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Multidimensional assessment of yield and quality of starchy potato cultivars

Wielowymiarowa ocena plonowania i jakości skrobiowych odmian ziemniaka

Summary. Tubers destined for starch production in potato industry need to meet certain commercial quality standards. The objective of the work was to conduct a multivariate assessment of yield potential and tuber quality of starchy potato cultivars. An analysis was performed of data describing potato cultivars listed in the National List of Potato Varieties (KRO) in Poland published by the Plant Breeding and Acclimatization Institute – National Research Institute at Radzików. Very early and early as well as medium late and late starchy potato cultivars were analysed in terms of 13 quantitative characteristic using principal component analysis and cluster analysis. It was demonstrated that, regardless of earliness group, the following traits had the greatest share in the total variation of starchy potato cultivars: tuber yield, starch content, starch yield and bioethanol yield. Cluster analysis allowed the division of very early and early cultivars into 3 groups. The cultivars Szyper, Zuzanna, Kuba and Jubilat, included in the first group, produced superior yields, the highest bioethanol yield and were the most resistant to potato blight. Medium late and late cultivars were divided into two groups. The first group (Pokusa, Gandawa, Rudawa, Hinga, Inwestor, Pasja, Pomorska and Ikar) gave poorer yields and lower bioethanol yields but were more resistant to potato blight in comparison with the second group (Sonda, Kuras, Jasia, Bzura, Skawa and Danuta). The multidimensional methods applied allowed a simultaneous assessment of starchy potato cultivars in terms of many characteristics, and grouping into clusters sharing similar traits.

Key words: cluster analysis, industrial potato, principal component analysis

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INTRODUCTION AND WORK'S OBJECTIVE

Potato (*Solanum tuberosum* L.) is an arable crop whose tubers have multiple uses [Zgórska and Grudzińska 2012]. Cultivars are a basic link in potato production. A great number of very different cultivars offers a wide variety to choose from taking into account the intended use as well as environmental conditions [Rembeza 2004, Bombik et al. 2007, 2019, Rykaczewska 2010]. The most important starchy potato characteristics include tuber yield, starch content and stability of technological properties. Of the characteristics, starch content seems to be an important parameter which, according to the standard PN-75/ R-74451, should be at least 15% as lower contents are economically non-viable [Bombik and Wolska 2004, Fontes et al. 2010, Zgórska and Grudzińska 2010, Mystkowska et al. 2016].

A set of properties which determine a cultivar's suitability for different uses is called "an appropriate raw material quality" or "processing value", and this applies to both external and internal tuber characteristics [Zgórska and Grudzińska 2010]. Research is conducted to create cultivars endowed with the greatest number of desirable characteristics but, until they have been registered, growers should choose cultivars characterised by as many desirable traits as possible. Hence, a complex assessment of cultivars ought to include as large number of characteristics determining their functional value as possible, which makes it necessary to apply multivariate statistical procedures. Research comparing cultivars in terms of many characteristics considered separately does not sufficiently explain the complexity of a given phenomenon as it does not allow a complex assessment of their quantitative variation and grouping of objects with multi-trait similarity. Multidimensional methods make it possible to characterise, group and indicate genotypes with high functional value. Of these methods, principal component analysis (PCA) and cluster analysis (CA) are the most frequently utilised to this end. The methods provide a complete assessment of cultivar variation which includes both the division of objects into groups which are homogenous in terms of all the studied characteristics, and a full analysis of their multivariate variability. Such methods include multidimensional statistical methods such as principal component analysis (PCA), cluster analysis and discriminant analysis [Mądry 2007, Kaczmarek and Mańkowski 2011]. The methods serve as a tool for assessing the structure of potato line and cultivar variation, and were applied by Domański et al. [2012a, 2012b] and Rymuza [2015]. Literature on the subject lacks works presenting multi-trait comparison of starchy potato cultivars grown in Poland. The few available ones pertain to an assessment of cultivars in terms of several or so characteristics that are considered separately, which precludes their complex evaluation [Kołodziejczyk et al. 2013, Lisowski et al. 2016]. Multivariate methods, which do not present a computational challenge any more, assist in multi-trait assessment and comparison of cultivars, and they are increasingly frequently utilised to analyse data from research into many agricultural crop plants [Dubey et al. 2018, Karim et al. 2022, Leite et al. 2022]. Multivariate statistical analysis, including PCA and CA, allows selection of cultivars characterised by the greatest number of desirable characteristics reflecting agricultural performance, resistance to diseases and tuber quality. The objective of the work was to perform a comprehensive assessment of yield performance and tuber quality of starchy potato cultivars and their grouping using multidimensional statistical analysis, which will make it possible to indicate cultivars characterised by the greatest number of desirable traits associated with agricultural performance, resistance to diseases and tuber quality.

