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Estimation of genetic variability of yielding traits and physical properties of seeds of spring barley (*Hordeum vulgare* L.) mutants

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Abstract. The material for performed studies comprised 19 hull-less barley mutants, their initial form 1N/86, as well as six hulled forms – three fodder and three malting cultivars. In field trial the mutants and their initial form were analysed for yield structure traits, and for all objects for geometric properties of grains and their resistance to squashing as expressed by stress, strain, and energy. As compared to the initial form, the mutants were characterized by broader genetic variability of yield structure. It allowed to select a few mutants with higher grain yield per plot as well as higher yield structure parameters. A broad variation was also observed for geometric properties of grains and their resistance to squashing. For those traits great differences were noticed not only among the hull-less mutants but also among the hulled cultivars. Based on obtained results a comparison between both groups of barley forms was performed.

Keywords: hull-less barley, geometric properties, resistance to squashing, mutants, yield structure

INTRODUCTION

Among the hulled cultivars of cereals grown in Poland, increasing economic significance is gained by their hull-less forms. In the Polish Crop Register, among 37 cultivars of spring barley grown on an area of about 1 million hectares there was one hull-less cultivar (Rastik), and among 25 cultivars of oats, grown on an area of about 550 thousands ha – two cultivars – Akt and Polar (Kolasińska and Boros, 2003). New hull-less cultivars, due to the reduced fibre content, high content of proteins with favourable amino acid composition, and – in the case of oats – increased content of valuable fats, find an application in feeding monogastric animals as well as in the food industry.

Kernel hulls constitute approximately 10-13% of dry kernel mass (Bhatty *et al*., 1975), with barley hulls containing primarily cellulose, hemicellulose, lignin, and a slight amount of low-value proteins. Ridding the kernel of the hull, therefore, enhances its attractiveness for animal feeding (Xue *et al*., 1997; Zheng and Bhatty, 1998) and for the food processing industry (Bhatty and Rossnagel, 1998), especially in groats production (Bhatty, 1997). Studies on hull-less cultivars of barley, concerned with their proteins content and amino acid composition, content of digestible fibre, digestibility of proteins, their biological value and degree of utilisation, showed higher nutritional value of such cultivars when compared to hulled forms of barley (Boros *et al*., 1996). Kernel hull-lessness is determined by a single recessive gene *nud* (other symbols for the gene *k, n, s* or *h*), localized close to the centromere on the long arm of chromosome 1 (7H) (Górny, 2004). The expression of the gene precludes permanent adhesion of hulls to the kernel, thus reducing the content of sparingly soluble fibre (Xue *et al*., 1997).

Kernel hull-lessness is a very stable feature – environmental conditions have only a negligible effect on its expression (Górny, 2004). Highly variable, however, is the crop yielding of hull-less forms, their crops being usually 15-35% lower than those of hulled forms, with weaker productive branching and 20-25% greater weight of 1000 kernels (Dziamba and Rachoń, 1988; Paris, 1999). Moreover, according to Kolasińska and Boros (2003), hull-less cultivars introduce undesirable problems related to the sowing value of the kernels. Those authors suggest that the kernel structure, lack of hulls, causes naked kernels to be more exposed to crushing and compression *eg* during harvest than hulled kernels. Hence, apart from the estimation of the yielding traits, the study was also aimed at estimating the aforementioned physical parameters of kernels in laboratory tests on the example of kernels of hull-less mutants of spring barley.

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MATERIAL AND METHODS

Initial material for the induction of mutation consisted of kernels of the hull-less bred strain 1N/86 (initial form). As a result of treatment of the kernels with chemomutagens – N-nitroso-N-methylurea (MNU) and sodium azide (NaN_3), generation M_1 was obtained, whose kernels were used to obtain generation M_2 from which the mutants were selected. After successive reproductions 19 mutated forms were selected, which in terms of their morphotype and yielding capacity differed significantly from the initial form 1N/86. The material and the initial form constituted the objects of field experiments conducted over three consecutive years on the Experimental Field of the Institute of Plant Genetics, Polish Academy of Sciences, in Cerekwica. The experiments were set up following the random blocks method in three replications. Sowing was performed with the help of a plot seeder. Plot size was 2 by 1 m, and sowing density was 330 seeds per 1 m^2. Prior to harvest, 25 spikes were collected from each plot and each experiment replication, and spike length as well as the number and weight of kernels per spike were determined. The plants were harvested using a plot combine, and the yield of kernels per plot was determined. The results obtained were processed statistically (second year of the experiment), determining the mean values, coefficients of variability, standard deviation, and coefficient of correlation. Estimation and results of testing of mean value comparisons for the examined traits between the initial form and the mutants was determined in the form of contrasts (Caliński *et al*., 1976; Ceranka *et al*., 1977).

