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PHENOTYPIC VARIABILITY OF THE YIELD AND STRUCTURE OF MID-EARLY POTATO CULTIVARS

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ABSTRACT

Background. In order to properly direct the breeding work of cultivars of a given potato earliness group it is necessary to know the range of variability and relationships between their characteristics, both in a given year and between years. Therefore, the purpose of this study was to determine the structure of the variability of the quantitative traits of mid-early potato cultivars, which would facilitate in selecting cultivars with the highest stability of the desired characteristics.
Material and methods. The analysis was based on a strict field experiment carried out in the years 2010–2012 at the Experimental Station in Uhnin (Lublin Province), (51°34' N; 23°02' E), on lessive soil, slightly acidic. The experiment was performed in randomized blocks in three repetitions. Eighteen potato cultivars were studied, four very early cultivars and six early cultivars. Cultivation techniques were conducted in accordance with the principles of Good Agricultural Practice and conservation measures in line with the recommendations of the IOR-PIB. Organic fertilizers and minerals for potato were at the same level each year (20 $Mg \cdot ha^{-1}$ white mustard for ploughing, 90 kg N, 39.3 kg P, and 112.0 kg $K \cdot ha^{-1}$.
Results. The dominant role in the variability of tuber yield and its structure was played by the interaction between the cultivar and the environment (3.2%–92.7%). Genotype accounted for 2.9%–27.9% of variance in the total variance of the studied characteristics, and the test conditions for 3.7%–73.9%. Interaction between the genotype and the environment was the most conducive to: total yield, commercial yield, yield of seed potatoes, and proportion of tuber mass of <4, 5–6 and >6 cm in diameter. It did not, however, significantly affect the number of shoots per plant. The most stable characteristic of the activity of the tested cultivars was mass proportion of commercial tubers, and the most variable one was their yield.
Conclusion. Analysis of the main components identified five groups of cultivars with specific characteristics that can be used in decision-making in the breeding of new cultivars.

Key words: potato cultivars, shoot number, tuber fractions, tuber yield, variability

INTRODUCTION

The basic value criterion of a cultivar, which makes it possible to obtain significant income from the cultivated unit, is its yield (Stypa, 2014). Polish potato cultivars are becoming more productive and, under experimental conditions and depending on the characteristics of a given cultivar and environmental conditions, it is possible to obtain potato yield at the level of 100–120 $Mg \cdot ha^{-1}$ (Michałek *et al.*, 2000; Michałek and Sawicka, 2005; Balzarini *et al*. 2011; Pszczółkowski, 2017). Potato yield is conditioned by

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many qualitative characteristics that are derived from complicated, polygenic inheritance of yield in combination with the high effect of environmental factors (Stefańczyk and Śliwka, 2013; Kamiński, 2015). Polygenic yield determination, tetrasomic trait inheritance, and low potato reproduction factor make it difficult to obtain rapid advancement in enhancing this characteristic (Kamiński, 2015). Diversification of the weather and soil conditions in which potato is grown, namely water availability, air and soil temperature, sunshine duration, contents of carbon dioxide, as well as others, cause modifications in the processes of internal regulation, both within the plant, as well as in plant variability in the field, related to years and location (Jankowski *et al*., 2006; Rymuza *et al*., 2013; Sawicka *et al*., 2015). Air temperature above the optimum for potato causes shortening of the particular developmental stage of the plant, whereas a shortening of the day leads to earlier tuberization (Stefańczyk and Śliwka, 2013; Sawicka *et al*., 2015). Air temperature optimal for tuber formation and growth varies between 15°C and 23°C (Sawicka *et al*., 2012; 2015). Photosynthesis efficiency in potato fields depends on the intensity of sunlight that reaches the Earth, PAR (Photosynthetically Active Radiation) from 43% on cloudy days to 53% on sunny days and makes up. Also, the angle at which the light falls, air pollution, availability of minerals and water, as well as the combination of air and water relations in the soil affect photosynthesis efficiency and the ability to produce dry mass by the potato plant (Sawicka *et al*., 2015). Stomata activity in a potato plant depends on sunshine duration and air temperature. Low temperatures slow down photosynthesis, whereas too high temperatures increase transpiration. A given state of stomata affects carbon dioxide assimilation and transpiration (the so-called stomatal conductance of the leaf). Transpiration intensity depends, on the other hand, on the state of the stomata. At their full opening transpiration of stomata rate may be similar to water evaporation, while their closing can limit the process by over 95% (Maleszewski *et al*., 2003). Increased competition in the field caused by excessive potato plant density, infestation, and factors that cause plant growth inhibition and limit the assimilation surface of leaves (for example potato bug, *Phytophthora infestans*, alternariosis, viral disease), as well as agrotechnical treatments related to the system of potato growth all contribute to limiting potato yield (Pytlarz-Kozicka, 2004; Gugała *et al*., 2014; Sedlákowá *et al*., 2011; Sawicka *et al*., 2012; 2015; Zarzyńska and Goliszewski, 2007). In order to give appropriate direction to work on the breeding of cultivars of given earliness groups, knowledge on the range of variability and interdependence of characteristics is essential, both in a given year, as well as between years. Therefore, the aim of this study was to find variability structures of chosen qualitative characteristics of mid-early potato cultivars, which in the future would enable easier selection of cultivars with the highest stability of the desired growth characteristics.

