUM FERTILIZATION ON MAIZE GRAIN YIELD AND PLANT NUTRITIONAL STATUS AT A CRITICAL GROWTH STAGE

Krzysztof Bąk[1], Renata Gaj[2]

[1]Rychnowy, Akacjowa 10, 77-300 Człuchów, bakkrzysztof@wp.pl
[2]Chair of Agricultural Chemistry and Environmental Biogeochemistry
Poznań University of Life Sciences

Abstract

Optimal nutrition of cultivated plants at critical growth stages is of great importance for the achievement of full crop yield potential. The aim of this study was to assess the maize yield response and plant nutritional status at a critical stage of growth (BBCH 17) under the most favourable and reduced fertilization with phosphorus and potassium. It was assumed that the nutritional status of maize at BBCH 17 stage significantly influenced the plant growth and yielding. The hypothesis was tested in a one-factorial trial, carried out on the maize variety Veritis in 2007-2011, which was a part of a long-term study started in 2000 according to a randomized complete block design. The factor tested comprised different phosphorus and potassium doses applied at constant levels of nitrogen and magnesium fertilization. The yields of maize significantly differed between the treatments and in relation to the control. In each year, maize responded with a lower yield to the no-phosphorus treatment when compared to the no-potassium treatment. Irrespective of the fertilization variants, the content of the nutrients tested (except iron) was below the standard value. A significant relationship was shown between the nutritional status of maize at the stage of 7 leaves unfolded (BBCH 17) and grain yield. The coefficients of determination ranging from 59% to 94% showed that, irrespective of which treatment was applied, the mineral nutrient content in maize leaves at BBCH 17 stage had the strongest influence on the maize yield.

Keywords: maize, phosphorus and potassium rates, nutritional status.

dr hab. Renata Gaj, Chair 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

Many producers believe that maize is a crop with low nutritional requirements, as a result of which the yields harvested are often much lower than could be expected on fertile sites. A satisfying economic result can be achieved only when maize cultivation relies on adequate agricultural techniques that include plant nutrition management as well as the recognition of a factor or a group of factors responsible for maize yielding. The right fertilization practice plays a key role in enhancing yields of cultivated plants and achieving a sustainable crop production increase (Huang et. al. 2010).

Knowledge of the actual availability of nutrients in soil and their specific uptake is crucial for preparing an adequate maize fertilization plan. The specific nutrient uptake index reflects the amount of grain yield in relation to a given nutrient accumulated in the aerial biomass at the stage of crop maturity (harvest) (Grzebisz, Gaj 2007). Literature has thus far provided scarce information on the content of soil nutrients that would allow one to determine fertilization doses of phosphorus (P) and potassium (K) that ensure the maximum maize yield. The currently available research results indicate that 50% - 80% of P applied as fertilizer is absorbed by soil, and no information is available regarding a P fertilizer dose which could ensure a sufficient supply of available form of this nutrient without causing adverse effects on yields (Shenoy and Kalagudi 2005, Vogeler et al. 2009). Another critical element in maize cultivation is potassium, whose soil deficiency has become a global problem (Dobermann et al. 1998, Hedlund et al. 2003, Malo et al. 2005, Tan et al. 2012). In Europe, more than 25% of soils are low in available K (Rőmheld, Kirkby 2010). Smil (1999) reported that potassium fertilizers, in contrast to phosphorus, are applied at much lower doses, and less than 50% of the K removed by crops is replenished. In Poland, it is alarming that the consumption of potassium fertilizers has been dramatically declining, which in the near future can become a significant limiting factor for the stability of yields of maize and other agricultural plants. It is therefore urgent to monitor the soil K reserves in order to make precise fertilizer recommendations (Zorb et al. 2014). The risk of yield reduction can be minimized by a balanced mineral fertilization plan, including all nutrients (Öborn et al. 2005). The effects of phosphorus and potassium on agricultural yields arise mainly from the role these nutrients play in counteracting the impact of biotic and abiotic stresses. Plants fully supplied with P and K are considerably less vulnerable to water stress, low temperatures and pathogenic agents (Ma et al. 2006). Yield-forming actions of phosphorus and potassium are dissimilar as these nutrients produce different effects on plant growth during the plant growing season. However, both nutrients affect the nitrogen management in high-yield agricultural crops (Marschner 1996).

