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The effect of nitrogen fertilization on yield efficiency and quality of tubers potato varieties cultivated in an integrated production system

Wpływ nawożenia mineralnego azotem na efektywność plonowania i jakość bulw odmian ziemniaka uprawianych w integrowanym systemie produkcji

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The aim of the research conducted in the years 2016 – 2018 was to perform the effect of nitrogen on the total yield and quality evaluation of edible and starch potato varieties harvested after tuber maturity, as well as to establish fertilization efficiency indices. The quality of tubers was expressed: yield structure, share of deformations, content of starch and nitrates (V), but the nitrogen utilization efficiency as agronomic efficiency (AE) and fertilizer recovery efficiency (FRE) in tubers. Two experimental factors were researched: nitrogen doses (0, 50,100, 150 kg·ha^{-1}) and varieties (Impresja, Mazur, Otolia, Szyper and Widawa) tested under different weather conditions. The total yield fresh matter between nitrogen doses ranged from 42.8 to 53.7 t·ha^{-1} and for varieties from 42.1 (var. Szyper) to 54.8 t·ha^{-1} (var. Impresja). Increasing nitrogen doses caused an increase share in the yield structure big tubers (diameter above 60 mm), nitrates (V) and total nitrogen content and nitrogen uptake with tuber yield, but decrease starch content and nitrogen fertilization efficiency indicators. On the basis of quadratic function parameters, it was shown that the varieties of Impresja, Szyper and Otolia were characterized by greater requirements in relation to the optimal nitrogen dose than the varieties of Mazur and Widawa. More assessed features determined the weather conditions during the growing season than the factors studied: the nitrogen fertilization dose and the variety. In the year with the highest amount of rainfall in relation to the average of many years, the largest decrease was recorded: tuber yield, share of big tubers in the yield structure, nitrogen uptake and agronomic efficiency. Year with the most rainfall was characterized by the highest reduction the yield of tubers, share big tubers in the yield structure, nitrogen uptake and its agronomic efficiency.

Key words: efficiency indicators, nitrogen doses, potato varieties, quality, yield.

Celem badań przeprowadzonych w latach 2016–2018 było określenie wpływu nawożenia mineralnego azotem na plon ogólny i wybrane cechy jakości bulw odmian jadalnych i skrobiowych ziemniaka zbieranych po dojrzeniu bulw, a także ustalenie wskaźników efektywności nawożenia. Jakość bulw oceniono na podstawie ich struktury, zdeformowania, zawartości skrobi i azotanów, a wydajność nawożenia azotem mineralnym wyrażono efektywnością agronomiczną (AE) i efektywnością odzyskania nawozów (FRE) przez bulwy. W badaniach uwzględniono dwa czynniki doświadczalne: dawkę azotu (0, 50, 100, 150 kg·ha^{-1}) i odmiany (Impresja, Mazur, Otolia, Szyper i Widawa) uprawiane z uwzględnieniem warunków pogodowych. Ogólny plon świeżej masy bulw pomiędzy dawkami azotu (0–150 kg·ha^{-1}) zawierał się od 42,8 do 53,7 t·ha^{-1}, a dla odmian od 42,1 (odmiana Szyper) do 54,8 t·ha^{-1} (odmiana Impresja). Zwiększenie dawki azotu spowodowało wzrost udziału w strukturze plonu bulw dużych (o średnicy powyżej 60 mm), zawartości azotanów (V) i azotu ogólnego oraz pobranie azotu z plonem bulw, natomiast wpłynęło na zmniejszenie zawartość skrobi w bulwach i wskaźników efektywności nawożenia azotem. Na podstawie parametrów funkcji kwadratowej wykazano, że odmiany Impresja, Szyper i Otolia charakteryzowały się większymi wymaganiami w stosunku do optymalnej dawki azotu niż odmiany Mazur i Widawa. Więcej ocenianych cech determinowały warunki pogodowe w okresie wegetacji, niż badane czynniki: dawka nawożenia mineralnego azotem i odmiana. W roku o najwyższej ilości opadów w stosunku do średniej z wielolecia stwierdzono największe zmniejszenie: plonu bulw, udziału bulw dużych w strukturze plonu, pobrania azotu i efektywności agronomicznej.

