POLISH JOURNAL OF NATURAL SCIENCES
Abbrev.: Pol. J. Natur. Sc., Vol 34(2): 199–212, Y. 2019

THE IMPACT OF NITROGEN FERTILIZATION STRATEGIES ON SELECTED QUALITATIVE PARAMETERS OF SPRING WHEAT GRAIN AND FLOUR

***Małgorzata Warechowska*[1], *Arkadiusz Stępień*[2], *Katarzyna Wojtkowiak*[3], *Agnieszka Nawrocka*[4]**

[1] ORCID: 0000-0002-3592-9472
[2] ORCID: 0000-0002-1138-9715
[3] ORCID: 0000-0001-5782-0171
[4] ORCID: 0000-0001-8618-2092
[1] Department of Systems Engineering
[2] Department of Agroecosystems
[3] Department of Heavy Duty Machines and Research Methodology
University of Warmia and Mazury in Olsztyn, Poland,
[4] Institute of Agrophysics
Polish Academy of Sciences, Lublin, Poland

Key words: grain quality; flour quality; nitrogen fertilization, protein, wheat.

Abstract

The quality of wheat grain determines the quality of flour and this becomes important in subsequent processing stages and impacts the end products. The objective of the studies was to determine whether a method of applying nitrogen both with and without compound fertilizers at different growth stages of spring wheat impacted the crop yield and qualitative parameters of grain and flour. A three-year field experiment was in north-eastern Poland at the Teaching and Research Station of the University of Warmia and Mazury in Olsztyn. Spring wheat was cultivated with the application of different treatments of nitrogen fertilization with a total dose of 120 kg ha^{-1}. The nitrogen fertilizers were applied to the soil or to soil and on leaves (foliar application) with and without microelements at the following growth stages: tillering, stem elongation and heading. It was concluded that the fertilization methods did not impact the grain yield. Soil urea application at doses of 40 kg ha^{-1} at the tillering and stem elongation stages mostly increased the protein content in grain and flour, vitreousness of grain, gluten content and alveographic – *W* parameter compared to the other fertilization variants. Soil application of the fertilizer with macronutrients and trace minerals generally produced worsened grain parameters, especially the protein grain content and the Zeleny index. The weather conditions most affected the grain yield and such grain and flour parameters as kernel weight, kernel diameter, hardness

Address: Małgorzata Warechowska, University of Warmia and Mazury, ul. Heweliusza 14, 10-719 Olsztyn, Poland, phone: +48 (89) 523 34 13, e-mail: gosiaw@uwm.edu.pl

index and P/L index. The soil urea application at a dose of 40 kg ha^{-1} at the elongation stages contributes to better grain quality than foliar application of urea at doses of 20 kg N ha^{-1} at the stem elongation and heading stages.

Introduction

The quality of wheat grain is influenced by numerous factors, of which its genotype is the major one; in addition, it is also impacted by environmental factors during the growing season and cultivation techniques (KNAPOWSKI et al. 2010, STĘPIEŃ and WOJTKOWIAK 2016, HELLEMANS et al. 2018). It is believed that of the cultivation procedures and techniques, nitrogen fertilization plays a basic role in determining the quality of grains, with the key role being attributed to the dose and allocation of nitrogen during the cultivation cycle, the type of fertilizer and the time and method of application (RALCEWICZ et al. 2009, ABEDI et al. 2010, FUERTES-MENDIZÁBAL et al. 2010, BLANDINO et al. 2015b, RANSOM et al. 2016, XUE et al. 2016a). Wheat slowly uptakes and accumulates nitrogen during the early growth stages until tillering; afterwards, the uptake of nitrogen is rapid till the heading stage and then it slows down again after flowering till the milk ripening stage (MCGUIRE et al. 1998). The accumulation of nitrogen in the early and intermediate-early growth stages mainly serves to increase the grain yield, whereas during heading and afterwards its main purpose is for cereal protein synthesis. Under proper environmental conditions, the application of divided nitrogen doses results in higher nitrogen uptake by plants (ERCOLI et al. 2013). The use of divided nitrogen doses increases the total protein content in the grain in comparison with the same dose of nitrogen applied once. There are also some results indicating the lack of impact of divided nitrogen doses on the protein content in the grain (SCHULZ et al. 2015). The availability of nitrogen for plants is determined by the form of nitrogen found in a fertilizer. The source of nitrogen (urea, nitrate-N, and ammonium-N) may impact the protein content and quality of wheat mainly by changing the absorption of nitrogen by plants (XUE et al. 2016a). Numerous studies indicate a positive effect of nitrogen applied at the heading and anthesis stages, implicating it as a useful tool for increasing the protein content (BLANDINO et al. 2015a, DICK et al. 2016, RANSOM et al. 2016). In different wheat varieties, there is a tendency for varied reactions to nitrogen fertilization (RANSOM et al. 2016). The content of protein in the grain is often negatively correlated with the yield since higher grain filling is linked to increased starch storage (BLANDINO et al. 2015b). Protein is the main parameter in evaluating the quality of wheat grain since the content and composition of protein in the grain (and consecutively in flour) impact the quality of bread (ZHANG et al. 2009). Dividing the total dose of nitrogen and applying it at different growth stages affects the quality of wheat flour because belated nitrogen application favours the accumulation of protein over starch and prolongs the grain filling time (XUE et al. 2016b). The other factors determining the quality of grain include: grain size, bulk density, hardness, flour extraction rate, ash content and flour colour – these are the basic parameters of grain milling quality (CAMPBELL et al. 2012, PAGANI et al. 2014). The quality of wheat grain determines the quality of flour and this becomes important in subsequent processing stages and impacts the end products (ZHANG et al. 2005, PAGANI et al. 2014).

