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The effect of nitrogen use efficiency on significant traits of potato starch production

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Abstract

The improvement of nitrogen use efficiency (NUE) in potato (*Solanum tuberosum* L.) can reduce the required N input. As a result, economic benefits will increase, and environmental pollution will decrease due to N loss. The aim of the study was to determine the NUE of potato genotypes and to evaluate the relationship of NUE with the tuber yield, starch yield, and starch content at different N fertiliser rates. During a two-year experiment, the performance of 19 potato genotypes was evaluated by different farming practices involving the varying levels of N fertiliser rates. These practices included the integrated farming (IF) system with three different N fertiliser rates and the organic farming (OF) system without N fertilisation. The N fertilisation in both farming systems was stated as plant-available N in soil and as N added with a fertiliser. A significant effect of the genotype and the farming system on the tested traits was determined. The potato genotype tuber yield correlation with NUE was high or moderate in the farming system with different N fertiliser rates in both years. The tuber yield of potato grown in the farming system with a comparatively higher N fertilisation usually did not increase significantly; therefore, a decrease in genotype NUE was detected. The correlation between starch yield and NUE was high and strong in both farming systems, although high and moderately strong correlation was determined between tuber yield and starch yield. NUE had a weak correlation with the starch content in potato tubers, so genotype characteristics and growing conditions had the greatest influence on this trait. An increase in N fertilisation did not lead to an increase in starch yield due to a decrease in starch content and a slight insignificant increase in tuber yield. However, genotypes with higher NUE produced a higher tuber yield and starch yield than genotypes with relatively lower NUE, even in the farming systems with different N fertiliser rates in both experimental years.

Keywords: *Solanum tuberosum*, nitrogen use efficiency, starch content in tubers, starch yield, tuber yield.

Introduction

Potato (*Solanum tuberosum* L.) is known as the third most important food crop in the world according to Q. Dongyu, Director-General of the Food and Agriculture Organization of the United Nations (FAO) at the World Potato Congress 2022 (WPC, 2022). Potato tubers are rich in antioxidants, vitamins, essential amino acids, and important minerals in addition to a high amount of carbohydrates such as starch and sugars (Van Dingenen et al., 2019).

Potato requires a large amount of nitrogen (N) during the formation of yield, and there are several sources of N: soil organic matter, plant residues from previous years, atmospheric depositions, N accumulated by fixing bacteria, and synthetic N fertilisers (Haverkort et al., 2003). High N fertilisation combined with a shallow potato root system can lead to leaching of nitrates and contamination of the surrounding environment (Milburn et al., 1990; Sharifi, Zebarth, 2006).

The fundamental goal of crop production is to optimise high nutrient efficiency in crops. One way to limit N usage is the breeding of N use-efficient potato cultivars. Improvement of nitrogen use efficiency (NUE) in potato genotypes can reduce the N requirements. As a result, economic benefits will be increased, and environmental pollution due to nitrate loss will be reduced (Getahun et al., 2020; Stefaniak et al., 2021). One of the important

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factors determining potato yield is the variable N in soil. Tuber yield increased with the increasing N supply in the soil and the growing cycle of potato cultivars (Tiemens-Hulscher et al., 2014; Getahun et al., 2020), although higher N doses did not significantly increase tuber yield (Ruža et al., 2013; Stefaniak et al., 2021). During plant development, N fertilisation influences many processes: physiological stages, morphological traits, yield component characteristics such as photosynthetic rate, distribution of dry matter (DM) in the tubers, tuber starch content, tuber final number, harvest index, and final tuber yield (Tiemens-Hulscher et al., 2014). The available N positively affects canopy development influencing starch content and starch yield (Koch et al., 2020). Most of previous studies reported a negative effect of increased available N on starch content in potato tubers (Öztürk et al., 2010; Ruža et al., 2013; Van Dingenen et al., 2019; Bachmann-Pfabe, Dehmer, 2020; Getahun et al., 2020). Nitrogen deficiency results in a more intensive accumulation of carbohydrates such as starch and sugars (Scheible et al., 2004). However, Kumar et al. (2007) and Brazinskiene et al. (2014) indicated that potato tuber quality is mostly determined by genotype. A particular study confirmed a negative relationship between potato tuber yield and starch content (Schönhals, 2014); however, other studies found no significant correlation between tuber yield and starch content (Bombik et al., 2019).

NUE is highly correlated with potato canopy cover characteristics and maturity and is generally higher for later maturing potato cultivars than for early maturing ones (Ospina et al., 2014; Tiemens-Hulscher et al., 2014; Getahun et al., 2020). High phenotypic correlation coefficients were found between NUE and tuber number per plant, tuber DM or starch content under low and high N input conditions, but the direct effect of DM or starch content on NUE variation was minor (Getahun et al., 2020). Potato genotypes with higher NUE use efficiently N in soils with limited N availability or fertilisation, but in soils with high N availability, these genotypes exhibit better N uptake and utilisation resulting in higher yields compared to genotypes with relatively lower NUE. The effect of NUE on starch content or DM content was minor. Although the effect of NUE on starch yield is not clear, starch yield is a parameter combining tuber yield and starch content. This relationship is particularly important for potato starch production in various farming systems with different N fertiliser rates in the soil.

The aim of this study was to determine the NUE of potato genotypes and to evaluate the relationship of NUE with tuber starch content, tuber yield, and starch yield under organic and integrated farming systems with different N fertiliser rates.

