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YIELD AND QUALITY OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) IN RESPONSE TO DIFFERENT SYSTEMS OF FOLIAR FERTILIZATION*

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Abstract

Foliar fertilizers are increasingly often used in agricultural practice to maximize the yield potential of *T. aestivum* L. Foliar fertilization can effectively reverse nutritional deficiencies (macronutrients), and it can be used as the main method for supplying plants with the required micronutrients. The objective of this study was to determine the effect of various systems of foliar micronutrient and macronutrient fertilization on the yield and quality of wheat grain. A field experiment was carried out in 2012-2015, in the Agricultural Experiment Station in Bałcyny, owned by the University of Warmia and Mazury in Olsztyn. The highest grain yield (10.16 Mg ha^{-1}) of winter wheat was noted in the treatment where foliar fertilizers were supplied in 5 applications. It was higher by 230-430 to 660 kg ha^{-1} than in plots where foliar fertilizers were supplied in 2 applications. Intensified foliar fertilization increased nitrogen (54%) and potassium (12%) concentrations, but decreased the magnesium (10%) content of winter wheat straw. The concentrations of phosphorus (0.34 g kg^{-1} dry matter (DM)), potassium (0.23 g kg^{-1} DM), calcium (0.40 g kg^{-1} DM) and sulfur (0.05 g kg^{-1} DM) in winter wheat grain increased in response to intensified foliar fertilization. Foliar application of liquid macronutrient and micronutrient fertilizers increased micronutrient concentrations in winter wheat straw (copper, zinc, manganese, iron) but decreased the micronutrient content of grain (copper, zinc, iron). Intensified foliar fertilization significantly reduced total protein content (1.1 g kg^{-1} DM) and gluten content (0.9%) and deteriorated protein quality. The influence of different foliar fertilization systems on the falling number was determined by precipitation levels during heading and ripening of winter wheat. The rheological properties of dough (development, stability and softness) improved each year in response to intensified foliar fertilization with macronutrients and micronutrients.

Keywords: macronutrients, micronutrients, milling quality, flour strength, rheological properties.

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INTRODUCTION

Wheat is one of the staple cereals around the world. In the last three business cycles, global wheat production has reached 671-713 Tg, which accounts for approximately 26% of total cereal production. Wheat is also the principal cereal in Europe. The leading wheat producers responsible for around 71% of Europe's wheat output are the Russian Federation, France, Germany, the UK, Ukraine and Poland (FAOSTAT 2015).

Europe's leading status in wheat production can be attributed to its extensive wheat acreage as well as the high yield potential of this cereal species. The average wheat yield in Europe is 20% higher than in North America and Asia, and 40-45% higher than in South America and Africa (FAOSTAT 2015).

Fertilization is the key yield-forming factor in wheat production. The macronutrient uptake of winter wheat per Mg ha^{-1} of grain and straw yield is estimated at 15-26 kg N, 2-7 kg P, 11-22 kg K, 1-2 kg Mg, 2-5 kg Ca (Nogalska et al. 2012). In agricultural practice, crops can be effectively supplied with the above amounts of nutrients only when fertilizers are applied to soil. An alternative method such as foliar fertilization is only effective in reversing nutritional deficiencies in crops (Fageria et al. 2009). Foliar application can be the main technique for supplying plants with micronutrients. Foliar fertilizers improve nutrient availability, reduce fertilization costs, decrease fertilizer runoff and minimize eutrophication, which is a vital environmental consideration in the face of the dwindling biodiversity of agricultural ecosystems (Sharpley et al. 1994).

Under normal agricultural conditions, foliar supply of macronutrients and micronutrients to wheat crops increases grain yield by 2-13% (Garrido-Lestache et al. 2005, Ranjbar, Bahmaniar 2007, Tea et al. 2007, Kocoń 2009) to even 30-40% (Woolfolk et al. 2002). The yield-forming effects of foliar fertilization are enhanced in wheat grown on sandy soils, which are characterized by low fertility. Zeidan et al. (2010) reported an estimated 3.3 Mg ha^{-1} (approx. 70%) increase in grain yield in wheat supplied with foliar fertilizers on sandy soil. Mineral fertilization is not only the main yield-forming factor in agricultural systems, but it is also a factor that strongly modifies the chemical composition of plant tissues (Jankowski et al. 2015*c*) and the content of organic compounds which determine the nutritional value of crops (Luo et al. 2000, Abad et al. 2004, Garrido-Lestache et al. 2005, Jankowski et al. 2015*a*,*b*).

Most research into foliar fertilization of wheat focuses on the influence of individual nutrients on grain yield and grain quality. The existing studies have evaluated the effect of selected fertilizer components on the yield and processing suitability of grain. In agricultural practice, however, foliar fertilizers generally differ in their chemical composition (macronutrients, micronutrients), form (chelates, salts) and the number of applications. In this study, the effects of foliar fertilization with macronutrients and micronutrients (2, 4 and 5 applications) on grain yield, straw yield, the chemical composition of post-harvest biomass, the milling quality and flour strength of winter wheat were evaluated in 4 systems.