The objective of the studies was to evaluate the impact of nitrogen application method, both with compound fertilizers added and without at different spring wheat growth stages on the content of protein and other qualitative parameters of the grain and flour.

Materials and Methods

The studies were carried out in north-eastern Poland at the Teaching and Research Station of the University of Warmia and Mazury in Olsztyn (5372N, 2042E). The field trial was conducted in 2009–2011 on brown soil of a granulometric composition of light loam. Its composition was as follows: 2.8–3.2% of fractions with their diameters below 0.002 mm; 30.4–31.9% of fractions with their diameters range – 0.002–0.050 mm, and 64.9–66.8% of fractions with their diameters range 0.050–2.00 mm, respectively.

Table 1

Chemical characteristics of soil before the start of the experiment

Measurement	Values
Soil acidity [1 mol L^{-1} KCl]	5.5–6.1
Humus [%]	2.02
Total N [g kg^{-1}]	1.23–1.25
P [mg kg^{-1}]*	63.7–97.2
K [mg kg^{-1}]*	141.1–199.2
Mg [mg kg^{-1}]*	46–56

*– available forms

The selected parameters of soil sampled before the trail are presented in Table 1. The experiment was based on a random block design in three repetitions. The area of cultivation plots was 6.25 m^2 and the harvesting plots were 4 m^2. Two varieties of spring wheat (*Triticum aestivum* ssp. *vulgare*) Parabola and Radunia were selected to compare the applied fertilization methods. The wheat grains were sown at a density of 5 million grains ha^{-1}, with row spacing of 10.5 cm. The dose of 30.2 kg P ha^{-1} as 46% triple superphosphate and 83.1 kg K ha^{-1} as potassium salt was applied. The dosage of nitrogen fertilization was 120 kg ha^{-1} yet 40 kg ha^{-1} N as ammonium nitrate was applied before wheat was sown. The remaining nitrogen dose was delivered according to four different nitrogen fertilization strategies (T_1–T_4):

T_1, to soil at 40 kg ha^{-1} N as 46% urea at the tillering stage (GS 23) and to soil at 40 kg ha^{-1} N as 46% urea at the stem elongation stage (GS 31),

T_2, to soil at 20 kg ha^{-1} N as 46% urea and at 20 kg ha^{-1} N as the Azofoska fertilizer at the tillering stage (GS 23) and to soil at 40 kg ha^{-1} N as 46% urea at the stem elongation stage (GS 31),

T_3, to soil at 40 kg ha^{-1} N as 46% urea at the tillering stage (GS 23) and at 20 kg N as foliar application of 10% urea solution at the stem elongation stage (GS 31) and at 20 kg N ha^{-1} as foliar application as 10% urea solution at the heading stage (GS 52),

T_4, to soil at 40 kg ha^{-1} N as 46% urea at the tillering stage (GS 23) and at 20 kg N as foliar application of 10% urea solution with the Ekolist mikro Z product at a dose of 1 dm^{-3} ha^{-1} at the stem elongation stage (GS 31) and at 20 kg N as foliar application of 10% urea solution with the Ekolist mikro Z product at a dose of 1 dm^3 ha^{-1} at the heading stage (GS 52).

The amounts of macronutrients and trace minerals applied with the Azofoska fertilizer and the Ekolist mikro Z product are presented in Table 2. The fungicides (a.s. ciproconazole + propiconazole and azoxystrobin) were used to protect wheat against fungal diseases and a herbicide (a.s. florasulam + 2,4-dichlorophenoxyacetic acid) was applied to reduce weed infestation. At crop maturity, grain was harvested using a plot combine.

Table 2

Amounts of macronutrients and trace elements applied with Azofoska and Ekolist mikro Z fertilizers

Type of fertilizer	N	P	K	Mg	S	Cu	Zn	Mn	Fe	Mo	B
Azofoska [kg ha^{-1}]	20.0	2.69	23.3	3.98	13.52	0.26	0.07	0.39	0.25	0.06	0.07
Ekolist mikro Z [g ha^{-1}]	104.8	–	–	79.2	112.6	9.18	23.6	25.6	26.2	0.14	0.42

The grain samples were analysed for moisture content with the ICC 110/1 method. Hardness index (HI), kernel weight (KW), and kernel diameter (KD) were determined on 300 kernels using the Single Kernel Characterisation System (SKCS) type 4100, Perten Instruments North America Inc., Reno, USA (Method AACC 55-10, 2002). The evaluation of Test Weight (TW) was performed in accordance with the AACC 55-31 method. Grain vitreousness was assessed by analysing the cross sections of grain and expressed as a percentage of vitreous kernels on a 50-item sample.