Material and methods

Experimental conditions and design. Potato production was evaluated under organic (OF) and integrated (IF) farming systems with three different nitrogen (N) fertiliser rates in the Priekuli location (57°19′ N, 25°20′ E) of the Institute of Agricultural Resources and Economics, Latvia, in 2020 and 2021. The experiment was carried out in fields with loamy sand texture *Albeluvisol* (WRB, 2022). The availability of nutrients in the soil at a ploughing depth (0.25 m) and other soil characteristics are described in Table 1. The soil characteristics were determined by the following methods: pH_{KCl} potentiometrically in a 1 M KCl suspension (LVS ISO 10390-2006), organic matter (OM) photometrically, K_2O and P_2O_5 by the Egner-Riehm method, Mg and Ca by the atomic absorption spectrometric method according to LMA regulation No. 21 (29082014). The amount of plant-available phosphorus in the soil was high in both farming systems, but the amount of potassium was low in the soil of OF in 2020, moderate in the soil of IF in 2020 and of OF in 2021, and high in the soil of IF in 2021.

Table 1. Characterisation of soil properties during experimental years (2020 and 2021)

Year	2020				2021			
Farming system / soil properties	Organic	Integrated N fertiliser rate kg ha^{-1}			Organic	Integrated N fertiliser rate kg ha^{-1}		
		60	120	180		60	120	180
pH_{KCl}	5.7	5.5			5.6	5.0		
Organic matter %	2.3	2.3			2.7	2.1		
K_2O mg kg^{-1}	56	137			132	190		
P_2O_5 mg kg^{-1}	101	179			164	175		
Ca mg kg^{-1}	736	663			939	1214		
Mg mg kg^{-1}	143	539			127	121		
Estimated plant-available soil N kg ha^{-1}	71	69			83	58		
Estimated total plant-available N kg ha^{-1}	71	129	189	249	83	118	178	238

The field experiment in the IF plots was arranged in a split-plot design with N fertiliser rates in the main plots and genotypes in 3.4 m^2 subplots. To develop three different N fertilisation treatments under the IF system, the basic fertiliser rates of 90 kg ha^{-1} K_2O and 55 kg ha^{-1} P_2O_5 and three different N fertiliser rates of 60, 120, and 180 kg ha^{-1} N were applied (Table 1). Each potato genotype was planted in a single row with a 0.3 m distance between tubers and 0.7 m between rows. The 4-row isolation was used between the main plots with different N fertiliser rates. Four replications were applied in the main plots. No additional N fertiliser was applied in the OF plots. Four replications with a randomised plot design were also used in the OF plots. The available soil N differed between the OF and three different N fertilisation treatments under the IF system depending on the soil N content and the amount of fertiliser applied.

The N provision for each farming system included the plant-available N in the soil and the amount of N applied with fertilisers. Total N accumulated in the soil was calculated based on soil acidity (pH_{KCl}) and organic matter content (1) according to Kārkliņš (1995):

$$y = (0.0762x^3 - 1.54x^2 + 10.7x - 20.3) \times 0.01 \text{ OM}, \quad (1)$$

where y is total N in soil (%), x is soil pH_{KCl}, and OM is organic matter in soil (%).

According to Ros et al. (2011), during one growing season the amount of mineralised inorganic plant-available N in the soil OM varied from 0.2% to 5.0%. In the present experiment, 2% of available N was used for plants from total N in soil, as suggested by the National Research Council (1993). In total, four treatments were considered in both experimental years: OF and IF systems with three different N fertilisation treatments.

As a pre-crop before establishment of each experimental field, winter rye (*Secale cereale* L.) was used. Agronomic practices were applied according to the OF and IF requirements. In 2020, in the OF, potatoes were planted on 6 May and harvested on 3–4 September, and in the IF, potatoes were planted on 11 May and harvested on 1–2 October. In 2021, the planting date was 11 May in both farming systems, and harvesting dates were 9 September and 20–21 September in the OF and IF, respectively.

Research material. In the experimental years, 19 potato (*Solanum tuberosum* L.) genotypes were included in the farming systems: 10 cultivars developed in Latvia with low (<14%) starch content (SC): 'Agrie Dzeltenie' and 'Madara', medium SC (14–18%): 'Monta', 'Rigonda', 'Prelma', 'Lenora', and 'Magdalena', and high SC (>18%): 'Brasla', 'Imanta', and 'Jogla'; five promising clones from the breeding programme with some excellent trait values and different SC: S 03067-33 (early, large tubers, low SC), S 01085-21 (good for crisp production, medium SC), S 04065-2 (high yielding, medium early, high SC), S 11161-85 (purple fleshed, medium SC), and S 11152-7 (high yielding, high SC); four popular foreign cultivars: 'Vineta' (low SC), 'Jelly' (medium SC), and 'Verdi' (high SC), developed in Germany, and 'Kuras' (widely used for starch production, high SC), originated from the Netherlands. To obtain more detailed data on the variation in starch yield (SY) in relation to potato genotype nitrogen use efficiency (NUE), a diverse range of genotypes was selected depending on the SC in tubers.

Evaluated traits. For potato genotypes, tuber yield (TY), SC, SY, and calculated NUE were determined. Tuber yield was measured after harvest and expressed in t ha^{-1}. To determine SC and dry matter (DM) in the tubers as a percentage of fresh weight (FW), underwater weight was used (Tiemens-Hulscher et al., 2013). Starch yield was calculated according to equation (2):

$$SY = \frac{TY \times SC}{100}, \quad (2)$$

where SY is the starch yield (t ha^{-1}), TY is the tuber yield (t ha^{-1}), and SC is the starch content (%).