MATERIAL AND METHODS

The field experiment was carried out in the years 2010-2012 at the Experimental Station for Cultivar Evaluation in Uhnin (φ = 51°34' N; λ = 23°02' E; H = 155 m a.s.l.), which is part of the Research Centre for Cultivar Testing (COBORU). The experiment was carried out in randomised blocks in three repetitions. The research subjects were 18 mid-early potato cultivars, including 14 edible cultivars (Bartek, Benek, Cekin, Finezja, Gawin, Irga, Kolia, Legenda, Sante, Satina, Stasia, Tajfun, Tetyda, and Wiarus) and four starch cultivars (Adam, Glada, Harpun, and Pasat). In the experiment, constant NPK fertilization was applied at the doses of: 90 kg N, 39.3 kg P, and 112.0 kg $K \cdot ha^{-1}$, and also in the preceding autumn white mustard aftercrop was ploughed in (circa 20 $Mg \cdot ha^{-1}$). Potato forecrop was winter triticale. Tubers were planted in the last ten days of April in ridges, with spacing 67.5 cm × 37 cm. Seed potato material was tubers of C/A class. Plot area for harvest amounted to 15 m^2. Cultivation treatments and plant protection against potato bug, *Phytophthora infestans*, and alternariosis were carried out according to the principles of Good Agricultural Practice. During the growth period, three to four sprayings against alternariosis and *Phytophthora infestans* were carried out, whereas potato bug was controlled at the time of occurrence with available chemicals. Tuber harvest was carried out at their full physiological ripeness, namely at stage 99 of the BBCH-scale. Subsequently, tuber yield was determined and samples collected for structure marking. Yield structure was marked according to the fraction: <4, 4–5, 5–6, and >6 cm in diameter. Yield of >4 cm to >6 cm in diameter was recognized as commercial yield, excluding tubers damaged mechanically or by pest, as well as green ones. Tuber yield 4–6 cm in diameter was accepted as seed potato yield, excluding tubers damaged by pest or those mechanically damaged to a high degree.

The field experiment was carried out on lessive soil, formed from light loamy sands, very good rye complex, class IVa. Contents of the assimilable forms of phosphorus, potassium and magnesium were diversified in the research years (Table 1). Assimilable phosphorus content varied between high and very high; potassium content fell within the range of average soil richness in this element; assimilable magnesium content varied between average and very high for soil richness in this macroelement. Soil pH was slightly acidic (5.7 to 6.3 pH), (Table 1).

Table 1. Richness of the experimental soil in assimilable phosphorus, potassium, and magnesium and soil pH (2010–2012)

Year	Contents of assimilable forms $mg \cdot 100\ g^{-1}$ in soil dry mass			pH [1M KCl]
	P_2O_5	K_2O	Mg	
2010	20.3	11.7	4.3	5.7
2011	21.3	12.7	8.1	6.3
2012	15.9	13.3	7.4	6.1
Mean	19.2	12.6	6.6	6.0

Statistical analysis of the results was carried out with the use of two-factor analysis of variance (ANOVA). Analyses were concerned with comparisons of the effect of cultivar type on the studied variables, and study years were the random factor. Multiple comparison t-Tukey's tests made detailed comparative mean analyses possible through singling out statistically homogenous mean groups and setting the so-called lowest significant differences of means (LSD), which in the Tukey's tests are marked as HSD (Tukey's Honest Significant Difference). The significance of variability sources was tested with the Fisher-Snedecor F-test. In order to determine the proportion of particular variability sources and their interactions in the total variability, analysis of variance components was carried out, using the following markers:

- σ^2_e – evaluation of environmental variability, related to observation repetition or measurement in time;
- σ^2_G – evaluation of genotype (cultivar) variability;
- σ^2_p – evaluation of phenotype (total) variability.

Empirical values of mean squares obtained from the analysis of variance were subsequently compared with their expected values. By solving equations with the above method, an estimation of variance components that corresponded to the particular variability sources was obtained. Mutual relations of the set variance component evaluations and their percentage structure was the basis for the evaluation of the effects of cultivar and year per tuber yield variability and yield structure characteristics. In order to group the cultivars with similar multi-characteristic properties, data clustering was performed. Data clustering was based on the square of Euclidean space (Crossa and Franco, 2004). As a linking method, the single linkage method was applied. Clustering was obtained through dendrogram division with the Mojena's rule (Rymuza, 2015), according to which the cut-off point is the linkage distance that meets the criteria for Milligan and Cooper (Gauch *et al.*, 2008) formula for inequality: $d_{i+1} > \bar{d} + ks_d$, where: $\bar{d}$ – mean, s_d – standard deviation, d_i, k – certain constant within the range of 2.75 to 3.50 (Rymuza *et al.*, 2013). Cut-off point was set at the level of 75%. Analysis of variance and data clustering were carried out in the statistical packet SAS® 9.2 (SAS Institute, 2008).

Weather conditions in the study years were diversified. Sielianinov's hydrothermal index, which measures precipitation effectiveness in a given month, was calculated during potato growth. On that basis, years 2010 and 2011 may be counted as wet, whereas the year 2012 as average (Table 2). The best thermal conditions were recorded in the year 2010, which was characterized by air temperature higher than the many-years' average. Year 2011 was characterized by excessive precipitation in the first half of growth, whereas in August and September drought or extreme drought occurred. Year 2012 was characterized by high air temperatures and drought in May, July and September, very humid June, and average April and August (Table 2).

