Evaluation of the effect of nitrogen fertilizers on nitrogen use efficiency in grain maize

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Abstract

The study presents the results of 3-year field experiments aimed at assessing the effect of (i) nitrogen dose (N_f), (ii) balanced for N_{min} content (mineral nitrogen), depending on its soil profile distribution and the influence of (iii) nitrogen fertilizer type on maize grain yield and partial factor productivity of fertilizer nitrogen ($PFPF_N$). Nitrogen applied in the form of mineral fertilizer (N_f) is characterized by greater efficiency in comparison to N_{min} contained in soil, which is manifested by a significantly higher grain yield. Slow-release nitrogen fertilizers, such as ammonium sulfate or urea, are the optimal choice for maize fertilization, as they are potentially more suited to the rhythm of its vegetation. This is evidenced by the higher partial factor productivity of fertilizer nitrogen ($PFPF_N$). The productivity of fertilizer nitrogen (N_f) depends on the content of mineral nitrogen present in the deepest soil layers. Climatic conditions, mainly atmospheric precipitation, shape grain yield and partial factor productivity of fertilizer nitrogen ($PFPF_N$).

Abbreviations

dt – decitonnes
N – nitrogen
N_f – nitrogen dose
N_{min} – mineral nitrogen
$PFPF_N$ - partial factor productivity of fertilizer nitrogen

Introduction

Nitrogen (N) is one of the basic nutrients determining the intensification of plant production (Scharf *et al.*, 2002; Szulc *et al*. 2020). Proper and rational fertilization with this component increases not only the height and stability of crop yielding, but also improves the biological and technological crop value, soil chemical fertility and does not cause negative effects in the natural environment (Andraski *et al.*, 2000; Szulc and Bocianowski, 2013; Grzebisz and Łukowiak, 2021). Maize is characterized by a high natural capacity to absorb nutrients supplied on a regular basis (as a result of fertilization); however, high yields cannot be expected without increasing soil fertility level and simultaneous pH regulation. Therefore, doses of mineral fertilizers, including nitrogen, should correspond to the nutritional needs, taking into account the amount of components that can be absorb from the soil (Zeidan *et al.*, 2006). Nitrogen in maize cultivation should be used at a dose suitable for production purposes, but simultaneously meeting environmental standards (Ciampitti and Vyn, 2012). Formation of basic grain yield component, i.e. the ear, begins in maize as early as the 3-leaf stage (BBCH 13) and lasts to the 5-leaf stage (BBCH 15). The number of leaves and ears with spikelet primordia is determined during this period (Viet *et al.*, 1993). Hence, it is very important that maize plants are properly nourished in the juvenile stage and show good initial growth vigor (Szulc, 2013). Numerous scientific studies showed (Subedi and Ma, 2005; Fageria and Baligar, 2005; Szulc, 2013) that errors in maize nitrogen nutritional status up to the 6-leaf stage reduced maize grain yield even by 12%. Binder *et al.* (2000) demonstrated that delaying nitrogen application to the 6-leaf stage reduced grain yield by 12%. Szulc *et al.* (2011) reported that proper plant nutrition in the juvenile stage ensured the utilization of the full yield potential of maize hybrids. Maize grain yield has also been positively correlated with dry mass

