Fragm. Agron. 34(4) 2017, 152–170

A MINERAL PROFILE OF GRAIN MAIZE AT PHYSIOLOGICAL MATURITY FERTILIZED WITH BIOGAS DIGESTATE SOLIDS
PART I. MACRONUTRIENTS

Katarzyna Przygocka-Cyna[1]

Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego 77F, 60-625 Poznań

Abstract. Biogas digestate solids (BDS) obtained from agricultural biogas plant and used as organic fertilizer, significantly affect dry matter and nutrient partitioning among parts of seed crop, increasing, in turn, the yield of grain. This hypothesis was verified through a series of field experiments with maize, conducted between 2014 and 2016 at Brody, Poland. A two-factorial experiment consisted of the DBS application method (broadcast and row) and its rate: 0; 0.8, 1.6, 3.2 t·ha^{-1}. The effect of BDS on the development of yield components was reflected in higher biomass of stems and corncobs, which then increased the number of rows (NR) and grains per row (NGR), respectively. The key nutritional factor, controlling the yielding potential of the maize cob (dry mater; number of grains per cob, NGC) was N concentration in the corncob. The BDS effect on maize grain yield was revealed through enhanced translocation of dry matter and nutrients into grain in expense of vegetative maize parts, mainly stems (N, P, K), and leaves (N, Mg). The BDS impact on potassium management by maize was most apparent in dry 2015, ameliorating the effect of water stress. The applied BDS increased magnesium concentration in grain, thus raising its nutritional value. The row method of BDS application showed the advantage over the broadcast one, resulting in (i) the same amount of N taken up by maize, but applying half the amount of the fertilizer, (ii) increased grain harvest index and nutrient harvest indices, compared to the control treatment, fertilized only with nitrogen.

Key words: biogas digestate solids, application method and rate, maize parts, dry matter, nutrients, partitioning

INTRODUCTION

The re-use of agricultural wastes is a common practice in crop production. There is a wide range of benefits, both for soil fertility and for the environment, taking into account a decreased requirement for mineral fertilizers. The increasing needs for energy, on the one hand, and limited reserves of non-renewable energy sources, on the other hand, are driving forces for alternative solutions. The anaerobic fermentation, although known for a very long time, only in the last 20 years has formed the basis for intensive growth of biogas plants. The main product is a mixture of methane (CH_4) and carbon dioxide (CO_2). The liquid residue, termed as slurry or biogas digestate (BD), can be managed in different ways, depending on the used substrate. A slurry of biogas plants based on agricultural wastes (manure, slurry) or crops such as maize produced for silage, can be used in agriculture for crop plant fertilization [Łagocka et al. 2016, Makádi et al. 2012].

In the common opinion, frequently expressed in scientific papers, BD is rich in nutrients and other substances (enzymes, hormones) of potentially positive impact on plant growth. This is

---

[1] *Corresponding address* – Adres do korespondencji: kasiac@up.poznan.pl

true, however their concentration is extremely low due to an exceptionally low content of dry matter, which seldom exceeds 5%. The concentration of nutrients in biogas slurry is significantly dependant on the composition of used substrates and the type of digestion process. The effective agricultural management of digestate includes two alternative solutions. The direct management of raw slurry relies on its application on fields. There are two main disadvantages of this solution. The first one is a high cost of transportation, and the second one are reservoirs for slurry storage during winter months [Alburquerque et al. 2012, Möller and Müller 2012]. In Poland, this period extends from the 1st of December to the end of February [Dz. U. 2008]. The alternative solution is a separation of raw slurry into liquid and solid fractions. The first one can be reused as a source of water for a biogas plant. The obtained solids are much richer in those substances, which are not water soluble, i.e. phosphorus and organic nitrogen [Chiew et al. 2015].

The biogas digestate impact on plant growth and yield is frequently related to the content of nutrients and their availability to plants [Makádi et al. 2012]. It is necessary to take into account the fact, that during the anaerobic fermentation the easily degradable substances, like cellulose, undergo degradation. The remaining organic residues are less degradable, but behave like humus substances [Kolář et al. 2008]. The biogas digestate solids (BDS) can be used for plant fertilization in the same way as solid manure is applied [Buckley et al. 2008]. Gutser et al. [2005] exerted an opinion that the fertilizing value of BDS is comparable to dried poultry manure.

Maize is a crop of a huge yielding potential, but at the same time highly sensitive to both shortage of water and nutrients [Tollenaar et al. 2002]. It is sensitive to N supply during the long growing period, extending from the stage of 5th leaf and ending at the watery stage during the kernel growth [Subedi and Ma 2005]. The most important stage of yield element formation, known as *the critical window*, extends from tasseling to the watery stage of grain growth (BBCH 71). In the temperate regions of the world, it takes place during summer [Otegui et al. 1995, Ritche and Alagarswamy 2003]. The mineralization processes, which can be potentially accelerated by an application of manures and/or organic fertilizers, are important for crops such as maize [Loecke et al. 2012, Szmigiel et al. 2006]. Therefore, maize seems to be an excellent crop for testing fertilizer value of biogas digestate applied as solids.

In the light of the current knowledge, assuming, the multi-functional impact of biogas digestate on both soil properties and plant growth, the optimal rate of applied digestate, is still a matter of controversy. The key objective of the study was to evaluate the impact of progressively increased rates of biogas digestate solids applied on the entire soil surface (broadcast) or into a row on the grain yield of maize. The minor objective was to evaluate the dry matter and macronutrients partitioning between maize organs at harvest in response to the manner and rate of applied digestate.

MATERIALS AND METHODS

Studies related to the impact of biogas digestate solids (BDS) on maize were verified based on a series of field experiments carried out in 2014, 2015, and 2016 at RGD Brody (Poznan University of Life Sciences Experimental Station, 16°28′ E and 52°44′ N). According to the FAO/WRB, the studied soil was classified as typical Luvisols. The sum of precipitation during the growing season (April-September) was 410 mm in 2014, 284 mm in 2015, and 417 mm in 2016, whereas the long-term average is 317 mm. In 2015, maize vegetation was affected by drought in August with precipitation of 15 mm and concomitant temperature of 22.1°C versus 17.6°C (long-term average).

The two-factorial trial consisted of two application methods: i) broadcast (Br), ii) row (Ro) and four rates of BDS: 0.0, 0.8, 1.6, 3.2 t·ha^{-1}. The characteristics of BDS and the amounts of applied nutrients are presented in Table 1. The broadcast applied BDS was incorporated into soil just before maize sowing and mixed within the soil layer of 7 cm in depth. The row applied BDS was incorporated into soil just after sowing. The application row was prepared by the knife method, in the distance of 7 cm from the seed row and at the depth of 7 cm. Maize (Eurostar variety, FAO 240) was used as a test plant. The individual plot size, replicated four times, was 22.4 m^2. At maturity, crops were harvested from the area of 11.2 m^2. The grain yield was adjusted to 85% of dry matter weight.

Table 1. Chemical composition and amounts of elements applied with progressive rates of biogas digestate solids (BDS)

Rate of applied BDS (t·ha^{-1})	OS	N_t	N-NH_4	P	K	Mg	Fe	Mn	Cu	Zn	Pb	Cd
	g·kg^{-1}						mg·kg^{-1}					
	711	26.1	0.4	3.4	46.5	5.4	982	165	325	210	2.80	1.64
	kg·ha^{-1}						g·ha^{-1}					
0.8	569	20.8	0.32	2.71	37.2	4.3	786	132	260	168	2.24	1.31
1.6	1138	41.8	0.64	5.42	74.4	8.6	1571	262	520	336	4.48	2.62
3.2	2275	83.5	1.32	10.84	14.8	17.2	3142	528	1 040	672	8.96	5.24

The amount of mineral nitrogen (N_{min}) in spring, including both soil N_{min} resources (0.6 m) and N fertilizer (N_f as ammonium nitrate), was established at 140 kg·ha^{-1}. Any other nutrients, except N, were not applied. The basic properties of soil under study are shown in Table 2. All other agro-technical measurements were carried out in accordance with the best farming practice in maize production.