Partially vitreous kernels were categorized as semi-vitreous grains and their number on a sample was multiplied by 0.5 factor. The protein content in the grain (g kg^{-1} dry matter, DM) was measured with the Kjeldahl (N 5.7) method on a KjelFlex K-360 apparatus (Buchi, Germany). The ash content in the grain and flour was determined following the ICC 104/1, 1990 method. Following preliminary humidification to 15% moisture content, grain was milled in a Quadrumat Jr laboratory Mill (Brabender, Germany) equipped with a 70 GG cylindrical sieve (PE 236 µm). The grain samples of 125 g were weighed on a WLC 2/A1 electronic scale (Radwag, Poland, d = 10 mg) and were then processed and milled according to the laboratory procedure. Three samples of each type of material were ground. Flour extraction rate was defined as the percentage of straight-grade flour. The wet gluten content in grain, Zeleny sedimentation index and flour moisture level, flour protein content (the result was expressed at 12% moisture basis – mb) and flour water absorption were determined on a NIR System Infratec 1241 Grain Analyser with flour module (FOSS, Hillerod, Denmark) that takes transmission measurements of near-infrared waves (570–1050 nm). This device was also used to determine two major alveographic parameters in flour: W – mechanical deformation of dough (energy) and P/L – the ratio of maximum resistance and elasticity of dough.

The results were statistically analysed with two-way analysis of variance (ANOVA) taking the treatment and variety as the independent variables. The ANOVA analysis was run individually for each year. The significance of differences between the means was determined with Tukey's test. The correlations between the individual parameters were evaluated with the Pearson's test. Statistical calculations were performed with STATISTICA for Windows v. 10 software (StatSoft Inc.). Statistical hypotheses were tested at $p \leq 0.05$.

Results and Discussion

In 2009–2011, the weather conditions during the growing season are presented in Table 3. Of the three wheat growing seasons, the highest temperature was recorded in 2010 (13.2°C) and it was higher than the average multiannual temperature. Considering the monthly distribution of temperatures, it was found that July and August in 2010 were much warmer than the corresponding months from the other growing seasons.

The average precipitation level from March till August 2009 was 320.1 mm and thus comparable to the average multiannual precipitation. In the 2010 and 2011 growing seasons, precipitation was high and higher than the amount of precipitation in 2009 (by 39.7% and 42.6%, respectively).

Table 3

Climate conditions during wheat vegetation

Factor/Years	Months						Average
	Mar.	Apr.	May	Jun.	Jul.	Aug.	
	Temperature [°C]						
2009	1.3	9.4	12.4	14.9	19.2	17.6	12.5
2010	2.1	8.1	12.0	16.4	21.1	19.3	13.2
2011	1.6	9.1	13.1	17.1	17.9	17.6	12.7
1961–2005	1.2	6.9	12.8	15.9	17.8	17.7	12.1
	Sums of monthly precipitation [mm]						Sum
2009	57.9	4.8	52.9	136.9	48.3	19.3	320.1
2010	36.7	18.2	131.9	84.8	80.4	95.3	447.3
2011	16.3	22.5	51.1	81.7	202.0	82.1	456.5
1961–2005	27.6	35.7	51.9	78.5	75.1	66.1	334.9

From May till the end of June, i.e. during tillering and stem elongation and when spring wheat has the highest demand for water, the lowest level of precipitation was recorded in 2011 (132.8 mm) while the highest was in 2010 (216.7 mm). The nitrogen fertilization treatments did not impact the grain yield (Table 4), which is consistent with the results presented by SCHULZ et al. (2015). However, due to different climatic conditions, the yield average varied in the individual growing seasons. In 2010, proper distribution of precipitation during tillering and stem elongation contributed to the highest grain yield. The varieties significantly differed in the grain yield in two growing seasons (2009 and 2011). A reaction of the varieties to weather conditions was different and this thus influenced the volume of crop yield. In 2009 the Radunia variety produced a significantly higher yield and the same was reported was the Parabola variety in 2011, whereas, in 2010, no significant differences were found. The differences in crop yield of the individual varieties may result from a varied capacity for nitrogen uptake by each of them (XUE et al. 2016a).

Grain test weight (TW) depended on the fertilization procedures and the variety itself, with higher test weight being reported for the Radunia variety. Foliar urea application at GS 31 and GS 52 (T_3) produced the highest value of grain test weight in each growing season (Table 4). RUSKE et al. (2003) reported a similar relation with increased test weight resulting from the application of additional nitrogen (as urea) at the anthesis stage. BLANDINO et al. (2015a) reported that TW was significantly increased when nitrogen was applied late in the growing season and in the form of ammonium nitrate. The author's research (data not shown) demonstrated a negative correlation between the grain yield and TW (r = -0.48).