MATERIAL AND METHODS

Field experiment

Field experiments investigating winter wheat (*Triticum aestivum* L.) were conducted in 2012–2015 at the Agricultural Experiment Station in Bałcyny (53°35′46.4″N, 19°51′19.5″E, 137 m a.s.l.), owned by the University of Warmia and Mazury in Olsztyn (north-eastern Poland). Wheat crops were supplied with macronutrients and micronutrients in 4 systems characterized by different intensity of foliar fertilization (Table 1).

Table 1

Foliar application of macronutrients and micronutrients in winter wheat

Fertilization date (BBCH stage *)	Foliar fertilizer (dose in dm^3 ha^{-1})**			
13-14	–	–	–	FoliQ Mikromix (1)
29-30	–	–	FoliQ Uniwersalny (5) FoliQ Cu (2)	FoliQ Uniwersalny (5) FoliQ Cu (2)
31	FoliQ 36 Azotowy (5)	FoliQ Uniwersalny (5) FoliQ Cu (2)	FoliQ 36 Azotowy (5) FoliQ Mg (3)	FoliQ Kombimax (3)
39	FoliQ 36 Azotowy (5)	FoliQ 36 Azotowy (5) dm^3 ha^{-1}	FoliQ 36 Azotowy (5)	FoliQ 36 Azotowy (5)
51	–	–	FoliQ 36 Azotowy (5)	FoliQ 36 Azotowy (5)
Treatment	A	B	C	D

* Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie
** FoliQ 36 Azotowy (5 dm^3 ha^{-1}) = 1800 g ha^{-1} N; 124 g ha^{-1} Mg; 1.1 g ha^{-1} micronutrients
FoliQ Uniwersalny (5 dm^3 ha^{-1}) = 700 g ha^{-1} N; 109 g ha^{-1} P; 291 g ha^{-1} K; 2.1 g ha^{-1} micronutrients
FoliQ Cu (2 dm^3 ha^{-1}) = 400 g ha^{-1} N; 135 g ha^{-1} Cu; 13.5 g ha^{-1} Mn; 13.5 g ha^{-1} Zn
FoliQ Mg (3 dm^3 ha^{-1}) = 391 g ha^{-1} Mg; 168 g ha^{-1} S
FoliQ Mikromix (1 dm^3 ha^{-1}) = 120 g ha^{-1} N; 125 g ha^{-1} K; 25 g ha^{-1} Mg; 28 g ha^{-1} S; 4.4 g ha^{-1} B; 7.3 g ha^{-1} Cu; 14.5 g ha^{-1} Fe; 21.8 g ha^{-1} Mn; 0.2 g ha^{-1} Mo; 14.5 g ha^{-1} Zn
FoliQ Kombimax (3 dm^3 ha^{-1}) = 840 g ha^{-1} N; 523 g ha^{-1} K; 112 g ha^{-1} Mg; 18.8 g ha^{-1} micronutrients

The experiment followed a randomized complete block design with three replications. The plot size was 14.75 m^2. Each year, the experiment was established on Haplic Luvisol developed from boulder clay (IUSS 2006). The soil had slightly acidic pH, ranging from 5.36–6.51 in 1 mol dm^{-3} KCl. Soil nutrient levels were as follows: 1.02-2.06% C_{org} (Kurmies method), 56-72 mg kg^{-1} P (Egner-Riehm method), 104-133 mg kg^{-1} K (Egner-Riehm method), 49-63 mg kg^{-1} Mg (atomic absorption spectrometry – AAS, Carl Zeiss Jena, Germany), 3.8-8.9 mg kg^{-1} (Bardsley and Lancaster method), 0.48-0.52 mg kg^{-1} B (colorometry, Specol 11 spectro-colorimeter, Carl Zeiss Jena, Germany), 1.9-2.7 mg kg^{-1} Cu (AAS), 8.4-14.4 mg kg^{-1} Zn (AAS), 131-184 mg kg^{-1} Mn (AAS), and 2100-2450 mg kg^{-1} Fe (AAS).

Winter rapeseed was the forecrop. Presowing soil treatments included disking, medium-deep tillage, cultipacking and harrowing. Presowing fertilizers were applied at 30 kg ha^{-1} P (granular triple superphosphate, 20% P) and 79 kg ha^{-1} K (potash salt, 50% K). In spring, 170 kg ha^{-1} N was supplied in the form of ammonium nitrate (34%) in three separate applications: 100 kg ha^{-1} (22-25 BBCH), 45 kg N ha^{-1} (33 BBCH) and 25 kg N ha^{-1} (59 BBCH).