Dry matter yield was calculated according to equation (3):

$$DMY = \frac{TY \times DM}{100}, \quad (3)$$

where DMY is dry matter yield (t ha^{-1}), TY is the tuber yield (t ha^{-1}), and DM is the content of dry matter (%).

NUE was determined as the tuber DMY produced per unit of total N supply or total plant-available N of farming system (kg kg^{-1}) (Tiemens-Hulscher et al., 2014; Hawkesford, Griffiths, 2019) according to equation (4):

$$NUE = \frac{DMY}{total\ plant\ available\ N} \quad (4)$$

Meteorological conditions. During the experimental years, the meteorological conditions varied greatly between vegetation periods. The beginning of the growing season (May) was very dry in 2020, and the amount of precipitation in May 2021 exceeded that of the previous year by four times: 33.6 and 120.4 mm in 2020 and 2021, respectively. The difference in average air temperature in May was 1°C: 9.6°C and 10.6°C in 2020 and 2021, respectively. Later, meteorological conditions changed greatly, and the amount of precipitation in June and especially in July 2020 was higher (99.3 and 133.0 mm, respectively) than that in the same period in 2021 (62.0 and 43.5 mm, respectively). The average air temperature in both experimental years differed during the same period (18.5°C and 16.2°C in June and July 2020 and 19.2°C and 21.7°C in June and July 2021, respectively). In 2021, dry and hot weather negatively affected potato yield formation and nutrient uptake. The last part of the growing season in 2020 had lower precipitation and more warm and sunny days (39.7 mm and 16.8°C in August 2020) and was favourable for starch accumulation. A higher amount of precipitation (94.0 mm) and mostly appropriate average air temperature (15.6°C) in August 2021 could be the reason of the recovery of tuber development, but impaired redevelopment negatively affected starch formation and accumulation. The amount of precipitation during harvesting provided acceptable humidity in both experimental years (68.1 and 49.7 mm in September 2020 and 2021, respectively). The difference in average air temperature in September was 3.6°C (14.0°C and 10.4°C in 2020 and 2021, respectively), so the conditions for tuber maturation were more favourable in 2021.

Statistical analysis. To determine the effects of the main factors: genotype, farming system, and growing year, three-way (analysing the data from both experimental years) and two-way (analysing the data from each year) analysis of variance (ANOVA) was applied. A post hoc LSD test at the $\alpha = 0.05$ probability level was used to compare groups when significant differences were found. To determine the strength of the relationship between traits, Pearson's correlation coefficient was calculated. The significance of the correlation coefficient was determined ($p < 0.05$), and the strengths of the relationships were evaluated: very weak correlation if the correlation coefficient was less than 0.3, weak if it was between 0.3 and 0.5, medium if it was between 0.5 and 0.7, and high or strong if it was higher than 0.7. For data processing, the Microsoft Excel data analysis tool and *add-in* Real Statistics were used. To describe the influence of the main factors on the evaluated traits (TY, SC, SY, and NUE), the partitioning variance components (PVCs) were calculated from the ANOVA sum of squares as a percentage of the factor sum of squares from the total sum of squares.

Results

The effect of potato genotype and farming system. The effect of the genotype on the evaluated traits TY, SC, SY and NUE was significant ($p < 0.001$) in each experimental year separately and in both years together. The effect of the farming system depending on N fertilisation and experimental year was significant in each year separately and in both years together (Table 2). The average value of the SY, TY, and NUE traits was higher in 2020 than in 2021: in 2020, it exceeded the value in 2021 by approximately two times.

The PVCs for the effect of potato genotype on SC were high in each experimental year separately and in both years together (Table 3). The effect of the farming system and of interaction of both factors on SC was very low. The influence of the genotype and the farming system on SC was approximately the same in both experimental years, but when evaluating the PVCs for the effect of the year on SY in both years taken together, the influence of the year (38%) exceeded the influence of the genotype (18%) and farming system (20%). Similar PVCs of the year were found for TY and NUE. The excessive effect of this factor on traits can be explained by very different meteorological conditions in each year: the amount of precipitation was lower and air temperature was higher in 2021 than in 2020. Because the variance between years was so high, the results were analysed for each year separately.

Table 2. Two-way and three-way ANOVA *p* values for the effects of potato genotype, farming system, and year and trait value description in 2020 and 2021 separately and both years together

Factor	DF	Starch content %			Starch yield t ha^{-1}			Tuber yield t ha^{-1}			NUE kg kg^{-1}		
		2020	2021	both years	2020	2021	both years	2020	2021	both years	2020	2021	both years
Genotype (G)	18	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Farming system (E)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Year (Y)	1	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001
G × E	54	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G × Y	18	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001
E × Y	3	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001	ns	ns	<0.001
G × E × Y	54	ns	ns	<0.001	ns	ns	0.016	ns	ns	0.008	ns	ns	<0.001
Average		16.35	13.94	nu	6.70	3.43	nu	44.33	25.40	Nu	67.94	35.96	nu
Min		12.19	8.86	nu	4.59	1.08	nu	28.08	12.49	Nu	44.21	13.96	nu
Max		21.38	16.57	nu	10.68	5.47	nu	56.98	37.34	Nu	101.56	53.81	nu

DF – degrees of freedom; ns – not significant at $P < 0.05$, nu – not used

Table 3. Partitioning variance components (PVCs) (%) for the effect of potato genotype, farming system and year on starch content, starch yield, tuber yield and nitrogen use efficiency (NUE) in 2020 and 2021 separately and both years together