It means that smaller wheat kernels were produced with a higher crop yield. Lower test weight may implicate smaller kernel filling, which translates into lower flour yield (RUSKE et al. 2003).

Table 4

Effect of N strategies and cultivar on grain yield, test weight, kernel weight, kernel diameter, hardness index and vitreousness in years 2009, 2010 and 2011

Years	Factor	Treatment	Grain yield [t ha^{-1}]	TW [kg hL^{-1}]	KW [mg]	KD [mm]	HI [-]	Vitreousness [%]
2009	N (*A*)	T_1	6.28^a	77.8^b	44.7^a	3.06^a	62.9^a	36^a
		T_2	6.16^a	77.8^b	43.7^a	3.02^a	63.3^a	26^b
		T_3	6.03^a	78.0^a	44.6^a	3.06^a	61.8^a	22^{bc}
		T_4	6.08^a	77.6^c	44.0^a	3.05^a	63.8^a	21^c
		P(F)	ns	***	ns	ns	ns	***
	cultivar (*B*)	Parabola	5.94^b	77.3^b	49.6^a	3.11^a	63.5^a	35^a
		Radunia	6.33^a	78.3^a	38.9^b	2.98^b	62.5^a	18^b
		P(F)	***	***	***	***	ns	***
	A x *B*	P(F)	ns	***	ns	ns	ns	***
2010	N (*A*)	T_1	6.82^a	76.4^a	41.4^a	2.95^a	64.4^{bc}	49^a
		T_2	6.79^a	76.4^a	40.8^a	2.93^a	64.1^c	42^b
		T_3	6.74^a	76.6^a	40.8^a	2.95^a	66.3^{ab}	46^{ab}
		T_4	6.80^a	76.1^b	40.5^a	2.95^a	67.6^a	44^b
		P(F)	ns	***	ns	ns	***	**
	cultivar (*B*)	Parabola	6.85^a	75.7^b	44.3^a	2.98^a	67.4^a	55^a
		Radunia	6.73^a	77.1^a	37.5^b	2.92^b	63.8^b	35^b
		P(F)	ns	***	***	***	***	***
	A x *B*	P(F)	ns	***	***	**	ns	***
2011	N (*A*)	T_1	5.68^a	78.1^b	46.8^{ab}	3.12^b	67.1^a	56^a
		T_2	5.92^a	78.1^b	45.8^b	3.10^b	66.8^a	56^a
		T_3	6.06^a	78.8^a	48.3^a	3.18^a	66.2^a	57^a
		T_4	5.75^a	77.9^c	45.8^b	3.09^b	66.7^a	49^a
		P(F)	ns	***	***	***	ns	*
	cultivar (*B*)	Parabola	6.27^a	77.3^b	48.9^a	3.16^a	66.9^a	53^a
		Radunia	5.43^b	79.1^a	44.5^b	3.09^b	66.4^a	55^a
		P(F)	***	***	***	***	ns	ns
	A x *B*	P(F)	ns	***	***	***	ns	***

a, *b*, *c* – averages designated by the different small letters in the columns of the table, separately for year, are significantly different at $p \leq 0.05$

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability level, respectively

ns – not significant at the 0.05 probability level

The variety and climatic condition in the individual growing seasons influenced the kernel weight (KW) and kernel diameter (KD) the most. The interactions between the variety and nitrogen fertilization methods were significant in 2010 and 2011 for kernel weight and in 2011 for kernel diameter. Of the two varieties used in the trial, Parabola's wheat grain had higher weight and diameter. Weather conditions in the individual growing seasons influenced differently on the wheat varieties cultivated and therefore the Parabola variety had the highest kernel weight and diameter in 2009 and Radunia in 2011, but their yield was lowest in these seasons. The tested nitrogen fertilization treatments did not influence the kernel weight or diameter in the first two wheat growing seasons. In the third growing season (2011), there was an impact of foliar urea application at the GS 31 and GS 52 stages (T_3). In comparison with the other treatments, T_3 variant contributed to an increase in both the weight and diameter of the kernels.

Kernel hardness was most impacted by the weather conditions in the individual wheat growing seasons, with the grain from 2011 being the hardest. The wheat varieties and fertilization treatments affected the kernel hardness only in one growing season, i.e. in 2010. In this season significant differences in kernel hardness were demonstrated between the treatment that differed in the way nitrogen was applied: to soil (T_1 and T_2) and on leaves (T_3 and T_4). Foliar urea application combined with Ekolist mikro Z product and without it substantially increased the hardness of grain. The Parabola variety was harder than Radunia. Kernel hardness was significantly ($p < 0.001$) correlated with kernel vitreousness ($r = 0.78$); the data is not shown. Kernel vitreousness was most influenced by the year of cultivation. The variety and nitrogen fertilization variants exerted an impact on kernel vitreousness in the first two growing seasons (2009 and 2010). In these seasons, soil urea fertilization at the tillering (GS 23) and stem elongation (GS 31) stage (the T_1 option) produced the grains of the highest vitreousness, although this value was higher in the Parabola variety. The environmental condition, particularly the temperature and sunny weather, may have contributed to the differences in kernel vitreousness, as reported in other studies (OURY et al. 2015).