Winter wheat (cv. Cubus) was sown in the second half of September at 450 dressed kernels per m^2 of plot area. Row spacing was 12.50 cm. Weeds were controlled at the first true leaf stage (BBCH 11-12) with 500 g ha^{-1} pendimethalin, 250 g ha^{-1} isoproturon, 28 g ha^{-1} metribuzin, 84 g ha^{-1} flufenacet and 3.75 g ha^{-1} chlorsulfuron. Pest control comprised three pesticide applications: (1) 525 g ha^{-1} cyprodinil, 100 g ha^{-1} propiconazole and 360 g ha^{-1} fenpropidin (BBCH 30); (2) 600 g ha^{-1} chlorotalonil, 120 g ha^{-1} azoxystrobin and 87.5 g ha^{-1} epoxiconazole (BBCH 55); (3) 125 g ha^{-1} propiconazole and 40 g ha^{-1} cyproconazole (BBCH 69). Wheat was harvested at the fully-ripe stage at the end of July or at the beginning of August.

Yield components, grain and straw yield

The number of spikes per 2 m^2 (4 × 0.5 m^2) was counted in each plot before harvest. Spikes were sampled from an area of 0.5 m^2 (2 × 0.25 m^2) in each plot to determine the number of kernels. Grain yield and 1000 kernel weight were adjusted to standard moisture content (14%). Straw yield was determined on a dry matter (DM) basis. The harvest index (HI) was calculated with the use of the below equation:

$$HI = \frac{\text{grain yield (Mg ha}^{-1}\text{ DM)}}{\text{grain and straw yield (Mg ha}^{-1}\text{ DM)}}.$$

Determination of macronutrient and micronutrient concentrations in biomass

Macronutrient and micronutrient content was determined in the straw and grain of winter wheat on a DM basis. Samples of dried straw and grain were ground in a laboratory mill (GM 300, Retsch, Germany). Phosphorus content was determined by the vanadium-molybdenum method, calcium and potassium content – by atomic emission spectrometry (AES, Jenway LTD

PFP 7, United Kingdom), magnesium content – by AAS, and total nitrogen content – by the hypochlorite method. Total S was determined turbidimetrically in plant material that had been incinerated with nitric acid and magnesium nitrate to the sulfate form. The concentrations of Cu, Zn, Mn and Fe were determined by Flame AAS.

Processing suitability of grain

Grain was analyzed to evaluate its bulk density (PN-73/R-74007:1973, ZBPP RPT 0177 density meter, Poland), vitreousness (PN-70/R-74008:1970, Farinotom S, ZBPP Ltd., Poland), protein content (ICC Standards 1995, Infratec 1241, Foss, Denmark), gluten content (PN-77/A-74041:1977, SZ–1 rotary batch mixer, SŻ mechanical separator, SZ centrifuge separator, ZBPP Ltd., Poland). Flour quality was evaluated based on four analytical indicators: sedimentation value - Zeleny test (SWD – 89, ZBPP Ltd., Poland), falling number (PN-EN ISO 3093:2010, SWD-SŻ, ZBPP Ltd., Poland), color (PN-A-74029:1999P, TBM, ZBPP Ltd., Poland) and ash content (PN-EN ISO 2171:2010, Infratec 1241, Foss, Denmark). The rheological properties of dough were assessed in a farinograph. The farinographic evaluation involved the determination of the water absorption capacity of flour, development time, stability and softening of dough (ICC Standards 1995, Konsystograf SZ–5, ZBPP Ltd., Poland).

Statistical analysis

The results of chemical analyses were processed by analysis of variance (Anova) in accordance with the experimental method. The foliar fertilization system and years were the fixed effects, and replication was the random effect. The significance of differences between means was evaluated with the Duncan's test ($P \leq 0.05$). Data were processed in the Statistica 10.1 PL application (StatSoft Inc. 2011).

RESULTS AND DISCUSSION

Weather conditions

The 2012/2013 season featured a very short autumn growing season (38 days) and a long and cold period of winter dormancy (168 days) – Table 2. The above conditions did not support winter wheat tillering in autumn, and they were responsible for a significant (nearly 20%) decrease in crop density in spring. Yield was estimated at 10.2-10.4 Mg ha^{-1}, and it was limited by the number of spikes per m^2 (Table 3). In the third growing season, spike density per m^2 was also low (Table 3) due to low precipitation in May and June (41-59% of the multi-year average) (Table 2) in the final stages of stem elongation, heading and inflorescence emergence. Low precipitation in the above stages of phenological development also decreased the number of kernels per spike and 1000 kernel weight (Table 3). The third year of the experiment was characterized by the lowest yield (6.9-7.6 Mg ha^{-1}), whereas the highest yield was noted in the second year of the study (12.1-12.5 Mg ha^{-1}) – Table 3 when precipitation was low during the ripening in July, but was preceded by abundant rainfall during the flowering in June (Table 2).

