Int. Agrophysics, 2009, 23, 257-267

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Estimation of geometric and mechanical properties of seeds of Polish cultivars and lines representing selected species of pulse crops

W. Rybiński[1]*, *B. Szot*[2], *R. Rusinek*[2], *and J. Bocianowski*[3]

[1]Institute of Plant Genetics, Polish Academy of Sciences, Strzeszyńska 34, 60-479 Poznań, Poland
[2]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland
[3]Department of Mathematical and Statistical Methods, Poznań University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland

Received March 5, 2009; accepted March 30, 2009

A b s t r a c t. The attempt was made at estimation of mechanical loads on seeds, taking into account their geometric properties. Material chosen for the study comprised 24 Polish cultivars and lines of pulse crops representing four species of lupine, sowing and edible pea, vetch, lentil, and grasspea. The initial material for the experiments were air-dry seeds obtained directly from breeders from Polish plant breeding centres. This ensured high level of genetic purity as well as high homogeneity of seed batches. The first stage of the study included determinations of moisture and mass of 1 000 seeds, as well as their geometric parameters, followed by static loading tests. Moisture content of the seeds did not exceed 10%, and mass of 1 000 seeds determined at that moisture level was from 2.02 g for vetch cv. Alba to 31.7 g for white lupine cv. Boros. Among the four lupine cultivars the smallest seeds were characteristic of Andean lupine. Apart from the obvious cultivar-related differences among the various seeds in terms of the mass of 1 000 seeds, the study revealed a high degree of differentiation in the resistance of the seeds to static loading. The observed differences concerned not only inter-variety differences, but also intra-variety differences related with the varied genetic origin of the cultivars and lines as a result of using various parent materials in the breeding process.

K e y w o r d s: pulse crops, seed geometry, static loading of seeds, cultivars, lines

INTRODUCTION

The problem of deficit of protein fodders in Poland relates to their quantities as well as their quality. The basic fodders, in this respect, are seeds of pulse crops, extraction meals, and – until recently – waste products of animal origin. In view of the threat of BSE, as of the 1st of November, 2003, in Poland there is prohibition of production and use in animal feeding of meat-and-bone meals that had constituted 6-8% of fodders prior to that date. In poultry feeding, for example, those meals have been replaced with cereals and soybean meal, and the final result of the situation is the observed increase of fodder prices. With the new fodders, the animals grow more slowly and have to eat more to attain the required body mass. The effect of elimination of high-energy fodders of animal origin and controversies around genetically modified soybean (GMO) may further aggravate the present deficit of protein in animal feeding, at the same time emphasising the role of domestic sources of proteins from pulse crops.

Ensuring high-quality proteins in human and animal feeding is an important issue in EU countries. At present those countries import 70% of vegetable proteins, mainly in the form of soybean extraction meal and seed. In Poland, meeting the fodder needs requires ca. 1 mln t of proteins per annum, with 80% of the fodder requirements being covered by import of soybean meal. Meanwhile, a greater part of that requirement could be covered from own cultivation of pulse crops specific to the moderate climate (Pahl, 2002; Święcicki *et al*., 2007). Unfortunately, the area of cultivation of such crops, both in Poland and in Europe (1 and 3% in the crops structure, respectively), is not in any way commensurable with the undoubted advantages of pulse crops, such as binding of atmospheric nitrogen (lower requirement for nitrogen fertilization) and high quality of proteins. In consequence, this entails a reduction of energy consumption in agriculture, the seeds are a source of proteins for feed and fodder, and the crops contribute to the biological diversity of crop rotations and permanent grasslands, breaking up the cereal monoculture (Święcicki *et al*., 2007). A significant shortcoming of those crops is unstable yielding (Von

*Corresponding author's e-mail: Wryb@Igr.Poznan.pl

Richthoffen, 2006a, b). Progress in pulse crops breeding in terms of improvement of yield quality indices – increase in protein content, enhanced amino acid composition, reduction of the content of anti-nutritive components, improvement of structural elements of yield, shortening of the vegetation period, limitation of the susceptibility of plants to lodging, diseases and pests, should be related with the ultimate goal of the breeder *ie* increase and stabilization of the yield of seed (Prusiński, 2007; Święcicki, 1993).

Among the abovementioned traits that affect the level of attractiveness of pulse crops cultivation, the mechanical properties of seeds are an element that is underestimated and still little known. Knowledge of the physical parameters of seeds has a particular importance for optimization of technologies of harvest, drying and storage, which relates to minimization of quantitative losses and mechanical damage (Szot and Tarkowski, 1997). The biological value of seeds, characterized – among other things – by their germination capacity, is determined by a number of external factors, beginning from the time of seed ripening under field conditions and ending with the effect of forces acting in the threshing assembly of harvesters, seed cleaning devices, sorting and drying equipment, in transport and in storage. The technological processes listed above have an effect on the physical status of seeds, which leads to diversification of their resistance to mechanical loads. Micro- and macrodamage formed in those processes may have a negative impact on the quality of sowing material and the level of yields. Variability of physical properties of seeds depends on a great variety of external factors, as well as on species- and cultivar-related traits. Literature reports indicate the occurrence of notable inter-variety differences in the resistance of seeds to mechanical deformations, even at identical geometric parameters of the seeds. This creates a possibility of suitable selection of components for cross-breeding and directed breeding. With the aim of determining not only the above inter-variety differences but also inter-species differences, an attempt was under-taken at estimating the resistance of seeds to mechanical loads based on Polish cultivars and lines representing selected species of pulse crops.