Table 2. Precipitation, air temperature, and Sielianinov's hydrothermal index during potato growth, according to the meteorological station in Uhnin in the years 2010–2012

Year	Month	Precipitation, mm				Air temperature, °C				Hydrothermal index*
		period of the month (10 days)			month	period of the month (10 days)			mean	
		1	2	3		1	2	3		
2010	April	12.4	1.1	3.6	17.1	8.5	9.7	9.5	9.2	0.6
	May	35.8	41.3	15.9	93.0	14.0	15.5	15.1	14.9	2.0
	June	27.5	36.3	0.0	63.8	19.2	18.2	17.1	18.2	1.2
	July	19.0	10.3	33.8	63.1	20.2	24.1	21.3	21.9	0.9
	August	65.4	11.1	64.6	141.1	21.1	21.8	17.4	20.0	2.3
	September	47.9	9.3	20.1	77.3	11.8	12.9	12.0	12.2	2.1
	Total				455.4					
2011	April	17.6	18.7	3.6	39.9	8.7	7.4	12.7	9.6	1.4
	May	19.2	12.7	14.3	46.2	8.7	15.1	17.7	14.0	1.1
	June	53.6	17.9	45.7	117.2	21.0	17.0	17.3	18.4	2.1
	July	81.2	31.8	56.7	169.7	16.8	21.2	18.2	18.7	2.9
	August	13.6	14.7	14.6	42.9	18.2	18.3	17.9	18.1	0.8
	September	5.2	0.0	3.7	8.9	14.5	15.6	12.9	14.3	0.2
	Total				424.8					
2012	April	7.7	21.9	0.4	30.0	4.1	9.2	15.0	9.4	1.1
	May	5.7	30.8	1.5	38.0	16.1	12.0	16.6	15.0	0.8
	June	23.8	56.2	20.8	100.8	15.1	18.8	18.7	17.5	1.9
	July	34.5	12.1	6.5	53.1	25.2	18.6	21.6	21.8	0.8
	August	7.7	50.1	12.3	70.1	21.2	17.0	18.0	18.7	1.2
	September	2.8	7.4	23.8	34.0	15.8	15.2	12.1	14.3	0.8
	Total				326.0					

* index was calculated according to the formula: $k = \frac{10P}{\sum t}$, (Skowera, 2014), where: P − sum of monthly precipitation in mm, Σt – monthly total air temperature > 0ºC

Ranges of values of this index were classified as follows: extremely dry − k ≤ 0.4; very dry − 0.7 ≤ k < 0.4; dry − 1.0 ≤ k < 0.7; rather dry − 1.3 ≤ k < 1.0; optimal − 1.6 ≤ k < 1.3; rather humid − 2.0 ≤ k < 1.6; humid − 2.5 ≤ k < 2.0; very humid − 3.0 ≤ k < 2.5; extremely humid − 3.0 > k

RESULTS

The dominant role in the variability of total and commercial yield, seed potato yield, commercial tuber and seed potato proportion, shoot number, and tuber mass of all the fractions was played by the interaction between the cultivars and study years, and fluctuated between 57.9% and 75.8% of the variance proportion in the total variance (Table 3). Genetic characteristics of the tested cultivars determined from 20.1%-32.5% of the phenotypic variability of the studied yield characteristics and their structure. The lowest effect on phenotypic variability was exerted by the conditions in the study years (0.0% to 9.7% of the variance proportion in the total variance of the studied characteristics), (Table 3).

Table 3. Effect of cultivars and years on the total yield, commercial tuber yield, seed potato yield, proportion of potato seed mass, proportion of tuber mass with the diameter of <4, 4-5, 5-6, >6 cm, shoot number, and the percentage value of the proportion of cultivars, years, and interactions between cultivars × years in the total variance

Characteristic	Significance of the effect			Percentage proportion of variance in the total variance		
	cultivars	years	cultivars × years	cultivars	years	cultivars × years
Number of shoots per plant, piece	**	ns	**	24.8	0.0	75.3
Tuber yield, Mg·ha^{-1}	**	*	**	26.1	4.3	69.6
Proportion of tuber mass ∅ <4 cm, %	**	*	**	21.2	8.4	70.5
Proportion of tuber mass ∅ 4-5 cm, %	**	*	**	25.7	7.9	67.4
Proportion of tuber mass ∅ 5-6 cm, %	**	*	**	28.3	5.5	66.2
Proportion of tuber mass ∅ >6 cm, %	**	*	**	32.5	9.7	57.9
Proportion of commercial tubers, %	**	*	**	26.4	4.3	68.1
Commercial tuber yield, Mg·ha^{-1}	**	*	**	27.0	5.4	67.6
Proportion of seed potatoes, %	**	ns	**	23.6	0.7	75.8
Yield of seed potatoes, Mg·ha^{-1}	**	*	**	20.1	7.6	72.4

* significant at $p \le 0.05$; ** significant at $p \le 0.01$
ns – not significant at $p \le 0.05$

Average shoot number per potato plant varied between 3.8 and 7.5, depending on the cultivar. The edible cultivar Finezja had the highest stability in shoot-formation, whereas the highest variability was demonstrated by the starch cultivar Adam (Table 4).

Shoot number per plant turned out to be the characteristic most related to the cultivar and study years interaction (75.3%). Genetic traitss of the studied cultivars determined 24.8% of the above factor, whereas study years had no effect on shoot number per plant (Table 3).

Total tuber yield was found to depend to the greatest extent on the interaction between the cultivars and growth conditions (69.6%), and to a lesser extent on the genetic characteristics of the studied cultivars (26.1%). Study years decided only to a small extent the values of this characteristic (0.7%–7.6%), (Table 3).

The highest tuber yield in the group of edible cultivars was obtained from the cultivar Satina, whereas in the group of starch cultivars Pasat was the most productive. The other cultivars were found to be homogenous in regard to this characteristic. The cultivar Tajfun was the most stable in yield (V = 17.9%), whereas cultivars Cekin and Sante gave the most variable yields (V = 38.2% and 38.0%), (Table 4).

The highest proportion in the total yield was made by tubers with a diameter of 4-5 cm (63.3%), whereas the lowest was by the biggest tubers >6 cm (3.0%), (Table 5). Tuber yield structure had low stability, and the components of phenotypic (total) variability turned out differently. Interaction between the cultivar and study years played a dominant role in tuber variability of all size fractions (57.9–70.5%). Cultivar type influenced to a significantly lower degree the tuber size structure (21.2%–32.5%), and study years played the smallest part in total variability in this area (5.5%–9.7%), (Table 3).