MATERIALS AND METHODS

Research material

The studied material consisted of data published by the Plant Breeding and Acclimatization Institute – National Research Institute (IHAR – PIB) at Radzików, Jadwisin Branch, pertaining to the economic value and qualitative assessment of starchy potato cultivars representing all earliness groups [Descriptive Cultivar List, Agricultural plants, 2012–2016]. The present work is based on results of research aiming at an assessment of KRO-listed cultivars in terms of their agrotechnological and functional characteristics. The research is conducted by IHAR – PIB at Radzików, Młochów and Bonin as well as the Research Centre for Cultivar Testing (COBORU) which carries out cultivar registration studies and coordinates Post-registration Variety Experimentation (PDO). As a rule, research on every cultivar takes three years and it follows IHAR – PIB and COBORU methodologies.

The analysis included 13 starchy potato cultivars representing very early and early groups as well as medium late and late groups. Variation assessment and comparison were conducted for the following quantitative characteristics: X_1 – total tuber yield (t·ha^{-1}), X_2 – dry matter content (%), X_3 – dry matter yield (t·ha^{-1}), X_4 – starch content (%), X_5 – starch yield (t·ha^{-1}), X_6 – bioethanol yield (l·ha^{-1}), X_7–X_{10} – resistance to pathogens (a scale of 1–9 where 1 – the lowest resistance, 9 – the highest resistance), X_7 – resistance to virus Y, X_8 – resistance to virus L, X_9 – resistance to potato blight, X_{10} – resistance to common scab, X_{11} – tuber size (a scale of 1–9 where 1 – the smallest tubers, 9 – the largest tubers), X_{12} – shape regularity (a scale of 1–9 where 1 – irregular shape, 9 – very regular shape), X_{13} – eye depth (a scale of 1–9 where 1 – very deep eyes, 9 – shallow eyes).

Statistical analysis

Preliminary analysis included descriptive statistics methods. The following statistics were calculated for each quantitative characteristic: arithmetic mean and standard deviation. In order to analyse the multidimensional variation of objects and determine the type of covariation of the characteristics, principal component analysis (PCA) was conducted. PCA is a linear dimensionality reduction technique that can be utilised for extracting information from a high-dimensional space by projecting it into a lower-dimensional subspace. It tries to preserve the essential parts that have more variation of the data and remove the non-essential parts with less variation [Krzyśko 2009].

Following Kaiser's criterion [1958], only the characteristics whose eigenvalues were more than 1 were selected for analysis and interpretation. Next, in order to group the cultivars with similar multivariate properties, and based on the obtained principal components whose eigenvalues were higher than 1, cluster analysis was conducted using Ward's method with Euclidean distance as a measure of multivariate dissimilarity of objects [Mohammadi and Prasanna 2003]. Cluster analysis (CA) is a tool serving as a technique for grouping n objects described by means of a vector of non-empty, disjoint, the most "uniform" possible k groups – clusters. Objects forming a given cluster should be similar to one another, and objects from different clusters ought be as dissimilar as possible. Hence, the analysis consists in finding objects which are more similar to the objects forming a given group than objects outside this group. The resulting groups of objects should be homogeneous internally and heterogeneous externally [Krzyśko 2009]. Clusters were obtained by dividing the dendrogram according to Mojena's rule [Mojena 1977].