The aim of the present study was to assess the yield response of maize and its nutritional status at a critical growth stage (BBCH 17) under the conditions of lower than optimal phosphorus and potassium fertilization.

MATERIAL AND METHODS

In 2007-2011, a single factor experiment was conducted on the maize variety Veritis (FAO: 230-240) on a field lying in a village called Wieszczyczyna, near Śrem (52°02′ N 17°05′E). The trial belonged to a long-term study carried out since 2000 and established in a randomized complete block design with four replications. The experimental factor comprised differentiated mineral fertilization doses of phosphorus and potassium (Table 1). The experiment was set up on lessive soil (soil quality class IIIb in the Polish soil classification system) developed from shallow light clayey sands on glacial tills. The soil properties are summarized in Table 2. Winter wheat was grown as a preceding crop before maize during the experiment. Wheat straw

Table 1

Design of field experiment

Treatment	Description
Control (KA)	no fertilizer application in 2007-2011
WPN	no phosphorus fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
WKN	no potassium fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
W25	25% of PK recommended dose as compared to optimally fertilized treatment; optimal fertilization with N and Mg
WP50	50% of P recommended dose as compared to optimally fertilized treatment; the rest of nutrients were applied at optimal doses
WK50	50% of K recommended dose as compared to optimally fertilized treatment; the rest of nutrients applied at optimal dose
W100	100% of P and K recommended dose; treatment optimally balanced with regard to nitrogen
W100 P as PAPR)	100% of P and K recommended dose; phosphorus applied as partially acidulated phosphate rock (PAPR)

Table 2

Soil physical and chemical properties

Year	P available (mg P kg^{-1})	K available (mg K kg^{-1})	Sand (%)	Silt (%)	Clay (%)	pH 1M KCl
2000 (establishment of the long-term experiment)	85.0	145.0	84	10	6	6.55
2007	51.2	113.1	84	10	6	4.90
2011 (after harvest)	43.2	97.4	84	10	6	4.60

was removed from the field after harvest each year. Maize was seeded with a seeding machine coupled with a seed drill (rows spaced at 0.75 m). All cultivation and harvest practices were carried out in accordance with the agricultural requirements for maize. An optimal fertilization dose (W100) was determined by taking into account the soil nutrient availability, specific uptake and expected yield in each year. Mineral fertilization doses applied in the study are presented in Table 3. The phosphorus dose for the W100 treatment (optimally balanced with reference to nitrogen) was 26 kg P ha^{-1} $year^{-1}$ (except for 2007: 35 kg P ha^{-1}), and potassium doses ranged from 100 kg K ha^{-1} to 133 kg K ha^{-1}. P and K doses applied in the subsequent treatments were reduced to 50% (W50) and 25% (W25) of treatment W100. Additionally, there were control treatments: WKN and WPN, with constant doses of nitrogen and magnesium and no potassium or phosphorus added, respectively. P, K and Mg fertilization was performed in line with the experimental design after the harvest of the preceding crop plants. Potassium was applied as potassium chloride (60% K_2O), phosphorus (P_2O_5) – as single superphosphate, and magnesium – as kieserite (27% MgO). The W100 variant included an additional treatment with partially acidulated phosphate rock (W100-PAPR), applied as an alternate source of phosphorus for single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. the amount of sulphuric acid used up during the technological process run to obtain the product was 50% of the amount necessary for the production of single superphosphate). Fertilization with nitrogen was carried out twice (70% before maize seeding and 30% at the stage of 4 leaves unfolded). In all the treatments analyzed, the plants for chemical analyses were randomly collected (10 plants/treatment) at the stage of 7 leaves unfolded (BBCH-17) and at the stage of technological maturity (BBCH 89). The yield of maize grain (app. 70% dry weight) was determined at BBCH 89 stage over an area of 24 m^2 (two 16-meter-long central rows). The total grain yield value was adjusted to the 14% moisture content. The analysis of the content of nutrients was carried out using the standard methods (N – Kjeldahl's method, P – calorimetrically, K and Ca – flame photometry, Mg, Zn, Cu, Mn, Fe – atomic absorption spectroscopy AAS).