Table 1 - Nitrogen fertilization scheme employed in the experiment

Factor and factor levels			Years		
			2012	2013	2014
Ammonium nitrate	Dose of kg N ha^{-1}	0-0.3m			
		0-0.6m	150	150	150
		0-0.9m			
		0-0.3m	150 - 63.8 N_{min}	150 – 65.5 N_{min}	150 – 61.5 N_{min}
		0-0.6m	150 - 99.3 N_{min}	150 – 103.7 N_{min}	150 – 98.7 N_{min}
		0-0.9m	150 - 135.2 N_{min}	150 – 134.3 N_{min}	150 – 137.7 N_{min}
Urea	Dose of kg N ha^{-1}	0-0.3m			
		0-0.6m	150	150	150
		0-0.9m			
		0-0.3m	150 - 63.8 N_{min}	150 - 65.5 N_{min}	150 - 61.5 N_{min}
		0-0.6m	150 - 99.3 N_{min}	150 - 103.7 N_{min}	150 - 98.7 N_{min}
		0-0.9m	150 - 135.2 N_{min}	150 - 134.3 N_{min}	150 - 137.7 N_{min}
Ammonium sulphate	Dose of kg N ha^{-1}	0-0.3m			
		0-0.6m	150	150	150
		0-0.9m			
		0-0.3m	150 - 63.8 N_{min}	150 - 65.5 N_{min}	150 - 61.5 N_{min}
		0-0.6m	150 - 99.3 N_{min}	150 - 103.7 N_{min}	150 - 98.7 N_{min}
		0-0.9m	150 - 135.2 N_{min}	150 - 134.3 N_{min}	150 - 137.7 N_{min}
Calcium nitrate	Dose of kg N ha^{-1}	0-0.3m			
		0-0.6m	150	150	150
		0-0.9m			
		0-0.3m	150 - 63.8 N_{min}	150 - 65.5 N_{min}	150 - 61.5 N_{min}
		0-0.6m	150 - 99.3 N_{min}	150 - 103.7 N_{min}	150 - 98.7 N_{min}
		0-0.9m	150 - 135.2 N_{min}	150 - 134.3 N_{min}	150 - 137.7 N_{min}

of the aerial part of a single plant and dry matter yield in the juvenile stage (Szulc and Bocianowski, 2012a; Szulc, 2013). A very important observation is that determining soil nutrient fertility (soil analysis) and regulating soil pH are the basis for rational maize fertilization. Light soils, which are inherently less fertile and more susceptible to drought (Eshel and Beeckman, 2013), are particularly prone to acidification. Meanwhile, maize is increasingly grown on class V soils, as the acreage under maize cultivation increases. Proper pH regulation is a prerequisite to obtain sufficiently high and stable maize yields on such soils. Maize development and yielding is limited on soils requiring liming due to the poorer availability of many nutrients. Moreover, aluminum (Al^{3+}) and manganese (Mn^{2+}) ions are activated in the acidic soil solution and exert toxic effects on roots, forcing plants to continuously regenerate dying roots (Eshel and Beeckman, 2013). In addition, a decrease in soil pH poses a potential threat of nitrate leaching, which on the one hand results in lower efficiency of nitrogen application, and, on the other hand, is a potential danger to the natural environment through soil contamination with this nutrient (Andraski *et al.*, 2000; Kim *et al.*, 2009). Therefore, determining the nitrogen dose in maize cultivation is not easy, because it requires taking into account mineral nitrogen (N_{min}) present in the soil at the beginning of vegetation, as well as the amount of nitrogen released from soil resources during the growing season (Cui *et al.*, 2008).

Therefore, the aim of the study was to elucidate the effect of nitrogen fertilizer form, nitrogen dose and N_{min} content in three soil profiles on maize yield and partial factor productivity of fertilizer nitrogen ($PFPF_N$).

Material and methods

Experimental field trials

The field experiment was carried out at the Department of Agronomy of Poznań University of Life Sciences, on the fields of the Experimental and Educational Unit in Swadzim (52°26' N; 16°45' E) in the years 2012-2014. The experiments were conducted in a split-split-plot system with three experimental factors in 4 field replicates. The experiment tested the effect of four nitro-

Table 2 - Mean monthly air temperature and monthly sum of precipitation in Swadzim in 2012-2014

Years	Temperature [°C]							
	IV	V	VI	VII	VIII	IX	X	Mean-Sum
2012	9.3	16.3	17.0	20.0	19.8	15.0	8.6	15.4
2013	8.9	15.6	18.4	22.0	20.2	13.2	10.8	15.6
2014	11.4	14.6	17.9	23.2	18.8	16	11.2	16.1
Years	**Rainfall [mm]**							
2012	17.4	84.4	118.1	136.2	52.7	28.4	36.4	473.6
2013	10.5	95.5	114.9	52.9	32.4	75.9	15.3	397.4
2014	50.3	80.7	44.6	51.5	56.5	39.2	29.0	351.8

