Crop yield and micronutrient contents (Cu, Fe, Mn and Zn) in spring wheat grain depending on the fertilization method

Plonowanie oraz zawartość mikroelementów (Cu, Fe, Mn i Zn) w ziarnie pszenicy jarej w zależności od sposobu nawożenia

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Abstract

This study analyzed the effectiveness of the application method and nitrogen dose with and without the addition of multi-component fertilizers in various development phases of spring wheat on grain yield and micronutrient concentration (Cu, Zn, Mn and Fe) in the grain and their removal with the crop. A three-year field experiment involving the cultivation of Parabola and Radunia spring wheat cultivars was conducted in the years 2009-2011 at the Educational and Experimental Station of the University of Warmia in Mazury in Olsztyn. The research factors included two cultivars of spring wheat as well as varied levels and methods of fertilization. An increase in the nitrogen dose from 80 to 120 kg·ha^{-1} only increased the grain yield for Parabola cultivar, and the highest yield was obtained by supplementing the basic fertilization with Azofoska fertilizer. The grains of Parabola wheat cultivar were characterized by higher Cu and Zn contents, and greater removal of Cu and Zn with the grains, as well as a lower Mn content as compared with Radunia cultivar. Fertilization with nitrogen at a dose of 80 kg·ha^{-1} contributed to an increase in Cu concentration in grains and Cu uptake with the crop for Parabola wheat cultivar, which resulted from both to-the-soil and foliar fertilization with urea and foliar fertilization with urea and Ekolist Mikro Z fertilizer. An increase in the dose of applied nitrogen up to 120 kg·ha^{-1} resulted in an increase in Fe content in grains of wheat cultivar Parabola, and greater removal of Fe with the grain crop for both cultivars. Fertilization with ammonium nitrate as well as to-the-soil and foliar fertilization with urea contributed to the highest concentration of Fe in grains and Fe uptake with the crop for both Parabola and Radunia cultivars. Correlation coefficient r indicated a positive correlation between the content of Mn and Cu content in the grain. The Zn content was positively correlated with Mn content in the grain of both cultivars. Noteworthy is the strong correlation between Zn content and Mn content, with r = 0.874 for Parabola cultivar, and r = 0.868 for Radunia cultivar, respectively.

Keywords: output of micronutrients, grain yield, cultivars, multi-component fertilizers

Streszczenie

Celem badań było określenia skuteczności sposobu aplikacji oraz dawki azotu bez i z dodatkiem nawozów wieloskładnikowych w różnych fazach rozwojowych pszenicy jarej na plon ziarna, koncentrację mikroelementów (Cu, Zn, Mn i Fe) w ziarnie i ich wyniesienie z plonem. Trzyletnie badania polowe z uprawą pszenicy jarej odmian Parabola i Radunia przeprowadzono w latach 2009-2011 w Zakładzie Dydaktyczno-Doświadczalnym Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. Czynnikami badawczymi były dwie odmiany pszenicy jarej oraz zróżnicowany poziom i sposób nawożenia. Zwiększenie dawki azotu z 80 do 120 kg·ha^{-1} zwiększyło plon ziarna tylko odmiany Parabola, a najwyższy plon uzyskano poprzez uzupełnienie podstawowego nawożenia Azofoską. Ziarno pszenicy odmiany Parabola charakteryzowało się większą zawartością i większym wyniesienie z plonem ziarna Cu i Zn oraz niższą zawartością Mn aniżeli odmiana Radunia. Nawożenie azotem w ilości 80 kg·ha^{-1} wpłynęło na wzrost koncentracji Cu w ziarnie i pobranie z plonem pszenicy odmiany Parabola, było to efektem doglebowego i dolistnego nawożenia mocznikiem oraz dolistnie mocznikiem z Ekolistem Mikro Z. Zwiększenie dawki nawożenia azotem do 120 kg·ha^{-1} spowodowało wzrost zawartości Fe w ziarnie pszenicy odmiany Parabola i wyższe wyniesienie Fe z plonem ziarna w obu odmianach. Nawożenie saletrą amonową, mocznikiem doglebowo oraz dolistnie wpłynęło na najwyższą koncentrację Fe w ziarnie i pobranie Fe z plonem zarówno odmiany Parabola i Radunia. Wykazano dodatnią korelację pomiędzy zawartością Mn a zawartością Cu oraz Zn i Mn w ziarnie obu odmian. Na uwagę zasługuje silna korelacja między zawartością Zn i zawartością Mn w ziarnie, odpowiednio dla odmiany Parabola i Radunia: r = 0,874 i r = 0,868.