Trait	Starch content			Starch yield			Tuber yield			NUE		
Factor / year	2020	2021	both years	2020	2021	both years	2020	2021	both years	2020	2021	both years
Genotype (G)	83	86	65	40	31	18	25	34	13	29	20	15
Farming system (E)	9	6	4	37	31	20	50	43	31	50	28	20
Year (Y)	ns	ns	18	ns	ns	38	ns	ns	30	ns	ns	38
G × E	2	3	0.8	8	11	4	6	7	3	8	12	3
G × Y	ns	ns	4	ns	ns	5	ns	ns	5	ns	ns	5
E × Y	ns	ns	2	ns	ns	1	ns	ns	0.5	ns	ns	6
G × E × Y	ns	ns	1	ns	ns	2	ns	ns	2.5	ns	ns	3

ns – not significant at $P < 0.05$

Starch content (SC) in tubers between potato genotypes varied from 12.19% to 21.38% in 2020 and from 9.22% to 16.67% in 2021. In both experimental years, the lowest amount was for 'Agrie Dzeltenie' and the highest for 'Jogla' (Table 4). The average of SC differed significantly between OF and IF systems. In the IF, when the N supply increased, the average of SC decreased significantly in 2020. The differences in the average of SC between farming systems were significant, except for IF with additional 60 and 120 kg ha^{-1} N in 2021. The average of SC in IF with additional 180 kg ha^{-1} N was significantly lower than that in other farming fields in 2021, and the highest was found in OF. The decreasing trend in SC with increasing plant-available N fertilisation was found for almost all genotypes, providing a wide range of SC with some exceptions: 'Kuras' in 2020 and 'Rigonda, S 03067-33, 'Lenora', S 04065-2, 'Verdi', and 'Magdalena' in 2021, when SC at 180 kg ha^{-1} N insignificantly exceeded SC at 120 kg ha^{-1} N.

Table 4. Starch content (%) in potato genotypes grown under two (OF and IF) farming systems with different nitrogen (N) fertilisation treatments in 2020 and 2021

Year	2020					2021				
Farming system / treatment	Organic	Integrated			Average	Organic	Integrated			Average
		N fertiliser rate kg ha^{-1}					N fertiliser rate kg ha^{-1}			
		60	120	180			60	120	180	
'Agrie Dzeltenie'	13.7	13.9	11.9	10.8	*12.2 r*	9.7	9.5	9.1	8.7	*9.2 i*
'Madara'	16.2	16.3	14.0	13.7	*14.6 lm*	13.9	13.2	12.6	12.5	*13.1 e*
'Monta'	17.0	18.1	16.9	15.0	*16. 7i*	14.5	14.0	14.2	13.7	*14.1 d*
'Rigonda'	15.4	16.7	14.9	13.7	*15.1 kl*	14.3	14.3	13.2	13.3	*13.8 d*
S 03067-33	14.2	15.2	13.9	13.1	*14.1 n*	13.5	12.9	12.2	12.2	*12.7 ef*
'Vineta'	13.3	14.0	12.0	11.5	*12.5 pr*	11.5	10.5	10.3	9.9	*10.6 h*
'Lenora'	17.3	18.6	16.6	16.4	*17.2 h*	14.8	13.8	13.4	13.5	*13.9 d*
'Prelma'	12.5	14.6	12.2	11.7	*12.8 p*	13.3	12.5	12.4	11.5	*12.4 fg*
S 01085-21	16.8	17.2	15.2	15.1	*15.8 j*	14.8	13.8	13.9	13.4	*14.0 d*
S 04065-2	18.2	20.2	19.3	17.6	*19.0 de*	16.6	16.7	16.1	17.0	*16.6 ab*
S 11161-85	14.1	15.9	13.9	13.0	*14.3 mn*	14.9	12.4	12.2	12.0	*12.9 e*
'Verdi'	20.7	21.8	20.9	19.3	*20.7 b*	15.8	15.7	15.1	15.6	*15.5 c*
'Brasla'	16.8	19.6	18.4	17.5	*18.5 f*	16.9	14.8	15.0	14.7	*15.3 c*
'Imanta'	19.2	20.0	18.1	17.0	*18.4 f*	17.0	15.9	16.3	15.6	*16.2 b*
'Jogla'	21.5	23.1	21.2	20.0	*21.4 a*	17.5	16.7	16.7	15.8	*16.7 a*
'Magdalena'	15.5	16.5	15.2	14.8	*15.5 jk*	13.5	12.4	12.7	12.9	*12.9 ef*
'Kuras'	21.1	20.4	18.8	18.9	*19.3 cd*	16.8	17.3	16.5	15.8	*16.6 ab*
'Jelly'	14.7	14.2	13.2	12.7	*13.3 o*	12.6	12.7	12.4	11.2	*12.2 g*
S 11152-7	17.8	18.8	17.8	16.6	*17.8 g*	18.0	15.2	16.4	15.9	*16.4 ab*
Average	*16.6 b*	*17.6 a*	*16.0 c*	*15.2 d*	nu	*14.7 a*	*13.9 b*	*13.7 b*	*13.4 c*	nu

Note. Different letters indicate significant differences ($P < 0.05$) between cultivars (average data within columns) and farming systems (average data within row in separate years) according to LSD tests; nu – not used.