Table 2. Soil agrochemical properties before maize sowing

Year	Soil layer (m)	pH[1]	P[2]	K[2]	Mg[2]	N-NO_3	N-NH_4	N_{min}[3]	N_f[4]
			mg·kg^{-1} soil			kg·ha^{-1}			
2014	0.0-0.3	5.6	180^{H}	330^{H}	220^{G}	39	10	49	51
	0.3-0.6	5.8	128^{G}	240^{G}	250^{G}	30	10	40	
2015	0.0-0.3	5.7	170^{H}	280^{G}	180^{G}	35	15	50	46
	0.3-0.6	5.9	150^{H}	230^{G}	230^{G}	32	12	44	
2016	0.0-0.3	6.2	149^{H}	220^{G}	172^{G}	25	21	46	61
	0.3-0.6	6.4	110^{G}	210^{G}	122^{L}	22	11	33	

[1]1 M KCl; [2]Mehlich 3; classes: G – good; H – high; L – low; [3]0.01 M $CaCl_2$; [4]total sum of $N_{min} + N_f = 140$ kg·ha^{-1}

Composite soil samples (0–30; 30–60 cm) for N_{min} determination, were collected at the beginning of the experiment. For N_{min} determination, 20 grams of soil samples were shaken for 1 h with 100 ml of a 0.01-M $CaCl_2$ solution (soil/solution ratio 5:1; m/v). Composite soil samples

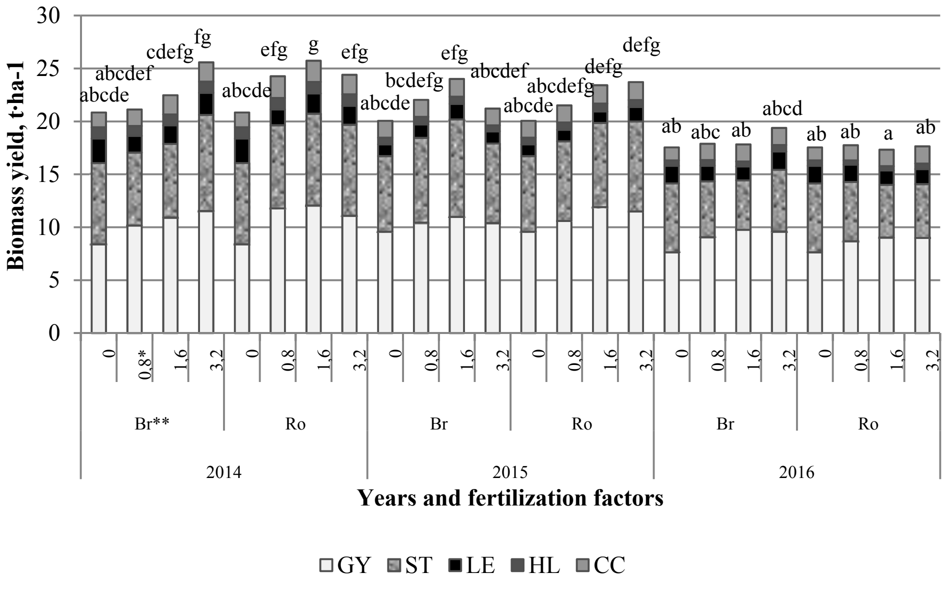
(0–30 cm) for a determination of available nutrients (P, K, Mg) were collected at the beginning of the experiment. The extractable nutrients were determined based on the Mehlich 3 method [Mehlich 1984]. The content of available P in the extract was determined colorimetrically, while the contents of K, Mg were determined using a FAAS.

Plant samples for dry mater and nutrient partitioning determination were taken up from an area of one m^2 at BBCH 89. The harvested plant sample was divided into sub-samples of grains (acronym GR), true leaves (LE), stems (ST), husk leaves (HL), corncobs (CC) and then dried (65°C). The harvested samples of maize grain used for the determination of nutrient concentration were first dried at 65°C. Nitrogen concentration was determined using a standard macro-Kjeldahl procedure. The plant materials for elements determination were mineralized at 600°C. The obtained ash was then dissolved in 33% HNO_3. The phosphorus concentration was measured by the vanadium-molybdenum method using a Specord 2XX/40 at a wavelength of 436 nm. The concentrations of K and Mg were determined using a FAAS.

The experimentally obtained data were subjected to the conventional analysis of variance using the computer program STATISTICA 10®. The differences between the treatments were evaluated with the Tukey's test. In tables and figures, results of the F test (***, **, * indicate significance at the *P* < 0.001; 0.01, and 0.05, respectively) are given. The stepwise regression was applied to define the best set of variables for the yield discriminative crop characteristics.

RESULTS AND DISCUSSION

The total biomass of maize was significantly affected by interaction of experimental factors, being modified by year-to-year variability (Fig. 1, Table 3). The total biomass produced



Legend: * – BDS rate, t·ha^{-1}; ** – method of BDS application: Br – broadcast, Ro – row
Numbers marked with the same letter are not significantly different;

Fig. 1. The partitioning of maize biomass between organs at harvest

Table 3. Characteristics of total biomass and yield elements

Factor	Level of factor	Components of maize biomass							Yield elements			
		LI	ST	HL	CC	GY	TB	HI (%)	TGW (g)	NR (No cob^{-1})	NGR (No row^{-1})	NGC (No cob^{-1})
		t·ha^{-1}										
Year (Y)	2014	1.90 c	7.93 b	1.05 c	1.74 b	10.5 b	23.2 b	45 a	304 b	15 b	33	489 b
	2015	1.21 a	7.87 b	0.67 b	1.64 ab	10.6 b	22.0 ab	48 b	272 a	15 b	33	498 b
	2016	1.53 b	5.56 a	0.49 a	1.48 a	8.8 a	17.9 a	49 b	271 a	13 a	32	420 a
F test value		67.9***	57.6***	177.7***	23.6***	44.1***	87.2***	13.6***	42.3***	35.3***	2.3	22.4***
Application method (AM)	Br	1.58	7.06	0.73	1.59	9.9	20.8	48	281	14	32	463
	Ro	1.52	7.18	0.74	1.65	10.1	21.2	48	283	14	33	476
F test value		1.4	0.3	0.18	3.5	1.7	1.1	0.2	0.6	0.6	3.1	1.6
BDS rate (R) (t·ha^{-1})	0.0	1.69 b	7.11	0.74	1.41 a	8.5 a	19.5 a	44 a	282	14 a	31 a	437 a
	0.8	1.42 a	6.86	0.73	1.63 b	10.1 b	20.8 ab	49 b	281	14 a	33 ab	456 b
	1.6	1.48 a	7.07	0.74	1.73 c	10.8 b	21.8 b	50 b	283	15 b	34 b	501 c
	3.2	1.59 ab	7.44	0.75	1.70 c	10.5 b	22.0 b	48 ab	283	15 b	33 ab	482 bc
F test value		6.0**	1.3	0.14	22.0***	31.5***	11.2***	17.3	0.1	6.5***	7.9***	7.5***
F value for the selected interactions												
AM x R		0.3	0.2	0.1	0.7	0.5	0.5	0.0	1.4	1.1	1.1	0.8
Y x AM x R		2.3*	2.0	0.8	2.2	1.5	2.5*	1.3	0.8	0.8	1.3	1.4

Legend: LI – leaves; ST – stems; HL – husk leaves; GY – grain yield; TB – total biomass; HI – harvest index; TGW – thousand grain weight; NR – number of rows per cob; NGR – number of grain per row; NGC – number of grains per cob

Numbers marked with the same letter are not significantly different; ***, **, * significance at 0.001; 0.01; 0.05, respectively

by maize decreased in the following order: 2014 ≥ 2015 > 2016. In 2014, the effect of the BDS rate depended on the application method. On the treatment with broadcast applied BDS, the harvested biomass increased progressively with its rate. On the treatment with row applied fertilizer, it followed the quadrate regression model, reaching the maximum production on the plot treated with 1,6 t BDS·ha^{-1}. Quite reverse models were observed in 2015. In 2016, the total yield of maize biomass was low and only slightly depended on the applied BDS.

The relative contribution of particular maize parts in the total biomass crop decreased in the following order:

GY (48%) > ST (34%) > CC (8%) ≥ LE (7%) > HL (3%).