MATERIAL AND METHODS

The experimental material included seeds of 24 cultivars and lines representing selected species of pulse crops. Seeds of lupine represented four species, among which two cultivars represented yellow lupine (*Lupinus luteus* L.), two cultivars white lupine (*Lupinus albus* L.) and three – narrow-leaved lupine (*Lupinus angustifolius* L.). Andean lupine (*Lupinus mutabilis* Sweet) was represented by two Polish lines of mutation origin. Seeds of the above cultivars and lines of lupine were obtained from lupine breeding centres in Przebędów and Wiatrów (Wielkopolska Province). Representatives of sowing pea (*Pisum sativum* L.) included seeds of three cultivars, also obtained from those breeding centres. Seeds of spring vetch (*Vicia sativa* L.) – cv. Jaga and cv. Ina, came from the breeding station in Szelejów (Wielkopolska), while seeds of the other six cultivars and lines of vetch, with varied content of cyanogenic compounds, were obtained from an experiment on those forms, conducted by Szwed and Urbaś (Milczak *et al*., 2001). The above species, commonly grown in Poland (with the exception of Andean lupine), were complemented by the choice of two prospective species (unjustly marginalized in Polish agriculture) *ie* lentil (*Lens culinaris* L.) and sowing grasspea (*Lathyrus sativus* L.). Two cultivars of each of those species were acquired from the Breeding and Seed-Producing Company in Nochowo (Wielkopolska Province).

The collected seeds were analysed in terms of their physical properties. The first stage of the determination included seed thickness, seed length and seed width. These parameters were measured using an adapted dial gauge and an electronic slide caliper with the accuracy of 0.01 mm. To obtain detailed distributions of this property in air-dry seed samples, 300 replications were made on the same seeds selected at random.

The resistance of individual seeds to static loading was determined by means of the INSTRON model 6022 strength tester. The results obtained were used to determine the compressive strength of the seeds. The results of the determination were expressed in values of maximum force and force of elasticity (N), maximal deformation and elastic deformation (mm), energy (mJ) and seeming modulus of elasticity (MPa).

The results obtained were analysed statistically. Analysis of variance was made for the individual features, giving mean square values. Estimation was made of the mean values, maximum and minimum values, variance, and coefficient of variation for the features studied. Standard deviation values were given for every result in the estimation of mechanical loads and geometric features of the seeds. Estimation of interrelations among the analysed traits was performed on the basis of coefficients of correlation estimated on the basis of mean values for particular objects. Similarity between all pair of evaluated species, represented by cultivars and lines, with respect to the analysed features and traits combined, were expressed by means of suitable Mahalanobis distances. Graphical distribution of the cultivars and lines on a plane, including all the traits and features jointly, was possible through the application of analysis of canonical variables (Camussi *et al*., 1985). All statistical analyses were performed using the GenStat v. 7.1 statistical software package (Payne *et al*., 2003).

RESULTS AND DISCUSSION

Calculated mean squares from analysis of variance showed that in terms of parameters of mechanical loading of seeds and of their thickness the cultivars under estimation combined differed significantly with relation to each of the features at the level of 0.001 (Table 1). This was supported by the characteristics of variables expressed by mean values, by the range of maximum and minimum values, variance, and of values of coefficient of variability for the objects combined and for each of the features individually (Table 2). Prior to the estimation of the resistance of the seeds to mechanical loads, determinations were made of the mass of 1000 seeds (WTS) and of their geometric properties (Table 3). In terms of values of WTS, the cultivars under evaluation can be classified in three groups. The first group, characterized by the largest seeds, included white lupine cultivars (273-317.1 g) and pea cultivars (187.9-278.8 g). The second group, with medium-sized seeds, with mass of 1000 seeds ranging from 119.4 to 173.8 g, included seeds of yellow lupine, narrow-leaved lupine and sowing grasspea. The group of small-seeded cultivars, with WTS at the level of 100 g and less, included seeds of Andean lupine, lentil, and sowing vetch. Although WTS is a cultivar-related trait, its values are subject to considerable environmental variation with relation to applied tillage and cultivation measures, type of soil, and climatic conditions during the vegetation period. According to COBORU, in the years 2003-2005 WTS of yellow lupine cv. Parys and Polo was 144 and 142 g (Paszkiewicz, 2007), and was only slightly higher than WTS of both yellow lupine cultivars represented in this study. Values similar to our are given by Księżak (2007) with relation to narrow-leaved lupine cv. Cezar (137 g), by Sawicka (1993) for a line of Andean lupine (108-164 g), by Wiatr and Dolata (2007) for pea cultivars Marych, Set and Merlin (194, 288 and 253 g, respectively), and by Szponar-Krok *et al*. (2007) for lentils cv. Tina and Anita (26.6 and 31.9 g). According to Milczak *et al*. (2001), based on a four-year field experiment, mean values of WTS for sowing grass pea cultivars Krab and Derek were 193 and 115 g, respectively, that is on a level similar to the values obtained in our study. In studies on sowing grasspea, three groups have been distinguished with relation to WTS values, as follows: small-seeded forms (50-150 g), forms with medium-sized seeds (150-200 g), and coarse-seeded forms with WTS values above 250 g (Dziamba, 1997). Hence, seeds of grasspea cv. Derek can be classified among the small-seeded cultivars (119.4 g), and those of cv. Krab (173.8 g) as medium-sized seeds. Some Italian forms of grasspea may attain WTS values as high as 400 g (Rybiński *et al*., 2008). This indicates notable genetically-determined intraspecies variation with considerable environmental modifications.