Table 3

Mineral fertilization dose during the study, in 2007-2011 (kg ha^{-1})

Years	Nutrients (kg ha^{-1})			
	N	P	K	Mg
2007	120	35	100	16
2008	120	26	125	16
2009	150	26	133	16
2010	150	26	125	16
2011	150	26	125	16

Statistical tests

The results of the maize grain yield and plant nutrient content were tested with two-way Anova. The factors analyzed were: the study year and the dose of mineral fertilization with phosphorus and potassium. Multiple regression analysis was applied for an evaluation of the cause and effect relationships between the parameters. The regression model was built based on an algorithm used in backward stepwise regression with the bidirectional elimination testing at each step for variables to be included or excluded. The final model determined the variables with decisive effects on the maize nutrient content and grain yield.

RESULTS AND DISCUSSION

Yield response

The analysis of variance of the maize grain yield achieved during the experiment showed highly significant differences between the treatments with phosphorus and potassium mineral fertilization (Figure 1). In each year, a significant increase of yield was observed in all the treatments when compared to the control. Significant differences were also observed between the treatments tested, which means that the phosphorus and potassium doses applied had significant effects on the maize yield quantity. The largest yields (7.5-9.8 t ha^{-1}) were harvested in 2007 and 2008. In general, the effect of mineral fertilization was indistinct and differed in the study years. The treatments with no phosphorus (WPN) and potassium (WKN) deserve special attention. The lack of fertilization with these nutrients resulted in a maize yield decrease when compared to the treatment optimally balanced with re-

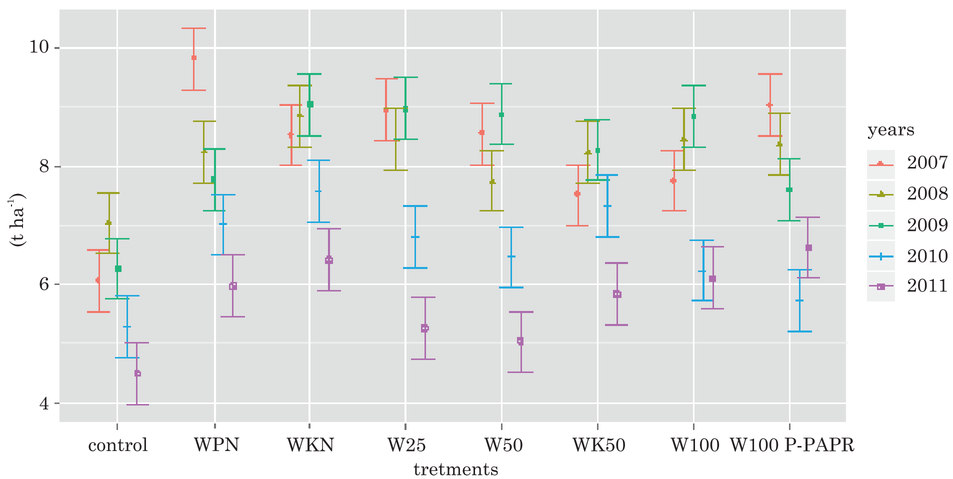

Fig. 1. Effects of phosphorus and potassium fertilization on maize grain yield (t ha^{-1})