The above presented order clearly indicates a slight advantage of the vegetative parts of maize at harvest over the reproductive (grain). The harvest index (HI) is a simple indicator of dry matter partitioning among vegetative and generative parts of the growing crop [Hay 1995]. Therefore, it is a very important characteristic of grain yield response both to the course of weather and to applied fertilizers. In the studied case, HI was significantly affected by the course of weather in consecutive years and by BDS rate (Fig. 1). The impact of weather was dominant, because the highest values of the HI indices were recorded in years with stress, i.e. in 2015 and 2016. The effect of the BDS rate, averaged over other treatments, can be described by the quadrate regression model, reaching the maximum in the plot treated with 1.6 t BDs·ha^{-1}. A detailed analysis of the Y x R interaction (data not shown but available by the author) documented the HI response to the BDS rate, was year specific. In 2014, the maximum was recorded on the plot with 0.8 t·ha^{-1}, but in 2016 on the plot with 1.6 t·ha^{-1} of the applied bio-fertilizer. In the last case, it exceeded 50%, clearly indicating favorable growth conditions during the grain filling period. Any response of HI to the studied factors was recorded in 2015, but its average value was high.

The grain yield of maize showed a significant response to the interaction of years and the application method. In the first two years of the study, an advantage of a row applied BDS was observed. The quite reverse situation was revealed in 2016. A detailed analysis of Fig. 1, shows that the grain yield followed the general trend of the total biomass yield, which is typical for maize [Hay 1995]. In addition, the effect of the progressive BDS rate was also recorded in 2016. The significant dependence of the grain yield (Y) on the total biomass yield (BY) is corroborated by the equation:

$$Y = 0.41BY + 1.389 \text{ for } R^2 = 0.70 \text{ and } n = 72 \quad [1]$$

The average contribution of stems in the total biomass of maize was 34%, ranging from 29 to 37% (Fig. 1). The highest values were, in general, the attribute of the N control plots. It is necessary to stress that stems showed an annual variability in the same manner as recorded for grain yield. The yield of leaves responded to interaction of all factors, including years. The effect of years was quite specific, because the lowest biomass was recorded in the dry 2015. The effect of BDS depended on its rate. As a rule, the lowest rates of BDS resulted in a significant decrease in biomass of leaves. The yield of husk leaves showed only dependence on years, decreasing in the following order: 2014 > 2015 > 2016. The yield of corncob showed quite an opposite trend to the application of BDS, showing a positive response to its increasing rates. The analysis of maize parts indicates a significant impact of BDS on dry matter partitioning among maize parts. This conclusion is supported by three sets of equations:

1. GY: $GY = 1.08 - 0.77LE + 0.29ST + 4.97CC$ for $R^2 = 0.85$ and $n = 72$ [2]
2. GY: $GY = 0.78 + 5.7CC$ for $R^2 = 0.78$ and $n = 72$ [3]
3. HI: $HI = 46.7 + 2.3GY - 2.0LE - 2.3ST - 2.8CCL$ for $R^2 = 0.99$ and $r = 72$ [4]

The yield of corncob, considered as the single predictor, explains 78% of the grain yield variability. The effect of stems on HI depended on the treatment. In 2014 and 2016, the application of BDS resulted in the stem biomass decrease compared to the N control, leading to the grain yield increase.

The second group of maize yield characteristics refers to yield components. The number of rows per cob (NR) due to its firm genetic background can be considered as the conservative yield components [Ritchie and Alagarswamy 2003]. It showed, however, a strong year-to-year variability, responding positively to BDS (Table 3). The number of grains per row (NGR) was only affected by the BDS, as long as the BDS rate did not exceed 1,6 t·ha^{-1}. Consequently, the number of grain per cob (NGC) followed the pattern recorded for NR. The lower NR in 2016, concomitant with the same number of grains per row suggests a strong shortage of nitrogen supply to plants before flowering [Subedi and Ma 2005]. The thousand grain weight (TGW) showed only a year-to-year variability. It was significantly lower in 2015 and 2016 compared to 2014. It means that the growing conditions during the grain filling period in 2014 were much more favorable in 2014 with respect to other years.

The grain yield evaluation based on the yield components corroborates the limiting effect of both primary components:

$$GY = -7.04 + 0.46NR + 0.32NGR \text{ for } R^2 = 0.54 \text{ and } n = 72 \qquad [5]$$

However, a question of the impact of maize vegetative parts on the degree of both yields component development, still remains. NR was found to be significantly dependant on the stem yield:

$$NR = 10.9 + 0.5ST \text{ for } R^2 = 0.31 \text{ and } n = 72 \qquad [6]$$

This equation clearly indicates a strong reduction in the NR due to low biomass of stem. This situation was apparent in 2016, a year with a low supply of N maize. The degree of NGR expression was governed by the yield of corncob:

$$NGR = 23.1 + 5.76CC \text{ for } R^2 = 0.33 \text{ and } n = 72 \qquad [7]$$

The yield of corncob was significantly reduced in 2016. The observed reduction was concomitant with the lower set of grains per cob (NGC).

The degree of nitrogen concentration (N_c) variability among maize parts was much lower compared to their seasonal fluctuation (Table 4). The impact of years should be considered separately for each part of maize. The lowest variability in N_c was recorded for grain (GR) and corncob (CC). For both organs, the lowest N_c showed in 2016. Its seasonal variability was much stronger for CC than for GR. The analysis of yearly trends of N_c indicates a shortage of N supply to both maize organs in 2016 and for CC in 2015. The low supply of N to the corncob corroborates findings presented in equations No. 5 and 7. This negative trend was partially overcome by the application of BDS. The maximum N_c was reached on plots fertilized with 1.6 t BDS·ha^{-1}. The seasonal trend of N_c in stems and husk leaves was quite opposite to that observed for CC. At the same time, it responded progressively to BDS rates. In leaves, N_c showed only a year-to-year variability, decreasing in the following order: 2016 > 2014 > 2015. Its low value for 2015, concomitant with high NGC, indicates a strong remobilization of N from leaves. The main reason for that was water shortage, which took place during the grain filling period. In contrast, the high N_c in leaves and stems concomitant with low NGC indicates its low remobilization rate from both organs due to paltry sink capacity [Szczepaniak et al. 2015]. This conclusion is supported by the equation:

$$NGC = 194.5 + 169.8CCc \text{ for } R^2 = 0.38 \text{ and } n = 72 \qquad [8]$$

The shortage of N_c in CC was probably the main reason for the weak development of the cob sink, resulting in a lower number of grain per cob. The grain yield of maize was significantly governed by N_c in two maize parts, i.e. leaves and corncob. The N_c in leaves exerted a negative, while in the corncob a positive impact on the grain yield (Fig. 2).

Table 4. Nitrogen profile of maize: concentration and partitioning among plant parts

Factors	Level of factor	Plant parts – N concentration					Plant parts – N accumulation					TOT	NHI (%)
		GRc	STc	LEc	HLc	CCc	GR	ST	LE	HL	CC		
		g·kg^{-1} DW					kg·ha^{-1}						
Year (Y)	2014	15.5 b	6.63 a	11.7 b	6.09 a	1.74 c	163.5 b	53.4 a	22.3 b	6.42	7.04 b	252.6 b	65.0 b
	2015	15.1 b	7.67 b	9.1 a	7.09 b	1.64 b	160.2 b	60.4 b	11.1 a	4.69	7.74 b	244.2 b	65.6 b
	2016	14.4 a	8.44 c	14.1 c	7.83 c	1.48 a	126.9 a	47.3 a	21.7 b	3.86	6.31 a	206.0 a	61.6 a
F test value		13.9***	23.9***	65.6***	27.2***	23.6***	56.0***	11.1***	71.5***	40.3***	14.2***	35.9***	10.7***
Application method (AM)	Br	15.1	7.71	11.9	6.99	1.59	149.6	54.3	19.0	4.92	6.55 a	234.4	63.9
	Ro	14.9	7.45	11.4	7.02	1.65	150.7	53.1	17.7	5.06	7.51 b	234.1	64.3
F test value		2.1	1.5	2.0	3.5	3.5	0.1	0.3	2.2	0.4	19.2***	0.0	1.7
BDS rate (R) t·ha^{-1}	0.0	14.6 a	7.10 a	11.9	6.88 ab	1.41 a	125.3 a	49.8 a	19.8 b	4.62 a	5.26 a	204.9 a	61.1 a
	0.8	15.0 ab	7.57 ab	11.4	6.74 a	1.63 b	152.3 b	51.8 ab	16.7 a	4.74 a	6.77 b	232.2 b	65.5 bc
	1.6	15.4 b	7.60 ab	11.9	6.81 ab	1.73 b	156.1 bc	53.7 ab	17.3 a	4.91 ab	8.51 c	251.4 c	66.6 c
	3.2	15.0 ab	8.05 b	11.4	7.58 b	1.70 b	167.0 c	59.4 b	19.8 b	5.7 3b	7.59 b	248.7 c	63.1 b
F test value		4.2*	3.2*	1.0	4.0*	22.0***	32.0***	3.3*	3.7*	4.5**	39.4***	20.0***	10.4***
F value for the selected interactions													
AM x R		3.9*	1.9	0.9	1.2	0.7	2.7	1.1	1.3	0.2	21.2***	3.2*	0.6
Y x AM x R		0.4	1.7	1.0	6.9***	2.2	1.1	3.0*	1.9	3.7**	8.5***	1.9	2.3