Due to the variability of the characteristics of the percentage proportion of tuber mass of different size in the yield, the tubers may be classed as follows: with the diameter of 4–5 > 5–6 > below 4 cm > above 6 cm (Table 5).

Table 4. Average number of shoots per plant, average tuber total yield, and coefficient of variation V (%) in the years 2010–2012

Earliness group	Cultivar	Number of shoots per plant, piece		Total tuber yield, $Mg \cdot ha^{-1}$	
		mean	V*	mean	V*
Mid-early, edible	Bartek	5.6	24.3	38.5	24.3
	Benek	6.2	29.1	42.7	28.0
	Cekin	3.9	21.3	41.5	38.2
	Finezja	3.8	6.4	35.2	22.1
	Gawin	4.6	29.6	34.3	19.2
	Irga	5.0	23.3	34.9	23.6
	Kolia	5.2	13.1	38.2	23.7
	Legenda	4.4	27.1	39.3	37.6
	Sante	4.6	8.8	42.2	38.0
	Satina	5.3	20.2	53.6	27.0
	Stasia	7.5	16.7	37.1	37.6
	Tajfun	5.0	21.9	43.7	17.9
	Tetyda	5.4	27.4	40.5	29.0
	Wiarus	5.1	21.1	46.2	29.1
Mid-early, starch	Adam	5.8	43.4	33.9	31.1
	Glada	6.1	13.2	33.3	30.8
	Harpun	4.2	20.1	35.1	21.0
	Pasat	5.3	10.6	32.6	37.4
Mean		5.2	21.0	39.0	28.6
$HSD_{0.05}$ cultivar		1.7		2.0	

* coefficient of variation in %

The lowest variability in the formation of tubers <4 cm in diameter was characteristic for the cultivar Bartek (V = 12.4%), whereas for the biggest tubers in the yield it was for the cultivar Harpun (V = 85.4%). The highest variability of the biggest tubers in the yield was characteristic for cultivars Gawin and Adam (V = 300.0%), (Table 5).

The proportion of commercial tubers in the total yield was high and amounted to, on average, 93.6% (Table 6). Interaction between cultivars and years had a significant effect (68.1%), cultivar features by 26.4%, while study years only had a 4.3% proportion in the total variability (Table 3).

The strongest effect on the size of commercial tuber yield was exerted by the interaction between the cultivars and years (67.6%), while cultivars decided by 27%, and years by 5.4% about the phenotypic variability of this characteristic (Table 3). Both the proportion and yield of seed potatoes were determined most strongly by the characteristics of the studied cultivars in relation to the conditions of the study years (respectively, 75.8% and 72.4% of the total variability). Cultivar determined 7.6% of total variability of seed potato yield, while for seed potato proportion it was only 0.7% (Table 3).

Table 5. Average proportion in the yield of tuber mass with the diameter of <4, 4-5, 5-6 > 6 cm and coefficients of variation V (%) in the years 2010–2012

Earliness group	Cultivar	Tuber diameter, cm							
		<4		4–5		5–6		>6	
		mean	V*	mean	V	mean	V	mean	V
Mid-early, edible	Bartek	5.1	12.4	61.2	15.3	30.7	22.5	3.0	72.3
	Benek	4.5	16.9	75.8	8.5	18.7	25.5	1.0	151.0
	Cekin	3.9	36.0	54.6	28.2	37.4	42.1	4.1	57.2
	Finezja	3.0	25.0	60.0	9.8	33.8	11.6	3.2	113.0
	Gawin	11.2	34.2	73.5	5.7	14.7	44.7	0.6	300.0
	Irga	5.9	25.1	77.5	9.8	16.5	55.5	0.1	158.0
	Kolia	5.3	22.5	55.3	20.1	35.1	17.0	4.3	150.0
	Legenda	5.8	54.8	50.4	34.2	37.8	41.9	6.0	95.6
	Sante	5.7	47.3	71.5	9.9	21.3	41.7	1.5	62.3
	Satina	4.2	57.5	36.2	34.0	46.5	26.4	13.1	111.0
	Stasia	8.0	32.1	79.6	3.7	11.6	33.8	0.8	153.0
	Tajfun	3.8	84.2	61.6	22.9	32.1	35.5	2.5	121.0
	Tetyda	3.6	28.7	41.6	16.5	47.1	13.1	7.7	84.7
	Wiarus	2.6	31.9	42.3	29.6	44.1	17.8	11.0	75.9
Mid-early, starch	Adam	12.4	30.5	76.5	3.5	10.9	51.0	0.2	300.0
	Glada	8.4	21.2	73.2	8.9	17.8	37.2	0.6	123.0
	Harpun	6.2	42.6	60.3	22.6	31.6	43.0	1.9	85.4
	Pasat	11.2	18.8	66.8	6.3	21.6	18.4	0.4	94.6
Mean		6.4	34.5	63.3	16.1	27.4	32.2	3.0	128.0
$HSD_{0,05}$		0.3		3.3		1.4		0.2	

*coefficient of variation in %

Cultivar Satina was characterized by the highest commercial and seed potato yield among the edible cultivars, whereas among the starch cultivars the highest values of those characteristics were found for cultivar Harpun. The lowest variability in commercial and potato seed yield was found for cultivar Tajfun (respectively, V = 17.1% and 14.8%), whereas the highest variability in commercial yield was found for cultivar Stasia, and in potato seed yield for cultivar Cekin (both 39.7%), (Table 6).