gen fertilizers [ammonium nitrate (NH_4NO_3), urea ($CO(NH_2)_2$), ammonium sulphate ($(NH_4)_2SO_4$), calcium nitrate $Ca(NO_3)_2$], two nitrogen doses of 150 kg N ha^{-1} (N_f) and 150 kg N ha^{-1} minus Nmin soil content (sum of NH_4 + NO_3) (150-Nmin)] and Nmin content in soil profiles (0-0.3 m, 0-0.6 m, 0-0.9 m) on yield and production efficiency of fertilizer nitrogen ($PFPF_N$) in maize cultivation. The same level of supplemental fertilization was adopted for all experimental objects: 70 kg P_2O_5 ha^{-1} and 130 kg K_2O ha^{-1}. Phosphorus was applied in the form of triple granulated superphosphate; potassium in the form of potassium salt. The nitrogen dose of 150 kg N ha^{-1} in the form of fertilizer was applied according to the levels of the 1st order factor. The mineral nitrogen content in the soil in the spring was measured at three levels (layers) before establishing the experiment. N_f doses were determined on this basis, as shown in Table 1. The experiment used Fortran (FAO 210-220) maize cultivar (Euralis Semences, S.C. single hybrid, grain type: flint). Soil abundance in basic macronutrients (P, K, Mg) was on the average level in individual years of the study, while its pH, measured in 1 M KCl, ranged from 5.4 in 2012 to 6.0 in 2014. The Fortran cultivar was the most genetically similar to SY Mascotte, whereas the lowest similar to NK Cooler and PR 39 K 13 (Nowosad *et al.*, 2017).

Grain moisture determination

Random samples were collected from the threshing mass of the grain on each plot to determine grain moisture. The measurements were performed using a Super Matic electronic moisture meter. The weight of the samples collected to determine the moisture content was 250 grams

Table 3 - Dry grain yield [dt/ha]

Factor - Factor levels		Years			Mean
		2012	**2013**	**2014**	
Type of nitrogen fertilizer	Ammonium nitrate	94.48	87.35	56.36	79.40
	Urea	95.99	90.11	59.08	81.73
	Ammonium sulphate	99.46	92.69	63.43	85.19
	Calcium nitrate	92.36	86.97	55.71	78.35
$LSD_{0.05}$		3.716	n.s.	n.s.	3.065
Dose of kg N ha^{-1}	150 (N_f)	101.35	92.04	59.87	84.42
	150-N_{min}	89.79	86.52	57.42	77.91
$LSD_{0.05}$		3.718	3.055	n.s.	1.790
Content of N_{min} kg ha^{-1}	0-0.3m	91.878	91.20	60.52	81.19
	0-0.6m	96.04	91.38	60.13	82.52
	0-0.9m	98.81	85.27	55.28	79.79
$LSD_{0.05}$		2.341	2.833	2.591	1.174
Mean		95.57	89.28	58.64	81.17
Control 0 kg N ha^{-1}		77.17	67.33	46.65	63.72

n.s. – non-significant difference

Table 4 - Partial factor productivity of fertilizer nitrogen [kg grain kg^{-1} N]

Factor	Factor levels	Years 2012	2013	2014	Mean
Type of nitrogen fertilizer	Ammonium nitrate	185.72	163.02	118.94	155.89
	Urea	187.67	167.27	121.02	158.65
	Ammonium sulphate	193.62	167.55	121.69	160.95
	Calcium nitrate	183.01	162.27	116.12	153.80
$LSD_{0.05}$		2.486	n.s.	2.019	3.214
	150 (N_f)	67.80	61.36	39.91	56.36
	150-N_{min}	307.20	268.70	198.97	258.29
$LSD_{0.05}$		8.810	11.963	15.719	6.711
Content of N_{min} kg ha^{-1}	0-0.3m	82.12	84.43	54.70	73.75
	0-0.6m	123.11	127.04	78.47	109.54
	0-0.9m	357.28	283.62	225.16	288.68
$LSD_{0.05}$		8.945	9.386	12.748	5.959
Mean		187.50	165.03	119.44	157.32

n.s. – non-significant difference

Partial factor productivity of fertilizer nitrogen, $PFPF_N$

$PFPF_N$ = Y/Nr, kg grain kg N (Szczepaniak, 2016)