Statistical analysis was performed using the software STATISTICA 12.5.

RESULTS AND DISCUSSION

With their specific genotypes, starchy potato cultivars introduce specific functional characteristics. At present, the criterion of cultivar selection for production is associated not only with the yield-forming potential but also technological traits. Taking into account all of these characteristics may be the basis of drawing adequate conclusions as to the cultivars' value for cultivation and use. There are few studies evaluating potato cultivars and they assess the quality of starch obtained from the cultivars [Pycia et al. 2012, Phogat et al. 2020, Khlestkin et al. 2019, Vasilyev et al. 2021, Khlestkin et al. 2022]. The analysis reported in the present work will fill this gap, and the findings can be used by both cultivar breeders and starchy potato growers who search for cultivars with superior attributes which will provide high levels of quality yields conditioning economic effectiveness.

Table 1. Mean, minimum and maximum values and coefficients of variation for characteristics of starchy potato cultivars

Trait	Very early and early cultivars		Medium late and late cultivars	
	$\bar{x}$*	V(%)**	$\bar{x}$*	V(%)**
X_1	41.09	9.42	44.46	11.34
X_2	26.57	6.33	26.45	9.64
X_3	10.88	8.41	11.70	10.68
X_4	19.65	6.20	19.31	8.60
X_5	8.09	12.00	8.55	11.65
X_6	4942.5	12.85	5482.7	8.65
X_7	7.88	12.72	8.38	10.37
X_8	6.15	11.19	5.69	19.49
X_9	4.81	19.70	6.23	18.99
X_{10}	5.73	9.16	5.42	12.40
X_{11}	7.04	11.77	7.08	13.79
X_{12}	6.72	5.19	6.55	6.91
X_{13}	6.46	4.92	6.47	9.20

X_1 – total tuber yield (t·ha^{-1}), X_2 – dry matter content (%), X_3 – dry matter yield (t·ha^{-1}), X_4 – starch content (%), X_5 – starch yield (t·ha^{-1}), X_6 – bioethanol yield (l·ha^{-1}), X_7–X_{10} – resistance to pathogens (a scale of 1–9 where 1 – the lowest resistance, 9 – the highest resistance), X_7 – resistance to virus Y, X_8 – resistance to virus L, X_9 – resistance to potato blight, X_{10} – resistance to common scab, X_{11} – tuber size (a scale of 1–9 where 1 – the smallest tubers, 9 – the largest tubers), X_{12} – shape regularity (a scale of 1–9 where 1 – irregular shape, 9 – very regular shape), X_{13} – eye depth (a scale of 1–9 where 1 – very deep eyes, 9 – shallow eyes)
* arithmetic mean, ** coefficient of variation

The total tuber yield of very early and early cultivars of starchy potato (Tab. 1) was slightly over 40 t·ha^{-1} and dry matter content and yield were almost 27% and 11 t·ha^{-1}, respectively. Starch content was found to be up to 20%, which, when related to the tuber yield, gave the starch yield of slightly over 8 t·ha^{-1}. The average bioethanol yield was close to 5000 l·ha^{-1}. Medium late and late cultivars had more favourable characteristics than early cultivars. Compared with earlies, they produce higher total yields (by 3.37 t·ha^{-1}), dry matter yields (by 0.82 t·ha^{-1}) and bioethanol yields (by 540.2 l·ha^{-1}). Early and late cultivars had similar values of all tuber characteristics, and resistance to diseases, excluding potato blight, late cultivars being more resistant to potato blight (by 1.42° on a 9° scale). The variation of starchy potato characteristics measured with the value of variation coefficient, was at a similar level, differences not exceeding 4.00% (Tab. 1). The only differences occurred for bioethanol yield which was higher for early cultivars (by 4.20%), and resistance to virus L and eye depth, both of which were higher for late cultivars (by 8.30 and 4.28%, respectively). A detailed description of these characteristics can be found in the work by Bombik et al. [2019].