Słowa kluczowe: wskaźniki efektywności, dawki azotu, odmiany ziemniaka, jakość bulw, plon

Introduction

Potato, despite the decrease of its crop area in recent years, remains one of the main nutritional products, together with rice and wheat (Dzwonkowski, 2017). One of the main reasons for reducing the crop area of potato in the sowing structure is the fact that this plant is becoming less and less competitive in terms of expenditure incurred for its production in comparison to other field crops. Therefore, solutions that would contribute to the best use of the yield potential of this plant should be sought. One of the main goals in this aspect is to increase the efficiency of some treatments in the cultivation technology of this species. An element of potato production, which significantly affects the expenditure on its cultivation, is fertilization, including the most important mineral nitrogen, the tuber component that most determines their quality and yield (Maltas et al., 2018). The use of mineral nitrogen, for example because of the environmental aspect or growing price of fertilizers, should be limited in order to apply precise doses for specific potato cultivars (Baishya et al., 2013; Fontes et al., 2010; Rens et al., 2018) . A properly determined dose

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of nitrogen ensures that appropriate quality parameters and the highest possible efficiency in relation to the tuber size are obtained and its quantity received from the fertilizers is optimal (Cohan et al., 2018). The above assumptions regarding mineral nitrogen fertilization are consistent with the standards in force since 2014 in the area of the integrated potato production system (IP), which generally assumes limiting the chemicalization of agriculture (Nowacki, 2013). It should be emphasised that potato has relatively high nutritional needs, but is characterised by a lower use of this component from fertilizers compared to other crop species (Goffart et al., 2008). According to Vos (2009), fertilizer nitrogen recovery efficiency is 45%. In Canada, nitrogen recovery efficiency for tubers ranged from 21 to 62% (Cambouris et al., 2008; Zebrath et al., 2012). According to Polish studies, nitrogen recovery by early potato cultivars harvested after maturation ranges from 45 to 50% for the lowest nitrogen dose, i.e. 50 kg·ha^{-1}, and from 25 to 35% for the highest nitrogen dose, i.e. 200 kg·ha^{-1} (Kopiński, 2017; Trawczyński, Wierzbicka, 2014). This indicates that part of the applied mineral nitrogen may remain unused and as a waste penetrate into the atmosphere or groundwater, becoming a threat to the environment. The differences in the yield and the quality of potato tubers, as well as the efficiency of fertilization may result from the impact of specific biotic and abiotic factors. These include, among others, properties of the cultivars, fertilizer dose or changes in weather conditions during the growing season.

The aim of the study was to assess the impact of nitrogen fertilization on the yield, selected quality characteristics of tubers, as well as values of the uptake, use and use efficiency of this ingredient for new potato cultivars grown in accordance with the integrated production system.

Material and Methods

In field experiments conducted in 2016–2018 in the Jadwisin Department of the Plant Breeding and Acclimatization Institute, National Research Institute (52°45 'N, 21°63' E), the response of potato cultivars to mineral nitrogen fertilization was determined. The analysed factors included:

1. nitrogen doses (4): 0, 50, 100, 150 kg·ha^{-1},
2. potato cultivar (5): Impresja (table cultivar, very early), Mazur (table cultivar, mid-early), Otolia (table cultivar, mid-early), Szyper (starchy cultivar, mid-early) and Widawa (starchy cultivar, mid-early).

The experimental design was a split-plot randomised block in three replications. A plot consisted of four rows spaced at a distance of 0.75 m, with a distance of 0.33 cm between seeds within each row. The size of the field was 14.85 m^2. The number of plants per one plot was 60.

The research was carried out on arable light soil classified as belonging to soils with clay translocation, type Luvisols, subtype Stagnic Luvisols (Marcinek et al., 2011). The soil was characterised by acid pH, high phosphorus content, and average content of mineral nitrogen, potassium and magnesium. The content of organic carbon in the soil was low (Table 1).

Table 1
Soil chemical properties in the field before planting

Year	N mineral (kg·ha^{-1})	C organic (g·kg^{-1})	pH in KCl	Content in the soil (mg·kg^{-1})		
				P	K	Mg
2016	50	6.8	5.4	89	112	32
2017	50	8.4	5.0	88	122	22
2018	60	8.8	5.4	79	104	26

Organic fertilizer consisted of cut winter triticale straw, ploughed after the harvest, at an amount of 5 t ha^{-1} and the green mass of white mustard stubble crop at an amount of 15–16 t·ha^{-1} and it served as a fertilizer applied in the autumn. Mineral phosphorus and potassium fertilization was carried out in early spring at doses of 26.2 kg·ha^{-1} P (triple superphosphate — 17.4% P) and 99.6 kg·ha^{-1} K (potassium salt — 49.8% K), based on the content of available forms of these components in the soil. Nitrogen fertilization on plots with up to 100 kg·ha^{-1} N was applied in spring before planting tubers, while on plots with 150 kg·ha^{-1} N a supplementary dose of 50 kg·ha^{-1} N was added right before the emergence of potato plants. Nitrogen was used in a form of ammonium nitrate (nitrochalk — 27% N). Potatoes were planted manually in the third decade of April and harvested after the maturation of tubers in the second decade of September.