Meteorological conditions

Thermal and humidity conditions during the growing season during the years of the experiment were very diverse for maize growth and development (Table 2). Total precipitation in the IV-IX period was 473.6 mm in 2012, 397.4 mm in 2013 and 351.8 mm in 2014. The average daily air temperature measured at a height of 2 m ranged from 15.4°C in 2012 to 16.1°C in 2014. Generally, it can be concluded that in two growing seasons, i.e., 2012 and 2013, thermal and humidity conditions were favorable for the growth and development of maize. The humidity conditions for maize were worse in the third year of research (2014) due to the lower total precipitation in the growing season.

Soil chemical analyses

The assessment of macronutrient contents, pH and mineral nitrogen in the soil was carried out in accordance with the research procedure/standard (OSCHR in Poznań) before establishing the experiment (0-0.3m, 0-0.6m, 0-0.9m): P2O5 – PB.64 ed. 6 from 17.10.2008; K_2O – PB.64 ed. 6 from 17.10.2008; Mg – PB.65 ed. 6 from17.10.2008; pH – PB.63 ed. 6 from 17.10. 2008; N-NH_4 – PB.50 ed. 6 from 17.10.2008; N-NO_3 – PB.50 ed. 6 from 17.10.2008
Quantity Nmin N ha^{-1} = Nmin conent in mg 100 g dry weight x 45 (Szulc, 2012), where: 45 – coefficient for light soil

Statistical analysis

The obtained results were subjected to one-way analysis of variance" not "single-factor variance analysis for orthogonal factor experiments, and subsequently synthesis for multi-year experiments was performed. Significance of differences was assessed at $\alpha = 0.05$ using the Student's *t*-test. Statistical processing of the acquired data was performed using the STATPAK program.

Results and discussion

Grain yield

The results indicated the significance of the variation in weather conditions between the study years on maize yield (Table 3). On average for the experimental years, maize had the lowest yield in 2014 (58.64 dt ha^{-1}), which was characterized by the lowest total atmospheric precipitation in the growing season (351.8 mm). On the other hand, the average highest grain yield was obtained in 2012 (95.57 dt ha^{-1}), which was characterized by the highest precipitation in the period of maize growth and development. It should be noted that as much as 136.2 mm of atmospheric precipitation was recorded that year during maize flowering (July) (Table 2). The above statement has confirmed that maize grain yield is largely determined by water availability. In dry years, the unit productivity of nitrogen fertilizer is lower, which in turn indicates low remobilization efficiency of fertilizer nitrogen during grain filling (Szulc, 2012; Szczepaniak, 2016). Sinclair and Rufty (2012) reported that increased plant yielding resulted from a combination of good cultivar, water and nitrogen availability. Water

Table 5 - Grain moisture content during harvesting [%]

Factor Factor levels		Years			Mean
		2012	2013	2014	
Type of nitrogen fertilizer	Ammonium nitrate	23.99	25.55	26.14	25.23
	Urea	23.79	25.06	25.87	24.90
	Ammonium sulphate	24.32	25.04	27.17	25.51
	Calcium nitrate	23.85	25.00	26.55	25.13
$LSD_{0.05}$		n.s.	n.s.	0.884	0.330
	150 (N_f)	24.06	25.08	26.62	25.26
	150-N_{min}	23.90	25.25	26.24	25.13
$LSD_{0.05}$		n.s.	n.s.	0.370	n.s.
Content of N_{min} kg ha^{-1}	0-0.3m	24.01	25.21	26.52	25.25
	0-0.6m	23.93	24.92	26.18	25.01
	0-0.9m	24.01	25.36	26.58	25.32
$LSD_{0.05}$		n.s.	n.s.	n.s.	n.s.
Mean		23.98	25.16	26.43	25.19
Control 0 N kg ha^{-1}	24.15	25.85	26.55	25.52	