Kernels from the second-year harvest and, additionally, kernels of six cultivated varieties of fodder and malting barley (Atol, Barke, Edgar, Rasbet, Rodos and Sezam) were used for the estimation of the physical properties of the kernels. The harvested kernels were analysed in the aspect of their physical properties, estimating – in the first stage – their width, length, thickness, and weight of 1000 kernels. Kernel thickness, width and length were measured by means of a specially adapted dial gauge and a digital slide caliper, with an accuracy of 0.01 mm. To obtain an accurate distribution of the trait, on air-dry samples 300 replications were made on the same random-selected kernels. The weight of 1000 kernels was determined with the help of an LN-S-50A kernel counter, in three replications.

The resistance of individual kernels to static loads was determined by means of an INSTRON model 6022 strength tester, in accordance with a method developed earlier, in 50 replications (Szot *et al*., 1994). On the basis of the results obtained the resistance of kernels to squashing was determined. The results were expressed in values of stress (N), strain (mm), and energy (mJ).

RESULTS AND DISCUSSION

Apart from recombination effects resulting from the crossing of plants, a valuable complement to the method in conventional plant breeding is induced mutation leading to an expansion of genetic variability of traits, providing a possibility of obtaining changes that never or rarely occur in nature (Ahloowalia and Małuszyński, 2001; Rybiński, 2001; Ahloowalia *et al*., 2004). Special significance of induced mutations occurs in the breeding of species characterised by a narrow range of variability (Sawicka, 1993). As far back as 1965 (Scholz), induced mutation was successfully applied to produce numerous hull-less kernelled mutants with improved protein content and yielding capacity. The mean values of the analysed traits (Table 1) indicate that, in terms of grain yield per plot and features of crop yield structure, the mutants – compared to the initial form 1N/86 – were characterized by broader trait variability. This was reflected in the range of extreme values (minimum and maximum) and in the values of the coefficient of variability (Table 2). The broadest variability was characteristic of the grain yield per plot (CV=25.12%), with similar values for the remaining traits (CV=7.32 – 7.85%).

As indicated by literature data, lower competitiveness of hull-less forms is related to their lower yielding capacity (Bhatty, 1986; Nam *et al*., 1990). Testing of comparisons for the examined traits between the mutants and their initial form (Table 3) indicates that in terms of grain yield per plot the mutants performed less well than the initial form (positive values of contrast). Five mutants yielded better than the initial form (M 4; M 5; M 7; M 10 and M 15 – negative values of contrast), but only for three of them (M 4; M 5 and M15) the values of contrast were statistically significant. Using the same chemomutagen (MNU), a number of mutants with hull-less kernels and enhanced protein content were obtained, but only seven of them yielded better than the initial form (Uhlik, 1991). In his studies Bhatty (1986) analysed numerous hull-less forms of barley in which increased content of proteins was shown and whose yield was at the level of 80-90% of that of hulled cultivars. A feature characterizing the hull-less forms was a reduction in the weight of single kernel, though in some lines the values of that trait were unexpectedly high (Persson, 1998). According to Lundquist (1991), reduction in the yielding of mutants was related to decreased spike length. This was not supported by our results, where as many as 10 mutants were characterized by longer spikes (Table 3) than the initial form 1N/86, and in seven of the ten the value of the trait was statistically significant.

With respect to the number of kernels per spike, five mutants showed higher values of the trait, though only two

Table 1. Mean values for analyzed traits of mutants and their initial form 1N/86

Initial form and mutants	Traits			
	Spike length (cm)	Number of grains per spike	Grain weight per spike (g)	Grain yield per plot (kg)
1N/86	8.0	22.6	0.93	0.76
M 1	7.9	21.2	0.97	0.63
M 2	8.0	22.6	1.0	0.71
M 3	7.5	21.1	0.89	0.56
M 4	8.8	25.9	0.98	0.86
M 5	9.1	24.3	1.01	1.18
M 6	8.5	23.8	1.04	0.73
M 7	8.5	22.0	0.79	0.80
M 8	8.2	21.6	0.95	0.65
M 9	8.1	22.8	0.96	0.76
M 10	7.9	19.8	0.87	0.78
M 11	7.7	19.5	0.88	0.63
M 12	8.5	22.5	0.91	0.61
M 13	9.5	22.8	0.95	0.63
M 14	8.9	22.3	1.01	0.58
M 15	8.1	20.3	0.86	1.05
M 16	7.9	20.9	0.89	0.66
M 17	7.3	19.5	0.85	0.60
M 18	7.4	20.8	0.92	0.60
M 19	8.0	20.8	0.95	0.77