Table 2

Weather conditions in 2012-2015 and the multi-year average of 1981-2010

Months	Mean temperature (°C)					Precipitation (mm)				
	2012	2013	2014	2015	1981- -2010	2012	2013	2014	2015	1981- -2010
January	-2.0	-4.5	-3.5	0.6	-2.4	87.7	34.6	44.0	28.5	30.1
February	-7.5	-0.8	2.0	0.3	-1.6	24.9	21.3	11.4	8.8	23.1
March	3.5	-4.0	5.5	4.6	1.8	21.3	14.0	55.7	46.0	30.7
April	8.4	6.3	9.5	7.2	7.7	44.7	22.5	26.1	23.4	29.8
May	13.9	15.0	13.3	12.1	13.2	42.5	46.2	34.9	25.4	62.3
June	15.2	17.4	14.8	15.7	15.8	107.2	45.4	72.2	43.0	72.9
July	19.0	17.9	21.0	18.0	18.3	112.2	163.8	20.4	71.0	81.2
August	17.9	18.0	17.9	21.3	17.7	25.7	25.3	59.2	13.0	70.6
September	14.0	11.5	14.5		13.0	41.0	69.3	30.8		56.2
October	7.9	9.3	9.5		8.1	57.6	15.4	21.3		51.2
November	4.9	4.9	4.4		2.8	48.5	23.2	21.2		46.1
December	-3.3	2.3	-0.6		-1.0	15.1	34.1	56.6		42.6

Yield components, grain and straw yield

In each year of the study, the lowest winter wheat yield (6.93-12.08 Mg ha^{-1}) was noted in the treatment with 2 foliar applications of nitrogen (the most popular fertilizing regime in Polish agricultural practice) at the first node stage and the flag leaf stage (treatment A) – Table 3. The addition of copper in BBCH stage 31 (treatment B) significantly increased grain yield by approximately 90-250 kg ha^{-1}. Four applications of macronutrient and micronutrient fertilizers in spring (treatment C) led to a significant increase of 170-270 kg ha^{-1} in grain yield in comparison with treatment A. The highest grain yield was noted in treatment D, where macronutrient and micronutrient fertilizers were applied 5 times, and it was higher than in the treatment receiving 2 applications of foliar fertilizers by 230-430 kg ha^{-1} (in the first and second year of the study, marked by the highest yields) and by 660 kg ha^{-1} (in the third year of the study, which was characterized by the lowest yield). In an experiment by Chwil (2014), winter wheat grain yield in the Lublin Region (Poland) increased by 200-400 kg ha^{-1} in response to foliar application of macronutrients and micronutrients. In a pot experiment by

Kocoń (2009), foliar application of macronutrients and micronutrients to winter wheat (1 application in autumn and 3 applications in spring) increased grain yield by approximately 4%, even with optimal soil moisture and soil fertilization levels. In Oklahoma (Midwestern USA), foliar N fertilization increased grain yield by 69 to 950 kg ha^{-1}, subject to weather conditions and location of the experimental site (Woolfolk et al. 2002).

Table 3

Influence of different foliar fertilization systems on yield components, grain yield and straw yield of winter wheat

Parameter	Foliar fertilization system			
	A	B	C	D
2012/2013				
Spikes m^{-2}	444*b*	469*ab*	500*a*	483*a*
Grains $spike^{-1}$	48.9	46.5	45.6	47.1
1000 kernel weight (g)	46.7	47.0	45.5	45.8
Grain yield (Mg ha^{-1})	10.16*b*	10.25*ab*	10.37*a*	10.39*a*
Straw yield (Mg ha^{-1} DM)	3.74*b*	3.80*b*	4.01*a*	4.01*a*
Harvest index	0.695	0.694	0.685	0.685
2013/2014				
Spikes m^{-2}	528b	551*ab*	555*a*	563*a*
Grains $spike^{-1}$	46.5	44.3	44.5	44.0
1000 kernel weight (g)	49.3	50.0	50.1	50.5
Grain yield (Mg ha^{-1})	12.08*c*	12.19*c*	12.35*b*	12.51*a*
Straw yield (Mg ha^{-1} DM)	4.39*b*	4.43*b*	4.65*a*	4.75*a*
Harvest index	0.698	0.698	0.690	0.689
2014/2015				
Spikes m^{-2}	401	407	398	420
Grains $spike^{-1}$	38.9	39.3	39.7	39.8
1000 kernel weight (g)	44.3*b*	45.0*ab*	45.1*ab*	45.4*a*
Grain yield (Mg ha^{-1})	6.93*c*	7.18*b*	7.10*bc*	7.59*a*
Straw yield (Mg ha^{-1} DM)	2.60*c*	2.71*bc*	2.82*ab*	2.94*a*
Harvest index	0.781	0.781	0.772	0.777
Across years				
Spikes m^{-2}	458*b*	476a	484*a*	488*a*
Grains $spike^{-1}$	44.8	43.4	43.3	43.6
1000 kernel weight (g)	46.8	47.3	46.9	47.2
Grain yield (Mg ha^{-1})	9.72*c*	9.87*b*	9.94*b*	10.16*a*
Straw yield (Mg ha^{-1} DM)	3.57*b*	3.65*b*	3.86*a*	3.87*a*
Harvest index	0.725*a*	0.724*a*	0.716*b*	0.717*b*

Values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test.

In this study, grain yield increased in response to an increase in grain plumpness only in the year characterized by low levels of precipitation during the spring-summer growing season (year 3). In the first and second year of the experiment (optimal precipitation levels), the increase in grain yield in response to foliar application of macronutrients and micronutrients resulted from a higher number of spikes per m^2 of plot area.