The broad spectrum of variation of WTS is related with the geometric features of seeds of the particular cultivars and species, as expressed by seed thickness, width and length (Table 3). Taking into account the shape of the seeds, seed thickness was determined for all experimental objects, seed width was also determined for cultivars of white lupine,

Table 1. Mean squares from analysis of variance for investigated traits of cultivar and lines chosen pulse crops

Source of variation	Degrees of freedom	Parameters						
		Force (max) (N)	Force of elasticity (N)	Deformation (max) (mm)	Elastic deformation (mm)	Energy (mJ)	Modulus (MPa)	Thickness (mm)
Objects	23	538 953*	52 582*	0.233*	0.008*	323 616.8*	64 944*	4.938*
Residual	48	1 099	1 081	0.0066	0.0005	673.9	4 791	0.0079

*significant at $\alpha = 0.001$.

Table 2. Characteristics of variation for analyzed traits of seeds

Parameters	Mean value	Values of minimum	Values of maximum	Variance	Coefficient of variation (%)
Force (max) (N)	404.5	118.1	1 839.6	175 333.60	103.5
Force of elasticity (N)	221.7	57.2	683.5	17 764.15	60.11
Deformation (max) (mm)	0.54	0.26	1.50	0.08	52.82
Elastic deformation (mm)	0.16	0.07	0.33	0	33.69
Energy (mJ)	139.7	12.6	1 298.1	105 289.20	232.2
Modulus (MPa)	709.8	396.1	1 076.4	24 277.22	21.95
Thickness (mm)	4.4	2.4	7.4	1.61	28.92
Width (mm)	7.3	5.8	9.5	2.33	20.80
Length (mm)	7.3	6.5	8.2	0.76	11.93

T a b l e 3. Mass of 1000 seeds and geometric properties of pulse crops seeds

Cultivars and lines	Mass of 1 000 seeds	Thickness (mm)		Width (mm)		Length (mm)	
		Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
			Yellow lupine				
Parys	127.8	4.30	0.45				
Polo	115.6	4.09	0.35				
			White lupine				
Butan	273.0	4.45	0.41	9.28	0.85		
Boros	317.1	4.95	0.32	9.25	0.65		
			Narrow-leaved lupine				
Cezar	128.8	5.02	0.36				
Baron	129.5	5.09	0.48				
Zeus	135.2	5.08	0.45				
			Andean lupine				
SK	93.8	4.22	0.31				
Epigonal	106.8	4.36	0.30				
			Pea				
Marych	187.9	6.61	0.37				
Set	278.8	7.23	0.49				
Merlin	268.4	7.14	0.39				
			Lentil				
Tina	59.8	2.79	0.19	6.02	0.65		
Anita	44.8	2.43	0.20	5.88	0.59		
			Sowing grasspea				
Krab	173.8	4.80	0.44	7.60	0.64	8.10	0.44
Derek	119.4	4.46	0.36	5.93	0.63	6.52	0.60
			Sowing vetch				
Jaga	83.3	4.46	0.43				
Ina	53.8	3.64	0.31				
Kamiko	73.6	3.97	0.32				
91/a/10/25/41	26.3	2.91	0.29				
Alba	20.2	2.58	0.37				
LGR 51a	59.7	3.85	0.33				
LGR 284/40	53.6	3.63	0.32				
LGR 72/8	29.7	3.05	0.36				

lentil and grasspea, while seed length was determined only for the irregular-shaped seeds of sowing grasspea. The mean thickness of seeds of all the cultivars and lines was 4.4 mm, with variability of that feature ranging from 2.4 to 7.4 mm (Table 2). The thickest seeds were characteristic of pea cultivars (6.61-7.14 mm) and of narrow-leaved lupine (5.02 -5.09 mm). Seeds of all other cultivars and species were characterized by thickness below 5 mm, the lowest values being those for sowing vetch and lentil. In terms of width, clearly dominant were the seeds of white lupine (above 9 mm), with lower values being recorded for lentil and grasspea (Table 3). The value of coefficient of variation for seed thickness was 28.92% and it was higher than for the other geometric parameters of the seeds (Table 2). Notable differences in values of geometric parameters of genetic mutants of grasspea are also indicated by results obtained by Rybiński *et al*. (2004), and Szot *et al*. (2005) for lentil, and for wheat by research results obtained by Geodecki and Grundas (2003), and Grundas (2004).

The quality of agricultural crops, and of agricultural materials in general, is usually associated with their utility value, as the fundamental measure of quality is their acceptability for consumption or for purposes other than food products. Estimation of the quality of a given agricultural material requires knowledge of the range of variability of its physical properties (Grundas, 2004), with reference to various species of crop plants (Szot *et al*., 2005). Damage to seeds may occur already in the pre-harvest period, when under specific unfavourable environmental conditions internal damage to seeds is observed in the process of seed filling, primarily due to high gradient of moisture in the seeds (Geodecki and Grundas, 2003). Mechanical damage to seeds is also encountered at each next stage of seed handling, beginning with harvest (cracking, breaking off of seeds fragments), through transport and storage, until the moment of their processing (milling or fragmentation).