Data range, as a difference between the maximum and minimum values of a given characteristic, is a measure that indicates the empirical variability of the analysed characteristics. However, it did not give complete information on the diversification of the particular values of characteristics in the population. This type of information is given by the coefficient of variation, which shows the stability of a given characteristic. Coefficient of variation values varied from very low in the case of commercial tuber mass proportion, to high for tuber mass proportion <4 cm ∅ (Table 7).

Shoot number of mid-early cultivars demonstrated to be significantly positively correlated with the proportion of tuber mass of <4 cm and of 4–5 cm, whereas negatively with the proportion of tubers of 5–6 cm and the proportion of commercial tubers in the total yield. Proportion of tuber mass of <4 cm was significantly positively correlated with the proportion of tuber mass of 4–5 cm, and negatively with the other tuber fractions and yield. The fraction of medium tubers (4–5 cm) demonstrated to be significantly positively correlated only with the proportion of seed potato mass, and negatively with all the other yield structure characteristics. Tuber fractions of 5–6 and >6 cm were significantly positively correlated with all the parameters of yield structure except seed potato proportion in the yield. In the case of the biggest tubers in the yield, seed potato proportion was found to be significantly negatively correlated with the proportion of seed potato fraction. Total tuber yield was, on the other hand, highly significantly correlated with commercial yield proportion and size, and negatively with seed potato proportion. Commercial tuber proportion in the total yield was positively correlated with commercial fraction yield and seed potato yield, and the yield of the above tuber fraction was found to be significantly positively correlated with seed potato yield, and negatively with the proportion of their mass in the yield (Table 8).

Table 6. Average proportion and yield of commercial tubers and seed potatoes and their coefficients of variation V in the years 2010–2012

Earliness group	Cultivar	Proportion of commercial tubers, %		Yield of commercial tubers, $Mg \cdot ha^{-1}$		Proportion of seed potatoes, %		Yield of seed potatoes, $Mg \cdot ha^{-1}$	
		mean	V*	mean	V	mean	V	mean	V
Mid-early, edible	Bartek	94.9	0.7	36.5	23.8	91.9	2.7	35.2	23.8
	Benek	95.5	0.8	40.7	28.1	94.5	2.1	40.4	28.8
	Cekin	96.1	1.4	40.1	39.5	92.0	2.1	38.1	39.7
	Finezja	97.0	0.8	34.2	22.2	93.8	4.6	33.0	22.0
	Gawin	88.8	4.3	30.4	18.6	88.2	5.6	30.2	18.4
	Irga	94.1	1.6	32.9	24.7	94.0	1.9	32.9	25.0
	Kolia	94.7	1.3	36.2	24.5	90.4	6.3	34.1	17.5
	Legenda	94.2	3.4	37.4	39.3	88.2	4.1	34.7	38.8
	Sante	94.3	2.8	39.9	38.0	92.8	2.5	39.2	38.3
	Satina	95.8	2.0	51.7	28.5	82.7	10.0	43.0	19.6
	Stasia	92.0	2.8	34.4	39.7	91.2	2.1	33.9	38.2
	Tajfun	96.2	3.3	41.9	17.1	93.7	3.9	40.7	14.8
	Tetyda	96.4	1.1	39.0	28.1	88.7	7.1	34.8	21.7
	Wiarus	97.4	0.8	45.1	29.7	86.4	8.8	39.5	27.3
Mid-early, starch	Adam	87.6	4.3	30.0	34.7	87.4	4.2	29.9	34.3
	Glada	91.6	2.0	30.6	32.5	91.0	2.0	30.4	32.6
	Harpun	93.8	2.8	32.9	20.9	91.9	2.0	32.2	20.3
	Pasat	88.8	2.3	29.0	37.5	88.4	1.7	28.7	37.5
Mean		93.6	2.1	36.8	29.3	90.6	4.1	35.1	27.7
$HSD_{0,05}$ cultivars		4.9		1.9		4.7		1.8	

*coefficient of variation in %

Table 7. Descriptive statistics for the number of shoots and yield and its structure of mid-early cultivars

Specification	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}
Mean	5.2	6.2	62.2	28.1	3.3	39.0	93.8	36.7	90.3	35.0
Minimum	2.0	1.0	23.7	3.63	0.0	18.1	82.6	16.4	64.7	16.4
Maximum	12.0	17.4	83.0	55.8	32.4	72.3	99.0	71.2	98.7	59.5
Coefficient of variation, in %	28.2	56.5	25.4	49.9	16.7	31.0	3.7	32.7	5.7	29.6

x_1 – shoot number, piece; x_2 – proportion of tuber mass of diameter <4 cm, %; x_3 – proportion of tuber mass of diameter 4–5 cm, %; x_4 – proportion of tuber mass of diameter 5-6 cm, %; x_5 – proportion of tuber mass of diameter >6 cm, %; x_6 – tuber yield, $Mg \cdot ha^{-1}$; x_7 – proportion of commercial tuber mass, %; x_8 – commercial tuber yield, $Mg \cdot ha^{-1}$; x_9 – proportion od seed potatoes, %; x_{10} – yield of seed potatoes, $Mg \cdot ha^{-1}$

Table 8. Pearson's linear correlation coefficients for mid-early cultivars

Variables	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}
X_1	1.00									
X_2	0.25*	1.00								
X_3	0.23*	0.52**	1.00							
X_4	-0.25*	-0.67**	-0.95**	1.00						
X_5	-0.16	-0.41**	-0.78**	0.59**	1.00					
X_6	0.12	-0.41**	-0.58**	0.54**	0.56**	1.00				
X_7	-0.24*	-0.99**	-0.52**	0.67**	0.41**	0.40*	1.00			
X_8	0.09	-0.49**	-0.61**	0.59**	0.59**	0.99**	0.49**	1.00		
X_9	0.02	-0.23	0.49**	-0.19	-0.78**	-0.29*	0.23	-0.27*	1.00	
x_{10}	0.14	-0.45**	-0.47**	0.51**	0.37*	0.96**	0.45**	0.96**	-0.06	1.00