gard to nitrogen (W100). The lack of P fertilization caused a decrease of maize yield in all the years except in 2007. The highest yield decrease was observed in 2011, i.e. 10 years of P and K fertilization absence. Yield reduction in WPN and WKN treatments was 21.5% and 9.0%, respectively, when compared to W100 treatment. The relationship observed confirms the common view that maize has specific requirements with regard to phosphorus. Shenoy and Kalagudi (2005) believe that an insufficient amount of available P can be responsible for a 10% -15% yield reduction compared to the maximum yield. Data reported in literature on phosphorus fertilization of various agricultural plants tested in long-term studies indicate that yield reduction due to the lack of P fertilization appears after a considerably long time interval (Jouany et al. 1996, Stępień, Mercik 1999, Kunzova, Hejcman 2010). Shen et al. (2004) observed yield response in plants cultivated without P fertilization after 11 years. Studies conducted by Gaj (2012) on winter triticale showed yield reduction after 10 years of P and K fertilization absence (5% and 13%, respectively). P deficiency is a crucial factor in tropical regions and in calcareous soils (Hinsinger 2001). Huang et al. (2010) showed that unbalanced mineral fertilization increased maize yield in a short-term time interval, although it affected negatively soil nutrient availability in a long-term perspective. This regularity was confirmed in the present study when the following consequences were observed after 10 years of soil cropping: a decrease of soil available nutrient contents (lower soil valuation class) as well as a change of soil reaction from slightly acidic to acidic. As a general rule, a decrease of soil pH value results in an increase of the exchangeable aluminum content in soil. It all negatively affects agricultural plants by inhibiting the root system growth and decreasing the plant's capability to uptake water and mineral nutrients. On the whole, the value of soil reaction dropping below the optimal value for a given nutrient has a negative effect on the crop yield response. Meanwhile, intensive processes occur in soil that are associated with regression of available forms of phosphorus, and the content of base cations decreases. Economic effects of redundant soil acidification are reflected in yield loss quantity, which is a product of many, often mutually dependent processes (Van Breemen et al. 1983, Marschner 1991, Kidd, Proctor, 2001, Grzebisz et al. 2006). Under the conditions of the present study, the unbalanced mineral fertilization associated with acidic soil reaction and the removal of preceding crop straw from the field resulted in a decreasing trend for maize yield quantity, observed most distinctly in the last year. Similar maize response to analogous factors was reported by other authors (Xu at al. 2003, Zhang, Xu 2005). The results of this study indicated that maize showed differentiated response depending on the chemistry of the phosphorus fertilizer applied (Figure 1). In 2009 and 2010, considerable yield losses were observed (16% and 30%, respectively) in the treatment with partially acidulated phosphate rock when compared to the single superphosphate treatment. The response to a fertilizer's chemical structure indicates that yield forming actions of the above fertilizers as P providers for maize cannot be viewed as identical. Studies by Kanabo, Gilkes (1988) proved that no significant yield response to phosphate rock (phosphorite) application should be expected under the conditions of soils with high P sorption capacity coinciding with low cation-exchange capacity (CEC), precipitation, organic matter content and microbial activity. According to literature (Vanlauwe et al. 2000, Li et al. 2001, Pypers et al. 2007), positive effects of rock phosphate on maize cultivation rely upon legume plants used in crop rotation, which act as acidifiers of the rhizosphere.

Maize demonstrates a strong demand for potassium, necessitated by this plant's production of abundant biomass. Under the conditions of the present study, maize yield response to differentiated K rates varied in the years. In comparison with the treatment optimally balanced with regard to nitrogen, yield increasing trend as a result of a K dose applied was observed only in 2007 (Figure 1). In the other years, and especially in 2011, opposite relationships were found, irrespective of the amount of K applied. Maize yield response to potassium fertilization was a result of maize cultivation in the soil with low contents of available potassium. According to Szczepaniak (2004), positive yield response of an agricultural plant to K fertilization can be expected under the conditions of low availability of soil potassium and water stress during the plant growing season. Merbach et al. (1999) showed that at medium potassium availability in the soil, reduced K fertilization doses resulted in a decrease of agricultural plants' yields. A decreasing trend was the strongest in root crops and the weakest – in cereals. On the other hand, studies carried out by Gaj (2010*a*,*b*) in soils with medium K availability showed no significant direct effects of differentiated K doses or long-term absence of K fertilization on yields of wheat and winter rape.