Słowa kluczowe: wyniesienie mikroelementów, plon ziarna, odmiany, nawozy wieloskładnikowe

Introduction

Most nutrients consumed by humans are provided with the everyday diet (Cakmak et al., 2010). The limited bioavailability of minerals in the soil to plants may be the main reason for their absence in plant products (Alloway, 2009).

Cereal grains and cereal products (particularly wholemeal ones) are an important source of micronutrients for humans (McKevith, 2004). A crop with the greatest economic importance is wheat, whose worldwide yield accounts for approx. 30% of the total production of cereals (FAO, 2014). According to Fan et al. (2008), grains of modern, highly productive cultivars of common wheat are generally characterized by decreased contents of essential micronutrients. The concentration of trace elements which are essential in human nutrition gradually decreases with an increase in the productivity of crops (Cakmak et al., 2010; Stępień and Wojtkowiak, 2016).

The content of minerals in wheat grains depends on a number of factors, such as genotype, type of soil, weather conditions and fertilization systems (Otteson et al., 2008; Stępień and Wojtkowiak, 2015). In order to obtain high yields of wheat grains, proper management of fertilization with nitrogen and other elements is required. Nitrogen use efficiency in cereal cultivation is estimated at approx. 30%. The distribution of nitrogen fertilizer doses as well as the method of application in plant vegetation is crucial to both the improvement of fertilizer use efficiency and the increase in the yield and quality of cereal grains (Ralcewicz et al., 2009; Ercoli et al., 2013; Wojtkowiak et al., 2014). One of the major reasons for low nitrogen use efficiency in practice is the lack of synchronization between the introduction of N to the soil and the plant requirements (Cassman et al., 2002; Fageria and Baligar, 2005). It has been reported that nitrogen fertilization brings about changes to the concentration of micronutrients in cereal grains (Stępień, 2004; Cakmak, 2010; Shi et al., 2010). Feeding plants with micronutrient fertilizers has an effect on the micronutrient content in grains (Wang et al., 2012; Wojtkowiak et al., 2014).

The aim of the study was to determine the effectiveness of the application method and the dose of nitrogen with and without the addition of multi-component fertilizers in various development phases of spring wheat on grain yield, concentration of micronutrients (Cu, Zn, Mn and Fe) in the grain and their removal with the crop.

Materials and Methods

Field plot experiment was initiated in the spring of 2009 and conducted in three growing seasons (2009, 2010 and 2011) at the Experimental Station (53°73’N 20°41’E) of Warmia and Mazury University, Olsztyn, in north-eastern Poland.

The experiment was performed on proper brown soil of light loam granulometric composition with very fine sand in the subsoil. Soil samples from each experimental field were collected at 0 -20 cm depth on all experimental fields before seeding for basic soil property analysis. Extraction of available forms of Cu, Zn, Fe and Mn was conducted using 1 M HCl dm^{-3}. Copper, Zn, Fe, and Mn in the extract were analyzed with an atomic-absorption spectrometer (AAS). The characteristics of the collected samples are listed in Table 1. The experiment was set up in a split-plot on a randomized complete block design with 3 replicates, with a plot area of 6.25 m^2 in which 4.0 m^2 was intended for harvesting. The experimental factors were as follows: (I) spring wheat cultivars: 1) Parabola and 2) Radunia; (II) dose of nitrogen fertilization (III) fertilization system (Table 2). A description of these cultivars can be found in the Common Catalogue of Varieties of Agricultural Plant Species (EU). Wheat of the Parabola cultivar was sown in the amount of 305.1 $kg \cdot ha^{-1}$ and in a 10.5 cm row spacing. The Radunia wheat cultivar was sown in the amount of 218.4 $kg \cdot ha^{-1}$ in a 10.5 cm row spacing.