The first 4 principal components accounted for over 84% of total variation (PC1) of very early and early starchy potato cultivars. The first principal component, explaining over 37% of variation, formed the strongest association with starch yield (r = –0.945), dry matter yield (r = –0.906) and total tuber yield (r = –0.762). Cultivars which contained the most dry matter and starch produced higher yields. The second principal component, accounting for over 20% variation, was the most strongly associated with dry matter content, starch content and resistance to common scab. The reciprocal multidimensional associations indicate that cultivars which were common scab-resistant contained less starch and dry matter. The third principal component explaining over 15% of multidimensional variation carried mostly information about resistance to potato blight and shape regularity. The fourth principal component associated with shape regularity and resistance to virus Y accounted for over 10% total variation (Tab. 2, Fig. 1a)

Cultivars whose first and second component had values close to zero, that is Widawa, Mieszko and Rumpel, reached average values of total yield, starch yield and dry matter yield. Tubers of cv. Passat, which had high values of second principal component, contained much starch and dry matter but, at the same time, their resistance to common scab was low (Fig. 2a).

The dendrogram demonstrated that very early and early potato cultivars formed three groups. The first group consisted of cv. Pasat, Widawa, Rumpel, Boryna, Kaszub and Cedron which had the highest average dry matter and starch contents, the highest average tuber size and the best resistance to potato blight. Within this group, cv. Rumpel and Widawa were the most similar. The second group consisted of cv. Jubilat, Kuba, Szyper and Zuzanna which produced superior yields and were the most resistant to virus Y. The third group was made up of cv. Harpun and Glada which shared the lowest average starch and dry matter yields, had the smallest tubers and the shallowest eyes (Tab. 3, Fig. 3a).

For medium late and late starchy cultivars, the first 3 principal components explained over 72% of total variation of traits. The first principal component, accounting for over 36% of variation was the most strongly correlated with the following yield characteristics: starch yield (r = 0.955), dry matter yield (r = 0.945), bioethanol yield (r = 0.936) and total yield (r = 0.788). Cultivars which produced the highest total yield, dry matter yield and starch yield had the highest bioethanol yield. The second principal component explained over 22% of variation of cultivar characteristics and it mainly carried information about starch content (r = 0.851) and dry matter content (r = 0.872). The third principal component accounted for almost 14% of multidimensional variation and was correlated with shape regularity (r = –0.775) and eye depth (r = –0.771), and these relationships indicate that cultivars with shallower eyes were less regular in shape (Tab. 2, Fig. 1b).

Cultivars Gandawa and Inwestor, whose values of second principal component were close to zero, had average values of traits associated with this principal component, that is starch content and dry matter content. Cultivars Rudawa and Hinga, having values of first principal component close to zero, produced average total yield, starch yield, dry matter yield, and bioethanol content (Fig. 2b).

Table 2. Eigenvalues, the proportion of the first four principal components (PC) in the total variation and correlation coefficients between the principal components and characteristics of starchy potato cultivars

Characteristic	Very early and early cultivars				Medium late and late cultivars		
	PC1	PC2	PC3	PC4	PC1	PC2	PC3
X_1	–0.762	–0.594	–0.182	0.006	0.788	–0.561	–0.092
X_2	–0.085	0.727	0.478	0.426	0.135	0.872	0.303
X_3	–0.906	–0.152	0.124	0.303	0.945	0.143	0.157
X_4	–0.687	0.631	–0.126	–0.107	0.232	0.851	0.404
X_5	–0.945	–0.153	–0.207	–0.045	0.955	0.036	0.183
X_6	–0.693	–0.535	–0.020	–0.315	0.936	–0.116	0.015
X_7	–0.584	–0.042	–0.022	0.537	0.843	0.151	–0.114
X_8	0.548	0.239	–0.242	–0.460	–0.451	0.147	0.067
X_9	–0.380	0.279	–0.770	–0.209	0.532	0.151	–0.091
X_{10}	0.218	–0.738	0.597	–0.022	–0.401	0.373	0.453
X_{11}	–0.553	0.528	0.257	–0.015	0.089	0.683	–0.200
X_{12}	–0.303	0.117	0.648	–0.511	0.023	0.367	–0.775
X_{13}	–0.648	0.265	0.382	–0.477	0.009	0.536	–0.771
Eigenvalue principal components	4.90	2.65	1.97	1.41	4.73	2.92	1.78
Explained proportion of total variance (%)	37.73	20.42	15.19	10.91	36.45	22.53	13.75
Cumulative proportion of total variance (%)	37.73	58.15	73.34	84.25	36.45	58.98	72.73