In terms of seed resistance to mechanical loads, expressed by the maximum force (Table 4), the mean value of that parameter for all the experimental objects combined was 404.5 N, with minimum and maximum values ranging from 118 to 1839 N, and with a high coefficient of variability of 103.5% (Table 2). Based on the results obtained (Table 3), one can conclude that the highest values of mechanical strength, by a large margin, were characteristic of seeds of white lupine cultivars (1 765.76 and 1 629.41 N). The group with the second highest values of that trait (from 406.21 to 536.35 N) included seeds of pea cultivars. Similar values were characteristic of seeds of cultivars of yellow lupine (365 and 367,76 N) and narrow-leaved lupine (362.67, 360.06 and 385.01 N). This indicates that the structure of seeds of the two latter species is very similar, and totally different from that of seeds of white lupine. Those lupine species are in contrast to the low values (129.92 and 136.21 N) obtained for the Andean lupine, typical of South America, analysed in broad genetic aspect and bred by Sawicka (1993). With relation to sowing grasspea, it was demonstrated that seeds of the small-seeded cultivar Derek are more resistant to external loads (352.37 N) than seeds of cv. Krab (274.28 N). Slightly higher values of maximum force in seeds of cv. Derek than those of cv. Krab (282 and 279 N) were recorded by Rybiński *et al*. (2004), with variation range of that parameter in grasspea mutants being from 234 to 328 N. Also in a study on European lines of grasspea the values of maximum force were higher for cv. Derek (265 N) than for cv. Krab (209 N), with a very broad range of variation of that feature in lines from Italy, Spain, France and Germany – from 154 to 354 N (Rybiński *et al*., 2008). In a study by Szot *et al*. (1998), in turn, the values of maximum force were only slightly higher for seeds of cv. Derek (261.8 N) than for cv. Krab (257 N). In the case of lentil seeds, the resistance to mechanical loads was greater in cv. Anita (179.2 N) than in cv. Tina (160.1 N), while in a study by Szot and Stępniewski (2000) higher values of maximum force were also obtained of seeds of cv. Anita than cv. Tina (159 and 156 N). For comparison, resistance to mechanical loads determined for kernels of spring barley cultivars and mutants varied within a range from 107 to 227 N (Rybiński and Szot, 2006).

With relation to the force of elasticity (Table 4), decidedly the highest values were characteristics of seeds of white lupine (566.33 and 508.1 N), and the lowest of seeds of Andean lupine (85.55 and 87.27 N). Noteworthy are the high values of that parameter obtained for seeds of pea cv. Set (471 N) compared to those of cv. Merlin and Marych (365.12 and 256.27 N). The mean combined value of force f elasticity for all experimental objects was 221.7 N, with a range of variability from 57.2 to 683.5 and a coefficient of variation value at the level of 60.1% (Table 2). A notably distinctive character of white lupine seeds compared to seeds of the other species is evidenced by the values of maximum deformation that for the two white lupine cultivars were 1.3 and 1.48 mm. Decidedly lower values were obtained for the other lupine species and for pea, and the lowest were recorded for some form of sowing vetch. In the study on European forms of grasspea (Rybiński *et al*., 2008), the values of maximum deformation for grasspea cultivars Krab and Derek were 0.44 and 0.54 mm, and were nearly identical with those obtained in the study presented here. According to other authors (Szot *et al*., 1998) maximum deformation values for cv. Krab and Derek were 0.41 and 0.35 mm, respectively, and for lentil cv. Anita and Tina – 0.40 and 0.26 mm (Szot and Stępniewski, 2000). In the study presented here, the mean value of maximum deformation for all the objects was 0.54 mm, with variation range from 0.26 to 1.5 mm and coefficient of variability on the level of 52.82% (Table 2).

The mean value of elastic deformation for all the objects combined was 0.16 mm, and the range of variation among the objects in terms of that feature was from 0.07 to 0.33 mm, with coefficient of variation value of 33.7% (Table 2). As in the case of the mechanical load parameters discussed earlier, the highest values of elastic deformation (Table 5) were recorded for seeds of white lupine (0.26 and 0.28 mm) and for seeds of pea cv. Set (0.25 mm). In the other species and cultivars the values of that parameter were similar to one another.

Among all analysed cultivars and lines, the highest values of mechanical loads as expressed by the value of deformation energy were characteristic of seeds of white lupine cultivars (1 147.95 and 1 255.49 mJ), and lower – of seeds of

Table 4. Estimation of resistance to mechanical loads of pulse crop seeds expressed by values of maximal force, force of elasticity and maximal deformation

Cultivars and lines	Force (max) (N)		Force of elasticity (N)		Deformation (max) (mm)	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
			Yellow lupine			
Parys	365.00	88.98	207.07	111.97	0.60	0.32
Polo	367.76	96.11	203.77	115.44	0.53	0.22
			White lupine			
Butan	1 765.76	298.99	566.63	318.48	1.30	0.32
Boros	1 692.41	203.62	508.10	315.19	1.48	0.28
			Narrow-leaved lupine			
Cezar	362.67	66.35	218.36	89.71	0.66	0.31
Baron	360.06	48.17	201.61	87.51	0.53	0.26
Zeus	385.01	45.64	209.26	76.5	0.55	0.11
			Andean lupine			
SK	129.92	29.53	85.55	27.27	0.50	0.27
Epigonal	136.21	35.60	87.27	20.95	0.47	0.33
			Pea			
Marych	406.21	112.90	256.27	119.06	0.50	0.31
Set	536.35	77.95	471.04	143.54	0.52	0.20
Merlin	525.65	115.50	365.12	157.56	0.42	0.13
			Lentil			
Tina	160.14	17.70	123.69	47.86	0.35	0.14
Anita	179.2	30.64	143.9	45.11	0.44	0.24
			Sowing grasspea			
Krab	274.28	70.35	218.97	101.99	0.44	0.20
Derek	352.37	48.72	283.10	94.82	0.51	0.29
			Sowing vetch			
Jaga	221.96	38.42	165.41	56.67	0.46	0.33
Ina	201.06	26.25	119.27	48.40	0.31	0.15
Kamiko	319.85	38.83	234.39	93.21	0.38	0.07
91/a/10/25/41	163.98	21.13	119.28	37.08	0.42	0.18
Alba	137.88	19.83	85.38	39.58	0.40	0.30
LGR 51a	275.13	28.67	177.67	78.90	0.40	0.14
LGR 284/40	233.29	18.15	153.63	63.70	0.36	0.03
LGR 72/8	170.19	26.95	113.93	58.73	0.30	0.04