Tuber yield (TY) of potato genotypes varied from 28.1 t ha^{-1} (S 11152-7) to 57.0 t ha^{-1} ('Kuras') in 2020 and from 12.5 t ha^{-1} ('Agrie Dzeltenie') to 37.3 t ha^{-1} (S 03067-33) in 2021. The lowest average TY was obtained in OF in both years, and the differences in the average TY in OF with the average TY in other farming systems were significant in both years (Table 5). The TY increased in IF when the N supply increased, but the TY in IF with 120 and 180 kg ha^{-1} N did not differ significantly in either year. TY in IF with 60 kg ha^{-1} N had significant differences from TY in other farming systems in both years. The TY in 2021 was lower than in 2020, although the trends of yield variation depending on N fertilisation were similar in both years. The TY of four genotypes was higher than the average TY in each farming system in both years: cultivars 'Rigonda', 'Magdalena', and 'Kuras' as well as breeding clone S 03067-33. Several genotypes exceeded the average TY in OF and IF with different N fertilisation treatments in one of the experimental years: 'Agrie Dzeltenie', 'Jogla', and 'Jelly' in 2020 and 'Prelma' in 2021.

Starch yield (SY). The obtained SY of potato genotypes ranged from 4.59 t ha^{-1} (S 11152-7) to 10.68 t ha^{-1} ('Kuras') in 2020 and from 1.08 t ha^{-1} ('Agrie Dzeltenie') to 5.47 t ha^{-1} ('Kuras') in 2021. The differences in average SY between OF and all three N fertilisation treatments in IF were significant in both years. Differences between SY in IF with 60 and 120 kg ha^{-1} N and with 120 and 180 kg ha^{-1} N were not significant in 2020. However, in 2021, no significant difference was found between the average SY values in all three N fertilisation treatments under the IF system (Table 6). The SY in OF was significantly lower than that in IF in both experimental years. SY decreased with significant differences in IF when the N supply increased in 2020 and did not change significantly in 2021. The SY depended on SC and TY, and genotypes with higher-than-average SC and TY, i.e., cultivars 'Kuras' and 'Jogla', produced a higher SY in both farming systems in both years. Several genotypes with lower-than-average SC and higher-than-average TY in each farming system provided higher-than-average SY in both farming systems: 'Magdalena' in 2020, and 'Prelma' and S 03067-33 in 2021.

Table 5. Tuber yield (t ha^{-1}) of potato genotypes grown under two (OF and IF) farming systems with different nitrogen (N) fertilisation treatments in 2020 and 2021

Year	2020					2021				
Farming system / treatment	Organic	Integrated N fertiliser rate kg ha^{-1}			Average	Organic	Integrated N fertiliser rate kg ha^{-1}			Average
		60	120	180			60	120	180	
'Agrie Dzeltenie'	27.0	53.0	57.4	58.9	*49.1 c*	6.5	13.2	15	15.3	*12.5 h*
'Madara'	22.9	42.2	36.8	31.8	*33.4 g*	10.7	23.2	27.5	23.1	*21.1 ef*
'Monta'	25.4	42.2	47.6	56.0	*42.8 de*	14.6	27.3	28.7	29.7	*25.0 cd*
'Rigonda'	30.8	55.2	59.0	61.9	*51.7 bc*	14.1	28.5	32.3	36.5	*27.9 c*
S 03067-33	30.4	53.6	52.5	55.8	*48.1 c*	21.4	36.3	44	47.7	*37.3 a*
'Vineta'	25.5	46.8	51.9	50.4	*43.6 d*	15.4	34.5	35.7	41.8	*31.6 b*
'Lenora'	23.8	40.8	51.5	60.7	*44.2 d*	12.1	31	28.5	29.9	*25.4 c*
'Prelma'	24.4	49.7	60.6	61.0	*48.9 c*	17.9	41.7	43.2	44.1	*36.7 a*
S 01085-21	21.0	44.7	52.0	47.0	*41.2 c*	10.6	30.6	33.9	34.6	*27.4 c*
S 04065-2	19.0	43.4	52.0	55.8	*42.6 def*	5.4	19	21.5	25.4	*17.8 fg*
S 11161-85	22.7	44.4	45.6	48.2	*40.2 ef*	9.6	24.7	23.2	27.4	*21.2 ef*
'Verdi'	19.7	39.2	51.3	46.5	*39.1 f*	6.9	20.9	21.2	23.8	*18.2 efg*
'Brasla'	21.6	44.0	43.8	42.8	*38.0 f*	12.8	22.4	28	23.1	*21.6 de*
'Imanta'	23.8	41.7	40.4	43.8	*37.4 fg*	8.6	20.2	25.6	26.4	*20.2 ef*
'Jogla'	31.3	59.8	63.5	59.5	*53.5 ab*	11.8	40.2	43	41.2	*34.1 ab*
'Magdalena'	32.4	63.5	67.4	54.5	*54.4 ab*	17.8	28.7	32.8	31.4	*27.7 c*
'Kuras'	30.8	60.8	68.8	67.5	*57.0 a*	12.7	40.7	39.4	42.6	*33.8 ab*
'Jelly'	29.4	59.6	56.0	69.9	*53.7 ab*	9.1	37.7	29.2	29.2	*26.3 c*
S 11152-7	13.8	31.9	32.9	33.8	*28.1 h*	9.6	17.8	19.6	16.5	*15.9 g*
Average	*25.0 c*	*48.2 b*	*52.2 a*	*52.9 a*	nu	*12.0 c*	*28.3 b*	*30.1 a*	*31.0 a*	nu

Explanation under Table 4

Table 6. Starch yield (t ha^{-1}) of potato genotypes grown under two (OF and IF) farming systems with different nitrogen (N) fertilisation treatments in 2020 and 2021