n.s. – non-significant difference

deficiencies in the plant limit the supply of leaf assimilates, which accumulate in the form of starch at early stages of kernel development, leading to ovary necrosis and discarding of young kernels. The number of kernels in an ear is determined during the flowering of female flowers (Cirilo and Andrade, 1994), while conditions just before this stage play the main role in shaping this component of grain yield. Both water stress and nutrient shortage in the plant extend the period between full pollination and flowering of female flowers. If this period is too long, pollen is released by male flowers before female flowers can accept it (Jacobs and Pearson, 1991). The number of kernels per ear is likely to be reduced due to an increase in the number of unfertilized individual flowers (Bänziger *et al.*, 2002). Therefore, the lowest yield of maize grain obtained in the last year of the study (2014) should be explained by this factor. The type of nitrogen fertilizer significantly modified the amount of grain yield only in one (2012) of three years of the experiment. Significantly higher grain yield was obtained for ammonium sulfate in relation to other nitrogen fertilizers. The same relationship, as described above, was observed in 2013 and 2014, but this difference was not confirmed statistically by the analysis of variance (Table 3). The highest average grain yield in the experimental years was obtained for ammonium sulfate (85.19 dt ha^{-1}) compared to other nitrogen fertilizers, for which this value was statistically similar. Hence, the dynamics of growth and nutrient accumulation by maize implies a nitrogen fertilization system with slow-release fertilizers, e.g., ammonium sulfate, as potentially more responsive to the rhythm of maize vegetation (Szulc and Bocianowski, 2012b). Grain yield in the current study also depended, in synthetic terms, on the nitrogen dose (N_f) and N_{min} content in soil (Table 3). Grain yield decreased with increasing mineral nitrogen content in the soil (lower dose of mineral fertilizer). It should also be noted that the value of this trait was statistically lower for N_{min} soil content in the 0-0.9 m profile compared to mineral nitrogen content in the 0-0.3 m and 0-0.6 m soil profiles, for which maize grain yield was statistically at the same level (Table 3). Grain yield was also significantly dependent on the interaction of nitrogen fertilizer type and nitrogen dose (Fig. 1). Application of the full dose of nitrogen fertilizer (N_f) resulted in a significantly higher maize grain yield for all nitrogen fertilizers, except calcium nitrate, compared to the nitrogen dose balanced for Nmin content in soil. In turn, ammonium sulfate was characterized by a significantly higher grain yield (12.06 dt ha^{-1}) for the tested nitrogen doses compared to ammonium nitrate (5.17 dt ha^{-1}), urea (6.50 dt ha^{-1}) and calcium nitrate (2.32 dt ha^{-1}) (Fig. 1).

Partial factor productivity of fertilizer nitrogen ($PFPF_N$)

Nitrogen is, assuming the same meteorological conditions for a given locality, the key growth factor limiting yield (Evans and Fischer, 1999). Hence, the amount of Nf or the whole N input at the beginning of the growing season becomes the principal independent variable, affecting both the plant growth rate during the growing season and its yield (Szulc *et al.* 2020; Szulc *et al.* 2021). Nitrogen productivity from nitrogen fertilizers was gre-

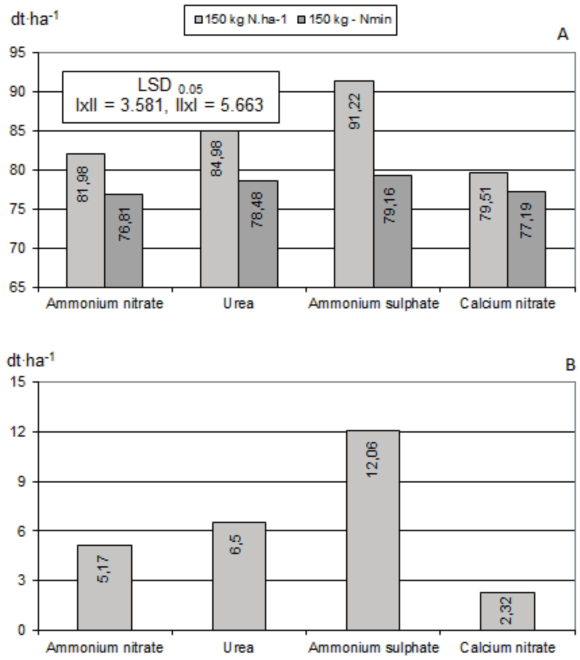

Fig. 1 - Influence of nitrogen fertilizer type and nitrogen dose on dry grain yield (A), increase in dry grain yield (B); (average for years 2012-2014)