cultivars of yellow lupine, narrow-leaved lupine and pea (Table 5). The lowest values of that parameter were recorded for both lentil cultivars – Tina and Anita (13.1 and 15.0 mJ). Absence of differences between the two cultivars was demonstrated by Szot and Stępniewski (2000), and the respective values for those cultivars were 12.1 and 12.3 mJ. In the case of sowing grasspea, the values of energy for cultivars Krab and Derek in the study presented here were 33.3 and 41.9 mJ, respectively, while in the study by Rybiński *et al*. (2004) 67.0 and 51.1 mJ, with variability range for the objects (mutants) from 41.5 to 110.9 mJ. For comparison, the value of energy for kernels of naked-seed

T a b l e 5. Estimation of resistance to mechanical loads of pulse crop seeds expressed by values of elastic deformation, energy and modulus

Cultivars and lines	Elastic deformation (mm)		Energy (mJ)		Modulus (MPa)	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Yellow lupine						
Parys	0.15	0.05	70.49	38.15	704.40	177.77
Polo	0.15	0.05	66.48	29.51	669.50	162.16
White lupine						
Butan	0.26	0.14	1147.95	412.30	969.25	292.34
Boros	0.28	0.15	1255.49	462.07	724.87	225.74
Narrow-leaved lupine						
Cezar	0.20	0.08	78.96	22.93	506.32	136.07
Baron	0.17	0.08	61.98	22.64	659.17	209.24
Zeus	0.19	0.09	97.61	53.66	567.15	175.84
Andean lupine						
SK	0.12	0.04	41.06	62.40	433.34	121.03
Epigonal	0.11	0.03	25.13	22.62	506.95	119.82
Pea						
Marych	0.16	0.07	48.04	27.89	873.12	260.15
Set	0.25	0.07	85.57	22.5	775.46	175.04
Merlin	0.19	0.08	74.46	33.42	953.99	253.90
Lentil						
Tina	0.11	0.03	13.12	3.96	714.02	230.34
Anita	0.10	0.03	15.03	3.41	868.53	258.56
Sowing grasspea						
Krab	0.14	0.05	33.33	16.86	901.10	261.42
Derek	0.17	0.05	41.93	9.33	836.48	170.27
Sowing vetch						
Jaga	0.12	0.04	21.74	7.47	804.38	185.41
Ina	0.10	0.03	17.40	5.37	811.75	191.87
Kamiko	0.17	0.07	42.35	8.53	704.85	154.31
91/a/10/25/41	0.12	0.04	17.56	3.66	581.32	140.78
Alba	0.10	0.04	14.13	4.04	573.29	183.19
LGR 51a	0.15	0.07	34.89	5.07	685.08	172.3
LGR 284/40	0.14	0.06	27.82	2.98	633.94	157.40
LGR 72/8	0.12	0.06	18.99	4.75	573.78	141.63

mutants of barley varied from 15.6 to 56.4 mJ. The mean value of energy for all experimental objects combined was 139.7 mJ, with a broad range of minimum and maximum values from 12.6 to 1 298.1 mJ (Table 2) The high level of the mean value is a result of the contribution of values for white lupine cultivars. The results obtained had a significant effect on the value of coefficient of variability (232.2%), the highest among the mechanical load parameters under analysis.

T a b l e 6. Coefficients of correlation for seeds traits of investigated cultivars and lines of pulse crops

Parameters	Force (max)	Force of elasticity	Defor-mation (max)	Elastic defor-mation	Energy	Modulus	Thickness	Width	Length
Force (max)	1								
Force of elasticity	0.880**	1							
Deformation (max)	0.947**	0.764**	1						
Elastic deformation	0.825**	0.928**	0.772**	1					
Energy	0.947**	0.764**	0.962**	0.719**	1				
Modulus	0.394	0.560*	0.189	0.262	0.273	1			
Thickness	0.306	0.606*	0.223	0.627**	0.134	0.331	1		
Width	0.748**	0.594*	0.758**	0.616**	0.795**	0.070	0.27	1	
Length	-0.027	-0.071	-0.038	-0.096	-0.004	0.065	0.04	0.325	1

*significant at 0.01, **significant at 0.001.

T a b l e 7. Estimation of similarity among species of pulse crop expressed by Mahalanobis distance for mechanical loads parameters together

Cultivars		Parys	Butan	Cezar	SK	Set	Tina	Krab	Jaga
1	Parys	0							
2	Butan	63.59	0						
3	Cezar	4.78	63.16	0					
4	SK	10.31	66.95	11.11	0				
5	Set	12.97	68.81	14.55	20.96	0			
6	Tina	7.01	68.23	9.57	6.76	16.37	0		
7	Krab	6.36	67.39	9.68	13.57	11.76	7.38	0	
8	Jaga	4.98	67.16	8.27	10.41	13.86	4.46	3.33	0

Cultivars represented followed species: 1 – *Lupinus luteus*, 2 – *Lupinus alba*, 3 – *Lupinus angustifolius*, 4 – *Lupinus mutabilis*, 5 – *Pisum sativum*, 6 – *Lens culinaris,* 7 – *Lathyrus sativus,* 8 – *Vicia sativa.*

T a b l e 8. Estimation of similarity among species of pulse crop expressed by Mahalanobis distance for mechanical loads parameters and seed thickness together

Cultivars		Parys	Butan	Cezar	SK	Set	Tina	Krab	Jaga
1*	Parys	0							
2	Butan	63.61	0						
3	Cezar	10.24	63.87	0					
4	SK	10.31	66.96	14.34	0				
5	Set	35.85	76.03	28.38	30.22	0			
6	Tina	18.71	70.67	28.09	18.61	53.34	0		
7	Krab	8.18	67.52	10.44	14.51	30.63	23.66	0	
8	Jaga	5.24	67.16	11.11	10.53	34.68	19.50	4.83	0

*Explanations as in Table 7.