Year	2020					2021				
Farming system / treatment	Organic	Integrated N fertiliser rate kg ha^{-1}			Average	Organic	Integrated N fertiliser rate kg ha^{-1}			Average
		60	120	180			60	120	180	
'Agrie Dzeltenie'	3.71	7.03	6.68	6.18	*5.90 fg*	0.63	1.18	1.28	1.25	*1.08 g*
'Madara'	3.72	6.75	4.73	4.05	*4.81 ij*	1.47	2.98	3.45	2.80	*2.67 f*
'Monta'	4.29	7.33	7.90	8.20	*6.93 cde*	2.11	3.83	4.00	4.03	*3.49 de*
'Rigonda'	4.73	7.05	6.03	6.10	*5.98 fg*	2.00	3.88	3.78	4.23	*3.47 de*
S 03067-33	4.29	7.60	6.83	6.73	*6.36 ef*	2.88	4.53	5.05	5.58	*4.51 b*
'Vineta'	3.37	6.28	5.48	5.18	*5.07 hi*	1.77	3.10	3.55	3.95	*3.09 def*
'Lenora'	4.09	7.28	8.28	9.50	*7.29 cd*	1.80	4.05	3.40	3.85	*3.28 def*
'Prelma'	3.05	6.45	6.28	6.33	*5.52 gh*	2.38	5.00	5.05	4.53	*4.24 bc*
S 01085-21	3.51	7.08	6.73	6.60	*5.98 fg*	1.57	4.00	4.35	4.38	*3.57 cd*
S 04065-2	3.45	8.08	9.45	9.18	*7.54 bcd*	0.90	3.00	3.18	4.08	*2.79 ef*
S 11161-85	3.22	7.03	6.33	6.03	*5.65 g*	1.43	2.93	2.70	3.20	*2.56 f*
'Verdi'	4.07	7.93	10.45	8.35	*7.07 bc*	1.09	3.08	3.08	3.55	*2.70 f*
'Brasla'	3.68	8.38	7.78	7.25	*6.77 e*	2.15	3.23	4.13	3.18	*3.17 def*
'Imanta'	4.58	8.10	7.13	7.38	*6.80 de*	1.42	2.95	4.13	4.00	*3.12 def*
'Jogla'	6.73	12.33	11.35	10.40	*10.20 a*	2.05	6.33	6.78	5.95	*5.28 a*
'Magdalena'	5.01	10.08	9.78	7.40	*8.07 b*	2.40	3.45	5.55	3.80	*3.80 bcd*
'Kuras'	6.50	11.70	12.30	12.20	*10.68 a*	2.15	6.85	6.33	6.55	*5.47 a*
'Jelly'	4.32	7.05	6.40	7.78	*6.39 ef*	1.13	4.53	3.48	3.25	*3.09 def*
S 11152-7	2.44	5.30	5.60	5.03	*4.59 j*	1.71	2.58	3.21	2.73	*2.56 f*
Average	*4.15 d*	*7.83 b*	*7.66 bc*	*7.36 c*	nu	*1.74 b*	*3.76 a*	*4.16 a*	*3.94 a*	nu

Explanation under Table 4

Nitrogen use efficiency (NUE) value between potato genotypes averaged from 44.2 kg kg^{-1} (S 11152-7) to 101.6 kg kg^{-1} ('Kuras') in 2020. In 2021, the NUE values were approximately two times lower compared to 2020 and ranged from 13.74 kg kg^{-1} ('Agrie Dzeltenie') to 53.81 kg kg^{-1} ('Kuras'). The highest average NUE values were found in OF and IF with 60 kg ha^{-1} N in 2020, and both values were not significantly different. When the N supply in IF increased, NUE decreased significantly in 2020. In 2021, NUE values differed significantly between farming systems, but NUE in IF with 60 kg ha^{-1} N significantly exceeded NUE values in OF and IF with 120 and 180 kg ha^{-1} N (Table 7). The NUE values of cultivars 'Jogla' and 'Kuras' were higher than the average NUE in each farming system in both experimental years. In 2020, cultivar 'Magdalena' had a higher-than-average NUE in each farming system. However, in 2021, the NUE of several potato genotypes (cultivars 'Rigonda' and 'Prelma' as well as breeding clone S 03067-33) exceeded the average NUE in each farming system.

Table 7. Nitrogen use efficiency (kg kg^{-1}) of potato genotypes grown under two (OF and IF) farming systems with different nitrogen (N) fertilisation treatments in 2020 and 2021