Explanations as in tab. 1
PC1–PC4 – principal components

Cluster analysis of data pertaining to medium late and late cultivars of starchy potato yielded 2 groups. The first group was formed by two most similar cultivars, that are Gandawa and Inwestor, whereas the other group consisted of cv. Kuras and Sonda. Cultivars in the first group produced poorer yields, had a lower bioethanol yield, were less resistant to virus Y but more resistant to potato blight. Moreover, their tubers were smaller but had a more regular shape and shallower eyes (Tab. 3, Fig. 3b).

Table 3. Mean values for groups formed by starchy potato cultivars using cluster analysis

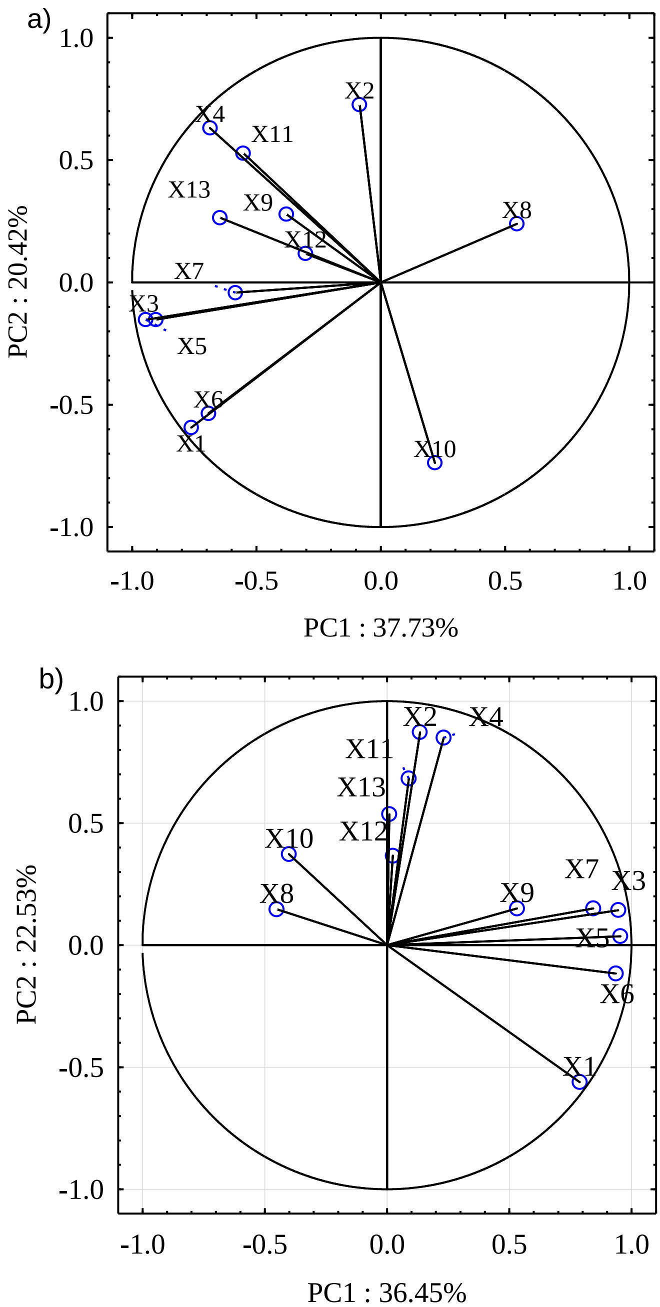
Trait	Very early and early cultivars			Medium late and late cultivars	
	group 1	group 2	group 3	group 1	group 2
X_1	38.8	45.3	38.8	41.0	46.1
X_2	27.4	26.0	25.4	25.7	27.7
X_3	10.5	11.7	10.0	10.5	12.7
X_4	20.1	19.7	18.0	18.8	20.0
X_5	7.78	8.98	7.00	7.68	9.20
X_6	4660	5670	4679	5128	5737
X_7	7.92	8.25	7.00	7.67	9.00
X_8	6.33	5.75	6.25	5.92	5.90
X_9	4.92	4.50	4.50	5.83	6.60
X_{10}	5.50	6.13	6.00	5.75	5.00
X_{11}	7.58	7.13	5.50	6.92	6.90
X_{12}	6.80	6.88	6.25	6.78	6.62
X_{13}	6.45	6.70	6.00	6.47	6.42