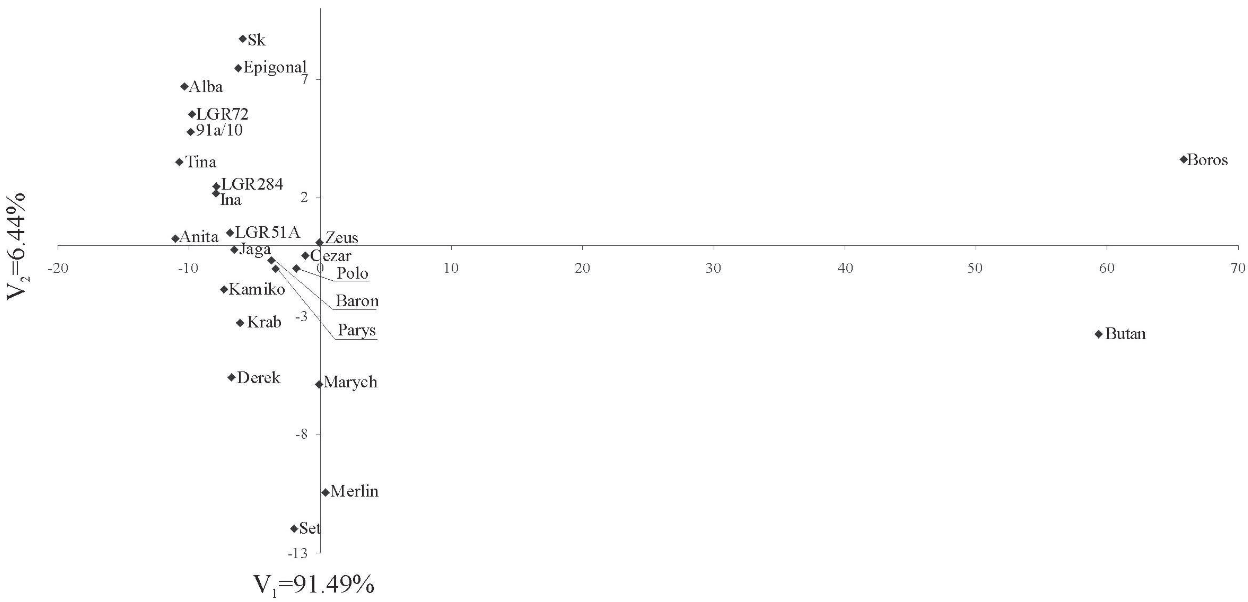

Fig. 1. Distribution of objects in the space of two first canonical variables for mechanical loads parameters combined.

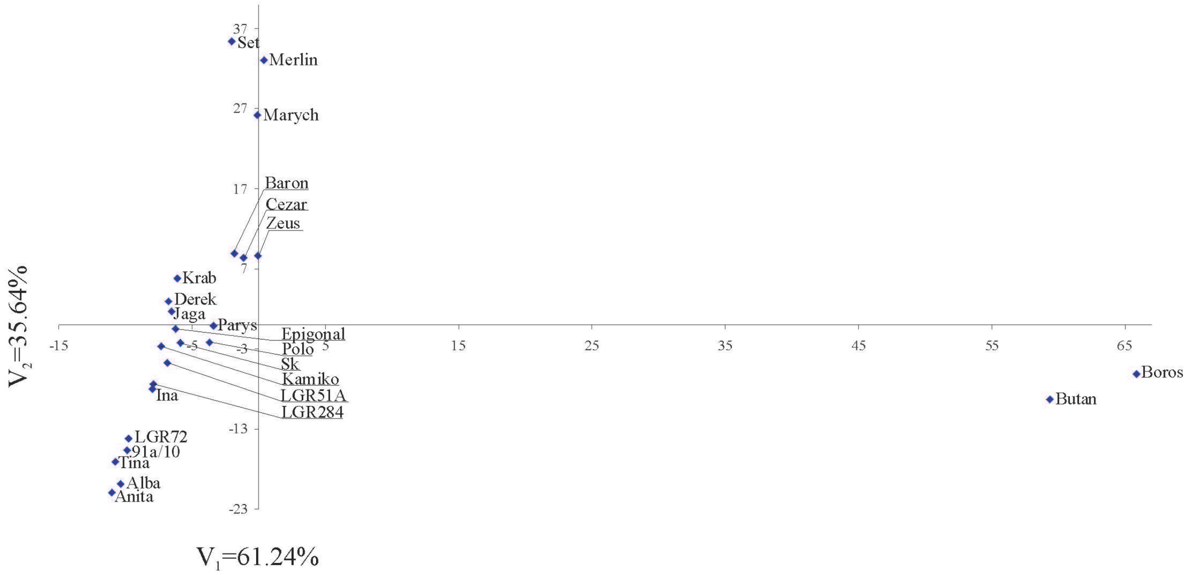

Fig. 2. Distribution of objects in the space of two first canonical variables for mechanical loads parameters and seed thickness combined.