Weather conditions in the years of the study were determined on the basis of the sum of rainfall and average air temperatures compared to the long-term average and Sielianinov's hydrothermal coefficients. The year 2016, compared to other years, was characterised by the sum of rainfall in the growing season, which was the closest to the long-term average. A slight rainfall deficit was recorded only at the beginning and the end of the growing season (April and September). In 2017, the most rainfall was recorded compared to other years, and the months of June and September were particularly wet. In turn, 2018 was one of the driest years. The sum of rainfall for the entire growing season was 79.2 mm lower compared to the average. The largest rainfall deficit was recorded at the beginning of the vegetation season, in May and June. In general, all analysed years of the study were warm, and especially

2018, when the air temperature throughout the growing season was 3.5° C higher than the long-term average. On the basis of the Sielianinov's hydrothermal coefficient, it was demonstrated that the years 2016 and 2017 were wet and that the year 2018 was dry (Table 2).

Weeds were removed mechanically (twice before the emergence of the potato plants) and chemically: one treatment immediately before the emergence (Afalon 450 SC at a dose of 2 $l \cdot ha^{-1}$) and the second one after the emergence of the potato plants (Titus 25 WG at a dose of 60 $g \cdot ha^{-1}$ + Trend 90 EC at a dose of 0.1 $l \cdot ha^{-1}$). During the growing season, fungicides against potato blight were applied four times (Ekonom 72 WP at 2 $kg \cdot ha^{-1}$, Pyton Consento 450 SC at 2 $l \cdot ha^{-1}$, Infinito 687.5 SC at 1.5 $l \cdot ha^{-1}$, Revus 250 SC at 0.6 $l \cdot ha^{-1}$). During the growing period, insecticides against Colorado potato beetle were applied three times (Actara 25 WG at 70 $g \cdot ha^{-1}$, Calypso 480 SC at 75 $ml \cdot ha^{-1}$ and Apacz 50 WG at 60 $g \cdot ha^{-1}$).

Table 2

Weather conditions in the study years (from the meteorological station in Jadwisin)

Year	Month						
	IV	V	VI	VII	VIII	IX	Sum/Mean
Sum of rainfalls (mm)							
2016	31.4	92.2	85.4	103.6	61.4	9.5	383.5
2017	8.9	10.1	107.5	78.8	57.0	140.8	407.1
2018	21.7	43.4	41.0	75.2	60.6	30.9	272.8
1967-2015	37.0	57.0	75.0	76.0	61.0	48.0	352.0
Mean air temperature (°C)							
2016	9.3	15.3	18.7	19.6	18.4	15.7	16.2
2017	7.3	14.1	18.1	18.4	19.4	13.8	15.2
2018	13.2	17.6	19.1	21.2	20.8	15.8	18.0
1967-2015	7.9	13.7	16.6	18.5	17.9	13.2	14.5
Sielianinov's hydrothermic coefficients (K)*							
2016	1.12	1.94	1.52	1.70	1.07	0.20	1.26
2017	0.40	0.23	1.98	1.38	0.95	3.39	1.39
2018	0.54	0.79	0.71	1.14	0.93	0.65	0.79

*Coefficient value (Bac et al., 1998); K< 0.50 severe drought; K: 0.51–0.99 drought; K: 1.00–2.00 humidity; K>2.00 high humidity

During the harvest, the total tuber yield was determined and two tuber samples were collected from each plot. In a sample of 5 kg of tubers, crop structure: the percentage of small tubers (with a diameter below 35 mm), medium tubers (with a diameter of 35 to 60 mm) and big tubers (with a diameter above 60 mm), as well as the percentage of deformed tubers was determined. Subsequently, a sample of 5 kg of tubers was collected in order to determine the following chemical characteristics: content of starch and nitrates in fresh weight, dry matter and total nitrogen in dry matter. The starch content was determined by the Ewers polarimetric method (PN-EN ISO 10520, 2002), where the hydrolysis of starch was carried out in a boiling water bath, and the protein was precipitated with phosphoric acid, with the use of readouts on a Polamat S automatic polarimeter. The nitrate content (NO_3) was determined by a colorimetric method based on the Griess test, using a mixture of zinc and manganese with the reduction of nitrates to nitrites, the dry matter content was assessed by two-stage drying, and the concentration of nitrogen in tubers was determined by the Kjeldahl method.

The dependence of potato yield on N fertilization doses was calculated according to the quadratic function:

$$Y = a + bX + cX^2$$

where, Y = tuber yield, X= nitrogen doses, a = yield for the 0 dose, b = yield increase per kg of N; c = yield decrease factor.