Table 1. Selected soil properties before the start of the experiment

Tabela 1. Wybrane właściwości gleby przed rozpoczęciem eksperymentu

Soil property			Cultivar	
			Parabola	Radunia
	pH in KCl		5.5- 6.05	5.75-6.1
	C_{org}	%	2.02	2.02
	Total N	$g \cdot kg^{-1}$	0.123	0.125
Available	P	$(mg \cdot kg^{-1})$	146-223	152-220
	K		180-240	170-240
	Mg		46-56	46- 54
	Zn		9.4-14.5	9.4-14.5
	Fe		1300-1600	1250-1600
	Cu		2.1-2.5	2.0- 2.4
	Mn		151-168	151-164

Shallow ploughing and harrowing were performed after harvest of the previous crop (winter triticale) and subsequently autumn ploughing was done. Fertilization with phosphorus and potassium was the same for all fertilization treatments (30.2 $kg \cdot ha^{-1}$ P in the form of triple superphosphate 46% and 83.1 $kg \cdot ha^{-1}$ K in potassium salt 56% was applied). Nitrogen fertilization was differentiated (Table 2). Two doses of nitrogen were considered, 80 and 120 $kg \cdot ha^{-1}$, which were divided into 40 $kg \cdot ha^{-1}$ doses. Ammonium nitrate was applied before sowing, and 46% urea (both with and without Azofoska in a dose corresponding to 20 kg of nitrogen) was applied in the tillering period (BBCH 23-29). Fertilization in the stem shooting period (BBCH 31-32) included the application of urea into soil and foliar spray in 10% solution, without or with Ekolist Mikro Z in a dose of 2.0 $dm^{-3} \cdot ha^{-1}$. The experiment (fertilization treatments 2, 4, 6, 8) introduced multi-component fertilizers containing macronutrients and a set of micronutrients, as recommended in agricultural practice (Table 3). All fertilizers used in this study were commercially available. The fungicides Artea 330 EC (0.4 x 10^{-3} $m^3 \cdot ha^{-1}$) and Amistar 250 SC (1.0 x 10^{-3} $m^3 \cdot ha^{-1}$) were applied to protect wheat against fungal diseases, whereas the herbicide Mustang (0.6 x 10^{-3} $m^3 \cdot ha^{-1}$) was used for weed reduction. At crop maturity, grain yield was measured by harvesting 4.0 m^2 of the plot using a plot combine. Each year during the experiment grain samples were subjected to chemical analyses.

Table 2. Field experiment scheme

Tabela 2. Schemat doświadczenia polowego

Treatments	Total N fertilization ($kg{\cdot}N{\cdot}ha^{-1}$)	Fertilizer type and applying time (kg N ha^{-1})		
		before sowing	spreading time (BBCH 23-29)	stalk shooting time (BBCH 31-32)
1	80	-	urea (40)	urea (40)
2	80	-	urea (20) Azofoska (20)	urea (40)
3	80	-	urea (40)	urea 40*
4	80	-	urea (40)	urea (40)*+ Ekolist Mikro Z*
5	120	ammonium nitrate (40)	urea (40)	urea (40)
6	120	ammonium nitrate (40)	urea (20) Azofoska (20)	urea (40)
7	120	ammonium nitrate (40)	urea (40)	urea (40)*
8	120	ammonium nitrate (40)	urea (40)	urea (40)*+ Ekolist Mikro Z*

* Foliar fertilization

Grain samples were ground in a stainless-steel grinder. A 1.0 g dry sample was digested with $HClO_4$-HNO_3, and the digested solution was analyzed with atomic-absorption spectrometer (AAS).

All data were analyzed using STATISTICA® (StatSoft Inc.). The statistical calculations applied a three-factor variation analysis, compliant with the mathematical model of the experimental layout in random blocks. Mean values were determined for individual experimental objects. The significance of differences between the means was determined with Tukey test. Correlation analysis was performed to explore the correlations between the contents of Fe, Zn, Mn, Cu and grain yield. The level of significance was $P<0.05$.