Year	2020					2021				
Farming system / treatment	Organic	Integrated N fertiliser rate kg ha^{-1} 60	120	180	Average	Organic	Integrated N fertiliser rate kg ha^{-1} 60	120	180	Average
'Agrie Dzeltenie'	80.57	82.56	56.48	41.06	*65.17 cd*	13.09	18.35	13.52	10.01	*13.74 g*
'Madara'	75.13	75.39	37.83	24.60	*53.2 f*	27.05	39.97	30.47	19.04	*29.13 f*
'Monta'	87.53	79.84	59.92	48.69	*69.00 c*	38.16	48.99	34.40	26.07	*36.91 bc*
'Rigonda'	99.13	78.29	47.09	37.35	*65.47 cd*	36.39	51.88	36.91	31.22	*39.10 b*
S 03067-33	92.25	86.82	54.50	41.57	*68.78 c*	53.31	61.47	47.75	38.62	*50.29 a*
'Vineta'	73.99	73.26	46.03	33.43	*56.68 ef*	34.56	44.75	34.80	29.72	*35.96 bcd*
'Lenora'	80.00	78.68	62.30	55.02	*69.00 c*	32.38	54.87	32.87	25.96	*36.52 bc*
'Prelma'	68.32	74.61	52.65	40.76	*59.09 def*	44.21	69.33	47.21	34.44	*48.80 a*
S 01085-21	71.69	77.52	52.51	38.96	*60.17 def*	28.22	54.18	40.21	29.82	*38.11 bc*
S 04065-2	68.97	85.27	68.92	52.11	*68.82 c*	15.71	38.57	28.33	25.87	*27.12 f*
S 11161-85	69.33	79.07	50.79	37.35	*59.14 def*	25.59	40.79	25.09	21.99	*28.36 f*
'Verdi'	78.92	82.36	74.47	46.18	*70.48 c*	19.20	40.50	26.57	22.90	*27.29 f*
'Brasla'	74.95	89.34	57.14	41.06	*65.62 cd*	37.19	41.64	34.80	21.17	*33.70 cde*
'Imanta'	72.21	85.85	52.78	42.37	*63.30 cde*	24.68	39.72	33.91	25.30	*30.90 def*
'Jogla'	129.20	126.36	80.69	56.83	*98.27 a*	35.23	81.85	57.91	39.73	*53.68 a*
'Magdalena'	104.87	112.21	75.93	43.98	*84.25 b*	44.38	47.34	36.43	26.28	*38.61 bc*
'Kuras'	125.33	123.06	90.48	67.37	*101.56 a*	37.12	84.53	52.62	40.98	*53.81 a*
'Jelly'	91.83	81.98	52.12	48.69	*68.66 c*	21.44	63.54	31.78	22.67	*34.86 bcd*
S 11152-7	49.13	56.98	41.53	29.22	*44.21 g*	29.20	33.94	26.00	16.16	*26.33 f*
Average	*83.86 a*	*85.76 a*	*58.64 b*	*43.51 c*	nu	*31.43 c*	*50.33 a*	*35.35 b*	*26.73 d*	nu

Explanation under Table 4

Relationships between evaluated traits. Positive and high or strong relationships were found between SC and SY as well as SY and NUE (Table 8). A high correlation between TY and NUE was found in both years. High and medium significant correlation coefficients were found between TY and SY in both years in OF and all three N fertilisation treatments in IF. A medium and weak but significant relationship between SC and NUE depending on the farming system was found in 2020, and weak and very weak correlations between these traits were found in 2021, except for OF. A mostly moderate relationship was found between SC and SY, except for OF in 2021, when the correlation coefficient was high. In the present study, potato genotypes with variable SC were included: if SC in tubers was low, SY was consequently low. No significant correlation was found between SC and TY in 2020 and 2021 in both farming systems.

Table 8. Correlation coefficient between studied traits of potatoes in 2020 and 2021 (n = 76)

Year		2020				2021			
Farming system / treatment		Organic	Integrated N fertiliser rate kg ha^{-1} 60	120	180	Organic	Integrated N fertiliser rate kg ha^{-1} 60	120	180
SC	TY	ns	ns	ns	ns	ns	ns	ns	ns
SC	SY	0.534***	0.564***	0.668***	0.649***	0.944***	0.467***	0.400***	0.373***
TY	SY	0.800***	0.644***	0.685***	0.692***	0.944***	0.914***	0.530***	0.873***
SC	NUE	0.355**	0.430***	0.548***	0.521***	ns	0.372***	0.316**	0.244*
TY	NUE	0.867***	0.735***	0.769***	0.784***	0.974***	0.954***	0.558***	0.931***
SY	NUE	0.949***	0.987***	0.988***	0.986***	0.994***	0.993***	0.995***	0.989***

SC – starch content, TY – tuber yield, SY – starch yield, NUE – nitrogen use efficiency; significant at: * – $P \le 0.05$, ** – $P \le 0.01$, and *** – $P \le 0.001$; ns – not significant

Discussion

Influence of meteorological conditions on traits of potato genotypes. A strong influence of the meteorological conditions of the year was found during the experiment. In July 2021, precipitation was approximately three times lower than in 2020 (133 and 43.5 mm in 2020 and 2021, respectively), and the average air temperature in July 2021 exceeded the average air temperature of the previous year by 5.5°C. As a result, the SY, TY and NUE for potato genotypes were approximately twice lower in 2021 than in 2020 (Table 2). Lower DMY, TY, and SY under water and higher temperature stress conditions were obtained in previous studies (Kasal et al., 2011; Pavlista, Groskopf, 2016; Aliche et al., 2018). A significant relationship between NUE and precipitation and temperature during the vegetation period due to TY formation was revealed by Kasal et al. (2011). In the present study, a significant influence of the year expressed as partitioning variance components exceeding the effects of the genotype and the farming system was found when analysing data from both years together (Table 3). The results were analysed separately for each year, but regardless of the influence of meteorological conditions, the trends of trait expression for the tested potato genotypes were similar in both experimental years.

Trait expression in studied farming systems. The potato genotype TY increased with increase in the availability of N in soil when comparing organic and integrated farming systems with 60 and 120 kg ha^{-1} N, but there was an insignificant increase in TY between integrated farming with 120 and 180 kg ha^{-1} N in both years (Table 5). The correlation of TY with NUE was high, but if TY did not increase significantly in the farming system with increased N supply, a decrease in the NUE values was found. Previous studies concluded that an increase in the N fertilisation above the optimum rate did not significantly increase TY and even had a negative effect (Vos, 1995; Ruža et al., 2013; Grzebisz et al., 2018; Ierna, Mauromicale, 2019; Nurmanov et al., 2019; Stefaniak et al., 2021). The increase in the N fertiliser rate did not result in an effective yield increase, but it was suggested to be a reason of environmental pollution with N compounds (Milroy et al., 2019).