In wheat, intensified foliar fertilization leads to a greater increase in straw yield than grain yield (Ranjbar, Bahmaniar 2007, Kocoń 2009, Zeidan et al. 2010, Chwil 2014, Table 3), which lowers the harvest index (Ranjbar, Bahmaniar 2007, Chwil 2014,Table 3).

Chemical composition of biomass

Winter wheat straw accumulated the highest amounts of potassium (12.45-13.95 g kg^{-1} DM), nitrogen (3.95-6.10 g kg^{-1} DM) and magnesium (3.20-3.55 g kg^{-1} DM), whereas winter wheat grain was a much richer source of nitrogen (22.68-22.90 g kg^{-1} DM), potassium (4.49-4.72 g kg^{-1} DM) and phosphorus (2.62-2.96 g kg^{-1} DM) – Table 4. Fordoński et al. (2015) also reported the highest accumulation of nitrogen, phosphorus and potassium in the grain of winter wheat than in straw. In this study, winter wheat grain contained 4.4 times more nitrogen and 3.6 times more phosphorus than straw. Wheat

Table 4

Influence of different foliar fertilization systems on the macronutrient content (g kg^{-1} DM) of winter wheat grain and straw (across years)

Macronutrient	Foliar fertilization system			
	A	B	C	D
Straw				
N	3.95*d*	5.30*c*	5.50*b*	6.10*a*
P	0.80	0.75	0.75	0.80
K	12.45*b*	13.80*a*	13.80*a*	13.95*a*
Ca	1.20	1.20	1.13	1.20
Mg	3.55*a*	3.45*b*	3.30*c*	3.20*d*
S	0.90	0.85	0.90	0.85
Grain				
N	22.87	22.90	22.68	22.70
P	2.73*b*	2.62*c*	2.75*b*	2.96*a*
K	4.72*a*	4.49*b*	4.72*a*	4.72*a*
Ca	1.25*c*	1.14*d*	1.48*b*	1.54*a*
Mg	0.38	0.46	0.37	0.46
S	0.97*b*	0.97*b*	0.97*b*	1.02*a*

Values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test.

straw was a richer source of potassium (2.9-fold) and magnesium (8.0-fold) than grain. Wheat grain and straw were characterized by similar levels of calcium (1.13-1.54 g Ca kg^{-1} DM) and sulfur (0.85-1.02 g S kg^{-1} DM) – Table 4. In a study by Chwil (2014), winter wheat straw accumulated 4 times more calcium but only 44% more potassium than grain. The content of the remaining nutrients was significantly higher in wheat grain than in wheat straw, from 1.5-1.9-fold (magnesium and sulfur) to 3.6-4.3-fold (nitrogen and phosphorus) (Chwil 2014).

In this experiment, intensive foliar fertilization increased nitrogen (by 2.15 g kg^{-1} DM) and potassium (by 1.50 g kg^{-1} DM) concentrations and decreased magnesium levels (by 0.35 g kg^{-1} DM) in winter wheat straw. In the study by Chwil (2014), foliar fertilizers led to a significant increase in the concentrations of nitrogen, phosphorus and magnesium, without differentiating the calcium and sulfur content of winter wheat straw. In this experiment, foliar fertilization resulted in a significantly greater increase in macroelement concentrations in winter wheat grain than in straw. Intensive foliar fertilization increased the content of phosphorus by 0.23-0.34 g ha^{-1}, potassium – by 0.0-0.23 g ha^{-1}, calcium – by 0.29-0.40 g ha^{-1}, and sulfur – by 0.05 g ha^{-1} in grain. In relative values, the said increase ranged from 5-13% (phosphorus, potassium and sulfur) to 35% (calcium) – Table 4. In the work of Chwil (2014), foliar fertilizers caused a significant increase in the nitrogen, calcium, magnesium and sulfur content of winter wheat grain. The increase in macronutrient concentrations, including nitrogen, in winter wheat grain was higher in the study by Chwil (2014) than in this experiment, which could be attributed to differences in yield potential (dilution effect) between the experiments. Grain yield was estimated at 9.9 Mg ha^{-1} in our study and at 4.1 Mg ha^{-1} by Chwil (2014).

In the present experiment, the copper and zinc content of winter wheat grain was on average 0.10 and 13.50 mg kg^{-1} DM higher, respectively, in comparison with straw. Winter wheat straw accumulated 4.33 kg^{-1} DM more manganese and 63.17 kg^{-1} DM more iron than grain. Intensified foliar fertilization significantly influenced micronutrient concentrations in post-harvest biomass, namely the micronutrient content increased in straw and decreased in grain (Table 5).

Processing suitability of grain

In this study, bulk density of grain was estimated at 81-84 kg hl^{-1}, and the evaluated samples contained 82-97% kernels with partially or completely vitreous endosperm. The percentage of kernels with vitreous endosperm was significantly higher in the treatment with the highest foliar fertilizer input (Table 6). Foliar fertilization also had a weak influence on the density of durum wheat grain in studies by Garrido-Lestache et al. (2005) and Abad et al. (2004). Buczek and Bobrecka-Jamro (2015) demonstrated that higher production inputs, including foliar fertilization, had a positive effect on grain vitreousness and plumpness.