Results and Discussion

Winter wheat fertilized with nitrogen doses at 80 and 120 $kg{\cdot}ha^{-1}$, both with and without the addition of multi-component fertilizers (Azofoska and Ekolist Mikro Z), produced the following grain yields (average values from the three years of the experiment): for Parabola cultivar, within a range from 5.60 t·ha^{-1} to 6.58 t·ha^{-1} and, for Radunia cultivar, within a range from 5.56 t·ha^{-1} to 6.24 t·ha^{-1} (Table 4).

Table 3. The amount of micro and macronutrients introduced into the soil with fertilizers: Azofoska i Ekolist Mikro Z

Tabela 3. Ilość mikro- i makroskładników wprowadzonych do gleby z nawozami Azofoska i Ekolist Mikro Z

Nutrients	Type of multifertilizer	
	Azofoska (kg·ha^{-1})	Ekolist Mikro Z (g·ha^{-1})
N	20.00	104.80
P	2.69	-
K	23.38	-
Mg	3.98	79.20
S	13.52	112.66
Cu	0.26	9.18
Zn	0.07	23.60
Mn	0.39	25.60
Fe	0.25	26,20
Mo	0.06	0.14
B	0.07	0.42

The obtained yields of grains of Parabola wheat cultivar were lower than those obtained in the study of Jarecki and Bobrecka-Jamro (2011a) which, with different amounts of grains per m^2 (350-750), were from 6.90 t·ha^{-1} to 7.26 t·ha^{-1}. The yield of grains of Radunia wheat cultivar was higher than found by Buczek et al. (2011), who recorded 4.44 t·ha^{-1} and 4.75 t·ha^{-1} with nitrogen fertilization in doses of 90 and 120 kg·ha^{-1}, respectively. In the author's own study, with an increase in a nitrogen dose from 80 to 120 kg·ha^{-1}, the yield of grains increased significantly (by 0.53 t·ha^{-1}) only for the Parabola cultivar. After analyzing the methods of fertilization and applying 120 kg·ha^{-1} nitrogen with the addition of Azofoska multi-component fertilizer at the BBCH stage of 23-29 (fertilization treatment 6), a significantly higher grain yield was obtained compared to a dose of 80 kg·ha^{-1} nitrogen applied either in the form of urea to the soil (fertilization treatment 1), urea with Azofoska fertilizer (fertilization treatment 2) or urea with Ekolist Mikro Z fertilizer (fertilization treatment 4).

Table 4. Yield of grain (averages values of years 2009-2011)

Tabela 4. Plon ziarna (średnie wartości z lat 2009-2011)

Treatments	Grain yield ($t \cdot ha^{-1}$)	
	P*	R
1	5.75[a]	5.89[a]
2	5.60[a]	5.56[a]
3	6.14[ab]	5.88[a]
4	5.79[a]	5.76[a]
5	6.34[ab]	6.18[a]
6	6.58[b]	6.00[a]
7	6.31[ab]	6.24[a]
8	6.19[ab]	6.23[a]
	Dose N fertilization	
N_{80}	5.82[a]	5.77[a]
N_{120}	6.35[b]	6.16[a]
	Cultivar	
Parabola	6.09[a]	
Radunia	5.98[a]	

a, b, c: Values denoted in the columns with the same letters do not differ significantly for P<0.05.

*P – cultivar Parabola, R – cultivar Radunia

The effects of cereal production, resulting from the supplementation of basic NPK fertilization with fertilizers containing a combination of macro- and micronutrients, are not uniform (Gomaa et al., 2015; Wojtkowiak et al., 2015; Zain et al., 2015). Wojtkowiak et al. (2015) found no effect of the extra to-the-soil fertilization with Azofoska and foliar fertilization with Ekolist on the yield of spring triticale grains. According to Domska at al. (2009), wheat and triticale did not always respond similarly to feeding with multi-component fertilizers. The application of Ekolist Mikro Z in the cultivation of triticale was more effective than fertilization with nitrogen only and with nitrogen in combination with multi-component fertilizers (Florogama – N, P, Mg, S, Cu, Zn, Mn, Fe, Mo and B, and Agrosol Z – N, P, Mg, Cu, Zn, Mn, Fe, Mo and B).