atly affected by weather patterns during the maize growing season (Table 4). The lowest average productivity of fertilizer nitrogen for the experimental years was recorded in 2014, which was characterized by the lowest total atmospheric precipitation in the growing season. In turn, the average highest yield of fertilizer nitrogen was obtained in 2012, which was characterized by the highest precipitation during maize growth and development. Poland, based on climatic criteria, belongs to a zone characterized by droughts during the growing season with frequent high air temperatures (Metzger *et al.*, 2005). Consequently, plants are exposed to biotic stresses during the growing season. Synthetically, partial factor productivity of fertilizer nitrogen ($PFPF_N$) significantly depended on the type of nitrogen fertilizer, nitrogen dose (N_f) and N_{min} content in soil (Table 4). Urea and ammonium sulfate were characterized by the highest partial factor productivity of fertilizer nitrogen compared to ammonium nitrate and calcium nitrate. A significantly higher productivity of nitrogen doses was demonstrated at the N_{min} dose of 150 compared to the dose of fertilizer nitrogen (N_f) (Table 4). Partial factor productivity of fertilizer nitrogen ($PFPF_N$) increased from 73.75 kg grain kg N (0-0.3 m) to 288.68 kg grain kg N (0-0.9 m) with a linear increase of Nmin content in soil (Table 4). The results indicated that nitrogen content present in the deepest soil layers determined the productivity of nitrogen fertilizer. The higher the nitrogen content in these layers, the higher the productivity of fertilizer nitrogen (N_f). Partial factor productivity of fertilizer nitrogen ($PFPF_N$) was also significantly dependent in this study on the interaction of nitrogen dose and N_{min} content in soil (Fig. 2). The productivity of fertilizer nitrogen increased significantly with increasing soil N_{min} content. This relationship was described in a linear fashion and the difference was as follows: 0-0.3 m (35.68 kg grain kg N), 0-0.6 m (105.21 kg grain kg N), 0-0.9 m (464.91 kg grain kg N). The productivity of fertilizer nitrogen (N_f), regardless of N_{min} content in soil, was statistically at the same level (Fig. 3).

Grain moisture

The present study showed that grain moisture content during harvest was significantly dependent on meteorological conditions during the maize growing seasons (Table 5). The highest average water content for the experimental years was recorded for maize grain collected in 2014 (26.43%), while the lowest for maize cultivated in 2012 (23.98%). In synthetic terms, only the type of nitrogen fertilizer significantly modified water content in the grain. Maize grain fertilized with urea (24.90%) had the lowest value of this trait, while grain fertilized with ammonium sulfate (25.51%) had the highest, and the difference was 0.61% (Table 5). It is worth noting that the highest maize grain moisture was recorded in the dry year of 2014, in which maize yielded the worst. Szulc and Bocianowski (2011) showed a