Table 2. Statistical characteristics of investigated traits for all objects together

Traits	Statistical characteristics				
	Mean	Min.	Max.	Coefficient of variability (%)	Standard deviation
Spike length (cm)	8.20	7.00	9.60	7.32	0.600
Number of grains per spike	21.85	18.90	27.10	7.85	1.716
Grain weight per spike (g)	0.93	0.78	1.05	7.69	0.071
Grain yield per plot (kg)	0.73	0.45	1.50	25.12	0.184

on them differed significantly from the control form (Table 3). In spite of the observed reduction in the number of kernels per spike, as many as 10 mutants were characterized by higher values of the weight of kernels per spike, though only for four of those the differences were statistically significant. Among the analysed mutants with higher yield of grain per plot, only two (M 4 and M 5) were characterized both by longer spike and by greater number and weight of kernels per spike (negative values of contrast). Even though in many cases other mutants were characterized by higher values of those yielding traits, their yield of grain per plot was lower. This may be related to reduced productive branching in hull-less forms, as indicated by works by Dziamba and Rachoń (1988) and by Paris (1999).

The yield of grain per plot was positively correlated with spike length and weight of kernels per spike, but negatively with the weight of 1000 kernels (Table 4). Spike length was significantly and positively correlated with the remaining traits, and especially highly with the number of kernels in a spike (r = 0.615). In turn, the number of kernels per spike showed significant and positive correlation with the weight of kernels per spike (r = 0.571) and negative correlation with the weight of 1000 kernels (r = -0.430).

Although generally hull-less forms are characterized by yielding reduced by 15-35% (Dziamba and Rachoń, 1988; Paris, 1999), it is possible to obtain high-yielding lines (Vaidya and Mahabalram, 1989) that can yield at the level of hulled cultivars while also showing higher tolerance of such

Table 3. Estimation of comparisons between mutants and their initial form for yield and yield structure parameters expressed in contrast value

Initial form and mutants	Traits			
	Spike length (cm)	Number of grains per spike	Grain weight per spike (g)	Grain yield per plot (kg)
1N/86-M 1	0.10	1.42*	-0.04	0.13*
1N/86-M 2	0.00	0.12	-0.07*	0.05
1N/86-M 3	0.51*	1.54*	0.02	0.20**
1N/86-M 4	-0.82**	-3.36**	-0.05	-0.10*
1N/86-M 5	-1.10**	-1.73**	-0.08*	-0.42**
1N/86-M 6	-0.51*	-0.69	-0.11**	0.03
1N/86-M 7	-0.52*	0.63	0.14**	-0.04
1N/86-M 8	-0.21	1.02*	-0.02	0.11*
1N/86-M 9	-0.11	-0.26	-0.03	0.01
1N/86-M 10	0.10	2.82**	0.06*	-0.02
1N/86-M 11	0.32	3.14**	0.05	0.13*
1N/86-M 12	-0.56*	0.12	0.02	0.15**
1N/86-M 13	-1.53**	-0.21	-0.02	0.13*
1N/86-M 14	-0.93**	0.31	-0.08*	0.18**
1N/86-M 15	-0.12	2.33**	0.07*	-0.29**
1N/86-M 16	0.13	1.74**	0.04	0.10*
1N/86-M 17	0.72**	3.15**	0.10**	0.16**
1N/86-M 18	0.65**	1.97**	0.01	0.16**
1N/86-M 19	0.00	1.82**	-0.02	-0.01

Significant at: * $\alpha = 0.05$, **$\alpha = 0.01$.