The average SC of potato genotypes in 2020 exceeded the average SC in 2021 in both farming systems due to unfavourable growing conditions in 2021. However, the trends of SC changes in the integrated farming with different N fertilisation treatments were similar in both experimental years. In 2021, under changing meteorological conditions, organic farming resulted in higher average SC for genotypes compared to integrated one. This differed from 2020, a year with more favourable growing conditions, when organic farming still yielded higher SC, except for integrated farming with 60 kg ha^{-1} N. The trait was mainly determined by the genotype, and PVCs of genotype influence were 86% and 83% in 2020 and 2021, respectively (Table 3). The SC in potato tubers was partly determined by the genotype, and similar observations have also been found in previous studies (Skrabule et al., 2013; 2022; Brazinskiene et al., 2014). However, a significant effect of the farming system on SC was also found. The SC of genotypes decreased significantly in integrated farming with increased N fertilisation in both experimental years (Table 4). Higher SC in potatoes grown under organic farming compared to integrated farming was found in a previous research (Hajŝlová et al., 2005), but several studies reported no significant difference between farming systems (Maggio et al., 2008; Brazinskiene et al., 2014; Tein et al., 2014) or higher SC under conventional or integrated farming (Skrabule et al., 2013). In previous studies (Vos, 1995; Ruža et al., 2013; Tein et al., 2014; Tiemens-Hulscher et al., 2014; Koch et al., 2020; Naumann et al., 2020), additional available soil N was found to promote excessive stolon and leaf development directing DM flow to other parts of the plant than the potato tubers, delaying leaf maturation and tuber bulking periods. As a result, TY and DM content were reduced. In a particular investigation (Öztürk et al., 2010), there was a slight decrease in SC with increased available soil N and P levels after fertilisation, but the effect was not significant.

The SY of potato genotypes is of great importance for potato starch production. Cultivars with a higher starch content are particularly valuable for efficient use in starch processing. A significant increase in SY between organic and integrated farming systems was found in both experimental years. A small and insignificant increase in TY and decrease in SC resulted in relatively stable SY in integrated farming with variable N fertilisation. This means that increasing N fertilisation in the soil did not increase SY due to a decrease in SC and a slight insignificant increase in TY.

The increase in available soil N increased TY, slightly increased or stabilised SY and significantly decreased NUE of the potato genotype (Tables 5–7). Part of these findings are consistent with previous studies (Kumar et al., 2007; Ruža et al., 2013; Ierna, Mauromicale, 2019; Stefaniak et al., 2021), where the value of agronomic NUE decreased with increasing N fertiliser rate. Potato genotypes with relatively increased NUE could use available soil N with low N availability more efficiently, i.e., in organic farming, and require less N fertilisers in integrated farming providing a higher-than-average potential TY. In the presented study, the NUE of 'Kuras' exceeded the average level in both farming systems in both years, and the TY of this cultivar was higher than the average of the tested potato genotypes in studied farming systems in both years. Other potato genotypes ('Rigonda', 'Prelma', 'Jogla', 'Magdalena', and S 03067-33) with higher-than-average NUE in the OF and IF systems with applied treatments produced high TY exceeding the average yield. However, for the potato genotypes with higher-than-average TY ('Agrie Dzeltenie' and 'Jelly'), the obtained NUE values were lower than the average TY of the tested genotypes in most of the studied treatments.

A high correlation between SY and NUE was found in studied farming systems in both experimental years (Table 8). High and moderate correlations between TY and NUE and high and medium relationships between SY and TY were found. The SY was mostly determined by SC, and the correlation between these traits was strong. A higher SY was obtained if a higher

SC of the potato genotype was found, as expected from previous experience, but no significant relationship between SC and TY was determined. However, several potato genotypes with lower-than-average SC yielded higher than average SY due to high TY. The SC values of the potato genotypes mostly had weak relationships with NUE. However, SC is one of the components determining SY, and another important component is TY; both SY and TY had a high correlation with NUE. Therefore, the potato genotypes with higher-than-average NUE mostly provided higher TY and SY in the farming system with different N fertiliser rates and even under changing meteorological conditions. In the present study, as the relationship of NUE with SC was mostly weak, the genotype SC determined SY, but genotype NUE had a weak influence on SC changes. The potato genotype NUE had a strong relationship with TY and SY but a weak correlation with SC.

Conclusions

1. The effect of potato genotype and farming system with different nitrogen (N) fertilisation on tuber yield (TY), starch yield (SY), and starch content (SC) and nitrogen use efficiency (NUE) was significant in both experimental years.

2. The NUE of potato genotypes decreased with increase in the availability of soil N, and this trend was similar in both experimental years under different meteorological conditions.

3. A high correlation between starch yield and NUE and a high and moderate correlation between tuber yield and NUE were found, and high and medium relationships between starch yield and tuber yield were revealed. Potato genotypes with higher NUE were found to have higher tuber yield and starch yield than genotypes with relatively lower NUE, even in the farming system with different N fertiliser rates. The most promising potato genotypes with high NUE values were cultivars 'Rigonda' and 'Prelma' and breeding clone S 03067-33.

4. Potato genotypes providing relatively higher NUE in the farming system with low N fertilisation or in the organic farming (OF) system had higher starch yield than other tested genotypes with similar starch content, but in the integrated farming (IF) system with increased N supply, when genotype NUE decreased, starch yield stabilised or decreased.

5. The NUE had low correlation with the starch content of potato genotypes, and this trait was mostly influenced by genotype-specific characteristics and growing conditions.

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