The optimal dose of nitrogen (X_{opt}) was calculated according to the equation:

$$X_{opt} = -b/2c$$

Maximal tuber yield (Y_{max}) for X_{opt} was calculated according to the equation:

$$Y_{max} = a - b2/4c$$

Agronomic efficiency (AE) for X_{opt} was calculated according to the equation:

$$AE\ X_{opt} = (Y_{max} - Y_0)/X_{opt}$$

Subsequently, nitrogen uptake (NUp) with tuber yield, as well as nitrogen use efficiency indicators: agronomic efficiency (AE) and fertilizer nitrogen recovery efficiency (FRE) for tubers were calculated. The calculated nitrogen use efficiency parameters for potatoes were adopted from Vos (2009) and Zebarth et al. (2008). They were determined using the following formulas:

Nitrogen uptake (NUp) with tuber yield was calculated according to the formula:

$$NUp;\ kg \cdot ha^{-1} = [(\%\ N\ in\ DM \times DW/100] \times 1000$$

where: DM-dry matter content (%); DW-tuber dry weight ($t \cdot ha^{-1}$).

Nitrogen agronomic efficiency (AE, $kg \cdot kg^{-1}$) was calculated according to the formula:

$$AE;\ kg \cdot kg^{-1} = [(Y_N - Y_0)/N_X],$$

As the ratio of difference between Y_N-tuber fresh weight yield at the fertilized plot and Y_0-tuber fresh weight yield at the unfertilized plot, and the dose N_X).

Fertilizer recovery efficiency (FRE, %) in tuber was calculated according to the formula: FRE; % = [(N uptake by tubers for N_X – N uptake by tubers for N_0)/N_X] ×100

Nitrogen uptake with the tuber yield at the fertilized plot (kg ha^{-1}) minus Nitrogen uptake with the tuber yield at the unfertilized plot (kg·ha^{-1}) divided by N_X. This parameter is also referred to as nitrogen use for potato tubers.

The results of the experiments were statistically analysed using the ANOVA software. The analysis of variance of the examined features (dependent variables) was carried out according to the nitrogen dose, cultivar and year (independent variables). There were 60 plots: 5 cultivars × 4 nitrogen doses × 3 years × 3 replications (180 items of statistical data). Comparisons of mean values were performed using the Tukey Test at $p < 0.05$ and at $p < 0.01$. The influence of the factors demonstrated by the Fisher–Snedecor distribution for all characteristics was presented. Non-linear regression analysis of total yield depending on the nitrogen fertilization, was used to determine optimal nitrogen doses. The components of variance were assessed in order to determine the sources of variability of the examined features in the total variability. The percentage of individual components of variance was used to assess the impact of weather conditions in given years, the applied nitrogen dose, the characteristics of the cultivars and their interaction on the variability of the tested components.

Results and Discussion

Significant differences in tuber yield and quality were obtained both in relation to the nitrogen dose, properties of the cultivars and weather conditions in the years of the study. Regardless of the tested cultivars and years, the yield of fresh tuber weight in the fertilization range of 0 -150 kg·ha^{-1} N equalled from 42.8 to 53.7 t·ha^{-1}. A significant gradual increase in the yield of fresh tuber weight was observed up to a dose of 100 kg·ha^{-1} N, and after exceeding this dose a decrease was noted (Table 3). The dependence of tuber yield on the increasing dose of mineral nitrogen fertilization was a confirmation of numerous previously conducted studies (Cohan et al., 2018; Fontes et al., 2010; Rens et al., 2016).

The precise determination of optimal nitrogen doses allows for the analysis of tuber yield depending on the dose of this component with the use of quadratic regression analysis (Cohan et al., 2018; Giletto, Echeverría, 2015; Maltas et al., 2018).

Table 3

Fresh weight yield FW (t·ha^{-1}) and quality of potato tubers depending on the study factors