Table 5. Cu, Fe, Mn and Zn content in grain of spring wheat (averages values of years 2009-2011)

Tabela 5. Zawartość Cu, Fe, Mn i Zn w ziarnie pszenicy jarej (średnie wartości z lat 2009-2011)

Treatments	Cu ($mg \cdot kg^{-1}$)		Fe ($mg \cdot kg^{-1}$)		Mn ($mg \cdot kg^{-1}$)		Zn ($mg \cdot kg^{-1}$)	
	P*	R	P	R	P	R	P	R
1	2.95^{ab}	2.69^{a}	22.9^{a}	24.3^{a}	37.5^{a}	46.3^{a}	33.5^{a}	32.6^{a}
2	2.87^{ab}	2.11^{a}	26.5^{ab}	24.7^{a}	38.8^{a}	49.2^{a}	36.7^{a}	33.3^{a}
3	3.30^{b}	2.22^{a}	31.6^{cd}	25.0^{a}	39.2^{a}	46.8^{a}	38.8^{a}	33.5^{a}
4	3.26^{b}	2.35^{a}	25.1^{a}	25.2^{a}	37.8^{a}	47.6^{a}	36.4^{a}	33.3^{a}
5	2.61^{ab}	1.93^{a}	34.7^{d}	37.9^{b}	39.6^{a}	47.5^{a}	38.8^{a}	36.4^{a}
6	2.16^{a}	2.25^{a}	30.4^{c}	26.2^{a}	37.6^{a}	48.9^{a}	36.9^{a}	36.4^{a}
7	2.44^{ab}	2.21^{a}	30.2^{bc}	25.2^{a}	37.4^{a}	47.9^{a}	37.6^{a}	34.8^{a}
8	2.68^{ab}	2.08^{a}	26.0^{a}	24.1^{a}	37.9^{a}	46.5^{a}	37.8^{a}	33.8^{a}
Dose N fertilization								
N_{80}	3.10^{b}	2.34^{a}	26.5^{a}	24.8^{a}	38.3^{a}	47.5^{a}	36.4^{a}	33.2^{a}
N_{120}	2.47^{a}	2.12^{a}	30.3^{b}	28.4^{a}	38.1^{a}	47.7^{a}	37.8^{a}	35.4^{a}
Cultivar								
Parabola	2.78^{b}		28.4^{a}		38.2^{a}		37.1^{b}	
Radunia	2.23^{a}		26.6^{a}		47.6^{b}		34.3^{a}	

a, b, c, d: Values denoted in the columns with the same letters do not differ significantly for $P<0.05$.

*P – cultivar Parabola, R – cultivar Radunia

The favorable effect of preparations Ekolist Mikro Z and Ekolist Mono Mn at two levels of nitrogen fertilization (0.8 g N and 1.6 g N per pot) on the yield and weight of a thousand grains of spring wheat was confirmed by Kulczycki et al. (2009). Jarecki and Bobrecka-Jamro (2011b) concluded that the applied fertilizers, namely, urea, Mikrokomplex (SO_3, MgO, Cu, Zn, Mn, Fe, Mo) and a mix of urea and Mikrokomplex did not significantly modify the number of grains in the ear or the weight of a thousand grains; however, the yield of grains on the extra-fed plots was higher than that obtained from a control plot and a significant difference was only found for the application of the mix of urea and Mikrokomplex. Although the contents of minerals in wheat grains are, to a large extent, a varietal characteristic, according to Warechowska (2009a, 2009b, 2009c); they are also determined by the type of soil (Gao et al., 2012), weather conditions (Stępień and Wojtkowiak, 2015), and agricultural factors (Barunawati et al., 2013). Korzeniowska et al. (2015) concluded that wheat grains (357 samples of winter wheat from fields located in medium intensive agricultural holdings throughout Poland) most often contain less Zn (38% samples) and Mn (29% samples) followed by Cu (21% samples) and B (38% samples).