The grain protein content depended on nitrogen fertilization treatments (Table 5), but the outcome of such procedures was determined by weather conditions in the individual growing seasons (amount and distribution of precipitation) that affected the availability of nitrogen and its absorption by plants. Importantly, there was also an impact temperature during the grain filling phase. In the 2010 growing season, when higher temperatures were recorded in June and August than in the other seasons,

Table 5

Effect of N strategies and cultivar on grain protein content, gluten content, Zeleny index and grain ash content in years 2009, 2010 and 2011

Years	Factor	Treatment	Protein content [g kg^{-1} DM]	Gluten content [%]	Zeleny index [cm^3]	Ash content [% DM]
2009	N (*A*)	T_1	136.2^a	34.0^a	56.8^{ab}	1.92^a
		T_2	129.7^b	32.5^b	54.2^b	1.96^a
		T_3	131.4^{ab}	33.8^a	57.4^a	2.00^a
		T_4	128.2^b	33.6^a	57.2^a	1.95^a
		P(F)	**	***	*	ns
	cultivar (*B*)	Parabola	138.5^a	36.0^a	62.5^a	1.99^a
		Radunia	124.5^b	31.0^b	50.3^b	1.93^b
		P(F)	***	***	***	*
	A x *B*	P(F)	*	*	**	*
2010	N (*A*)	T_1	136.3^a	35.0^{ab}	55.9^b	2.00^a
		T_2	132.1^b	34.6^b	53.7^c	1.97^a
		T_3	136.7^a	35.1^a	55.8^b	2.01^a
		T_4	137.4^a	33.1^c	57.5^a	2.00^a
		P(F)	***	***	***	ns
	cultivar (*B*)	Parabola	138.2^a	36.8^a	56.5^a	2.05^a
		Radunia	133.1^b	32.1^b	55.0^b	1.95^b
		P(F)	***	***	***	***
	A x *B*	P(F)	***	***	***	*
2011	N (*A*)	T_1	138.5^a	36.1^a	59.7^a	2.03^a
		T_2	133.9^b	33.0^c	58.6^b	2.01^a
		T_3	131.9^b	32.8^c	58.8^b	1.98^a
		T_4	130.8^b	34.0^b	56.1^c	2.00^a
		P(F)	***	***	***	ns
	cultivar (*B*)	Parabola	134.9^a	34.9^a	56.9^b	2.01^a
		Radunia	132.7^b	33.1^b	59.7^a	2.00^a
		P(F)	*	***	***	ns
	A x *B*	P(F)	ns	***	***	ns

a, *b*, *c* – averages designated by the different small letters in the columns of the table, separately for year, are significantly different at $p \leq 0.05$

*, **, *** significant at the 0.05, 0.01 and 0.001 probability level, respectively