Treatment	FW t·ha^{-1}	% of tuber fraction (mm)			D[1] %	Starch %	NO_3 (V) mg·kg^{-1}
		<35	35-60	>60			
0	42.8 c	4.4 a	71.4 a	24.2 c	6.7 b	15.5 c	18.8 d
50	48.8 b	3.3 a	62.9 b	33.8 b	8.4 a	16.1 b	28.0 c
100	54.5 a	3.2 a	55.3 c	41.5 a	7.5 ba	16.5 a	45.2 b
150	53.7 a	1.2 b	53.5 c	45.3 a	7.3 ba	16.2 b	60.5 a
Impresja	54.8 a	5.2 a	60.6 c	34.2 b	4.5 d	9.5 d	59.1 a
Mazur	52.9 b	0.8 d	39.6 d	59.6 a	11.0 a	15.8 b	27.3 d
Otolia	51.6 b	2.0 dc	67.2 b	30.8 b	6.5 c	14.6 c	50.5 b
Szyper	42.1 d	3.8 ba	75.9 a	20.3 c	8.7 b	20.2 a	21.0 e
Widawa	48.4 c	3.2 bc	60.5 c	36.3 b	6.7 c	20.2 a	32.7 c
2016	56.9 a	1.9 b	58.0 b	40.1 a	7.8 b	16.8 a	20.8 b
2017	45.4 c	4.9 a	70.8 a	24.3 c	9.6 a	16.3 b	14.4 c
2018	47.6 b	5.2 a	60.4 b	34.4 b	5.1 c	15.1 c	79.3 a
Significance of the impact							
Nitrogen dose (1)	xx	xx	xx	xx	x	xx	xx
Cultivar (2)	xx	xx	xx	xx	xx	xx	xx
Year (3)	xx	xx	xx	xx	xx	xx	xx
(1×2)	x	n.s.	n.s.	n.s.	n.s.	xx	xx
(1×3)	n.s.	xx	x	n.s.	x	xx	xx
(2×3)	xx	xx	xx	xx	xx	xx	xx
(1×2×3)	n.s.	n.s.	n.s.	n.s.	x	xx	xx
Percentage of total variability (%)							
Nitrogen dose (1)	27.6	18.4	19.1	18.1	3.1	1.0	13.8
Cultivar (2)	18.4	23.3	41.0	37.4	30.5	91.7	8.4
Year (3)	46.9	38.5	31.0	36.3	42.3	5.4	68.8
(1×2)	0.9	1.2	0.5	0.4	0.6	0.1	0.6
(1×3)	0.1	9.3	1.1	0.7	2.6	0.1	6.0
(2×3)	5.6	7.9	7.1	7.0	19.6	1.5	2.2
(1×2×3)	0.4	1.4	0.3	0.3	1.4	0.1	0.3

xx highly significant at $\alpha \leq 0.01$; x significant at $\alpha \leq 0.05$; n.s., not significant
Mean values with the same letter do not differ significantly;
1 Deformations

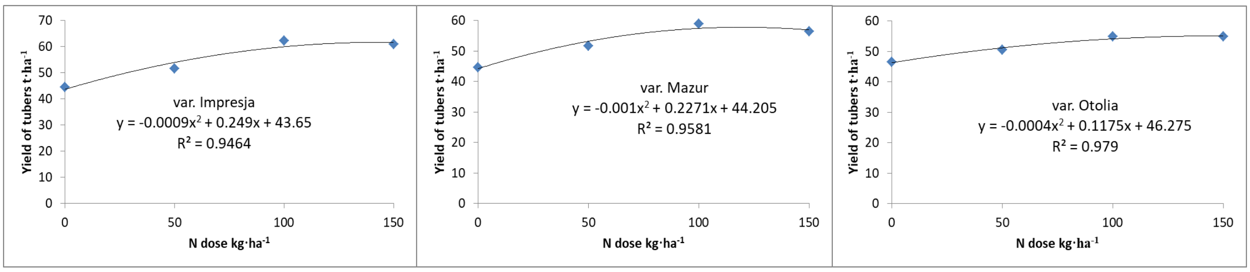

Fig. 1. Impact of N doses on tuber yield for table cultivars

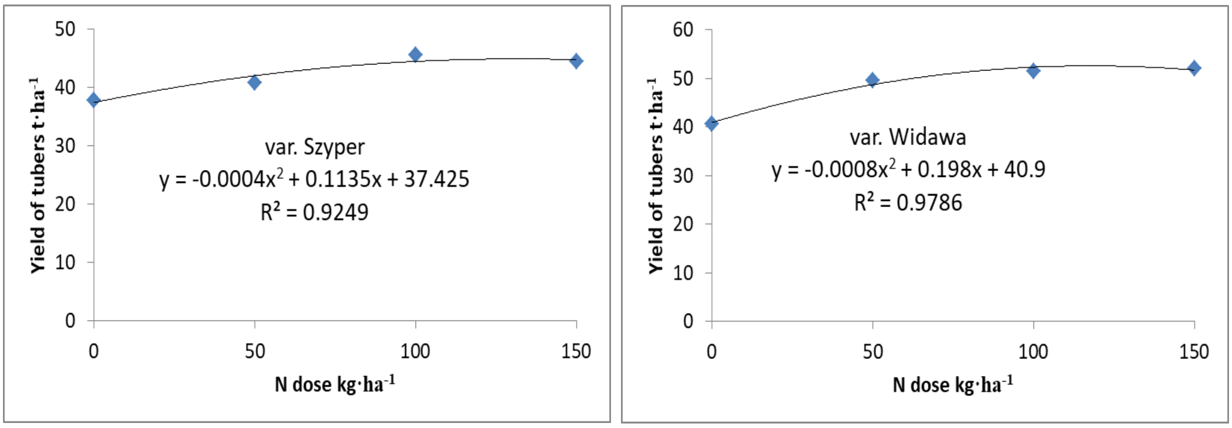

Fig. 2. Impact of N doses on tuber yield for starchy cultivars

The study showed that the needs of the cultivars in terms of the optimal dose of mineral nitrogen were different (Fig. 1–2).