The last of the mechanical load parameters under estimation was the modulus value (Table 5). The highest modulus value was characteristic of seeds of white lupine cv. Butan (969.2 MPa), with only slight lower values being recorded for pea cv. Merlin (953.9 MPa) or sowing grasspea cv. Krab (901.1 MPa). Modulus values for the remaining cultivars were below the level of 900 MPA. Notable variation of modulus values was observed for seeds of sowing vetch, from 811.7 MPa for cv. Ina to 573.3 MPa for cv. Alba. The mean value of modulus for all experimental objects combined was 709.8 MPa, with minimum and maximum values of 396.1 and 1 076.4 MPa and coefficient of variation value at the level of 21.95% (Table 2).

Table 6 presents the values of correlation coefficient for the mechanical load parameters and geometric features of the seeds. With the exception of the modulus, the remaining five parameters of mechanical load were significantly positive correlated with one another at the level of α=0.001. The modulus parameter was positively and statistically significantly correlated only with the force of elasticity at the level of α=0.01. Except for the modulus, all other load parameters were positively and statistically significantly correlated with seed width. Seed thickness, in turn, was positively correlated with the force of elasticity (α= 0.01) and with elastic deformation (α= 0.001). Seed length was not correlated significantly with any other of the parameters studied.

One of the statistical measures of estimation of similarity among the species studied in terms of the parameters and traits under analysis is Mahalanobis distances. Table 7 presents the values of calculated distances between selected cultivars, each of which represented one of the species of pulse crops. Estimation of inter-species similarity was performed based on the mechanical load parameters combined. The greatest distances (the least similarity) were obtained when comparing white lupine with the remaining species. This indicates notable uniqueness of seeds of white lupine in terms of mechanical strength. A low degree of similarity was also characteristic of seeds of pea and of Andean lupine (20.96). The greatest similarity of seeds response to the level of mechanical damage (shortest distances) were obtained in comparison of yellow lupine with narrow-leaved lupine (4.78), yellow lupine with vetch (4.99), and sowing vetch with lentil and grasspea (4.45 and 3.33). The notable uniqueness of white lupine seeds compared to the other species in terms of their response to the effect of external mechanical loads may be related with their different internal structure. Analysis of microstructure of the seeds might explain the observed differences, at least to a certain extent. Table 8 gives an estimation of similarity among the species extended by the feature of seed thickness. As in Table 7, the greatest distances (least similarity) was revealed in comparison of white lupine with the remaining species, followed by those for seeds of pea cultivars and the remaining species, and between sowing grasspea and lentil. The shortest distances, indicating minimal inter-species similarity in terms of the features and traits under analysis, were obtained in comparisons between yellow lupine and grasspea, and especially in those between sowing vetch and yellow lupine and grasspea.

Estimation of similarity of all the cultivars and lines in terms of mechanical loads on seeds, approached jointly, in spatial form and in the system of the first two canonical variables, is presented in Fig. 1. The two first canonical variables accounted for a total of 97.93% of the total variability, the greater share in that resulting from the variation of the first canonical variable. Therefore, the loss of information remaining for the other canonical variables was very low. The most remote spatial position (right-hand side of the figure) is characteristic of the white lupine cultivars Boros and Butan. The other cultivars under analysis occupy the area on the left-hand side of the plane, indicating greater mutual similarity and notable difference from the white lupine cultivars. Although the cultivars and lines are arranged in a vertical line on the left side of the lane, the differences in distances between them indicate a varied degree of similarity in the responses of their seeds to mechanical loads. The most extreme position in the bottom part of the plane is characteristic of the pea cultivars Set and Merlin, and of the third pea cultivar, Marych, and the sowing grasspea cultivar Derek. On the opposite extreme (top part of the plane) we can find the Andean lupine forms (SK and Epigonalny) and the spring vetch cultivar Alba. The remaining cultivars are positioned in the central part of the plane, indicating their greatest mutual similarity. The first canonical variable is positively correlated with the maximum force, force of elasticity, maximum deformation, elastic deformation, and energy. Whereas, the second canonical variable is negatively correlated with the force of elasticity, maximum deformation and modulus. The inclusion of the additional feature of seed thickness in the estimation of similarity only partially modified the spatial distribution, as presented in Fig. 2. In this case, the first two canonical variables accounted for a total of 96.88% of the total combined variability of the objects under study. We can distinguish here three concentrations of cultivars and lines. As in Fig. 1, the white lupine cultivars differ most emphatically from the remaining species. Another concentration, more visible than in Fig. 1, comprises the pea cultivars (Merlin, Marych and Set), while the third group includes all other species, most similar to one anther in terms of values of the complex of traits and features under analysis. The opposite positioning of pea cultivars Merlin, Marych and Set with relation to the second canonical variable in comparisons of the experimental objects on the basis of their mechanical load parameters and on the basis of the same features complemented with the parameter of seed thickness indicates a significant effect of tat feature on the similarity of the objects studied. The first canonical variable is positively correlated with the maximum force, force of elasticity, maximum deformation, elastic deformation, and energy, while the second canonical variable is negatively correlated with the force of elasticity, maximum deformation, and thickness.

CONCLUSIONS

1. Mean square values from the analysis of variance indicate statistically significant (α=0.001) differentiation among the estimated cultivars and lines in terms of each of the mechanical load parameters under analysis and of seed thickness.

2. Among the species under study, the greatest mass of 1000 seeds was characteristic of the white lupine cultivars, and the lowest of the lentil cultivars and certain lines of sowing vetch. In terms of the geometric features, the thickest seeds were characteristic of the pea cultivars and the lowest seed thickness was found in lentil and certain lines of vetch.

With relation to seed width, dominant were the seeds of white lupine cultivars, followed by seeds of lentil and sowing grasspea.