In the author's own study, grains of Parabola cultivar winter wheat were characterized by a higher Cu content (by 24.7%) and Zn (by 8.2%) and a lower Mn content (by 19.7%) (Table 5). Fertilization with a lower dose of nitrogen (80 $kg \cdot ha^{-1}$) contributed to an increase in Cu concentration in wheat grains, but the difference was only found to be statistically significant for the Parabola cultivar. This resulted from the to-the-soil fertilization with urea at the BBCH stage of 23-29, and foliar fertilization at the BBCH stage of 31-32 (fertilization treatment 3) as well as foliar application with urea in combination with Ekolist Mikro Z (fertilization treatment 4).

According to Kutman et al. (2011), an increase in the dose of nitrogen (from 40 to 50 $mg\ N \cdot kg^{-1}$ dry soil) increased the Fe content in wheat grains from 38% to 60%. In the author's own study, for Parabola cultivar, irrespective of the fertilization methods, increasing the dose of nitrogen up to 120 $kg \cdot ha^{-1}$ resulted in an average increase in Fe content in grains by 14.3%. However, fertilization at a dose of 120 $kg \cdot ha^{-1}$ to the soil in the form of ammonium nitrate, urea and urea applied foliarly in combination with Ekolist Mikro Z (fertilization treatment 8), contributed to a lower concentration of this element as compared with a dose of 80 $kg \cdot ha^{-1}$ (fertilization treatment 3). As for the analyzed methods of fertilization with 80 $mg\ N \cdot ha^{-1}$, the significantly highest Fe content was found on the plot fertilized with urea both to the soil and foliarly (fertilization treatment 3). The pre-sowing application of ammonium nitrate and to-the-soil application of urea (at the BBCH stages of 23-29 and 31-32 – fertilization treatment 5) resulted in the greatest accumulation of Fe in grains for all variants fertilized with 120 $kg\ N \cdot ha^{-1}$, for both Parabola and Radunia cultivars. As compared with a study of Wojtkowiak et al. (2014), fertilization with nitrogen at a dose of 120 $kg \cdot ha^{-1}$ in combination with Azofoska and Ekolist Mikro Z fertilizers contributed to an increase in Fe content in spring triticale grains, which was not found in the author's own study involving the cultivation of wheat.

The content of Zn in Parabola cultivar grains fell within a range from 33.5 to 38.8 $mg \cdot kg^{-1}$, and Radunia cultivar grains ranged from 32.6 to 36.4 $mg \cdot kg^{-1}$ (Table 5). Average amounts of Mn in Parabola cultivar grains ranged from 37.4 to 39.6 $mg \cdot kg^{-1}$, and Radunia cultivar grains ranged from 46.3 to 49.2 $mg \cdot kg^{-1}$. In contrast to a study of Warechowska (2009b, 2009c), no statistically significant effect of the applied fertilization on the contents of Zn a studies do not support these Mn in grains of the wheat cultivars under analysis was found.

Table 6. Correlation coefficients between grain yield and the Cu, Fe, Mn and Zn content in wheat grain

Tabela 6. Współczynniki korelacji między plonem ziarna i zawartością Cu, Fe, Mn, i Zn w ziarnie pszenicy

Specification		Grain yield	Zn	Mn	Fe
Parabola	Cu	-0.334	0.317	0.497*	-0.394
	Fe	0.414*	0.219	-0.138	
	Mn	0.088	0.874***		
	Zn	0.283			
Radunia	Cu	-0.519**	0.486*	0.699***	-0.517**
	Fe	0.276	0.146	-0.219	
	Mn	-0.575**	0.868***		
	Zn	-0.347			