* significant at $p_{0.05}$: ** significant at $p_{0.01}$
Explanations as for Table 7

Analysis of the major components demonstrated that in the first, separated cluster, the following cultivars were grouped: Bartek, Harpun, Finezja, Kolia, Legenda, Cekin, and Tajfun. Those cultivars were characterized by the lowest number of shoots, average yield, and average proportion of particular tuber fractions in the yield (Table 9, Fig. 1). In the second cluster, cultivar Satina occurred, with average shoot number, highest total yield, as well as highest yield for commercial and seed potato yield, which was the result of a high proportion of the biggest tubers in the yield, with the diameter of 5-6 and > 6 cm. In the third cluster, two cultivars were grouped (Tetyda and Wiarus), with an average shoot number, high proportion of the biggest tubers in the yield, a high and constant yield, and with the lowest proportion of the smallest tubers in the yield. In the fourth cluster, six cultivars were included (Adam, Gawin, Glada, Irga, Stasia and Pasat), with the highest shoot number and the lowest total yield, as well as lowest yield for commercial and seed potato yield, and at the same time with the highest proportion of the smallest tubers, and of the lowest proportion of the biggest tubers in the yield. In the fifth cluster, two cultivars could be found (Benek and Sante), with average shoot number, the smallest proportion of big tubers in the yield, average but stable total yield, as well as for commercial and seed potato yield (Table 9, Fig. 1).

Table 9. Average values of the analyzed characteristics of the five groups of mid-early and early potato cultivars on the basis of cluster analysis

Characteristic	Group				
	1	2	3	4	5
x_1 – number of shoots, pcs.	4.6	5.3	5.3	5.7	5.4
x_2 – tuber yield, Mg·ha^{-1}	38.8	53.6	43.4	34.4	42.5
x_3 – commercial tuber yield, Mg·ha^{-1}	37.0	51.7	42.1	31.2	40.3
x_4 – proportion of commercial tubers, %	95.3	95.8	96.9	90.5	94.6
x_5 – yield of seed potatoes, Mg·ha^{-1}	35.4	43.0	37.2	31.0	39.8
x_6 – proportion of seed potato mass, %	91.7	82.7	87.6	90.0	93.7
x_7 – proportion of tuber mass <4 cm, %	4.7	4.2	3.1	9.5	5.1
x_8 – proportion of tuber mass 4–5 cm, %	57.6	36.2	41.9	74.5	73.7
x_9 – proportion of tuber mass 5–6 cm, %	34.1	46.5	45.6	15.5	20.0
x_{10} – proportion of tuber mass >6 cm, %	3.6	13.1	9.4	0.5	1.2