Explanations as in tab. 1

Similar research was conducted by Domański at al. [2012a] who aimed at assessing the structure of multidimensional potato variation. The exploratory factor analysis (EFA) yielded 5 factors accounting for 68% of the observed total variation of lines. The first factor (21.7% of variation) was formed by traits responsible for overall tuber appearance, the second factor (15.5% of variation) was associated with yield-forming characteristics, the third factor (12.2% of variation) was related to processing traits and factor four and fifve carried information about tuber shape and appearance. Domański et al. [2012b] carried out a study whose purpose was to assess the genotype variation of potato lines and the structure of their multidimensional variation. They used PCA which yielded 5 principal components which accounted for 78.4% of total variation.

Rymuza [2015] conducted a complex assessment of table potato cultivars representing all earliness groups in terms of 14 characteristics. Using principal component analysis, the author demonstrated that, regardless of the earliness group, potato cultivars differed in terms of traits associated with the first five principal components which accounted for over 70% of multidimensional variation of the characteristics, mainly agricultural production-related traits, that is total yield, marketable yield and starch yield.

There is a lack of Polish reports regarding multivariate analysis of yielding, qualitative characteristics and technological productivity of starchy potato cultivars. The multivariate analysis consisting of principal component analysis and cluster analysis reported here proved to be a useful approach to assessing the variation of traits, and grouping the genotypes of starchy potato cultivars registered in Poland. Based on long-term experiments conducted by IHAR and COBORU in various conditions (localities), assessment of the effects of starchy potato cultivars may be performed using appropriate statistical



Explanation as in tab. 1

Fig. 1. Location of the diagnostic characteristics of starchy potato cultivars in the system of the first two principal components: a) very early and early cultivars, b) medium late and late cultivars

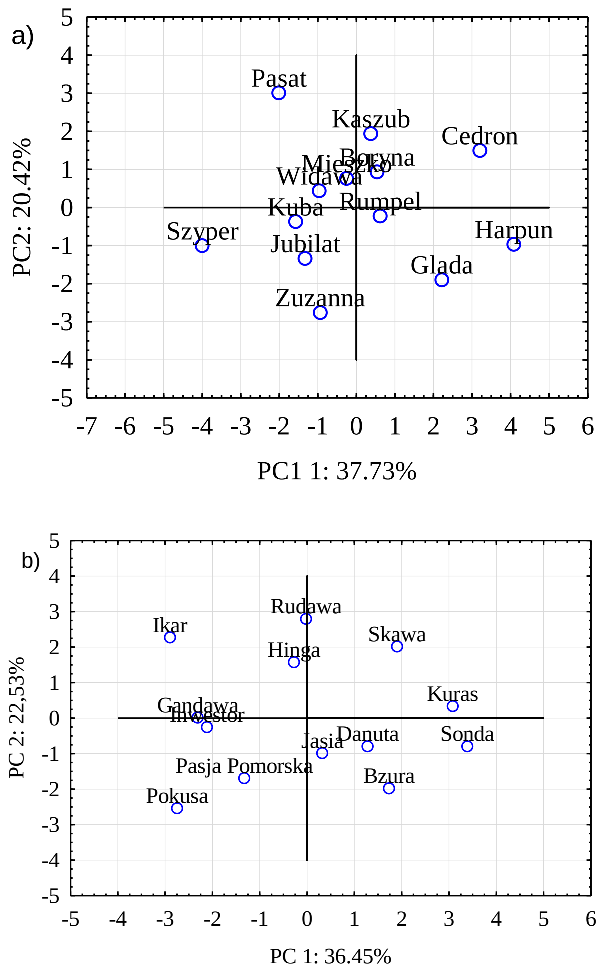


Fig. 2. Location in the system of the first two principal components of: a) very early and early cultivars, b) medium late and late cultivars of starchy potato