ns – not significant at the 0.05 probability level

the content of protein in kernels was highest. A positive impact of high temperature on protein synthesis during the grain filling phase in durum wheat was reported by De Stefanis et al. (2002). When hydration of wheat at the tillering and stem elongation stages (May 2009 and 2011) was comparable to the multiannual average value, soil urea application at GS 23 and GS 31 (T_1) increased the protein content in kernels in comparison to the other fertilization options. In these seasons, the biggest differences in grain protein content were demonstrated between the T_1 and T_4 fertilization variants, respectively 5.87 and 5.56%. However, in May 2010 when the precipitation level was over twice as high as the average multiannual precipitation level, soil urea application with Azofoska at GS 23 and urea at GS 31 resulted in a significant reduction of kernel protein content compared to the other fertilization variants (T_1, T_3, and T_4) by 3.18, 3.48 and 4.01%, respectively. Different nitrogen sources, such as urea, nitrate-N and ammonium-N, may affect the protein and quality of wheat mainly by modifying the uptake of nitrogen by plants (XUE et al. 2016a). The results of studies conducted by BLY and WOODARDA (2003) demonstrate that the total protein content is modified not only by the nitrogen dose but also by applying it at divided doses and at different time points. However, the finding of studies on the impact of divided nitrogen doses on the protein content are not unequivocal. The studies by SCHULZ et al. (2015) indicate a lack of the impact of divided nitrogen dose on the protein content in grain. In contrast, the results reported by XUE et al. (2016b) showed that dividing the nitrogen dose resulted in an increased content of cereal proteins, although the effect was more evident when nitrate-N was applied instead of urea. RANSOM et al. (2016) indicate that foliar urea ammonium nitrate application after flowering may increase the protein content in spring wheat as compared to applying a similar nitrogen dose at sowing. The collected data shows that divided nitrogen doses affects the protein content in kernels more than the grain yield, which was confirmed by the results reported in studies by BLANDINO et al. (2015b). Wheat yield and reaction of protein to nitrogen are divided into three phases: in the first phase, the yield of grains increases while the protein content drops as starch accumulation is more reactive than that of protein. In the second phase, the yield and protein content increase in response to increased nitrogen level and, in the third phase, the yield is maximized by nitrogen, but the protein content still increases together with higher N values (BROWN et al. 2005). In the presented studies, in 2010 the wheat crop yield was highest at the highest protein content, which may indicate the second reaction phase. In comparison with Radunia, the Parabola variety had higher protein levels in all growing seasons, with the highest protein content recorded in the season in which the grain yield was lowest, which may implicate a protein dilution effect in the other growing seasons. Considering the qualitative requirements for wheat grain for the milling industry (the minimum level of protein in food wheat should be 120 g kg^{-1} DM), it was found that these requirements were met in all fertilization variants. Like for protein, the gluten content and Zeleny index were substantially modified by nitrogen fertilization, weather conditions in the individual growing seasons and the variety. The highest gluten level in wheat kernels in the 2009 and 2011 growing seasons was demonstrated with soil urea application at GS 23 and GS 31 (T_1) (though in 2009 the difference was insignificant) whereas in 2010 it was T_1 with urea applied to soil and T_3 with both soil and foliar application. The gluten content in Parabola grain was significantly higher than in the Radunia variety. The reaction of wheat, expressed with the Zeleny index, to different nitrogen fertilization strategies differed in each growing season. However, the Zeleny index was found to be substantially reduced when urea was applied together with Azofoska at GS 23 (T_2) in the first two wheat growing seasons. The value of this index was also much affected by the variety. For the first two growing seasons, it was demonstrated that the Zeleny index was significantly higher for Parabola, while in the third season, it was higher for Radunia. ABBAD et al. (2004) showed that the sedimentation index was substantially higher when nitrogen was applied during flowering. Different variants of nitrogen fertilization did not impact the content of ash in kernels. The variety influenced the ash level in the first two growing seasons, with a higher content recorded in the Parabola wheat grain.

Flour yield (FY) was determined by the applied fertilization variants and the wheat variety (Table 6). In two growing seasons (2009 and 2011), the highest FY value was produced with foliar urea application at GS 31 and GS 52 (T_3). In these seasons, the grain with the highest TW was also harvested with the same fertilization treatment, which translated into the largest flour extraction rate. Higher flour extraction was always reported for the Radunia wheat variety. As with the results for grain protein, in 2009 and 2011 soil urea fertilization at GS 23 and GS 31 (T_1) increased the flour protein level in comparison with the other fertilization variants. However, in 2010 the highest protein content was demonstrated in flour produced from the grain after foliar urea application (T_3). In each wheat growing season, the flour from Parabola wheat had a significantly higher protein content.

None of fertilization strategies affected the ash content in flour, flour water absorption or the P/L index. These parameters depended mainly on the wheat variety and growing season in which they were cultivated. Contrary to Radunia, the Parabola wheat flour was characterized with higher values of these parameters. The results of the present studies that did not demonstrate significant differences in the P/L values are consistent with the findings reported by BLANDINO et al. (2016) and FUERTES-MENDIZÁBAL et al. (2010).

Table 6

Effect of N strategies and cultivar on flour yield and some flour quality traits in years 2009, 2010 and 2011