Table 4. Coefficient of correlations for grain yield and parameters of yield structure

Traits	Grain yield per plot (kg)	Spike length (cm)	Number of grains per spike	Grain weight per spike (g)	Weight of 1000 grains (g)
Grain yield per plot (kg)	1.00				
Spike length (cm)	0.252*	1.00			
Number of grains per spike	0.265*	0.615**	1.00		
Grain weight per spike (g)	0.427**	0.352**	0.571**	1.00	
Weight of 1000 grains (g)	-0.277*	0.314*	-0.430**	0.345**	1.00

Significant at: * $\alpha = 0.05$, ** $\alpha = 0.01$.

stress-inducing environmental factors as drought or low temperatures (Thair and Shevtsov, 1994) and enhanced nutritional values (Kapała and Rybiński, 1995). Also the results presented herein indicate a possibility of obtaining hull-less mutants with better yielding capacity.

Development of mechanization of agriculture and of food processing industry causes that knowledge of the physical properties of seeds is becoming indispensable. Cereal grain, as a material that is biologically living, is subject to changes under the effect of numerous factors, both external and internal (Woźniak, 2003a). Damage to kernels may occur already at the pre-harvest stage, when under certain unfavourable environmental conditions internal damage is observed in the process of grain filling, mainly as a result of high moisture gradient in the kernels (Grundas *et al*., 1990; Geodecki and Grundas, 2003). Grain wetting takes place in the pre-harvest period when fully ripe kernels are intensively wetted by rain or dew, and in the course of conditioning when grain is purposefully wetted in order to prepare it for *eg* grinding (Woźniak, 2003b). In turn, mechanical damage is encountered at every stage of subsequent treatment, beginning with harvest (broken, crushed or halved kernels, kernels without germs), transport and storage, until the moment of processing (milling or grinding). This situation is mainly encountered in the case of grain for the processing industry. The problem of damage to grain becomes definitely more complex when the grain is qualified as high value sowing material with strictly specified parameters of germination capacity. According to Kolasińska and Boros (2003), hull-less cultivars of barley and oats are characterized by good proliferacy, enhanced resistance to lodging, sometimes are more resistant to diseases (mould) and ripen earlier. Information gathered from producers and breeders shows that hull-less kernels of barley and oat are more frequently rejected in laboratory assessments due to their poorer germination capacity compared to kernels of hulled cultivars. Authors mentioned above analysed, on the basis of a field experiment, the circumstances of occurrence of potential damage to hull-less barley (with relation to harvest method) and the effect of damage on the germination capacity and the growth and development of seedlings. In our study we concentrated on estimation of the geometry of hull-less kernels and of their compressive strength in laboratory tests.

The results of kernel geometry estimations are presented in Table 5. With the exception of the hulled cultivar Atol and Sezam and the mutant M 2, for which grain moisture exceeded 13.5%, the range of variability of that trait for the remaining forms was from 8.2 to 12.4%, and usually fell within 9-11%. Cereal grain, depending on the level of moisture, may assume the form of an elastic body (dry material), through partially elastic, to plastic in the case of high moisture content (Woźniak, 2003a). Considering the fact that the moisture of the parenchyma may affect the physical properties of grain, the problem has an especially significant methodological aspect. Moreover, the values of force causing the destruction of seed structure depend on the seed moisture, and increase in the seed moisture content causes a drastic decrease in the resistance of the seeds to static loads (Szot *et al*., 1998). In our study the moisture content of the kernels was typical for dry material, which permitted comparisons of the results obtained.

Mean kernel thickness of the mutants was from 2.55 to 2.75 mm at the value for the initial form of 2.68 mm (Table 5). The thickest kernels were characteristic of the hulled cultivar Edgar (2.88 mm). Kernel width of the mutants was similar to that of the initial form (3.65 mm) and varied from 3.42 to 3.81 mm. The greatest range of variability of observed in the case of kernel length. Mean value of the trait in the mutants was from 7.48 mm to 8.83 mm (mutant M 16). Among the hulled cultivars as many as three (Atol, Edgar and Rodos) were characterized by kernels with length above 9 mm. The weight of 1000 kernels in the hulled cultivars did not exceed 46.5 g, while as many as nine of the mutants exceeded the level of 50 g. This indicates a greater weight of 1000 naked kernels, which is supported by literature data where the value of that trait was 20-25% higher compared to hulled cultivars (Dziamba and Rachoń, 1988).