The group of maize yield limiting factors also included mechanisms other than P and K actions. First of all, water and temperature conditions during the vegetation season should be implicated. Maize needs large quantities of water, since it promptly produces much vegetative biomass, which results in an almost twice as much yield as in other cereals. During the season, maize water requirements change (first critical phase occurs at the stage of 7 leaves unfolded). Regarding the weather as a factor, the least favourable conditions for maize yielding during the present study were observed in 2011. Considerable water deficiency associated with high temperatures in April, May and June caused yield reduction (on average by 27%, irrespective of the treatment applied) when compared to the other years. Rainfall measured in April, May and June 2011 (data obtained from the Institute of Meteorology and Water Management, Poznań) was only 19%, 29% and 75%, respectively, of the long-term precipitation averages. One of the main tasks of a farmer is to make the most of soil water (preventing surface runoff through securing good water infiltration down to the soil profile) as well as to enable cultivated plants to effectively manage water throughout their growth. The latter relies upon proper plant nutrition with potassium.

Nutrient content at the critical growth stage

The assessment of the maize nutritional status was carried out at the stage of 7 leaves unfolded – BBCH 17 (Table 4), based on the limit values

Table 4

Effects of different phosphorus and potassium fertilization doses on nutrient content in maize leaves (means of data from 2007-2011)

Treatments	(g kg^{-1} DM)					(mg kg^{-1} DM)			
	N	P	K	Ca	Mg	Zn	Cu	Mn	Fe
Control	31.00^{b*}	2.026^{c}	27.00^{b}	2.923^{a}	1.880^{b}	18.98^{b}	4.733^{abc}	17.00^{c}	147.3^{a}
WPN	36.76^{a}	2.111^{bc}	28.22^{ab}	2.919^{a}	1.785^{b}	22.90^{ab}	4.797^{abc}	30.26^{ab}	138.9^{a}
WKN	37.59^{a}	2.454^{a}	31.08^{a}	2.775^{a}	1.655^{b}	25.89^{a}	5.192^{ab}	31.58^{a}	139.2^{a}
W25	37.21^{a}	2.327^{ab}	28.48^{ab}	2.621^{a}	1.620^{b}	23.49^{a}	4.456^{c}	25.05^{b}	144.8^{a}
WP50	37.57^{a}	2.114^{bc}	28.65^{ab}	2.815^{a}	1.790^{b}	23.10^{ab}	5.231^{a}	30.20^{ab}	143.3^{a}
WK50	38.72^{a}	2.310^{ab}	26.90^{b}	2.862^{a}	2.435^{a}	24.00^{a}	4.356^{c}	28.43^{ab}	153.3^{a}
W100	38.00^{a}	2.083^{bc}	29.32^{ab}	2.829^{a}	1.630^{b}	22.97^{ab}	4.490^{bc}	27.25^{ab}	131.8^{a}
W100 P as PAPR	37.08^{a}	2.276^{abc}	29.41^{ab}	2.860^{a}	1.690^{b}	22.45^{ab}	4.406^{c}	29.52^{ab}	154.2^{a}

* means with the same letter are not significantly different

and with the use of mean values obtained in all the years, 2007-2011 (Schulte, Kelling 2000). The results showed that, notwithstanding the treatment applied, the plants were malnourished with both macro- and microelements. Iron was an exception because its content in maize plants was above the lower limit of the standard value. No significant differences were found in the phosphorus and potassium content in maize leaves between the treatments tested irrespective of the fertilization applied. Numerous literature data (Woodend, Glass 1993, Yang et al. 2004, Damon, Rengel 2007) indicate that genetic factors rather than a potassium dose applied as a fertilizer affect the K content of plants. The differences in adsorption of K among different plant species are attributed to variations in the root structure, such as root density, rooting depth and root hair length (Nieves-Cordones et al. 2014). Positive correlations between K uptake efficiency and root hair length in K-depleted soils have been reported for maize, and oilseed rape (Jungk 2001).