Level of significance: *P<0.05, **P<0.01, ***P<0.001

According to Svečnjak et al. (2013), grain yield is related to the content of basic micronutrients. Studies do not support these relationships (Table 6). Irrespective of nitrogen doses and fertilization methods, the removal of micronutrients with spring wheat grains was determined to a greater extent by their content in grains than by the yield. The removal with the crop of Parabola cultivar was as follows: for Cu, it was greater by 28.0%; for Zn it was greater by 10.8%; while for Mn, it was smaller by 17.7% (Table 7). Nitrogen at a lower dose (80 $kg \cdot ha^{-1}$) resulted in a higher uptake of Cu with the grain yield, which was caused by a higher content of this element and a lower yield of grains of Parabola cultivar spring wheat. However, the uptake of Cu with grains was significantly higher, due to fertilization with nitrogen at a dose of 80 $kg \cdot ha^{-1}$ on the plot fertilized to the soil with urea (fertilization treatment 3), than that on the plot fertilized to the soil with ammonium nitrate, urea with Azofoska fertilizer, urea (fertilization treatment 6), or on the plot fertilized to the soil with ammonium nitrate, urea or urea by foliar application (fertilization treatment 7) at a dose of 120 $kg \cdot ha^{-1}$.

Despite the lack of effect of the total nitrogen dose of 80 and 120 $kg \cdot ha^{-1}$ on the removal of Cu with the crop of grains of Radunia cultivar wheat, this uptake (significantly higher by 33.9%) was found on the plot fertilized to the soil with 80 kg $N \cdot ha^{-1}$ in the form of urea (fertilization treatment 1) as compared with 120 kg $N \cdot ha^{-1}$ in the form of ammonium nitrate and urea fertilized to the soil (fertilization treatment 5).

Table 7. Uptake of Cu, Fe, Mn and Zn by grain of spring wheat (averages values of years 2009-2011)

Tabela 7. Pobranie Cu, Fe, Mn i Zn z plonem pszenicy jarej (średnie wartości z lat 2009-2011)

Treatments	Cu ($g \cdot ha^{-1}$)		Fe ($g \cdot ha^{-1}$)		Mn ($g \cdot ha^{-1}$)		Zn ($g \cdot ha^{-1}$)	
	P*	R	P	R	P	R	P	R
1	16.9^{ab}	15.8^{b}	131.5^{a}	143.6^{a}	216.0^{a}	271.9^{a}	192.9^{a}	191.5^{ab}
2	16.1^{ab}	11.7^{a}	148.3^{ab}	137.5^{a}	217.6^{a}	273.0^{a}	205.8^{ab}	184.8^{a}
3	20.2^{b}	13.0^{ab}	194.5^{cd}	147.2^{a}	239.8^{a}	274.1^{a}	237.7^{ab}	196.2^{ab}
4	18.9^{ab}	13.5^{ab}	145.5^{ab}	145.3^{a}	218.8^{a}	273.2^{a}	210.8^{ab}	191.2^{ab}
5	16.5^{ab}	11.8^{a}	219.9^{d}	234.9^{b}	251.0^{a}	292.1^{a}	245.9^{b}	224.1^{b}
6	14.2^{a}	13.4^{ab}	199.8^{cd}	157.5^{a}	247.7^{a}	292.3^{a}	243.0^{b}	217.6^{ab}
7	15.5^{a}	13.7^{ab}	190.1^{c}	157.6^{a}	236.8^{a}	298.3^{a}	237.7^{ab}	216.7^{ab}
8	16.6^{ab}	12.8^{ab}	160.8^{b}	150.5^{a}	234.9^{a}	288.4^{a}	234.2^{ab}	209.7^{ab}
				Dose N fertilization				
N_{80}	18.0^{b}	13.5^{a}	$155,0^{a}$	$143,4^{a}$	$223,1^{a}$	$273,1^{a}$	$211,8^{a}$	$190,9^{a}$
N_{120}	15.7^{a}	12.9^{a}	$192,7^{b}$	$175,1^{b}$	$242,6^{a}$	$292,8^{b}$	$240,2^{b}$	$217,0^{b}$
				Cultivar				
Parabola	16.9^{b}		173.8^{a}		232.8^{a}		226.0^{b}	
Radunia	13.2^{a}		159.3^{a}		282.9^{b}		204.0^{a}	

a, b, c, d: Values denoted in the columns with the same letters do not differ significantly for $P<0.05$.

*P – cultivar Parabola, R – cultivar Radunia

Moreover, the significantly higher uptake of Cu was found as a result of the application of the same dose of N (80 $kg \cdot ha^{-1}$) in the form of urea fertilized to the soil (fertilization treatment 1) as compared with the application of urea with Azofoska fertilizer (fertilization treatment 2).