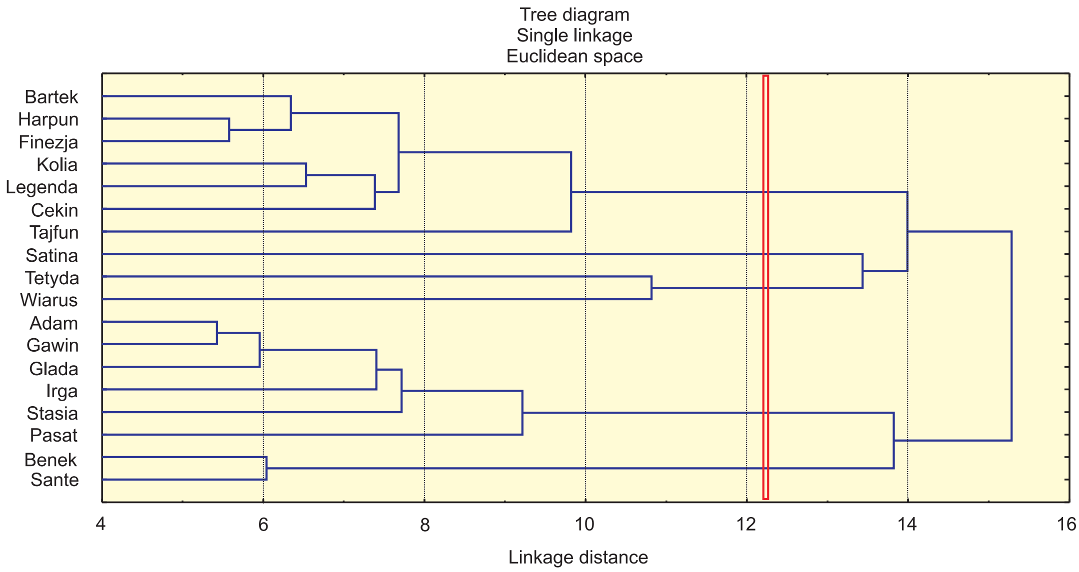

Fig. 1. Dendrogram that illustrates taxonomic distance between potato cultivars

DISCUSSION

The majority of analysed characteristics that are significant for potato production undergo high phenotypic variability that are dependent on the relationship between different habitats and genotype factors (Michałek *et al.*, 2000; Sawicka, 2001; Crossa and Franco, 2004; Jansky, 2008; Balzarini *et al.*, 2011; Arvanitoyannis *et al.*, 2012; Sawicka *et al.*, 2015; Bhandari *et al.*, 2017). Many potato characteristics are genetically determined (Sawicka, 2001; Crossa and Franco (2004), Domański *et al.*, 2004; Kamiński, 2015; Bhandari *et al.* 2017). In the conducted research, genetic factors most strongly determined the proportion of tuber mass of >6 cm in diameter (32.5% of the total variability), whereas tuber yield depended only to 26.1% on the genetic characteristics of the studied cultivars. The high effect of hereditary factors on yield has been reported in studies by Michałek *et al.* (2000), Sawicka (2001), Crossa and Franco (2004), Bussan *et al.* (2007), Styszko and Kamasa (2007), Kamiński (2015), Sawicka *et al.* (2015), and Sawicka and Pszczółkowski (2004; 2017). The high yields obtained at the stations by the Research Centre for Cultivar Testing (COBORU) indicates the great yield potential of Polish cultivars (Pszczółkowski, 2017). However, other cultivar characteristics are important that may cause differences in the yield, such as: earliness, rate of potato plant development, weed control in the field, competition between the plants within a bush, competition for photosynthesis products between the particular stolon nodes from which they are formed, competition between seedlings for nutrition from the maternal tuber, domination of the main bud and of the apical eye of the maternal tuber, and others (Bussan *et al.*, 2007; Sawicka, 2001; Stefańczyk and Śliwka, 2013; Sawicka and Pszczółkowski, 2017).

The majority of studies on yield genetics and its components comes from analyses of combining ability. Evaluations of the Significance of the General Combining Ability (GCA) and the Specific Combining Ability (SCA) occur the most frequently. However, the proportion of GCA in genetic variability is usually higher (Domański *et al.*, 2004; Flis *et al.*, 2014; Kamiński, 2015; Carputo *et al.* (2013), Stefańczyk and Śliwka, 2013). Nevertheless, what limits the usefulness of the combining ability evaluation methods is the fact that they give information on genetic variability only in the studied genotype group. Therefore, more universal evaluation methods of potato economic characteristics are still being looked for.

Besides genetic variability, environmental variability also occurs. The most important causes of environmental variability are: seed potato quality, lack of uniformity in soil conditions (soil properties: humidity, physio-chemical, pH, enzymatic activity, humus content), diverse effect of meteorological conditions (precipitation, temperature, atmospheric pressure, humidity, wind direction and speed, light, especially its intensity and duration, number of red light quanta (R) to far-red light (FR), photoperiod, weather anomaly such as: windstorms, twisters, heat waves, drought (atmospheric, soil, hydrological, physiological), etc.); gravity, magnetism, and cosmic rays (Anonimus, 2010). Also, elements of inanimate nature are part of the environmental variability (physiographic conditions: exposure, exposition) characteristic for a given environment that affect organisms that live in it, while also undergoing their influence. Too high variations, for example, of air temperature and humidity or chemical composition of water and soil, limit an organism development and the variability of those factors is often a result of the economic activities of man (Bienia, 2016). The light factor affects tuberization induction (Stefańczyk and Śliwka, 2013) and plant metabolism (assimilation, transpiration) (Maleszewski *et al.*, 2003; Balzarini *et al.*, 2011). In the conducted research, environmental factors had no significant effect on shoot number per plant and proportion of potato seeds, whereas they had most effect on the proportion of the biggest tubers in the yield. However, Sawicka (2001) demonstrated the significant effect of the environment on tuber yield, mass of tubers 5–6 cm in diameter, and the number of 3–4 cm tubers, which was confirmed by an evaluation in subsequent vegetative generations. According to Arvanitoyannis *et al.* (2012), this fact results from lowering competition between plants, decrease in stem number and total tuber mass, as well as a decrease in average tuber mass of every fraction. Pszczółkowski *et al.* (2016) state that water shortage during tuberization and flowering may decrease net assimilation value, and in some cultivars even the size of the assimilation area and, thereby, the yield.

Interaction between the cultivars and study years in the conducted research determined from 57.9% to 75.8% of the phenotypic variability of shoot number per plant, as well as the proportion and yield of seed potato. This is in line with the results of phenotypic variability evaluation by Sawicka (2001). According to Gauch *et al.* (2008), Kamiński (2015) and Bhandari *et al.* (2017) a major cause of differences between genotypes or cultivars is the expression of a given characteristic in response to changeable environmental conditions. Research by Bussan *et al.* (2007), Styszko and Kamasa (2007), Gauch *et al.* (2008), Kamiński (2015), Rymuza (2015) and Sawicka and Pszczółkowski (2017) also point to the high variability of the above those characteristics in research years.

Obtaining tuber yield of proper structure and quality depends not only on the cultivar and weather conditions, but also on edaphic factors, which are soil factors that condition growth and development of cultivated plants, namely: soil structure, its richness in nutrients, oxygen and water content, amount of humus, pH, amount and activity of organisms and soil enzymes, and, by implication, particular composition of organisms that inhabit the soil (Annicchiarico, 2002). Agricultural engineering should be adapted to both the weather conditions and plant demands. An extremely important role is played by carrying out agrotechnical treatments on time, as they depend on the weather conditions. One of the elements of agricultural engineering is proper plant density per area unit, which may be expressed through the number of planted tubers (Pytlarz-Kozicka, 2004), and their average size is related to the number of stems and tubers under the bush (Bussan *et al.*, 2007). The analysis of Pearson's linear correlation coefficient, carried out in the present study, demonstrated that the number of shoots of mid-early cultivars was significantly positively correlated with the proportion of small and average tuber mass, and negatively correlated with the proportion of tubers 5-6 cm in diameter. Balzarini *et al.* (2011), Gołębiewski *et al.* (2012) and Kang (2002) have shown the significant effect of the interaction between the genotype and the environment (GxE) and the significant interaction between the tested strain and the place of growth.