In the present study, the differentiated P and K rates applied had no significant effect on the content of nitrogen, calcium, magnesium and iron in plants and affected only the concentrations of copper and manganese. The content of calcium and magnesium in maize plants was particularly low. The reasons behind Ca and Mg deficiency are complex as this may result from both Ca and Mg shortage in soils as well as disturbed processes of nutrient uptake and transport within the plant during its growth. Calcium and manganese uptake is associated with the youngest root tissues, whose growth can be hindered by toxic aluminum in soil (White 2000). In the present study, the low content of Ca and Mg found in maize plants was due to the acidic soil reaction (pH from 4.7-5.12) observed since 2006 (after wheat harvest and the onset of a trial with maize cultivation) as well as the unfavourable weather conditions during the study.

Regression analysis concerning dependencies between maize grain yield and plant nutrient content at BBCH 17 stage observed in all the treatments showed significant relationships for the majority of the nutrients, and these were the most distinctly expressed for nitrogen, iron, zinc and manganese. The relationships for the treatments described by regression models are presented in Table 5. In all the treatments, the contribution of nutrients to

Table 5

Regression models of maize grain yield as the function of leaf nutrient content at BBCH 17 stage

Treatments	Regression models /(*p** – value)	R^2
Control	*y* = 0.757N + 3.367Ca – 0.111Zn + 0.003Fe + 2.273 (0.028) (0.175) (< 0.01) (0.073) (0.053)	0.7904
WPN	*y* = 0.546N – 29.529P + 0.578K – 11.084Mg + 0.042Mn + 0.006Fe + 10.240 (0.107) (< 0.01) (0.075) (0.061) (0.028) (< 0.01) (< 0.01)	0.9004
WKN	*y* = 0.810N – 5.013P + 0.0588Zn – 0.460Cu + 0.038Mn + 0.010Fe + 7.285 (< 0.01) (< 0.01) (< 0.01) (< 0.01) (0.043) (< 0.01) (< 0.01)	0.9375
W25	*y* = –1.660K – 2.995Ca + 0.583Zn + 0.193Mn + 0.005Fe + 4.881 (0.213) (< 0.01) (0.040) (0.107) (< 0.01) (0.126)	0.5922
WP50	*y* = 0.825N – 1.303K + 3.489Ca + 0.193Mn – 0.008Fe + 4.881 (0.213) (< 0.01) (0.040) (0.107) (< 0.01) (0.126)	0.8537
WK50	*y* = 1.018N + 6.810Mg + 0.065Zn + 0.578Cu – 0.088Mn – 0.008Fe + 6.448 (< 0.01) (0.064) (0.050) (0.061) (0.128) (< 0.01)	0.8346
W100	*y* = 1.503N – 11.192P – 5.404Ca + 10.110Mg + 0.037Zn + 3.120 (< 0.01) (0.065) (0.056) (0.061) (0.128) (< 0.01)	0.7815
W100 (P as PAPR)	*y* = 0.384N – 8.895P + 0.519K + 0.037Zn + 0.007Fe + 4.692 (0.103) (0.015) (0.045) (0.167) (< 0.01) (< 0.01)	0.8957

* *p* – empirical level of significance

shaping maize yield was substantial, which was confirmed by high values of the coefficients of determination ranging from 59% to 94%. The relationships observed suggested that the role of nutrients in yield formation gained importance in cases when the nutritional homeostasis was more severely impaired.

CONCLUSIONS

1. Under the conditions of the present study, differentiated rates of phosphorus and potassium fertilization significantly influenced the formation of maize grain yield. The action of the experimental factor was equivocal and showed high variability in the study years.

2. Maize responded with a higher yield reduction to the absence of phosphorus fertilization when compared to that of potassium.

3. The assessment of maize nutritional status at the stage of 5 - 7 leaves unfolded showed plant malnutrition with regard to all the mineral nutrients tested, except for iron, whose content was above the lower limit of the standard.

4. A significant relationship was found between the maize nutritional status at the stage of 5-7 leaves unfolded and grain yield. Regression analysis showed that, irrespective of the treatment applied, maize yield was determined in the range of from 59% to 94% by the nutrient content at 7 leaves unfolded.