Table 5

Influence of different foliar fertilization systems on the micronutrient content (mg kg-1 DM) of winter wheat grain and straw (across years)

Micronutrient	Foliar fertilization system			
	A	B	C	D
Straw				
Cu	1.20*d*	1.30*c*	2.70*b*	3.71*a*
Zn	5.75*b*	5.80*b*	9.00*a*	9.10*a*
Mn	21.40*d*	22.60*c*	27.30*b*	29.40*a*
Fe	86.65*c*	110.00*b*	111.10*b*	153.00*a*
Grain				
Cu	2.50*a*	2.39*ab*	2.22*b*	2.22*b*
Zn	21.16*ab*	21.39*a*	20.96*b*	20.14*c*
Mn	20.14*c*	20.59*b*	20.71*b*	21.96*a*
Fe	59.27*a*	53.14*b*	50.51*c*	45.17*d*

Values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test.

The total protein content of winter wheat grain varied considerably between years, from 137 (year 2) to 145 g kg^{-1} DM (years 1 and 3). The gluten content of grain ranged from 25-27% (years 1 and 2) to 32% (year 3). Higher supply of macronutrient and micronutrient fertilizers, regardless of environmental conditions, led to a significant decrease in total protein content and gluten content of winter wheat grain by 1.1 g kg^{-1} DM and 0.9%, respectively (Table 6). Similar results were reported by Abad et al. (2004) who did not observe an increase in the protein content of grain subjected to foliar nitrogen fertilization. In wheat, foliar supply of macroelements and microelements generally increases the protein content of grain by 3-10 g kg^{-1} DM (Bly, Woodard 2003, Garrido-Lestache et al. 2005, Tea et al. 2007, Ranjbar, Bahmaniar 2007) to 20 g kg^{-1} DM (Makarewicz et al. 2012), and gluten content by more than 10% (Makarewicz et al. 2012).

The sedimentation value (Zeleny test) was very high in each year of the study at 52 to 72 ml (Table 6), 7-9 points on a 9-point scale. Intensified foliar fertilization led to a minor, but statistically significant decrease in protein quality in winter wheat grain (sedimentation value decreased by 3-4 ml) – Table 6. Knapowski et al. (2010) also reported a drop in sedimentation value when nitrogen fertilizer was applied at > 30 kg ha^{-1} at the stem elongation stage or at 15 kg ha^{-1} during heading.

The activity of starch-degrading amylolytic enzymes is expressed by the falling number which was very high in each year of this study (330-451 s). When foliar fertilization was intensified in years with low precipitation after heading (2013/2014 and 2014/2015), the falling number was clearly reduced

Table 6

Influence of different foliar fertilization systems on the milling quality, flour strength and rheological properties of dough

Parameter	Growing season												Across years			
	2012/2013				2013/2014				2014/2015							
	Foliar fertilization system															
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Grain density (kg hl^{-1})	81.3	81.5	81.5	81.2	84.1	84.1	84.0	84.0	83.0*b*	83.6*a*	83.0*b*	83.0*b*	82.8*b*	83.1*a*	82.8*b*	82.8*b*
Grain vitreousness (%)	82.0*c*	82.0*c*	87.0*b*	93.0*a*	91.3	89.3	91.3	90.7	96.7	97.3	95.3	96.0	90.0*b*	89.6*b*	91.2*b*	93.2*a*
Total protein content of grain (g kg^{-1} DM)	145.8*a*	145.2*b*	144.1*c*	145.1*b*	137.4	137.7	135.3	136.5	145.7*a*	146.5*a*	145.9*a*	144.1*b*	143.0*a*	143.1*a*	141.8*b*	141.9*b*
Gluten content of grain (%)	25.0*b*	25.7*a*	25.2*b*	25.1*b*	26.7*a*	26.6*a*	25.5*b*	26.0*ab*	31.8*a*	30.1*bc*	30.6*b*	29.5*c*	27.8*a*	27.5*b*	27.1*c*	26.9*c*
Flour sedimentation value – Zeleny test (ml)	68.0	69.0	68.5	67.5	62.5*a*	60.0*b*	59.5*b*	52.0*c*	68.0*b*	69.5*b*	72.0*a*	69.0*b*	66.2*a*	66.2*a*	66.7*a*	62.8*b*
Falling number of flour (s)	392*c*	394*c*	427*a*	417*b*	451*a*	411*b*	409*b*	418*b*	400.7*a*	398.3*b*	385.0*c*	330.3*d*	414.4*a*	401.1*c*	407.1*b*	388.4*d*
Flour color (% whiteness value)	77.1	77.3	77.2	77.0	75.3*a*	74.9*b*	74.5*c*	74.1*d*	73.6*c*	75.5*a*	74.3*b*	75.4*a*	75.3*c*	75.9*a*	75.3*c*	75.5*b*
Ash content of flour (g kg^{-1} DM)	6.9*b*	6.9*b*	6.9b	7.1*a*	7.3	7.5	7.4	7.5	6.8	6.6	6.5	6.4	7.0	7.0	6.9	7.0
Water absorption capacity of flour (%)	61.0*c*	61.1*b*	61.1*b*	62.0*a*	58.9*b*	61.4*a*	61.0*a*	61.1*a*	61.4*a*	60.6*b*	60.4*c*	60.1*d*	60.4*c*	61.0*a*	60.8*b*	61.1*a*
Dough development (min)	2.8	3.1	2.7	2.4	2.3	3.7	2.4	4.1	3.8	3.6	3.7	3.4	2.9	3.5	2.9	3.3
Dough stability (min)	14.2	14.4	14.0	14.0	9.0*c*	9.6*bc*	9.8*b*	11.8*a*	13.7	14.1	14.7	14.5	12.3*a*	12.7*b*	12.8*ab*	13.4*a*
Dough softness (Brabender units)	20.2	22.0	25.1	28.2	50.5*a*	47.4*b*	34.6*c*	28.9*d*	21.1*b*	32.2*a*	22.0*b*	19.0*b*	30.6*b*	33.9*a*	27.2*c*	25.4*c*