Optimal nitrogen doses for each cultivar were as follows: Mazur — 114 kg·ha^{-1}, Widawa — 124 kg·ha^{-1}, Impresja — 138 kg·ha^{-1}, Szyper — 143 kg·ha^{-1} and Otolia 145 kg·ha^{-1}, whereas tuber yields at these doses accounted for: 57.1, 53.3, 60.8, 45.6 and 54.7 t·ha^{-1}, respectively (Table 4).

Table 4

Parameters of the quadratic model describing the relationship between tuber yield and nitrogen dose

Cultivar	Ymax t·ha^{-1}	Xopt kg·ha^{-1}	AE Xopt kg·kg^{-1}
Impresja	60.8	138	124
Mazur	57.1	114	114
Otolia	54.7	145	58
Szyper	45.6	143	57
Widawa	53.3	124	100

Large variation in the optimal nitrogen dose for different cultivars was demonstrated by Maltas et al. (2018) and Cohan et al. (2018). Optimal nitrogen doses in different years ranged from 78 to 194 kg·ha^{-1}, and the mean value for different years in case of Bintje and Laura cultivars amounted to 94 and 155 kg·ha^{-1} N, respectively, Maltas et al. (2018). In the study of Cohan et al. (2018) optimal nitrogen doses for the total tuber yield in case of five cultivars ranged from 130 to 170 kg·ha^{-1} N. Rens et al. (2018). The highest tuber yield was achieved for nitrogen doses from 114 to 138 kg·ha^{-1}. Regarding the cultivars, it was found that the Impresja cultivar had the significantly highest tuber yield, which a starchy cultivar, Szyper, the lowest one. Regardless of the dose of mineral nitrogen and the analysed years, the difference in fresh tuber yields between these cultivars was 30%. The year 2016 was the most favourable for high accumulation of tuber yields, as it was moderately cold and the sum of rainfall was closest to the long-term average throughout the growing season. In turn, the lowest tuber yield was obtained in 2017, which may result from the largest, compared to other years, excess rainfall. The difference in fresh tuber yield for these years was 25% (Table 3). The assessment of variance components showed that weather conditions in given years (46.9%) had the greatest impact on the variability of total tuber yield, while nitrogen doses (27.6%) and genotype (18.4%) had a significantly lower impact — Table 3. Similarly, a large impact of growing conditions during the tuber harvest, and the smallest one in relation to the genetic characteristics of the cultivars, Sawicka et al. (2011), were observed.

In addition to fresh weight yield, the size of tubers and different size percentage are basic characteristics of potatoes in case of table cultivars. The percentage of big and deformed tubers in the yield is the main measure of its commercial value. In the discussed studies it was found that as the mineral nitrogen dose increased, the percentage of small (smaller than 35 mm in diameter) and medium (35 to 60 mm in diameter) tubers decreased, and the percentage of large tubers (larger than 60 mm in diameter) gradually increased, which has been confirmed in previous studies by Maltas et al. (2018). The increase in the percentage of commercial tubers, including big ones, in the crop structure as a result of mineral nitrogen fertilization, was also obtained by Kołodziejczyk (2014). In their research, the percentage of commercial tubers in the total yield increased as a result of increasing doses of nitrogen (0–180 kg·ha^{-1}) from 94% to 98%, while the percentage of large tubers increased from 58% to 74%. The percentage of a fraction of above 60 mm in the crop structure was mainly determined by genotypic characteristics and weather conditions (Table 3). In the present study, the Mazur cultivar was characterised by the highest percentage of large tubers in the crop structure. A significant impact of genotypic characteristics on the tuber crop structure has also been found by Baranowska et al. (2019). It was also demonstrated that weather conditions in 2016, favourable for potato yielding, compared to other years, significantly contributed to the highest percentage of large tubers in the crop (Table 3), which was a confirmation of previous studies (Badr et al., 2006; Baranowska et al., 2019).

Deformed tubers in the crop structure, for the range from 0 to 150 kg·ha^{-1} N, constituted from 6.7 to 8.4%, and their percentage was not dependent on the nitrogen dose. The Impresja cultivar was characterised by the lowest percentage of deformed tubers in the crop, while the Mazur cultivar had the highest percentage of deformed tubers. The percentage of deformed tubers in the crop resulted mainly from weather conditions in given years (Table 3). The significantly highest percentage of deformed tubers was actually found in 2017, with the most uneven rainfall distribution during the growing season, as confirmed by Lutomirska and Jankowska (2012).