Years	Factor	Treat-ment	Flour yield [%]	Protein content [g kg^{-1} at 12% mb]	Ash content [% DM]	Water absorption [%]	W [J 10^{-4}]	P/L [-]
2009	N (*A*)	T_1	67.6^{ab}	125.1^{a}	0.61^{a}	61.2^{a}	427^{a}	0.32^{a}
		T_2	67.2^{b}	119.4^{c}	0.61^{a}	60.2^{a}	404^{c}	0.22^{a}
		T_3	68.3^{a}	124.1^{ab}	0.61^{a}	61.2^{a}	418^{b}	0.35^{a}
		T_4	67.1^{b}	122.7^{b}	0.60^{a}	61.0^{a}	415^{b}	0.28^{a}
		P(F)	**	***	ns	ns	***	ns
	cultivar (*B*)	Parabola	66.1^{b}	128.8^{a}	0.65^{a}	63.8^{a}	441^{a}	0.38^{a}
		Radunia	69.0^{a}	116.9^{b}	0.57^{b}	58.0^{b}	391^{b}	0.22^{a}
		P(F)	***	***	***	***	***	ns
	A x *B*	P(F)	*	*	ns	ns	**	ns
2010	N (*A*)	T_1	68.7^{ab}	124.2^{b}	0.64^{a}	59.0^{a}	378^{a}	0.63^{a}
		T_2	69.2^{a}	122.3^{c}	0.64^{a}	58.1^{a}	370^{a}	0.68^{a}
		T_3	68.2^{bc}	125.7^{a}	0.63^{a}	59.2^{a}	370^{a}	0.67^{a}
		T_4	67.9^{c}	124.4^{b}	0.63^{a}	59.1^{a}	370^{a}	0.58^{a}
		P(F)	***	***	***	ns	ns	ns
	cultivar (*B*)	Parabola	67.6^{b}	126.4^{a}	0.67^{a}	61.0^{a}	377^{a}	1.12^{a}
		Radunia	69.5^{a}	121.9^{b}	0.60^{b}	56.7^{b}	368^{b}	0.17^{b}
		P(F)	***	***	***	***	***	***
	A x *B*	P(F)	**	***	ns	ns	ns	ns
2011	N (*A*)	T_1	68.5^{b}	125.2^{a}	0.64^{a}	62.7^{a}	359^{a}	1.62^{a}
		T_2	69.6^{ab}	120.4^{b}	0.64^{a}	61.5^{a}	344^{b}	1.47^{a}
		T_3	70.2^{a}	119.1^{b}	0.64^{a}	62.3^{a}	339^{bc}	1.65^{a}
		T_4	68.7^{b}	119.1^{b}	0.64^{a}	62.3^{a}	332^{c}	1.62^{a}
		P(F)	**	***	ns	ns	***	ns
	cultivar (*B*)	Parabola	68.4^{b}	122.2^{a}	0.67^{a}	64.1^{a}	343^{a}	2.11^{a}
		Radunia	70.1^{a}	119.7^{b}	0.61^{b}	60.3^{b}	344^{a}	1.07^{b}
		P(F)	***	***	***	***	ns	***
	A x *B*	P(F)	*	ns	ns	ns	**	ns

a, *b*, *c* – averages designated by the different small letters in the columns of the table, separately for year, are significantly different at $p \leq 0.05$

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability level, respectively

ns – not significant at the 0.05 probability level

Soil urea fertilization at the tillering and stem elongation stages (T_1) increased the W index in comparison with the other fertilization variants. A similar effect was reported by BLANDINO et al. (2016) with applying ammonium nitrate to soil at the initial phase of heading.

Conclusions

The results of nitrogen fertilization strategies (time of application, type of fertilizer, and application techniques), expressed as the yield and the properties of grain and flour depended on weather conditions. Soil urea application at doses of 40 kg ha^{-1} at the tillering and stem elongation stages mostly increased the protein content in grain and flour, vitreous aspect of grain, gluten content and alveographic – *W* parameter compared to the other fertilization variants. Foliar application of urea at doses of 20 kg N ha^{-1} at the stem elongation and heading stages produced the highest value of grain test weight in each growing season. Soil application of the fertilizer with macronutrients and trace minerals generally produced worse grain parameters, especially the protein grain content and the Zeleny index. The weather conditions most affected the grain yield and such grain and flour parameters as kernel weight, kernel diameter, hardness index and P/L index. Our research shows, that soil urea application at a dose of 40 kg ha^{-1} at the elongation stages contributes to better grain quality than foliar application of urea at doses of 20 kg N ha^{-1} at the stem elongation and heading stages.

References

ABBAD A.J., LLOVERAS., MICHLENA A. 2004. *Nitrogen fertilization and foliar urea effects on Durum wheat yield and quality and on residual soil nitrate in irrigated Mediterranean conditions*. Field Crops Res., 87: 257–269.

ABEDI T., ALEMZADEH A., KAZEMEINI S.A. 2010. *Wheat yield and grain protein response to nitrogen amount and timing*. Aust. J. Crop Sci., 5: 330–336.

BLANDINO M., VACCINO P., REYNERI A. 2015a. *Late-season nitrogen increases improver common and durum wheat quality*. Agron. J., 107: 680–690.

BLANDINO M., MARINACCIO F., VACCINO P., REYNERI A. 2015b. *Nitrogen fertilization strategies suitable to achieve the quality requirements of wheat for biscuit production*. Agron. J., 107: 1584–1594.

BLANDINO M., MARINACCIO F., REYNERI A. 2016. *Effect of late-season nitrogen fertilization on grain yield and on flour rheological quality and stability in common wheat, under different production situations*. Ital. J. Agron., 11: 107–113.

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

BROWN B., WESTCOTT M., CHRISTENSEN N., PAN B., STARK J. 2005. *Nitrogen management for hard wheat protein enhancement*. A Pacific Northwest Extension Pub., Idaho Univ., Washington State Univ., PNW 578, pp.: 1–14.

CAMPBELL G.M., SHARP C., WALL K., MATEOS-SALVADOR F., GUBATZ S., HUTTLY A., P. SHEWRY. 2012. *Modelling wheat breakage during roller milling using the Double Normalised Kumaraswamy Breakage Function. Effects of kernel shape and hardness*. J. Cereal Sci., 55: 415–425.