Legend: Gr – grain; ST – stems; LE – leaves; HL – husk leaves; CC – corncob; c – concentration; TOT – total accumulation; NHI – nitrogen harvest index
Numbers marked with the same letter are not significantly different; ***, **, * significance at 0.001; 0.01; 0.05, respectively

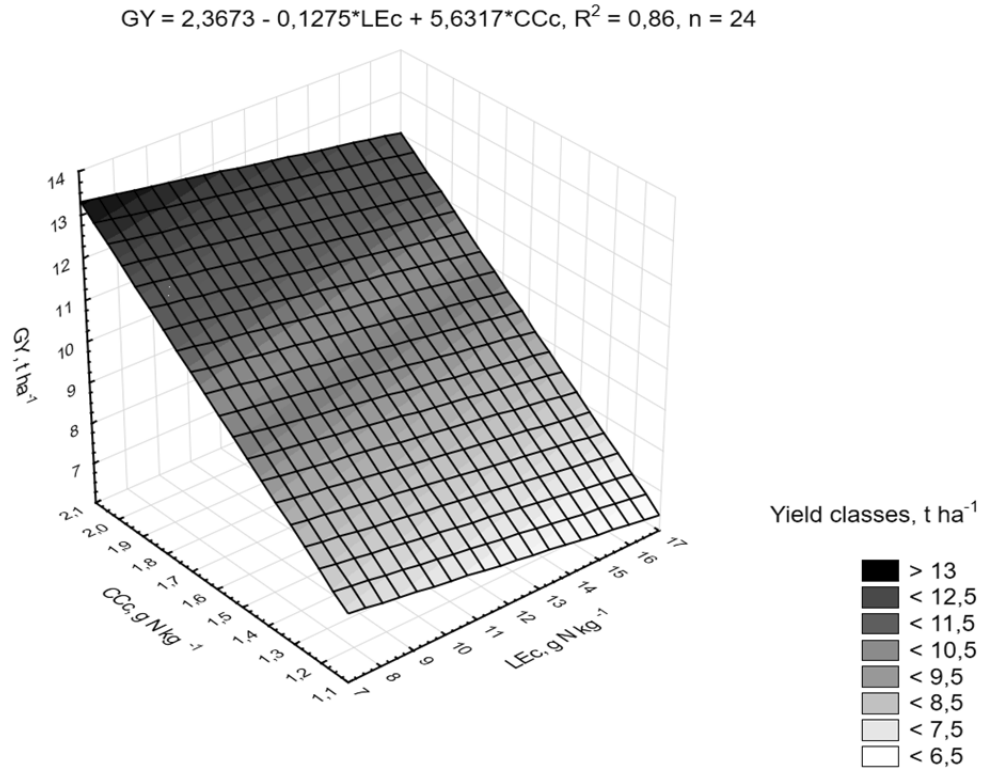


Fig. 2. The grain yield as a function of nitrogen concentration in vegetative maize parts

The total amount of N accumulated (N_a) in maize at harvest was significantly governed by interaction of the application method and BDS rate (Fig. 3). The linear regression model was recorded for the broadcast, but the quadrate one for the BDS applied row:

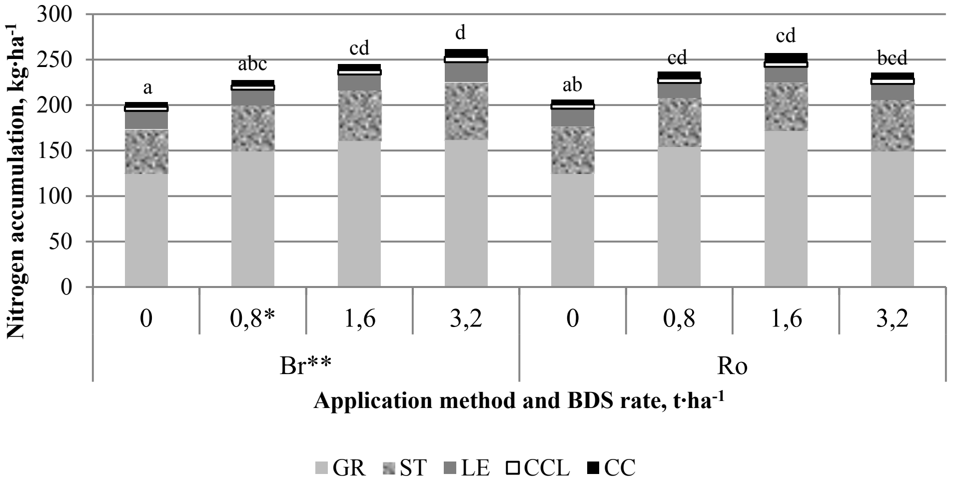
1. Br: $N_{TOT} = 17.5BDS + 210$ for $R^2 = 0.93$ and $n = 4$ [9]
2. Ro; $N_{TOT} = 13.6BDS^2 + 53.3BDS + 205.3$ for $R^2 = 0.99$ and $n = 4$ [10]

These two different models clearly indicate that the row applied with BDS at the rate of 1,96 t ha^{-1} was sufficient to achieve the maximum N uptake by maize.

The contribution of maize components in the total N uptake decreased, averaged over all treatments and years, in the order, as shown below:

GR (64%) > ST (23%) > LE (7,9%) CC (3,0%) > HL (2,1%).

The GR contribution into the total N uptake, termed as the Nitrogen Harvest Index (NHI), ranged from 61 to 67%. The obtained average is higher than that reported by Bender et al. [2013], but within the range reported by Szczepaniak [2016] for high-yielding maize. In the present study, the lowest NHI values were the attribute of the N control plots. The applied BDS resulted in the significant increase of NHI, which reached, irrespectively of the application method, the top values on plots fertilized with 1.6 t BDS·ha^{-1}. Quite opposite models were recorded for a contribution of other vegetative maize parts to the total maize biomass, excluding



Legend: * – BDS rate, t·ha^{-1}; ** – method of BDS application: Br – broadcast, Ro – row
Numbers marked with the same letter are not significantly different;