Values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test by 33-70 s. In the season characterized by low rainfall during heading and ripening (2012/2013), intensified foliar fertilization significantly increased the falling number (by 34 s) – Table 6. Makarewicz et al. (2012) also reported the highest falling numbers (416 and 414 s) in winter wheat grain treated with an aqueous solution of urea in BBCH stages 22 and 31 (increase by 16-18 s relative to the control treatment).

The ash content of flour ranged from 6.4-7.1 (years 1 and 3) to 7.5 g kg^{-1} DM (year 2). Intensified foliar fertilization increased ash concentrations in flour only when precipitation levels were high during the heading and ripening of winter wheat (year 1). In the remaining growing seasons, the relationship between the intensity of foliar fertilization and ash content of flour was statistically not significant (Table 6).

The water absorption capacity of flour is one of the key quality parameters based on which wheat grain is classified into quality groups. In our study, the above parameter was satisfactory in all three years (58.9-62.0%). Intensified foliar fertilization clearly increased the water absorption capacity of flour (Table 6). Dough made from the flour of winter wheat grain subjected to 2 applications of foliar fertilizers in BBCH stages 31 and 39 was characterized by the shortest development time (2.9 min) and stability (12.3 min) – treatment A. Intensified foliar fertilization increased dough development time and stability. An increase in the intensity of foliar fertilization also had a positive influence on dough softness which was decreased by 7-9 Brabender units (Table 6). Tea et al. (2007) evaluated wheat flour dough in an alveograph to reveal an increase in dough strength (by 10-37 units), dough swelling (1.8 - 2.2 mm H_2O), dough tenacity (2 - 3 mm) and dough extensibility (15 - 18 mm) under the influence of foliar fertilization with macroelements (N and N, S).

CONCLUSIONS

1. The highest yield of winter wheat grain (10.16 Mg ha^{-1}) was noted in the treatment subjected to 5 foliar applications of macroelements and microelements. It was higher by 230-660 kg ha^{-1} in comparison with plots where foliar fertilizers were supplied in 2 applications. The increase in the grain yield of winter wheat in response to foliar fertilization resulted from an increase in 1000 kernel weight (optimal precipitation levels) or an increase in the number of spikes per m^2 of plot area (low precipitation levels).

2. Intensified foliar fertilization increased nitrogen and potassium concentrations and decreased magnesium levels in winter wheat straw. Intensified foliar fertilization increased the phosphorus, potassium, calcium and sulfur content of grain. Treatments subjected to intensified foliar fertilization were characterized by increased micronutrient concentrations in straw (cop-

per, zinc, manganese, iron) and lower micronutrient levels in grain (copper, zinc, iron).

3. Intensified foliar fertilization significantly lowered total protein content, gluten content and protein quality (lower sedimentation value) in winter wheat grain. The influence of foliar fertilization on the falling number was determined by precipitation levels during the heading and ripening of winter wheat. Intensified foliar fertilization had a clearly positive impact on the development, stability and softness of dough.

REFERENCES

Abad A., Lloveras J., Michelena A. 2004. *Nitrogen fertilization and foliar urea effects on durum wheat yield and quality and on residual soil nitrate in irrigated Mediterranean conditions*. Field Crop Res., 87: 257-269.

Bly A.G., Woodard H.J. 2003. *Foliar nitrogen application timing on grain yield and protein concentration of hard red winter and spring wheat*. Agron. J., 95: 335-338.

Buczek J., Bobrecka-Jamro D. 2015. *Assessment of qualitative parameters of population and hybrid wheat grain depending on the production technology*. Acta Agrophys., 22(3): 247-259. (in Polish)

Chwil S. 2014. *Effects of foliar feeding under different soil fertilization conditions on the yield structure and quality of winter wheat* (*Triticum aestivum* L.). Acta Agrobot., 67(4): 135-144.

Fageria N.K., Barbosa Filho M.P., Moreira A., Guimaraes C.M. 2009. *Foliar fertilization of crop plants*. J. Plant Nutr., 32: 1044-1064.