Research on the genetic and environmental system is of particular significance in the process of regionalization of new cultivars (cultivar recommendation) in the lists of cultivars recommended for particular voivodships (Gacek and Behnke, 2017). The choice of regions for the growth of given cultivars depends on the proportions of variance of interaction effects: genotype (G) × environment (E) and variance of major genotype effects. In the conducted analysis, the proportion of genotype variance made up circa 25.6% of phenotype variability, but a significantly higher proportion was made up by the interaction between G × E (on average 69%). According to Annicchiarico (2002), Annicchiarico *et al.* (2011), Jankowska *et al.* (2015) and Bhandari *et al.* (2017), if the variation of major genotype effects prevails, it is acknowledged that the cultivar is widely adapted to the growth conditions, and in the opposite case it is characterized by low adaptation abilities.

Data clustering makes it possible to group cultivars into groups with similar properties (Crossa and Franko, 2004; Rymuza, 2015). On the basis of data clustering, we selected five groups of potato cultivars that differed among themselves in: the number of shoots per plant, total yield, proportion of tuber mass of the diameter <4, 4–5; 5–6 and >6 cm, proportion and yield of commercial tubers, and proportion and yield of seed potatoes. On the basis of the Mahanalobis distance (Rymuza, 2015), it may be stated that group four is the most dissimilar to others. Usefulness of data clustering has also been confirmed by the results obtained by Jansky (2008), Rymuza *et al.* (2012; 2013), and Rymuza (2015). This method may be helpful in the future for an evaluation and comparison of newly introduced potato cultivars.

The complex nature of the tested earliness group of potato cultivars required the use of multidimensional methods, since the comparative study carried out in regard to the many characteristics that were analysed separately did not clarify sufficiently the complexity of this phenomenon. It did not make it possible to completely evaluate their quantitative diversification or to group cultivars that were similar with regard to many characteristics at the same time. In the opinion of Crossa and Franko (2004), Mądry and Iwańska (2011), Kaczmarek and Mańkowski (2011), Rymuza (2015) and Bhandari *et al.* (2017), a complex evaluation of cultivar diversification may be carried out while using at the same time multi-characteristic methods of their diversification and their grouping (classification). Therefore, future cultivar studies need to be carried out in the above direction.

The high diversification of the studied cultivars, in regard to the analysed economic characteristics, enables the selection of favourable genotypes that are useful in creative potato cultivation. Cultivars with the best morphological, agricultural, economic, and immune characteristics should be used in the breeding process to create genotypes with the desired characteristics.

CONCLUSIONS

1. Genotype and environment significantly affected the variability of total, commercial, and seed potato yield and proportion of the particular tuber fractions and shoot number per plant.
2. Genetic variability, like environmental variability, determined to the highest degree phenotypic variability of the proportion of tuber mass ∅ >6 cm in the total yield.

3. Interaction of the genotype × environment most strongly affected seed potato proportion and yield, and shoot number per plant.
4. The most stable economic characteristic of the studied cultivars turned out to be the proportion of commercial tuber mass, and the most variable one the proportion of the biggest tubers per yield.
5. The best scores among the studied cultivars were obtained by: Satina, Tetyda, and Wiarus. The factors that decided about their advantage were: adaptation to less intensive production conditions, tendency to form tubers with higher diameters. Those cultivars may be recommended for ecological cultivation system.

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FENOTYPOWA ZMIENNOŚĆ PLONU I JEGO STRUKTURY ŚREDNIO WCZESNYCH ODMIAN ZIEMNIAKA

Streszczenie

Aby ukierunkować prace hodowlane nad odmianami danej grupy wczesności ziemniaka konieczne jest poznanie zakresu zmienności i współzależności cech, tak w danym roku, jak i pomiędzy latami. Dlatego celem badań było poznanie struktur zmienności cech ilościowych średnio wczesnych odmian ziemniaka, co pozwoli ułatwić typowanie do uprawy odmian o największej stabilności pożądanej cechy. Wyniki badań oparto na doświadczeniu polowym przeprowadzonym w latach 2010–2012 w Zakładzie Doświadczalnym Oceny Odmian w Uhninie (51°34' N; 23°02'E), na glebie płowej, lekko kwaśnej. Eksperyment wykonano w układzie bloków zrandomizowanych, w trzech powtórzeniach. Badano 18 średnio wczesnych odmian ziemniaka, w tym 14 odmian jadalnych i 4 odmiany skrobiowe. Zabiegi agrotechniczne roślin prowadzono zgodnie z zasadami Dobrej Praktyki Rolniczej, a zabiegi ochrony roślin – zgodnie z zaleceniami IOR-PIB. Nawożenie organiczne i mineralne pod ziemniak było na jednakowym poziomie (ok. 20 $Mg \cdot ha^{-1}$ gorczycy białej na przyoranie oraz 90 kg N, 39,3 kg P, 112,0 kg $K \cdot ha^{-1}$). Dominującą rolę w zmienności plonu bulw i jego struktury odgrywało współdziałanie odmian i lat badań (57,9–75,8%). Genotyp stanowił (20,1–32,5% udziału wariancji w wariancji całkowitej badanych cech, zaś warunki badań 0,0–9,7%. Interakcja genotyp × środowisko oddziaływała istotnie na wszystkie badane cechy w eksperymencie, natomiast warunki lat badań nie miały wpływu na liczbę pędów na roślinie. Najbardziej stabilną cechą gospodarczą badanych odmian okazał się udział masy bulw handlowych, zaś najbardziej zmienną – ich plon. Przeprowadzona analiza składowych głównych wyodrębniła pięć grup odmian o specyficznych właściwościach, które mogą posłużyć w podejmowaniu decyzji w hodowli nowych odmian.

Słowa kluczowe: frakcje bulw, liczba pędów, odmiany ziemniaka, plon bulw, zmienność