Fig. 3. The partitioning of nitrogen between maize organs at harvest

corncobs. It can be concluded that BDS significantly affecting N partitioning, increased then its accumulation in grain. The applied stepwise regression clearly indicates that the N accumulation in grain was the key predictor of the grain yield:

$$GY = 2.2 + 0.05GR \text{ for } R^2 = 0.90 \text{ and } n = 72 \quad [11]$$

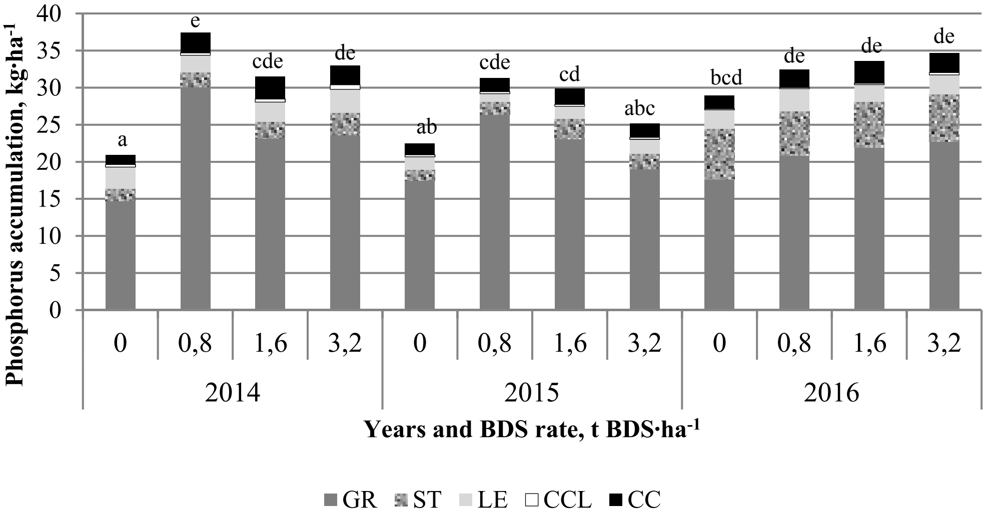
The highest phosphorus concentration (P_c) in maize grain was recorded in two contrastive years, i.e. 2014 and 2016 (Table 5). These results, concomitant with extremely high P concentration in stems and also high in other vegetative maize parts in 2016, indicate a sufficiently good supply of this nutrient to the plant during the growing season. In 2015, the low P concentration in grain and in other maize parts suggests an inefficient P uptake from soil during the grain filling period [Szczepaniak 2016]. In spite of that, the recorded P concentrations in grain were above the published ranges [Gąsiorowska et al. 2011]. The key reason for low P_c was probably the lack of application of P fertilizer. This conclusion is supported by a significant increase of grain P_c in response to applied BDS, irrespectively of its rate. The same positive effect of BDS was recorded for maize parts proximate to kernels, such as husk leaves and corncobs. Among the maize parts, the highest sensitivity to fertilizing treatments and weather fluctuation was recorded for leaves.

The total phosphorus accumulation (P_a) by maize at harvest was governed by the interaction of years and the BDS rate (Fig. 4). The effect of BDS on P_a was significant, but the pattern of response was year specific. In 2014 and 2015, the highest increase was the attribute of plants fertilized with 0.8 t BDS·ha^{-1}. In 2016, the amount of P in maize increased progressively along with BDS rates. The observed trends, concomitant with simultaneous increase in the Phosphorus Harvest Index (PHI), indicate a positive impact of BDS on P management by maize. In the first two years PHIs ranged from 70 to 84%. In 2014, the amount of P in grain harvested from the plot fertilized with 0.8 t·ha^{-1} doubled, and in 2015 increased by 51% compared to the respective

Table 5. Phosphorus profile of maize: concentration and partitioning among plant parts

Factors	Level of factor	Plant parts – P concentration					Plant parts – P accumulation					TOT	PHI (%)
		GRc	STc	LEc	HLc	CCc	GR	ST	LE	HL	CC		
		g·kg^{-1} DW					kg·ha^{-1}						
Year (Y)	2014	2.15 b	0.28 a	1.46 a	0.41	1.36 ab	22.90	2.22 a	2.76 b	0.43 b	2.42 b	30.7 b	73.9 b
	2015	2.02 a	0.25 a	1.32 a	0.39	1.11 a	21.50	1.99 a	1.61 a	0.27 a	1.83 a	27.2 a	78.5 c
	2016	2.36 b	1.15 b	1.73 b	0.41	1.66 b	20.79	6.36 b	2.62 b	0.20 a	2.46 b	32.4 b	64.0 a
F test value		8.3^{***}	245.6^{***}	9.4^{***}	0.1	18.5^{***}	2.7	121.5^{***}	24.1^{***}	29.3^{***}	9.9^{***}	14.4^{***}	56.8^{***}
Application method (AM)	Br	2.20	0.49 a	1.57	0.34 a	1.40	21.65	3.06 a	2.45	0.25 a	2.24	29.6	73.1
	Ro	2.16	0.63 b	1.43	0.47 b	1.35	21.81	3.99 b	2.22	0.35 b	2.24	30.6	71.1
F test value		0.3	12.2^{**}	2.9	16.4^{***}	0.5	0.0	13.1^{***}	2.5	16.5^{***}	0.0	1.4	3.2
BDS rate (R) (t·ha^{-1})	0.0	1.96 a	0.50	1.43	0.33 a	1.14	16.61 a	3.36	2.37	0.24 a	1.57 a	24.1 a	69.5 a
	0.8	2.53 b	0.53	1.48	0.36 b	1.42	25.77 b	3.24	2.14	0.26 a	2.34 b	33.7 b	76.2 b
	1.6	2.12 b	0.63	1.50	0.40 b	1.56	22.73 b	3.68	2.25	0.29 a	2.70b	31.6 b	71.9 a
	3.2	2.10 b	0.58	1.60	0.53 b	1.39	21.80 b	3.83	2.56	0.40 b	2.35 b	30.9 b	70.9 a
F test value		13.4^{***}	2.2	0.8	7.4^{***}	5.8^{**}	25.3^{***}	1.1	1.5	7.9^{***}	13.5^{***}	26.3^{***}	6.5^{***}
F value for the selected interactions													
AM x R		0.5	1.0	7.5^{***}	0.7	0.5	0.6	1.0	3.8^{*}	1.1	0.4	0.1	1.6
Y x AM x R		2.2	1.0	6.4^{***}	0.4	1.6	2.0	1.3	4.0^{**}	0.5	2.3^{*}	1.7	2.3

Legend: Gr – grain; ST – stems; LE – leaves; HL – husk leaves; CC – corncob; c – concentration; TOT – total accumulation; PHI – phosphorus harvest index
Numbers marked with the same letter are not significantly different; ***, **, * significance at 0.001; 0.01; 0.05, respectively



Legend: * – BDS rate, t·ha^{-1}; ** – method of BDS application: Br – broadcast, Ro – row
Numbers marked with the same letter are not significantly different;

Fig. 4. The partitioning of phosphorus between maize organs at harvest

N control. In 2016, PHI was much lower, but increased along with BDS rates from 61 to 66%. The obtained ranges are lower than those reported by Bender et al. [2013], but higher than the ones reported by Szczepaniak [2016] for high-yielding maize.

The amount of P_a in stems was 6.5 times lower compared to grain. The most important matter is that the relative P partition between grains and stems was in balance. In fact, the lower PHI, the higher P_a contribution in stems was recorded. This relationship was not observed for other vegetative parts of maize. It can be, therefore, concluded that P content in stems is the main source of this element for the growing maize kernels. The main reason for the high P content in stems, as recorded in 2016, was the low capacity of sink, i.e. NGC, resulting in paltry exploitation of the stem P reserves.

The conducted study did not show a strong predictive function of P_c in maize parts. However, as per results from the conducted stepwise regression, the grain yield can be well predicted based on P_a in particular parts of maize:

$$GY = 7.2 + 0.09GR - 0.3ST + 0.8CC \text{ for } R^2 = 0.54 \text{ and } n = 72 \quad [12]$$

This equation clearly corroborates the fundamental function of stems, as a P reservoir for developing kernels. The PHI can be predicted based on both, P_c or P_a in maize parts. The lower number of predictors was significant for P_c:

$$PHI = 66.4 + 9.2Gr_c - 14.4ST_c - 4.1LE_c \text{ for } R^2 = 0.81 \text{ and } n = 72 \quad [13]$$

These two equations, indicating the negative impact of stem P increase, i.e. P_c or P_a indirectly informs of the insufficient size of the cob sink, i.e. number of grains per cob.