DE STEFANIS E., SGRULETTA D., DE VITA P., PUCCIARMATI S. 2002. *Genetic variability to the effects of heat stress during grain filling on durum wheat quality*. Cereal Res. Commun., 30: 117–124.

DICK C.D., THOMPSON N.M., EPPLIN F.M., ARNALL D.B. 2016. *Managing late-season foliar nitrogen fertilization to increase grain protein for winter wheat.* Agron. J., 108: 2329–2338.

ERCOLI L., MASONI A., PAMPANA S., MARIOTTI M., ARDUINI I. 2013. *As durum wheat productivity is affected by nitrogen fertilisation management in Central Italy.* Eur. J. Agron, 44: 38–45.

FUERTES-MENDIZÁBAL T., AIZPURUA A., GONZÁLEZ-MORO M.B., ESTAVILLO J.M. 2010. *Improving wheat breadmaking quality by splitting the N fertilizer rate.* Eur. J. Agron., 33: 52–61.

HELLEMANS T., LANDSCHOOT S., DEWITTE K., VAN BOCKSTAELE F., VERMEIR P., EECKHOUT M., HAESAERT G. 2018. *Impact of crop husbandry practices and environmental conditions on wheat composition and quality*. A Review. J. Agric. Food Chem., 66: 2491–2509.

KNAPOWSKI T., SPYCHAJ-FABISIAK E., LOŽEK O. 2010. *Foliar nitrogen fertilization as a factor determining technological parameters of winter wheat.* Ecol. Chem. Eng. A, 17: 771–779.

MCGUIRE A.M., BRYANT D.C., DENISON R.F. 1998. *Wheat yields, nitrogen uptake, and soil moisture following winter legume cover crop vs. fallow.* Agron. J., 90: 404–410.

OURY F.X., LASME P., MICHELET C., ROUSSET M., ABECASSIS J., LULLIEN-PELLERIN V. 2015. *Relationships between wheat grain physical characteristics studied through near-isogenic lines with distinct puroindoline-b allele.* Theor. Appl. Genet., 128: 913–929.

PAGANI M.A., MARTI A., BOTTEGA G. 2014. *Wheat milling and flour quality evaluation,* pp. 19–53: in: *Bakery Products Science and Technology.* Eds. W. ZHOU, Y.H. HUI, I. DE LEYN, M.A. PAGANI, C.M. ROSELL, J.D. SELMAN, N. THERDTHAI. Second Edition. John Wiley and Sons, Ltd, Chichester, UK.

RALCEWICZ M., KNAPOWSKI T., KOZERA W., BARCZAK B. 2009. *Technological value of spring wheat of Zebra cultivar as related to the way of nitrogen and magnesium application.* J. Cent. Eur. Agric., 10(3): 223–232.

RANSOM J., SIMSEK S., SCHATZ B., ERIKSMOEN E., MEHRING G., MUTUKWA I. 2016. *Effect of a post-anthesis foliar application of nitrogen on grain protein and milling and baking quality of spring wheat.* Am. J. Plant Sci., 7: 2505–2514.

RUSKE R.E., GOODING M.J., JONES S.A. 2003. *The effects of adding picoxystrobin, azoxystrobin and nitrogen to a triazole programme on disease control, flag leaf senescence, yield and grain quality of winter wheat.* Crop Prot., 22: 975–987.

SCHULZ R., MAKARY T., HUBERT S., HARTUNG K., GRUBER S., DONATH S., DÖHLER J., WEISS K., EHRHART E., CLAUPEIN W., PIEPHO H.P., PEKRUN C., MÜLLER T. 2015. *Is it necessary to split nitrogen fertilization for winter wheat? On-farm research on Luvisols in South-West Germany.* J. Agric. Sci., 153: 575–587.

STĘPIEŃ A., WOJTKOWIAK K. 2016. *The effect of foliar application of Cu, Zn and Mn on the yield and quality indicators of the grain of winter wheat.* Chil. J. Agr. Res., 76: 220–227.

XUE C., RÜCKER S., KOEHLER P., OBENAUF U., MÜHLING K.H. 2016a. *Late nitrogen application increased protein concentration but not baking quality of wheat.* J. Plant Nutr. Soil Sci., 179: 591–601.

XUE C., SCHULTE AUF'M ERLEY G., ROSSMANN A., SCHUSTER R., KOEHLER P., MUEHLING K.H. 2016b. *Split nitrogen application improves wheat baking quality by influencing protein composition rather than concentration.* Front Plant Sci., 7: 738.

ZHANG Y., TANG J., YAN J., XIA X., HE Z. 2009. *The gluten protein and interactions between components determine mixograph properties in an F6 recombinant inbred line population in bread wheat.* J. Cereal Sci., 50: 219–226.

ZHANG Y., QUAIL K., MUGFORD D.C., HE Z.H. 2005. *Milling quality and white salt noodle color of Chinese winter wheat cultivars.* Cereal Chem., 82: 633–638.