FAOSTAT 2015. *Faostat Agriculture data*. Available at: http://www.apps.fao.org [04 October 2015].

Fordoński G., Pszczółkowska A., Krzebietke S., Olszewski J., Okorski A. 2015. *Yield and mineral composition of seeds of leguminous plants and grain of spring wheat as well as their residual effect on the yield and chemical composition of winter oilseed rape seeds*. J. Elem., 20(4): 827-838.

Garrido-Lestache E.L., Opez-Bellido R.J., Opez-Bellido L. 2005. *Durum wheat quality under Mediterranean conditions as affected by nitrogen rate, timing and splitting, nitrogen forms and sulfur fertilization*. Eur. J. Agron., 23: 265-278.

ICC Standards. 1995. *Standard Methods of the International Association for Cereal Science and Technology (ICC)*. Vienna, Austria.

IUSS Working Group WRB. 2006. *World Reference Base for Soil Resources. 2nd edition*. World Soil Resources Reports No. 103. FAO, Rome, 132.

Jankowski K.J., Budzyński W.S., Kijewski Ł., Zając T. 2015*a*. *Biomass quality of Brassica oilseed crops in response to sulfur fertilization*. Agron. J., 107(4): 1377-1391.

Jankowski K.J., Kijewski Ł., Dubis B. 2015*b*. *Milling quality and flour strength of the grain of winter wheat grown in monoculture*. Rom. Agric. Res., 32: 192-200.

Jankowski K.J., Kijewski Ł., Groth D., Skwierawska M., Budzyński W.S. 2015*c*. *The effect of sulfur fertilization on macronutrient concentrations in the post-harvest biomass of rapeseed (Brassica napus* L. ssp. *oleifera* Metzg*)*. J. Elem., 20(3): 585-597.

Knapowski T., Ralcewicz M., Spychaj-Fabisiak E., Łożek O. 2010. *Grain quality evaluation in winter wheat grown as exposed to varied nitrogen fertilisation*. Fragm. Agron., 27(1): 73-80. (in Polish)

Koćoń A. 2009. *Foliar top dressing efficiency of winter wheat and rape of chosen fertilizers in optimal fertilization and soil moisture conditions*. Ann. UMCS, Sect. E, 64(2): 23-28. (in Polish)

Luo C., Branlard G., Griffen W.B., McNeil D.L. 2000. *The effect of nitrogen and sulfur fertilization and their interaction with a genotype on wheat glutenins and quality parameters*. J. Cereal Sci., 31: 185-194.

Makarewicz A., Gąsiorowska B., Cybulska A. 2012. *The effect of foliar nitrogen fertilization on the selected quality parameters of winter wheat grain*. Fragm. Agron., 29(1): 105-113. (in Polish)

Nogalska A., Sienkiewicz S., Czapla J., Skwierawska M. 2012. *The effect of multi-component fertilizers on the yield and mineral composition of winter wheat and macronutrient uptake*. J. Elem., 17(4): 629-638.

PN-70/R-74008:1970. *Cereal grain – determination of grain vitreousness*. (in Polish)

PN-73/R-74007:1973. *Cereal grain – determination of bulk density*. (in Polish)

PN-77/A-74041:1977. *Cereal grain and cereal products – Determination of gluten quantity and quality*. (in Polish)

PN-A-74029:1999P. *Cereal products – Wheat and rye flour – Determination of flour whiteness*. (in Polish)

PN-EN ISO 2171:2010. *Cereal grain, legume seeds and their products – Determination of ash content by incineration*.

PN-EN ISO 3093:2010. *Wheat, rye and respective flours, durum wheat and durum wheat semolina - Determination of the falling number according to Hagberg-Perten*.

Ranjbar G.A., Bahmaniar M.A. 2007. *Effects of soil and foliar application of Zn fertilizer on yield and growth characteristics of bread wheat (Triticum aestivum* L.*) cultivars*. Asian J. Plant Sci., 6: 1000-1005.

Sharpley A.N., Chapra S.C., Wedepohl R., Sims J.T., Daniel T.C., Reddy K.R. 1994. *Managing agricultural phosphorus for protection of surface waters: Issues and opinions*. J. Environ. Qual., 23: 437-451.

StatSoft Inc. 2011. *Statistica* (*data analysis software system*), version 10. www.statsoft.com.

Tea I., Genter T., Naulet N., Lummerzheim M., Kleiber D. 2007. *Interaction between nitrogen and sulfur by foliar application and its effect on flour bread- making quality*. J. Sci. Food Agr., 87: 2853-2859.

Woolfolk C.W., Raun W.R., Johnson G.V., Thomason W.E., Mullen R.W., Wynn K.J., Freeman K.W. 2002. *Influence of late-season foliar nitrogen applications on yield and grain nitrogen in winter wheat*. Agron. J., 94: 429-434.

Zeidan M.S., Mohamed M.F., Hamouda H.A. 2010. *Effect of foliar of Fe, Mn and Zn on wheat yield and quality in low sandy soils fertility*. World J. Agri. Sci., 6(6): 696-699.