All maize parts showed a great year-to-year variability in potassium concentration (K_c) (Table 6). The descending order of maize organs is as follows:

Table 6. Potassium profile of maize: concentration and partitioning among plant parts

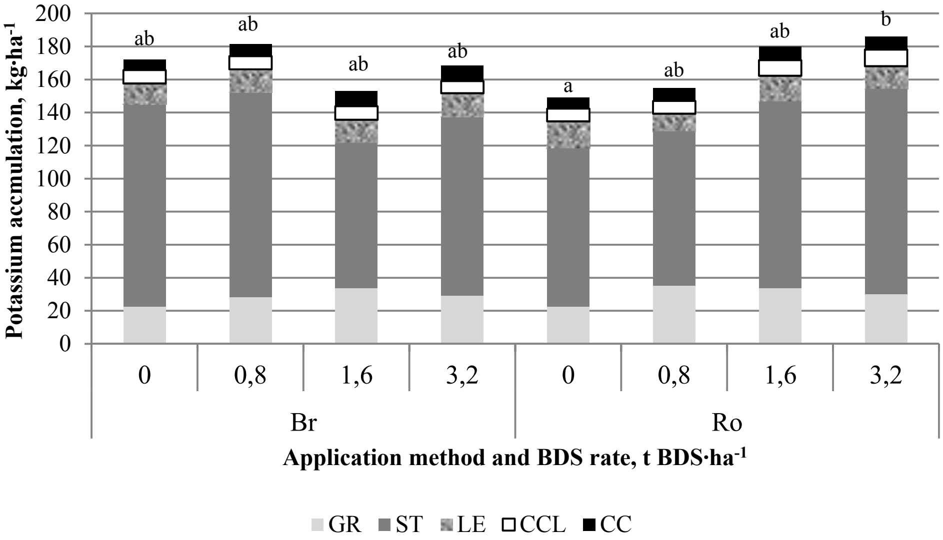
Factors	Level of factor	Plant parts – K concentration					Plant parts – K accumulation					TOT	KHI (%)
		GRc	STc	LEc	HLc	CCc	GR	ST	LE	HL	CC		
		g·kg^{-1} DW					kg·ha^{-1}						
Year (Y)	2014	4.02 c	16.66 b	8.16 a	8.89 a	5.34 b	42.6 c	132.1 b	15.4 b	9.3 b	9.3 b	208.7 c	20.7 b
	2015	2.66 b	16.54 b	10.94 b	17.37 b	3.73 a	28.4 b	128.5 b	13.3 a	11.6 c	6.1 a	187.8 b	15.6 a
	2016	1.96 a	11.88 c	7.90 a	8.24 a	5.62 b	17.3 a	66.3 a	11.9 a	4.0 a	8.3 b	107.9	16.3 a
F test value		246.4***	22.6***	34.1***	85.9***	32.4***	236.2***	62.0***	8.1***	79.3***	29.5***	115.0***	19.4***
Application method (AM)	Br	2.83	15.50	8.64 a	11.20	5.12 b	28.4 a	111.0	13.4	7.9	8.1	168.8	16.9
	Ro	2.93	14.55	9.36 b	11.81	4.68 a	30.4 b	106.9	13.7	8.7	7.7	167.5	18.2
F test value		1.8	2.1	4.5*	0.9	4.4*	4.5*	0.6	0.2	2.7	1.8	0.1	3.6
BDS rate (R) (t·ha^{-1})	0.0	2.63 a	15.30	8.66 a	12.02	4.79	22.6 a	109.5	14.0	7.9	6.6 a	160.7	14.1 a
	0.8	3.05 bc	15.49	8.66 a	10.60	4.64	31.7 bc	109.0	12.1	7.8	7.6 ab	168.2	18.9 bc
	1.6	3.07 c	14.05	9.86 b	11.55	5.02	33.7 c	100.7	14.5	8.8	8.7 b	166.5	20.4 c
	3.2	2.77 ab	15.27	8.81 a	11.84	5.14	29.6 b	116.6	13.7	8.7	8.7 b	177.3	16.8 b
F test value		7.9***	1.0	3.0*	1.0	1.2	25.4***	1.4	2.2	1.0	7.9***	1.4	14.4***
F value for the selected interactions													
AM x R		3.5*	7.8***	11.6***	2.8	1.7	3.1*	6.9***	4.6**	2.2	2.0	5.8**	9.2***
Y x AM x R		6.6***	2.2	9.7***	4.5**	0.5	3.1*	2.7*	5.7***	1.7	0.9	1.7	2.7

Legend: Gr – grain; ST – stems; LE – leaves; HL – husk leaves; CC – corncob; c – concentration; TOT – total accumulation; KHI – potassium harvest index
Numbers marked with the same letter are not significantly different; ***, **, * significance at 0.001; 0.01; 0.05, respectively

1. 2014, 2016: ST > HL > LE > CC > GR;
2. 2015: HL > ST > LE > CC > GR.

The greatest instability of K_c was recorded for grain and husk leaves. In grain, it reduced by half in 2016 compared to 2014. As a rule, BDS application resulted in the grain K_c increase, showing, however, a great seasonal variability with respect to the applied BDS rate. Potassium concentration in stems was the highest, but its seasonal variability was not as high as recorded in other maize organs. In the dry 2015, it was at the same level as recorded in the wet 2014. The true and husk leaves showed much stronger seasonal variability. The highest K_c was recorded in the dry 2015. In this particular year, its concentration was twice as high compared to other years. The positive effect of BDS on K_c in both organs was the strongest in 2015. The observed response stresses the importance of K content in leaves for maintaining plant functions during water shortage [Grzebisz et al. 2013]. The lack of K_c decrease in response to water shortage suggests that K supply to maize before the grain filling period was high enough and K content in true and husk leaves can be considered as a K buffer.

The total amount of K (K_a) in maize, averaged over fertilization treatments and years, was 170 kg·ha^{-1}, showing, however, a strong year-to-year variability (Table 6). The K_a variability was driven by the interaction of the application method and BDS rate. As shown in Fig. 5, the effect of BDS was much more predictable on plots with row applied fertilizer. The total K content increased progressively with BDs rates. The Potassium Harvest Index (KHI), amounting, on average, to 17%, ranged from 13 to 23%. Its slightly higher values were the attribute of plots with the broadcast applied BDS. The KHI reached the highest value at 1.6 t·ha^{-1} on plots with broadcast, but at 0.8 t·ha^{-1} on plots with a row applied fertilizer. The main reservoirs of K were



Legend: * – BDS rate, t·ha^{-1}; ** – method of BDS application: Br – broadcast, Ro – row
Numbers marked with the same letter are not significantly different;

Fig. 5. The partitioning of potassium between maize organs at harvest

stems, accumulating on average $^2/_3$ of its total content. Its relative contribution ranged from 57 to 71%. The effect of BDS application, especially on plots with a broadcast applied fertilizer, resulted in the decrease of K amount in stems. As a rule, the increase of KHI in grain led to the decrease of its relative contribution in stems. This conclusion is supported by the developing regression model of KHI:

$$KHI = 16.3 + 4.5GR_c - 0.78ST_c \text{ for } R^2 = 0.73 \text{ and } n = 72 \quad [14]$$

$$KHI = 16.7 + 0.43GR - 0.09ST - 0.12LE \text{ for } R^2 = 0.94 \text{ and } n = 72 \quad [15]$$

These two equations clearly inform that any increase in K_c or K_a in stems and leaves leads to the decrease of KHI. On the other hand, as presented below, the grain yield of maize significantly depended on K amount in grain:

$$GY = 7.59 + 0.08GR \text{ for } R^2 = 0.47 \text{ and } n = 72 \quad [16]$$

Magnesium concentration (Mg_c) in maize parts was year-to-year variable (Table 7). The descending order of maize organs was as follows:

1. 2014, 2016: CC > LE > HL > GR > ST;
2. 2015: CC > HL > GR > LE > ST.

As a rule, a much lower Mg_c in stems, leaves and corncob was recorded in the dry 2015. The effect of the application method was observed only for stems, showing significantly higher Mg_c for plants grown on plots with broadcast application of BDS. The effect of BDS was significant for all maize parts, except stems. For grain, the effect of increasing BDS rates was variable depending on the interaction of all studied factors. The effect of applied BDS was visible in all years, but the progressive increase in Mg_c was recorded in 2014. The average level of Mg_c recorded for the N control, amounting to 1300 mg·kg^{-1} DW, was within published ranges [Brikić et al. 2003, Szczepaniak et al. 2015]. The Mg_c showed a strong response to BDS application, increasing up to 1500 mg·kg^{-1} DW. It means that BDS can be treated as an important factor, influencing Mg supply to maize. An extremely high Mg_c concentration in grain and also in other maize parts at harvest, as evidenced in 2016, indicates its ample supply to plants during the seed filling period [Grzebisz 2015]. The interactional effect of all factors on Mg_c was as well observed for true leaves. The Mg_c reached extremely low values in the dry 2015. The water stress was partly overcome by broadcast applied BDS. The effect of BDS on Mg_c in husk leaves was significant, following the quadrate regression model.