3. The seeds under analysis were characterized by a broad range of variation in terms of their response to the effect of external mechanical loads. The observed variability concerned primarily the inter-species differentiation, as well as differences among cultivars and lines within a single species. On the basis of the results obtained, cultivars and lines with the greatest and the lowest seed resistance to the particular parameters of static load were identified.

4. The most unique in terms of seeds response to the mechanical loads applied was white lupine. That uniqueness was clearly observable not only with relation to the other three lupine species, but also with relation to the cultivars and lines of the remaining species of pulse crops. The notable resistance of white lupine seeds to mechanical loads as compared to the remaining species may be attributable to their different internal structure, and elucidation of the differences observed requires analysis of the microstructure of seeds of that species against the background of the other species.

5. With the exception of the modulus, the remaining parameters of mechanical loads were positively and statistically significantly correlated with one another (α=0.001). The modulus value, on the other hand, was positively and statistically significantly correlated only with elastic deformation (α=0.01). Apart from the modulus, al other load parameters were positively and statistically significantly correlated with seed width. Seed thickness, in turn, was positively correlated with the force of elasticity and with elastic deformation.

REFERENCES

Camussi A., Ottaviano E., Caliński T., and Kaczmarek Z., 1985. Genetic distance based on quantitative traits. Genetics, 111, 945-962.

Dziamba S., 1997. The biology and agrotechnics of chicken vetch (in Polish). Int. Sci. Conf. *Lathyrus sativus* L. – cultivation and nutritive value in animals and humans. June 9-10, Radom, Poland.

Geodecki M. and Grundas S., 2003. Characterization of geometric features of single winter and spring wheat kernels (in Polish). Acta Agrophysica, 97, 531-538.

Grundas S., 2004. Characteristics of physical properties of single kernels along length of heads in common wheat (*Triticum aestivum* L.) (in Polish). Acta Agrophysica, 102, 1-64.

Księżak J., 2007. Yielding of mixtures of narrow-leaved lupine with cereals on various soil types (in Polish). Zesz. Probl. Post. Nauk Roln., 522, 255-260.

Milczak M., Pędziński M., Mnichowska H., Szwed-Urbaś K., and Rybiński W., 2001. Creative breeding of grasspea (*Lathyrus sativus* L.) in Poland. Lathyrus Lathyrism Newsletter, 2, 18-23.

Pahl H., 2002. Grain Legumes: production, consumption and trade in the EU and the world. In: Legumes for Sustainable Agriculture. LINK Press, Strassburg, Austria.

Paszkiewicz Z., 2007. Cultivation of White Lupine (in Polish). BiznesAgroSerwis Press, Warsaw, Poland.

Payne R., Murrey D., Harding S., Baird D., Soutou D., and Lane P., 2003. GenStat for Windows. Introduction. VSN Press, Oxford, UK.

Prusiński J., 2007. Biological progress in lupin (*Lupinus* ssp.) – present state and historical background (in Polish). Zesz. Probl. Post. Nauk Roln., 522, 23-37.

Rybiński W. and Szot B., 2006. Estimation of genetic variability of yielding traits and physical properties of spring barley seeds (*Hordeum vulgare* L.) mutants. Int. Agrophysics, 20, 219-227.

Rybiński W., Szot B., and Pokora L. 2004. Estimation of genetic variation and physical properties of seeds for grasspea mutants (*Lathyrus sativus* L.). Int. Agrophysics, 18, 339-346.

Rybiński W., Szot B., and Rusinek R., 2008. Estimation of morphological and mechanical properties of grasspea seeds (*Lathyrus sativus* L.) originating from EU countries. Int. Agrophysics, 22, 261-275.

Sawicka E.J., 1993. Induced mutations in Andean lupine (*Lupinus mutabilis* Sweet.) (in Polish). Prace Ogrodu Botanicznego PAN, Monografie i Rozprawy, 3, 1-102.

Szot B., Milczak M., and Wąsik A., 1998. Characteristics of the physical properties everlasting pea (*Lathyrus sativus* L.) (in Polish). Proc. Conf. Legume Protein Plants. III. Grasspea and lentil. December 4, Lublin, Poland.

Szot B. and Stępniewski A., 2000. Mechanical properties of single kernels o Polish cultivars of lentil (in Polish). Proc. II PTA Conf., September 11-12, Lublin-Dąbrowica, Poland.

Szot B., Stępniewski A., and Rudko T., 2005. Agrophysical Properties of Lentil (*Lens culinaris* Medik.) (in Polish). IA PAS Press, Lublin, Poland.

Szot B. and Tarkowski C., 1997. Preliminary investigation on some physical properties of *Triticale* grain (in Polish). Roczn. Nauk Roln., 72(3), 15-24.

Szponar-Krok E., Bobrecka-Jamro D., Tobiasz-Salach R., and Buczek J., 2007. Reaction of edible lentil (*Lens culinaris* Medic) to seed inoculation with *Rhizobium leguminosarum*. Zesz. Probl. Post. Nauk Roln., 522, 341-350.

Święcicki W., 1993. Selected problems of lupine genetics and breeding (in Polish). Proc. Conf. Lupine in Human Life. November 29, Poznań, Poland.

Święcicki W., Chudy M., and Żuk-Gołaszewska K., 2007. Grain legumes in the EU framework programmes (in Polish). Zesz. Probl. Post. Nauk Roln., 522, 54-65.

Von Richthoffen J.S., 2006a. What do European farmers think about grain legumes systems. Grain Legumes, 45, 14-15.

Von Richthoffen J.S., 2006 b. Economic impact of grain legumes in European crops. Grain Legumes, 45, 16-19.

Wiatr K. and Dolata A., 2007. Cultivation of sowing pea – the Polish tradition (in Polish). BiznesAgroSerwis Press, Warsaw, Poland.