The estimation of the physical properties of kernels concerned also their resistance to mechanical loads (Table 6). The average value of force causing the destruction of the structure of individual kernels of the initial form 1N/86 was 168.5 N, while for the mutants it varied from 125.3 to 227.3 N. Among the hulled cultivars the value of the parameter did not exceed 184.7 N (Edgar). With respect to kernel deformation, the highest value was characteristic of the mutant M 3 (0.42 mm) and the lowest – M 14 (0.26 mm) at the mean value for the initial form at 0.31 mm. The highest degree of deformation among the hulled forms was characteristic of the Edgar cultivar. According to Woźniak (2003b), wheat grain wetting had no influence on kernel deformation, and with microwave drying the times applied had a significant differentiating effect on the parameter. Resistance to squashing, as measured by the values of energy, was strongly varied and depended on the genotype. The value of the parameter for the initial form was 33.24 mJ, and for the mutants from 21.55 to 56.4 mJ. Worthy of notice are the very low values for the hulled cultivars Rasbet, Rodos and Sezam, of 19.14, 17.15 and 15.6 mJ, respectively. An interesting aspect here is that those are solely malting cultivars.

The structure of the parenchyma may have an effect on the physical properties of grain and it has been shown that the Polish hull-less cultivar Rastik is characterized by very high susceptibility to parenchyma cracking (Woźniak, 2004). In our study we did not analyse parenchyma cracking, but one may assume that – as a result of the lack of hulls – this is a trait typical of all hull-less forms and that it could have had an effect on the level of compressive strength of the studied mutants. Table 7 presents the results of comparison of naked and hulled forms with respect to the geometry of kernels and their resistance to squashing. With respect to kernel thickness and width, the mean values of the parameters are very similar. Notably greater differences were recorded with respect to kernel length. On average, hulled kernels were longer than hull-less kernels. The hull-less mutants, in turn, were characterized by greater weight of 1000 kernels than the hulled forms. In terms of the resistance to squashing as measured by the compressive force and energy, notably higher mean values were characteristic for the hull-less forms than for the hulled cultivars. An opposite effect was observed in the case of kernel deformation.

Differences in the resistance to mechanical damage are observed not only between cereal species, such as barley, rye, triticale and wheat (Stępniewski and Szot, 1994), but also within a single species, where the determinant is the structure of the endosperm. For kernels of vitreous wheat (*Triticum durum*) the maximum force causing damage was significantly higher than in the case of other wheats (Szot *et al*., 1994). The type of structure of the endosperm of the Henika wheat (mealy and vitreous) had also a significant effect on the values of the mechanical parameters; kernels with vitreous type of endosperm were characterized by

Table 5. Geometrical properties of grain and their weight for hulled and hull-less forms of spring barley