Starch and nitrates are one of the basic qualitative components of the chemical composition of potato tubers strongly dependent on the genotype, fertilization and changes in weather conditions during the growing season. The level of these components mainly determines the nutritional value of tubers (Pobereźny et al., 2015; Rymuza et al., 2015). The studies demonstrated that the table Mazury cultivar had a significantly higher starch content than the Otolia and Impresja cultivars (Table 3). In turn, starchy cultivars did not differ in the tuber starch content, but the content of this component was 52% higher compared to table cultivars. As the nitrogen dose increased, a significant increase in tuber starch content was found up to a dose of 100 kg·ha^{-1}. Previous studies confirmed the adverse impact of high doses of nitrogen on the content of starch in tubers (Öztürk et al., 2010). Actually, the weather conditions in 2016, which provided a sufficient level of humidity and warmth, had the most beneficial effect on the starch content in tubers. The significantly lowest starch content in tubers was obtained in 2018, which was dry, which generally promotes the accumulation of starch in tubers (Rymuza et al., 2015), but probably the exceptionally high air temperature in July and August determined a high reduction of this component in tubers. Based on the previous research, it was also confirmed that the main factor differentiating the starch content in tubers included weather conditions during the growing season, while cultivar differences were less important, and the content of this component was least dependent on the amount of nitrogen (Wierzbicka et al., 2008). The present study demonstrated that the genotype and weather conditions in given years determine the starch content in tubers more than the nitrogen dose (Table 3). In turn, nitrogen fertilization had the greatest impact on the level of nitrates in tubers, which was also confirmed by previous studies (Hmelak Gorenjak, Cencič 2013; Hmelak Gorenjak et al., 2014). The dose of nitrogen fertilization affected the increase in nitrates for 50, 100 and 150 kg N·ha^{-1} by 9.2, 26.4 and 41.7 mg·kg^{-1} in comparison to the control (a plot without N). The permissible amount of 200 mg·kg^{-1} of tuber fresh weight specified in the Minister of Health regulation (Commission Regulation EC, 2005) was not exceeded. The Impresja and Otolia cultivars were characterised a higher tendency to accumulate nitrates in tubers than other cultivars. In addition to nitrogen fertilization, the study also revealed a very significant impact of weather conditions on nitrate content in tubers during growth. The highest level of nitrates in tubers was found in the samples from 2018 (Table 3). Grudzińska, Zgórska (2008) confirmed that a dry and warm growing season favoured the accumulation of nitrates in tubers.

Nitrogen doses, genotypic characteristics and weather conditions in given years had a significant impact on nitrogen uptake (NUp) and fertilizer recovery efficiency (FRE) – Table 5. N uptake increased gradually with increasing nitrogen doses from 95.6 at the unfertilized plot to 161.1 kg·ha^{-1} for the application of 150 kg·ha^{-1} N. A similar nitrogen uptake with an increase in application dose was proved by other authors (Jamaati-E-Somarin et al., 2009; Vos, 2009). The Widawa cultivar was characterised by the significantly highest nitrogen uptake by tubers, while the Impresja cultivar had the lowest uptake. The significantly highest nitrogen uptake by tubers was achieved in 2018, because of, among others, the high content of total nitrogen in tubers. The lowest nitrogen uptake by tubers in 2017, with the highest rainfall during the growing season, may indicate that the nutrient was partially flushed from the root zone into groundwater, as it was emphasised in other studies (Arriaga et al., 2009; Shrestha et al., 2010). The nitrogen uptake by tubers was largely determined by mineral fertilization with this component and weather conditions during the growing season. As the nitrogen doses increased, an increase in nitrogen uptake was noted, but at the same time its fertilizer recovery efficiency decreased significantly. This indicated a decrease in the efficiency of nutrient uptake from fertilizers applied to soil, which was also documented in the literature (Cohan et al., 2018; Maltas et al., 2018; Rens et al., 2018; Vos, 2009). In the fertilization range of 50–150 kg·ha^{-1} N, nitrogen recovery efficiency ranged from 50.6 to 43.6%. The tested cultivars differed in nitrogen recovery efficiency from 40.1% for the Otolia cultivar to 54.4% for the Mazur cultivar. In earlier studies, cultivars were characterised by similarly significant differences in nitrogen recovery, while weather conditions in given years, similarly to the results obtained in the present study, determined nitrogen recovery by tubers (Zebarth et al., 2012). The obtained tuber yield and the applied nitrogen dose determined the value of nitrogen agronomic efficiency (AE). This parameter was significantly differentiated mainly by nitrogen dose and cultivar. With the increase in nitrogen dose from 50 to 150 kg·ha^{-1} N the yield per 1 kg of applied nitrogen decreased from 120.0 to 72.6 kg of tubers. Regarding the cultivars, agronomic efficiency (AE) ranged from 63.4 to 169.2 kg of tubers per 1 kg of applied nitrogen (Table 5), and at the optimal nitrogen dose from 57 kg tubers for the Szyper cultivar to 124 kg tubers for the Impresja cultivar (Table 4).