tools. A complex analysis of commercially available cultivars can be attempted on the basis of the estimated values of functional characteristics. The procedures applied allowed a multidimensional assessment of relationships between characteristics, grouping of cultivars with similar attributes and indicating the characteristics which are the greatest sources of differences between groups. Grouping of cultivars with similar attributes assists farmers with deciding which cultivar to choose. The suggested approach does not unquestionably highlight the best cultivar; however, it points to the cultivars with similar "sets" of characteristics which make them suitable for a given type of production. In a way, the approach makes it easier for growers, who are often in search of popular cultivars and cautiously approach new even if very valuable cultivars, to make their choice. Further research of this type is recommended involving cultivars which are being offered on the market.

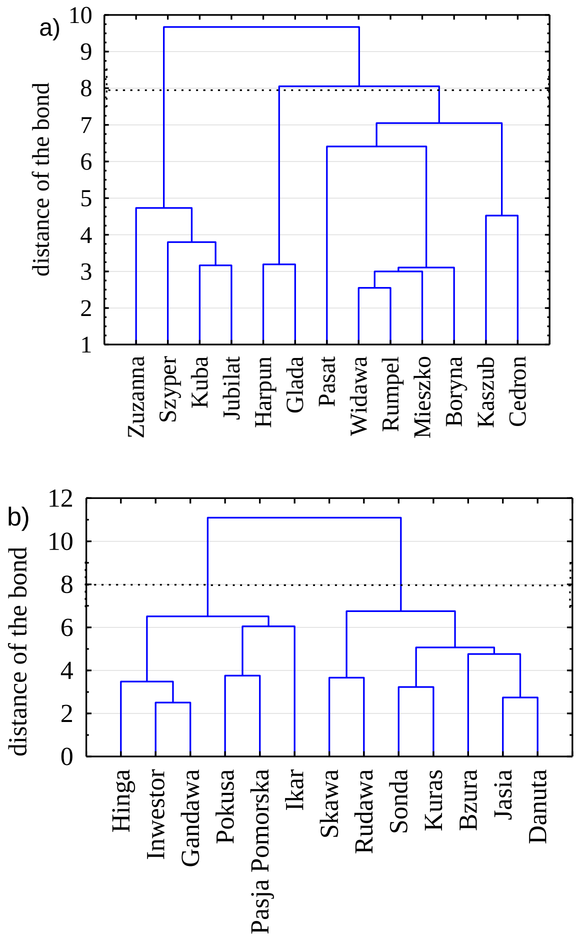


Fig. 3. Dendrogram for: a) very early and early, b) medium late and late cultivars of starchy potato

Multidimensional analyses may contribute to more efficient implementation, and be a very useful tool of potato breeding program.

CONCLUSIONS

1. The approach applied in PCA yielded precise multi-trait characterisation of the test cultivars, and made it possible to find the traits which contribute to the greatest differences between them.

2. Regardless of the earliness group, the following characteristics had the highest share in the total variation of starchy potato cultivars: tuber yield, starch content, starch yield and bioethanol yield.

3. Cluster analysis yielded three groups of very early and early cultivars and two groups of medium late and late cultivars. As some traits were negatively correlated, it is

not possible to equivocally indicate the group of cultivars with the highest functional value, that is with superior traits.

4. The applied multidimensional methods proved to be useful in achieving the assumed objective of the work. They allowed a simultaneous assessment of starchy potato tubers in terms of many characteristics as well as their grouping into clusters sharing similar traits, which will make it easier for growers to choose cultivars with the greatest number of desirable characteristics.

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