ACKNOWLEDGEMENTS

We express our sincere thanks to dr Anna Budka for help in statistical calculations as well as her valuable suggestions and comments on the manuscript

REFERENCES

Damon P.M, Rengel Z. 2007. *Wheat genotypes differ in potassium efficiency under glasshouse and field conditions*. Aust. J. Res., 58: 816-825.

Dobermann A., Cassan K.G., Mamarii C.P., Sheehy J.E. 1998. *Management of phosphorus, potassium, and sulphur in intensive, irrigated lowland rice*. Field Crop Res., 56: 113-138.

Gaj R. 2010*a*. *Effect of different level of potassium fertilization on winter oilseed rape nutritional status at the initiation of the main stem growth and on the seed yield*. Oilseed Crops, 31: 111-121. (in Polish)

Gaj R. 2010*b*. *Influence of different potassium fertilization level on nutritional status of winter wheat and on yield during critical growth stage*. J. Elem., 15(2), 269-277.

Gaj R. 2012. *The effect of different phosphorus and potassium fertilization on plant nutrition in critical stage and yield of winter triticale*. J. Central Europ. Agric., 13(4): 704-716. DOI: 10.5513/JCEA01/13.4.1116

Grzebisz W., Diatta J.B., Szczepaniak W. 2006. *Productive and ecological backgrounds of arable soil liming*. Fertilizers Fertilization, 2: 69-85.

Grzebisz W., Gaj R. 2007. *Integrated production system of maize.* IOR-PIB, Poznań, 19-24. ISBN 978-83-89867-16-2. (in Polish)

Hedlund A., Witter E., An B.X. 2003. *Assessment of N, P, and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam*. Eur. J.Agron., 20: 71-87.

Hinsinger P. 2001. *Bio-availability of soil inorganic P in the rhizosphere as affected by root induced chemical changes: a review*. Plant Soil, 237: 173-195.

Huang S., Zhang W., Yu X., Huang Q. 2010. *Effects of long-term fertilization on corn productivity and its sustainability in an Ultisol of Southern China*. Agric. Ecosyst. Environ., 138: 44-50.

Jouany C., Colomb B., Bosc M. 1996. *Long-term effects of potassium fertilization on yield and fertility status of calcareous soils of south-west France*. Eur. J. Agron. 5: 287-294.

Jungk A. 2001. *Root hairs and the acquisition of plant nutrients from soil*. J. Plant Nutr. Soil Sci., 164: 121-129.

Kanabo I.A.K., Gilkes R.J. 1988. *The effect of the level of phosphate rock application on its dissolution in soil and on bicarbonate-soluble phosphorus*. Fert. Res., 16: 67-85.

Kidd P.S., Proctor J. 2001. *Why plants grow poorly on very acid soils: Are ecologists missing the obvious*? J. Exp. Bot., 52, 357: 791-799.

Kunzova E., Hejcman M. 2010. *Yield development of winter wheat over 50 years of nitrogen, phosphorus and potassium appliction on greyic Phaeozem in the Czech Republic*. Eur. J. Agron., 33:166-174.

Li L., Sun J., Zhang F., Li X., Yang S., Rengel Z. 2001. *Wheat/maize or wheat/soybean strip intercropping*. I. *Yield advantage and interspecific interactions on nutrients*. Field Crops Res., 71: 123-137.

Ma Q., Niknam S.R., Turner D.W., 2006. *Responses of osmotic adjustment and seed yield of Brassica napus and B. junacea to soil water deficit at different growth stages*. Aust. J. Agric. Res., 57: 221-226.

Malo D.D., Schumacher T.E., Dooliile J.J. 2005. *Long-term cultivation impacts on selected soil properties in the northern Great Plains*. Soil Till. Res., 81: 277-291.

Marschner H. 1991. *Mechanisms of adaptation of plants to acid soils*. Plant Soil, 134: 1-20.

Marschner H., Kirkby E., Cakmak J. 1996. *Effect of mineral nutritional status on shoot-root partitioning of photo assimilates and cycling of mineral nutrients*. J. Exp. Bot., 47: 1255-1263.