Objects	Moisture of grain (%)	Thickness (mm)				Width (mm)				Length (mm)				Weight of 1000 grains (g)
		Mean	Min.	Max.	CV(%)*	Mean	Min.	Max.	CV(%)*	Mean	Min.	Max.	CV(%)*	
Atol	14.4	2.64	2.40	2.93	4.24	3.54	3.00	3.86	3.78	9.02	7.90	9.80	3.74	45.37
Barke	12.0	2.74	2.45	3.06	4.30	3.70	3.25	3.99	3.13	8.46	7.80	8.95	2.99	36.15
Edgar	11.1	2.88	2.45	3.36	5.92	3.79	3.35	4.14	4.38	9.10	7.85	8.90	4.98	46.32
Rasbet	10.4	2.59	2.40	2.75	2.83	3.47	3.25	3.70	2.61	8.27	7.50	8.90	3.37	39.91
Rodos	10.5	2.55	2.14	2.81	4.77	3.43	2.93	3.86	5.10	9.07	7.93	9.90	4.03	41.42
Sezam	13.5	2.76	2.04	3.06	5.43	3.65	2.88	4.20	4.75	8.39	7.80	8.91	3.33	40.27
1N/82	9.6	2.67	2.00	3.15	7.15	3.65	3.10	4.97	7.94	7.32	5.45	9.53	9.26	47.40
M – 1	10.6	2.68	2.17	3.01	5.56	3.74	3.12	4.13	5.20	7.89	6.71	9.01	6.37	53.16
M – 2	13.6	2.63	2.01	3.24	7.78	3.62	2.91	3.24	7.10	7.62	3.86	8.95	8.07	49.06
M – 3	10.0	2.71	2.16	3.99	8.26	3.75	3.00	4.12	5.54	7.88	6.83	9.80	7.36	52.85
M – 4	9.6	2.57	1.97	2.92	8.32	3.69	3.12	4.05	5.36	7.63	6.20	8.85	6.85	49.80
M – 5	9.7	2.63	2.14	2.95	6.46	3.52	3.00	3.90	5.74	7.48	6.50	8.70	4.50	38.18
M – 6	11.9	2.66	2.13	2.91	5.30	3.60	3.10	3.92	4.52	8.17	7.35	8.72	3.54	39.12
M – 7	11.9	2.61	2.18	3.05	5.62	3.65	3.04	4.07	4.26	7.88	6.89	8.80	6.18	47.46
M – 8	9.5	2.46	1.83	2.96	6.68	3.42	2.51	4.02	6.71	7.87	5.77	8.90	6.10	39.24
M – 9	10.4	2.63	2.25	3.20	6.66	3.66	3.02	4.17	5.99	7.89	6.63	8.96	6.34	48.05
M – 10	10.8	2.66	2.35	2.90	5.03	3.60	3.09	3.95	5.33	8.29	7.45	8.72	3.37	53.99
M – 11	8.2	2.75	2.30	3.02	5.27	3.79	3.29	4.20	5.24	8.15	6.98	9.02	5.58	52.86
M – 12	9.3	2.71	2.20	3.15	6.30	3.80	3.30	4.30	5.05	8.02	6.85	9.12	5.68	52.61
M – 13	11.3	2.56	2.23	2.85	4.99	3.53	3.15	5.85	4.38	8.02	6.60	8.65	5.57	44.11
M – 14	9.3	2.55	2.00	2.80	4.97	3.52	2.27	3.89	5.69	7.93	6.99	8.88	4.49	41.88
M – 15	10.1	2.75	2.50	3.22	4.59	3.81	3.45	4.15	3.62	8.71	7.70	9.20	2.45	50.37
M – 16	12.4	2.75	2.50	3.03	4.54	3.68	3.20	3.99	3.92	8.83	8.12	10.31	4.62	45.19
M – 17	9.3	2.67	2.20	2.90	4.91	3.74	3.30	4.20	4.66	8.52	7.11	9.13	3.27	53.73
M – 18	9.5	2.67	2.45	3.00	4.51	3.76	3.45	4.13	4.04	8.43	7.54	8.90	2.96	52.86
M – 19	12.0	2.63	1.81	3.17	6.22	3.63	3.21	4.10	4.70	8.32	6.81	9.21	5.30	52.14

*coefficient of variation.

T a b l e 6. Resistance to squashing of hulled and naked barley grains expressed by values of stress, strain and energy

Objects	Stress (N)				Strain (mm)				Energy (mJ)			
	Mean	Min.	Max.	CV(%)*	Mean	Min.	Max.	CV(%)*	Mean	Min.	Max.	CV(%)*
Atol	165.60	84.25	338.22	32.45	0.43	0.21	0.98	45.93	37.96	8.40	164.03	94.92
Barke	120.86	72.04	204.15	22.58	0.33	0.19	0.85	36.62	20.45	7.62	114.93	81.34
Edgar	184.71	99.39	350.92	30.15	0.47	0.21	1.08	44.27	43.36	9.49	134.30	78.20
Rasbet	118.76	75.46	253.97	22.98	0.33	0.19	0.97	47.26	19.14	5.95	64.00	67.33
Rodos	149.95	114.04	201.46	16.79	0.27	0.18	0.78	39.44	17.15	9.49	71.74	53.57
Sezam	107.65	28.82	154.34	22.62	0.32	0.20	0.67	28.58	15.63	2.68	43.12	48.22
1N/82	168.47	55.43	387.55	43.08	0.31	0.14	0.76	53.39	33.24	3.76	132.91	102.15
M – 1	227.27	97.92	492.06	39.30	0.39	0.16	0.76	45.99	56.08	7.35	137.48	85.12
M – 2	190.16	28.33	369.48	37.71	0.37	0.07	0.80	54.97	46.67	0.95	164.17	93.29
M – 3	210.70	70.57	367.28	34.55	0.42	0.18	0.84	51.75	56.40	7.17	161.23	84.23
M – 4	210.78	107.94	464.71	39.00	0.36	0.16	0.78	48.39	46.70	9.30	189.15	90.73
M – 5	154.48	19.05	387.06	47.60	0.39	0.05	0.86	46.61	37.73	0.55	157.59	92.81
M – 6	150.64	50.79	322.83	42.41	0.34	0.14	0.89	52.04	33.19	25.04	132.66	24.28
M – 7	177.24	56.61	320.64	32.89	0.35	0.16	0.88	49.14	39.62	4.78	163.00	91.25
M – 8	150.12	57.63	313.07	36.64	0.33	0.14	0.94	50.5	31.38	5.01	133.57	93.95
M – 9	190.26	64.78	464.96	42.96	0.35	0.17	1.07	53.69	45.07	4.68	306.74	114.67
M – 10	186.54	103.79	509.65	36.22	0.34	0.17	0.85	45.58	38.16	8.94	216.45	104.17
M – 11	187.25	67.40	475.95	40.37	0.29	0.14	0.69	43.45	33.21	4.20	182.84	108.46
M – 12	185.14	78.89	415.14	34.90	0.30	0.14	0.71	50.91	35.21	5.29	142.79	100.61
M – 13	128.05	53.48	293.28	42.85	0.27	0.11	0.61	48.88	23.34	4.18	92.96	95.41
M – 14	125.31	35.41	232.97	40.07	0.26	0.11	0.65	49.94	21.55	2.34	90.77	92.62
M – 15	175.83	52.02	465.20	52.99	0.32	0.13	1.00	66.17	39.95	3.66	222.33	130.68
M – 16	150.46	65.93	252.26	27.18	0.37	0.22	0.86	34.62	25.92	4.61	117.46	84.12
M – 17	188.19	108.43	309.40	25.66	0.33	0.15	0.74	48.35	28.69	7.91	125.89	85.80
M – 18	203.77	100.61	444.69	39.46	0.37	0.14	0.92	53.65	41.25	8.14	219.94	107.59
M – 19	202.17	65.45	443.71	39.17	0.36	0.14	1.00	60.82	45.97	6.65	214.77	103.24