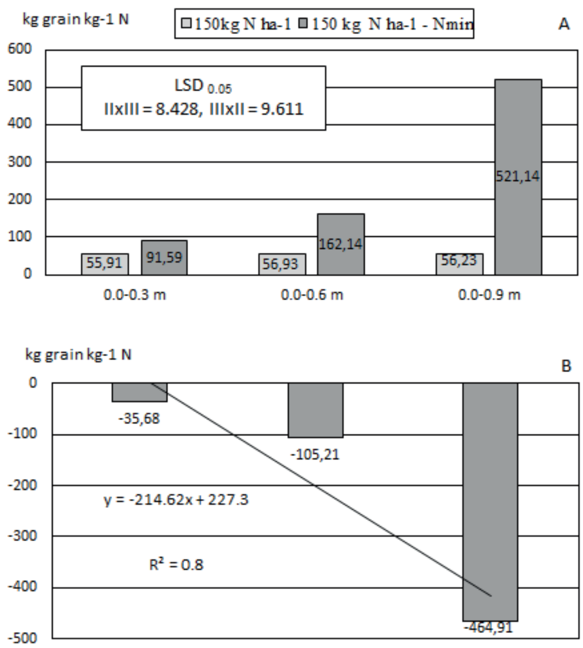

Fig. 2 - Influence of the type of nitrogen fertilizer and nitrogen dose on the partial factor productivity of fertilizer nitrogen $PFPF_N$ (A); increase in nitrogen production efficiency (B); (average for years 2012-2014)

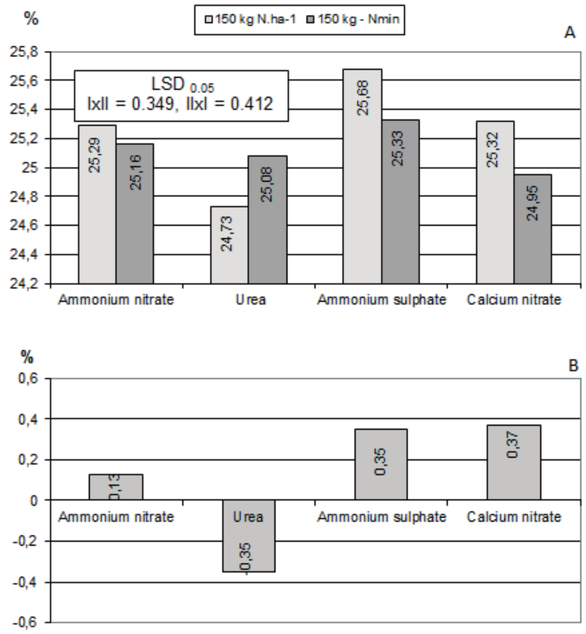

Fig. 3 - Influence of nitrogen fertilizer type and nitrogen dose on grain moisture content (A), increase in grain moisture content (B); (average for years 2012-2014)

similar correlation in the previous study with respect to grain yield and water content. Grain moisture during harvest was also significantly modified by the interaction of nitrogen fertilizer type and nitrogen dose (Fig. 3). The application of ammonium nitrate, ammonium sulfate and calcium nitrate at a dose of 150 kg N ha^{-1} [N_f] resulted in higher grain moisture compared to a similar nitrogen dose of 150 kg N ha^{-1}, but balanced with Nmin content in soil (Fig. 3). Considering the type of fertilizer, grain water content was significantly higher for ammonium sulfate and calcium nitrate. In turn, the use of urea in the full dose of mineral fertilizer before maize sowing significantly reduced grain moisture content compared to nitrogen dose balanced for soil mineral nitrogen content (Fig. 3).

Conclusions

Nitrogen applied in the form of mineral fertilizer (N_f) has a higher yielding efficiency compared to N_{min} contained in soil in the spring. Slow-release nitrogen fertilizers, such as ammonium sulfate or urea should be selected for maize fertilization as potentially better suited to the rhythm of its vegetation. This has been evidenced by higher partial factor productivity of fertilizer nitrogen ($PFPF_N$). The application of a full dose of mineral fertilizer in the form of ammonium sulfate increases grain yield, whereas urea reduces grain water content in comparison to a mineral fertilizer dose minus the amount of N_{min} in soil. It is most optimal to select nitrogen fertilizers, such as ammonium nitrate or calcium nitrate, to be able to balance the nitrogen dose for N_{min} content. This has been evidenced by the smallest differences in grain yield between mineral nitrogen used in the fertilizer (N_f) and the nitrogen dose balanced for soil content of this component (150-N_{min}). The productivity of fertilizer nitrogen (N_f) depends on the content of mineral nitrogen present in the deepest soil layers. It is sufficient to collect soil samples from two levels, i.e. 0-0.3 m and 0-0.6 m, to determine nitrogen doses based on mineral nitrogen (N_{min}) abundance in soil.

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