In 2016, the most favourable year in terms of weather conditions during the growing season, the highest value of nitrogen agronomic efficiency was obtained, but this difference was not statistically significant compared to the remaining years of the study. In the conducted study it was demonstrated that the value of agronomic nitrogen efficiency and recovery of this component by tubers was mostly determined by genotypic characteristics (Table 5). In the study it was emphasised that the values of mineral nitrogen fertilization efficiency indices are of key importance because, on the one hand, they determine the profitability of production, and on the other hand, they allow determining the impact of fertilization with this component on the environment (Cambouris et al., 2008; Fontes et al., 2010; Maltas et al., 2018).

Conclusions

The increase in fertilization up to a dose of 150 kg·ha^{-1} N had a significant negative effect on the starch content and nitrogen fertilization efficiency indices, and at the same time had a positive effect on the percentage of large tubers (diameter over 60 mm) in the structure, nitrates content, total nitrogen content and nitrogen uptake, as well as tuber yield.

The tested cultivars differed significantly in terms of tuber yield and crop structure, starch and nitrate content, nitrogen uptake, agronomic efficiency and recovery of this component.

The growing season with the highest rainfall was characterised by the largest reduction in tuber yield, percentage of large tubers in the crop structure, nitrogen uptake and agronomic efficiency for this component.

Mineral nitrogen fertilization largely determined nitrogen uptake and tuber yield, genotypic characteristics determined starch content and nitrogen agronomic efficiency index, as well as recovery of this component by potato tubers, while weather conditions in given years had the greatest impact on tuber yield, percentage of deformed tubers in the crop structure, nitrate content and total nitrogen content in tubers.

Optimal nitrogen doses obtained on the basis of tuber yield for the studied cultivars, which equalled from 114 to 145 kg·ha^{-1} N, ensured correct tuber quality and high fertilization efficiency of this element.

Table 5

Effect of the study factors on the dry weight yield, DW (t·ha^{-1}), nitrogen content, N (%), uptake, NUp (kg·ha^{-1}), agronomic efficiency, AE (kg·kg^{-1}) and fertilizer recovery efficiency, FRE (%) by tubers

Treatment	DW	N	NUp	AE	FRE
0	9.2 c	1.04 d	95.6 d	–	–
50	10.8 b	1.12 c	120.9 c	120.0 a	50.6 a
100	11.9 a	1.20 b	142.8 b	117.0 a	47.2 b
150	12.3 a	1.31 a	161.1 a	72.6 b	43.6 c
Impresja	8.3 c	1.27 a	105.4 c	169.2 a	48.2 ba
Mazur	11.9 b	1.11 c	131.6 ba	119.9 b	54.4 a
Otolia	10.7 d	1.27 a	132.1 ba	63.4 c	40.1 c
Szyper	11.3 c	1.12 b	126.5 b	73.8 c	44.2 bc
Widawa	12.9 a	1.07 d	138.0 a	122.0 b	50.3 ba
2016	13.0 a	1.02 c	132.6 b	116.2 a	47.5 a
2017	10.1 b	1.04 b	105.0 c	104.1 a	47.2 a
2018	10.0 b	1.45 a	145.0 a	108.7 a	47.5 a
Significance of the impact					
Nitrogen dose (1)	xx	xx	xx	xx	x
Cultivar (2)	xx	xx	xx	xx	xx
Year (3)	xx	xx	xx	n.s.	n.s.
(1×2)	x	xx	n.s.	x	xx
(1×3)	n.s.	xx	n.s.	n.s.	x
(2×3)	xx	xx	xx	xx	xx
(1×2×3)	n.s.	xx	x	x	xx
Percentage of total variability (%)					
Nitrogen dose (1)	22.3	13.4	48.7	17.0	9.9
Cultivar (2)	27.5	7.0	8.1	51.3	41.5
Year (3)	43.7	78.7	40.3	1.8	0.0
(1×2)	0.4	0.2	0.2	7.1	10.3
(1×3)	0.3	0.2	0.2	3.1	8.8
(2×3)	5.6	0.2	2.2	15.2	21.7
(1×2×3)	0.2	0.2	0.3	4.6	7.8

xx highly significant at $\alpha \leq 0.01$; x significant at $\alpha \leq 0.05$; n.s., not significant

Mean values with the same letter do not differ significantly

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