Merbach W., Schmidt L., Wittenmayer L. 1999. *Die Dauerdungungversuche in Halle (Saale*), B.G. Teubner, Stuttgart-Leipzing, 56-65.

Nieves-Corones M., Aleman F., Martinez V., Rubio F. 2014. *K^+ uptake in plant roots. The systems involved, their regulation and parallels in other organisms*. J. Plant Physiol., 171: 688-695.

Öborn I., Andrist-Rangel Y., Askekaard M., Grant C.A., Watson C.A., Edwards A.C. 2005. *Critical aspects of potassium management in agricultural systems*. Soil Use Manage., 21: 102-112.

Pypers P., Huybrighs M., Diels J., Abaidoo R., Smolders E., Merckx R. 2007. *Does the enhanced P acquisition by maize following legumes in a rotation result from improved soil P abvailabilty?* Soil Biol. Biochem., 39: 2555-2566.

Rőmheld V., Kirkby E.A. 2010. *Research on potassium in agriculture: needs and prospects*. Plant Soil., 335:155-180.

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

Shen J., Li R., Zhang F., Fan J., Tang C., Rengel Z. 2004. *Crop yields, soil fertility and phosphorus fractions in response to long-term fertilization under the rice monoculture system on a calcareous soil*. Field Crops Res., 86: 225-238.

Shenoy V.V., Kalagudi G.M. 2005. *Enhancing plant phosphorus use efficiency for suitable cropping*. Biotechnol. Adv., 23: 501-513.

Smil V. 1999. *Crop residues: Agriculture's largest harvest*. Bioscience, 49 :299-308.

Stępień W., Mercik S. 1999. *Changes in the phosphorus and potassium content in soil and crop yielding in a 30-year time period, on soil fertilized and not fertilized with these nutrients*. Zesz. Probl. Post. Nauk Rol., 467: 269-278. (in Polish)

Szczepaniak W. 2004. *Plants' response to potassium fertilization*. J. Elem., 9(4): 57-66. (in Polish)

Tan D., Jin J., Jiang L., Huang S., Liu Z. 2012. *Potassium assessment of grain production in North China*. Agric. Ecosyst. Environ., 148: 65-71.

Van Breeman, N., Nulder J., Driscoll C. T. 1983. *Acidification and alkalinization of soils*. Plant Soil, 75: 383-308.

Vanlauwe B., Diels J., ginga N., Carsky R.J., Deckers J., Mercky R. 2000. *Utilization of rock phosphate on a representative toposequence in the Northern Guinea savanna zone of Nigeria: Response by maize to previous herbaceous legume cropping and rock phosphate treatments*. Soil Biol. Biochem., 32: 2079-2090.

Vogeler I., Rogasik J., Funder U., Panten K., Schnug E. 2009. *Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake*. Soil Till. Res., 103: 137-143.

White P.J. 2000. *Calcium channels in higher plants*. Biochim. Biophys. Acta, 1465: 171-189.

Woodend J.J., Glas A.D.M., 1993. *Genotype-environment interaction and correlation between vegetative and grain production measures of potassium use-effciency in wheat (T. aestivum* L.*) grown under potassium stress*. Plant Soil, 151:39-44.

Xu R., Zhao A., Li Q., Kong X., Ji Q. 2003. *Acidity regime of Red Soils in a subtropical region of southern China field conditions*. Geoderma, 115: 75-84.

Yang X.E., Liu J.X., Wang W.M., Ye Z.Q., Luo A.C. 2004. *Potassium internal use efficiency relative to growth vigor, potassium distribution and carbohydrate allocation in rice genotypes*. J. Plant Nutr., 27:837-852.

Zhang M.K., Xu J.M . 2005. *Nestorian of surface soil fertility of an eroded red soil in southern China*. Soil Till. Res., 80: 13-21.

Zőrb Ch., Senbayram M., Peiter E. 2014. *Potassium in agriculture – status and perspectives*. J. Plant Physiol., 171: 656-669.