*coefficient of variation.

Table 7. Means and range of variability of geometric properties of grains and their resistance to squashing in groups of naked and hulled spring barley forms

Type of grain	Thickness (mm)			Width (mm)			Length (mm)			Weight of 1000 grain (g)			Stress (N)			Strain (mm)			Energy (mJ)		
	X	X_{min}	X_{max}	X	X_{min}	X_{max}	X	X_{min}	X_{max}	X	X_{min}	X_{max}	X	X_{min}	X_{max}	X	X_{min}	X_{max}	X	X_{min}	X_{max}
Hulled	2.69	2.55	2.88	3.59	3.43	3.79	8.72	8.27	9.10	41.5	36.1	46.3	141.2	107.7	184.7	0.358	0.29	0.47	25.6	20.45	43.36
Naked	2.64	2.46	2.75	3.65	3.42	3.81	8.04	7.32	8.83	48.2	38.2	53.4	175.0	125.3	227.3	0.341	0.26	0.42	38.2	21.55	56.40

notably higher values of the mechanical parameters compared to mealy kernels (Woźniak, 2003b). In a study on sowing grass pea, also variety-related differences were shown in the resistance of kernels to squashing (Rybiński *et al*., 2004). One can assume, therefore, that the differences observed between the hull-less barley mutants and their initial form 1N/86 in the sensitivity to mechanical loads have the character of genetic changes caused by the effect of the mutagen and related to the internal structure of the endosperm.

CONCLUSIONS

1. Induced mutation produced hull-less mutants of spring barley which, compared to their initial form 1N/86, were characterized by a broader range of variability of grain yield per plot and of the yield structure traits.

2. In spite of the observed tendency of the hull-less mutants towards lower grain yields, some mutants were selected that yielded above their initial form and, moreover, were characterized by higher values of spike length and of the number and weight of kernels per spike.

3. The mutagens applied had an effect on the differentiation of physical properties of mutant kernels as compared to the initial form. The observed variability concerned both the geometry of the kernels and their resistance to squashing as expressed by the values of stress, strain, and energy.

4. With respect to kernel thickness and width, the values obtained for the hull-less mutants and for the hulled cultivars were similar, while the hulled cultivars were characterized by notably longer kernels. The hull-less forms produced larger kernels than the hulled cultivars, which was reflected in their greater weight of 1000 kernels.

5. In comparison with the hulled cultivars, the hull-less mutants were characterized by different resistance to mechanical loads. In terms of resistance to squashing, the hull-less kernels – compared to the hulled cultivars – were characterized by higher mean values of force and energy parameters required to destroy the kernel structure. A reverse relation was observed for the parameter of kernel strain.

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