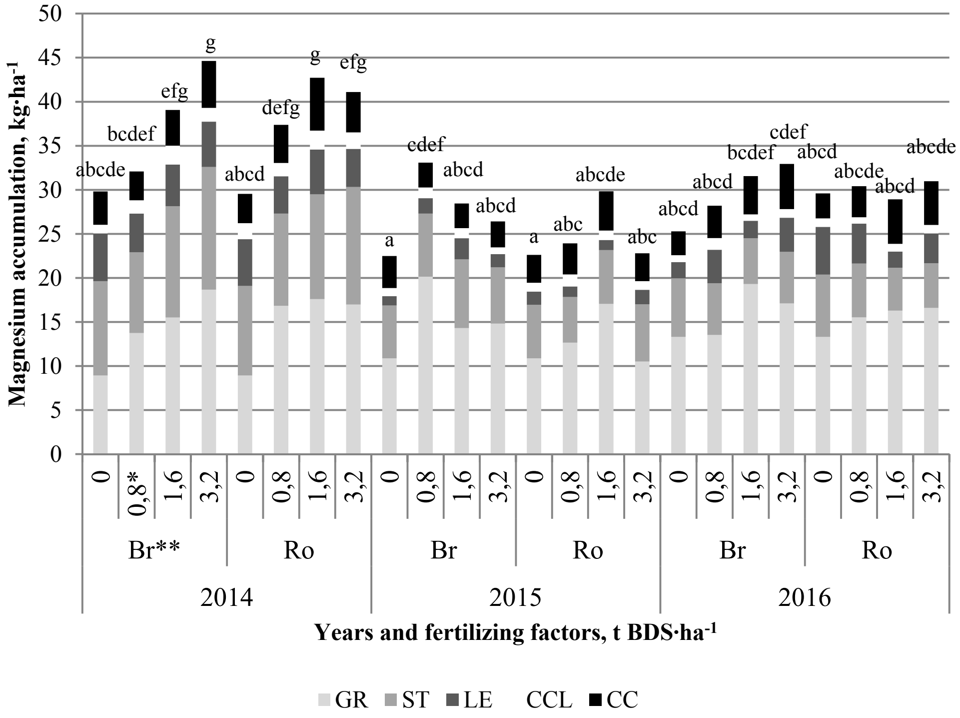
The total amount of Mg accumulated in maize crop at harvest (Mg_a) was significantly governed by the interaction of all factors (Table 7, Fig. 6). The effect of fertilization treatments was variable in consecutive years of study. In 2014, the linear model of the Mg_a response to the applied BDS was recorded on the broadcast, whereas the quadrate one, for the plots with the BDS treated rows. In 2015, the Mg accumulation models were non consistent, but the effect of BDS was positive. In 2016, the beneficial and the progressive effect of BDS were only recorded on plots with the broadcast applied fertilizer.

The relative contribution of grain in the total Mg accumulation by maize at harvest, i.e. the Magnesium Harvest Index, was 46%, ranging, however, from 30 to 59%. As a rule, much higher MgHI values were recorded in 2014. The effect of BDS was clear, reaching the highest values for the plot with 0.8 t BDS·ha^{-1}. In 2015, MgHI reached the highest values, but the effect of BDS was inconsistent. The strong MgHI increase in grain harvested in 2015, implicitly underlines the accelerated Mg flow to developing grains in response to water shortage, indicating its ameliorating function [Grzebisz 2013]. The contribution of stem in the total Mg_a lower by half compared to grain. It showed a specific balance with Mg partition into grain, decreasing in years with stress as in 2015, or in years with insufficient development of Mg sink, as in 2015. A particular attention should be paid to Mg content in true leaves, which varied from 4 to 18%. The main reason of the observed fluctuation was drought in 2015. The water shortage, covering the most

Table 7. Magnesium profile of maize: concentration and partitioning among plant parts

Factors	Level of factor	Plant parts – Mg concentration					Plant parts – Mg accumulation					TOT	MgHI (%)
		GRc	STc	LEc	HLc	CCc	GR	ST	LE	HL	CC		
		g·kg^{-1} DW					kg·ha^{-1}						
Years (Y)	2014	1.37 a	1.45 c	2.56 c	1.63 ab	2.49 b	14.7 ab	11.54 b	4.82 b	1.69 b	4.33 b	37.0 c	39.1 a
	2015	1.31 a	0.81 a	1.25 a	1.58 a	2.03 a	13.9 a	6.40 a	1.53 a	1.06 a	3.31 a	26.2 a	52.5 b
	2016	1.77 b	1.05 b	2.15 b	1.89 b	2.71 b	15.6 b	5.84 a	3.33 ab	0.92 a	4.03 b	29.7 b	52.3 b
F test value		30.4^{***}	115.9^{***}	72.4^{***}	4.5^{*}	9.4^{***}	4.3^{*}	100.1^{***}	106.7^{***}	43.1^{***}	9.9^{***}	81.3^{***}	84.5^{***}
Application method (AM)	Br	1.52	1.15 b	1.92	1.64	2.34	15.0	8.11	3.16	1.17	3.70	31.2	48.6
	Ro	1.45	1.07 a	2.05	1.76	2.48	14.4	7.73	3.30	1.28	4.07	30.8	47.3
F test value		1.9	5.1^{*}	2.3	1.7	1.0	1.5	1.1	0.6	2.2	3.7	0.2	1.9
BDS rate (R) (t·ha^{-1})	0.0	1.31 a	1.09	1.88 a	1.53 a	2.31	11.0 a	7.78	3.42	1.08	3.24 a	26.6 a	42.3 a
	0.8	1.54 b	1.08	2.25 b	1.83 b	2.17	15.4 b	7.32	3.32	1.27	3.52 a	30.8 ab	50.1 b
	1.6	1.57 b	1.15	1.80 a	1.83 b	2.58	16.7 b	8.08	2.86	1.36	4.45 b	33.4 b	51.0 b
	3.2	1.52 b	1.12	2.00 ab	1.60 ab	2.58	15.8 b	8.51	3.31	1.18	4.35 b	33.1 b	48.5 b
F test value		4.9^{**}	0.8	4.7^{**}	2.8^{*}	2.4	27.8^{***}	1.9	1.9	2.7	9.8^{***}	20.1^{***}	16.8^{***}
F value for the selected interactions													
AM x R		0.7	1.9	6.9^{***}	2.5	2.9^{*}	1.6	0.3	4.7^{**}	2.4	4.4^{**}	1.9	0.9
Y x AM x R		2.8^{*}	1.2	3.2^{*}	2.1	0.2	4.6^{***}	0.6	2.8^{*}	1.3	0.7	3.1^{*}	3.4^{**}

Legend: Gr – grain; ST – stems; LE – leaves; HL – husk leaves; CC – corncob; c – concentration; TOT – total accumulation; MgHI – magnesium harvest index
Numbers marked with the same letter are not significantly different; ***, **, * significance at 0.001; 0.01; 0.05, respectively



Legend: * – BDS rate, t·ha^{-1}; ** – method of BDS application: Br – broadcast, Ro – row
Numbers marked with the same letter are not significantly different;

Fig. 6. The partitioning of magnesium between maize organs at harvest

of grain filing period, resulted in a significant exhaustion of Mg from leaves. Mg remobilized from leaves, as indicated by simultaneously higher MgHI values, was allocated to grain. The value of this index can be well predicted based on Mg_c or Mg_a in respective maize parts:

$$MgHI = 48.1 + 18.0 - 13.1ST_c - 3.3LE_c - 2.4CC_c \text{ for } R^2 = 0.83 \text{ and } n = 72 \quad [17]$$

$$MgHI = 45.3 + 1.7GR - 1.3ST - 1.8LE - 1.3HL - 1.3CC \text{ for } R^2 = 0.98 \text{ and } n = 72 \quad [18]$$

These two equations clearly inform that any increase in Mg concentration or accumulation in vegetative parts of maize results in simultaneous decrease of Mg contribution in grain.