Due to the higher level of fertilization with N (120 $kg \cdot ha^{-1}$), the removal of Fe with the crop increased by, respectively, 24.3% for Parabola cultivar, and 22.1% for Radunia cultivar. Fertilization with nitrogen at a dose of 80 $kg \cdot ha^{-1}$ in the form of urea applied to the soil and foliarly (fertilization treatment 3) increased, only for Parabola cultivar (from 31.2% to 47.9%), the amount of Fe removed with the crop of wheat grains as compared with the plots fertilized with the same dose of nitrogen (fertilization treatments 1, 2, and 4). As for the analyzed methods of fertilization with a dose of 120 kg N·ha^{-1}, the application of ammonium nitrate and urea to the soil (fertilization treatment 5) contributed to the greatest removal of this element for both wheat cultivars. An exception was the absence of a significant effect of the fertilization of Parabola cultivar to the soil with nitrogen in the form of ammonium nitrate, urea and Azofoska fertilizer (fertilization treatment 6).

A higher nitrogen dose of 120 kg·ha^{-1} resulted in an increase, by 7.2%, in Mn uptake with the crop, but only for Radunia cultivar. The analyzed fertilization methods, irrespective of the applied N dose, had no effect on Mn uptake with the grain crop.

Fertilization with a higher dose of N (120 kg·ha^{-1}) resulted in output of Zn with the crop increased by 13.4% for Parabola cultivar and 13.7% for the Radunia cultivar, respectively. Fertilization methods, where the same dose was applied, had no significant effect on the Zn uptake with the crop.

Foliar application of nutrients led to an increase in the concentration of micronutrient in wheat grain and this effect may be attributed mainly to the vital physiological roles in plant cell whose roots uptake plant nutrients (Arif et al., 2006).

It was found a positive correlation between the grain yield and Fe content for Parabola cultivar (Table 6). The yield of Radunia cultivar grains was negatively correlated with the amounts of Cu and Mn in grains. For both wheat cultivars, a positive correlation between the Mn content and Cu content was found. Zn content was positively correlated with Mn content in grains of both cultivars, and Zn content with Cu content in grains of Radunia cultivar. Noteworthy is the strong correlation between Zn content and Mn content, with r = 0.874 for Parabola cultivar, and r = 0.868 for Radunia cultivar, respectively. Murphy et al. (2008) indicated high correlation coefficients (r = 0.900) between the following micronutrients: Zn and Mn, Cu and Mn as well as Cu and Zn. A negative correlation between Fe content and Cu content was found for Radunia cultivar.

Conclusions

1. An increase in the nitrogen dose from 80 to 120 kg·ha^{-1} only increased the grain yield for Parabola cultivar, and the highest yield was obtained by supplementing the basic fertilization with Azofoska fertilizer.

2. The grains of Parabola wheat cultivar were characterized by higher Cu and Zn contents, and greater removal of Cu and Zn with the grains, as well as a lower Mn content as compared with Radunia cultivar.

3. Fertilization with nitrogen at a dose of 80 kg·ha^{-1} contributed to an increase in Cu concentration in grains and Cu uptake with the crop for Parabola wheat cultivar, which resulted from both to-the-soil and foliar fertilization with urea and foliar fertilization with urea and Ekolist Mikro Z fertilizer.

4. An increase in the dose of applied nitrogen up to 120 kg·ha^{-1} resulted in an increase in Fe content in grains of wheat cultivar Parabola, and greater removal of Fe with the grain crop for both cultivars. Fertilization with ammonium nitrate as well

as to-the-soil and foliar fertilization with urea contributed to the highest concentration of Fe in grains and Fe uptake with the crop for both Parabola and Radunia cultivars.

5. Correlation coefficient r indicated a positive correlation between the content of Mn and Cu content in the grain. The Zn content was positively correlated with Mn content in the grain of both cultivars. Noteworthy is the strong correlation between Zn content and Mn content for Parabola cultivar and for Radunia cultivar, respectively.

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