CONCLUSIONS

1. The effect of BDS on grain yield of maize was due to its positive impact on biomass of stems and corncob, which strongly affected the degree of the primary yield components development such as the number of rows per cob (NR) and the number of grains per row (NGR).
2. The shortage of N supply to maize was the key reason for lower biomass of corncob, which in turn reduced the cob sink capacity, i.e. the number of grain per cob (NGC), thus leading to the grain yield decrease.

3. The BDS action on maize grain yield showed through enhanced translocation of dry matter and nutrients into grain in expense of vegetative maize parts, mainly stems (N, P, K), and leaves (N, Mg).
4. The BDS action on potassium management by maize was mostly revealed in the dry 2015. The application of BDS resulted in higher K concentration in true and husk leaves.
5. The BDS action on magnesium management by maize resulted in a significant increase of its concentration in grain.
6. The row method of BDS application showed its advantage over the broadcast one. The same amount of N was taken up, as well as higher indices of dry matter and nutrient contribution in grain was achieved by applying a half of the BDS rate.

REFERENCES

Alburquerque J.A., de la Fuente C., Ferre-Costa A., Carrasco L., Cegarra. J, Abad. M., Bernal M.P. 2012. Assessment of the fertiliser potential of digestates from farm and agro-industrial residues. Biomass Bioenergy 40: 181–189.

Bender R.R., Haegele J.W., Ruffo M.L., Below F.E. 2013. Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. Agron. J. 105: 161–170

Brkić I., Zdunić Z., Jambrović A., Ledencan T., Kovacević V., Kadar I. 2003. Combining abilities of cornbelt inbreed lines of maize for mineral content in grain. Maydica 48: 293–297.

Buckley K., Massé D., Gasser M.-O. 2008. Yield and nutrient export of grain corn fertilized with raw and treated liquid swine manure. Agron. J. 100: 1303–1309.

Chiew Y.L., Spanberg J., Baky A., Hansson P-A., Jonsson H. 2015. Environmental impact of recycling digested food waste as a fertilizer in agriculture – a case study. Res. Conserv. Rec. 5: 1–14.

Dz.U. 2008. Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 16 kwietnia 2008 r. w sprawie szczegółowego sposobu stosowania nawozów oraz prowadzenia szkoleń z zakresu ich stosowania. Dz. U. Nr 80 poz. 479.

Gąsiorowska B., Makarewicz A., Nowosielska A. 2011. The content of selected macroelements in maize cultivars grain sowed in three dates. Fragm. Agron. 28(3): 7–15 (in Polish).

Grzebisz W. 2013. Crop response to magnesium fertilization as affected by nitrogen supply. Plant Soil 368: 23–39.

Grzebisz W. 2015. Magnesium. In: Handbook of Plant Nutrition. Baker A.V., Pilbeam D.J. (eds.). CRC Press, 199–260.

Grzebisz W., Gransee A., Szczepaniak W., Diatta J. 2013. The effects of potassium fertilization on water-use efficiency in crop plants. J. Plant Nutr. Soil Sci. 176: 355–374.

Gutser R., Ebertseder T., Weber A., Schraml M., Schmidhalter U. 2015. Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. J. Plant Nutr. Soil. Sci. 168:439–446.

Hay R.K.M. 1995. Harvest index: a review of its use in plant breeding and crop physiology. Ann. Appl. Biol. 126: 197–216.

Kolář L., Kužel S., Peterka J., Štindl P., Plát V. 2008. Agrochemical value of organic matter of fermented wastes in biogas production. Plant Soil Environ. 54: 321–328.

Łagocka A., Kamiński M., Cholewiński M., Pospolita W. 2016. Korzyści ekologiczne ze stosowania pofermentu z biogazowni rolniczych jako nawozu organicznego. Kosmos 65(4): 601–607.

Loecke T.D, Cambardella C.A., Liebman M. 2012. Synchromy of net nitrogen mineralization and maize uptake following applicatios of compost and fresh manure in the Midwest U.S. Nutr. Cycl. Agroecosys. 93: 65–74.

Mehlich A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil. Sci. Plant. Analys. 15: 1409–1416.

Möller K., Müller T. 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. Eng. Life Sci. 1293: 242–257.

Otegui M.E., Andrade F.H., Suero E.E. 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. Field Crops Res. 40: 87–94.

Ritchie J.T., Alagarswamy G. 2003. Model concepts to express genetic differences in maize yield components. Agron J. 95: 4–9.

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

Szczepaniak W. 2016. Evaluating nitrogen use efficiency (NUE) indices on the background of mineral status of the seed crop at maturity: a case study of maize. Pol. J. Environ. Stud. 25: 2129–2138.

Szczepaniak W., Grzebisz W., Potarzycki J., Łukowiak R., Przygocka-Cyna K. 2015. The magnesium and calcium mineral status of maize at physiological maturity as a tool for an evaluation of yield forming conditions. J. Elementol. 21: 881–897.

Szmigiel A., Kołodziejczyk M., Oleksy A. 2006. Wpływ nawożenia organicznego i mineralnego na plon ziarna kukurydzy. Fragm. Agron. 23(3): 70–79.

K. Przygocka-Cyna

PROFIL MINERALNY KUKURYDZY ZIARNOWEJ W STADIUM DOJRZAŁOŚCI FIZJOLOGICZNEJ NAWOŻONEJ GRANULATEM POFERMENTACYJNYM

CZĘŚĆ I. MAKROELEMENTY

Synopsis. W pracy założono, że granulat pofermentacyjny z biogazowni rolniczej (BDS) zastosowany jako nawóz organiczny istotnie wpływa na rozdział suchej masy i składników pokarmowych między części rośliny nasiennej, co z kolei prowadzi do wzrostu plonu. Hipotezę tę zweryfikowano na podstawie serii eksperymentów polowych z kukurydzą, przeprowadzonych w latach 2014–2016 w miejscowości Brody, Polska. Eksperyment dwuczynnikowy składał się z metody aplikacji BDS (rzutowo i rzędowo) i dawki: 0; 0,8, 1,6; 3,2 t·ha^{-1}. Wpływ BDS na formowanie elementów struktury plonu wynikał z większej biomasy łodyg i rdzenia kolby kukurydzy, co z kolei zwiększyło, odpowiednio, liczbę rzędów (NR) i ziarniaków w rzędzie (NGR). Kluczowym czynnikiem pokarmowym, kontrolującym potencjał plonotwórczy kolby kukurydzy (sucha masa; ilość ziarniaków w kolbie, NGC) była zawartość N w rdzeniu kolby. Wpływ BDS na plon ziarna kukurydzy wynikał z większego przemieszczenia w okresie dojrzewania suchej masy i składników odżywczych do ziarna kosztem wegetatywnych części kukurydzy, głównie łodyg (N, P, K) i liści (N, Mg). Wpływ BDS na gospodarkę potasem przez kukurydzę ujawnił najbardziej w suchym 2015 roku, łagodząc wpływ stresu wodnego. Zastosowane BDS zwiększyło zawartość magnezu w ziarnie, poprawiając tym samym jego wartość odżywczą. Rzędowa metoda aplikacji BDS wykazała przewagę nad rzutową, skutkując (i) taką samą ilością pobranego N przez kukurydzę, lecz przy 2-krotnie mniejszej ilości nawozu, (ii) zwiększeniem wartości indeksu żniwnego ziarna i indeksów żniwnych składników pokarmowych w porównaniu do wariantu kontrolnego, nawożonego tylko azotem.

Słowa kluczowe: granulat pofermentacyjny, metoda stosowania i dawka, części kukurydzy, sucha masa, składniki pokarmowe, rozdział

Accepted for print – Zaakceptowano do druku: 20.11.2017

For citation – Do cytowania:
Przygocka-Cyna K. 2017. A mineral profile of grain maize at physiological maturity fertilized with biogas digestate solids. Part I. Macronutrients. Fragm. Agron. 34(4): 152–170.