In vivo evaluation of vigor in naked and husked oat cultivars under drought stress conditions

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ABSTRACT

Considering the prevention of crop production, aimed at adaptation to climate changes, searching for or developing genotypes resistant to water deficit is a challenge for modern agriculture and a strategic goal of plant breeding. The objective of the study was to determine the effect of drought stress on the vigor of naked and husked oat (*Avena sativa* L.) cultivars. The studies concerned eight naked oat cultivars and two husked oat cultivars characterized by high germination capacity (above 95%). Seeds of naked oat cultivars showed susceptibility to varied thermal conditions during drought simulated by the use of polyethylene glycol (PEG) at a concentration of -1.5 MPa. An increase in temperature from 10 to 20 °C resulted in an average 37% increase in the number of normally germinating seeds, and in a more than 40% increase in germination rate, as well as in a 25% decrease in average germination time. A distinct increase in osmotic potential from -1 to -2 MPa during drought stress induction resulted in 15% decrease in vigor of husked cultivars measured by the percentage of normally developed seedlings. The vigor of oat cultivars, evaluated on the basis of electrical conductivity of exudates, was modified by genotypic variability. In naked cultivars, on average, 60% lower values were noted. The coefficients of correlation between electrical conductivity of exudates and germination capacity (r = -0.784**) or frequency of normally developed seedlings (r = -0.919**) confirm the highly significant interrelationship between the methods used for the evaluation of oat seeds under drought conditions.

Key words: *Avena sativa*, drought stress, husked oats, naked oats, seed vigor.

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INTRODUCTION

Reproduction of sowing material characterized by high vigor seeds makes it possible to use fully the potential of cultivars only under appropriate growth and development conditions. Considering population growth, crop production is limited mostly by access to water, and in agriculture, the growing demand for this source of life is now 11 times higher than the attainable resources (FAO, 2011). By the middle of the present century in most countries of the world the annual average soil moisture (amount of water in the 10 cm soil layer just below the ground level) will be 1.6 mm lower, and surface water resources, due to decreased regular precipitation (especially in winter) and increased outflow, will be even 30% lower (Xiao et al., 2009). One of the problems in seed production is high sensitivity of seed of traditional crop varieties to water deficit during germination (Barnabás et al., 2008). Plants may be affected by drought at any time of life, but certain stages such as germination and seedling growth are critical. In countries with a temperate or cold climate, low temperatures in early spring affect the occurrence of soil drought, which may limit water availability during seed imbibition (Hillel, 2012). The diffusion barriers resulting from the presence of husks delay, during germination, the processes connected with the normal development of the basic plant organs (Beck et al., 2007). Under the conditions of an improper range of temperatures, the weekly developed fibrous roots limit or make it impossible to achieve optimal field emergence (Uga et al., 2013). Therefore, in the context of vigor understood as a sum of the properties which determine the level of activity and performance of seeds during germination and seedling emergence (Marcos Filho, 2015), the response to drought stress of more and more commonly grown naked oat cultivars seems to be of special interest. The seeds of this botanical form do not have a natural barrier, i.e. the husk, hence they swell more rapidly as compared with traditional seeds (Moś et al., 2008), which may considerably modify the course of germination or seedling development.

The objective of the study was to determine the effect of drought stress simulated by the use of PEG under varied thermal conditions on germination and vigor of naked and husked oat cultivars.

MATERIAL AND METHODS

Plant material and experimental design

The research was done for naked oat cultivars: Abel (Selgen a.s., the Czech Republic), Avenuda (Selgen a.s.u. Prestic, the Czech

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Republic), Bullion (IGER, UK), Cacko (HR Strzelce sp. z o.o., Poland), Izak (Selgen a.s., the Czech Republic), Pikant (Toft Planteforaedling Roslev, Denmark), Polar (HR Strzelce sp. z o.o., Poland), Saul (Selgen a.s., the Czech Republic), as well as husked oat cultivars: Cwał (Danko HR sp. z o.o. Choryń, Poland), Stoper (HR Strzelce sp. z o.o. IHAR, Poland). The material was propagated in the year 2014 in field experiments carried out at the Experimental Station of the Department of Plant Breeding and Seed Science in Prusy near Cracow (50°07'03'' N, 20°05'13'' E). A completely randomized design with two replicates was used. Seeds were sown in 20 rows 1.5 m long and at 0.15 m row spacing.

Harvest was carried out when the seed water content was 12.4%, by reaping the plants from 20 consecutive rows. Directly after the harvest the panicles were threshed using a laboratory threshing machine and the speed of 1.6 m s^{-1}. The obtained material was cleaned using a pneumatic separator, then seeds were sieved through a 1.75 diameter slotted screen. The initial characterization of the obtained material was done on the basis of ISTA regulations (ISTA, 2010) by determining: seed water content using the dryer method, weight of 1000 seeds (TKW), and seed density (hectoliter weight).

Germination under drought conditions in Petri dishes and vigor in plate germinators of the 'Szmal' type were evaluated in three-factor and two-factor completely randomized designs with three replicates, respectively.

Evaluation of germination under drought conditions

In the first experiment the response of naked and husked oat cultivars to drought stress induced by varied temperature: 10, 15 and 20 °C in the presence of polyethylene glycol (PEG 8000) with a potential of -1.5 MPa determined by Michel's equation, was evaluated (Zhang et al., 2010). The seeds were placed in Petri dishes between layers of blotting paper (3 layers at the bottom, 2 layers at the top) moistened with 16 mL PEG. During a period of 10 consecutive days seeds with shoots and roots 2 mm long were removed from the substrate. The determination was replicated thrice each time using 100 seeds. Seeds sown onto a substrate moistened with water, for which on the 10th day of observation germination capacity was also evaluated according to International Seed Testing Association (ISTA) methodology (ISTA, 2010), were the control. The obtained results were used for the determination of germination indices, i.e. germination rate (GR) according to Kamah'a and Maguire and average germination time (AGT) according to Pieper's formula (Ranal and Santana, 2006).

Evaluation of vigor

Electrical conductivity of exudates. In the first stage of the second experiment seed vigor of both oat forms was determined by the conductometric method, using ISTA methodology (ISTA, 2010). The determination was replicated thrice for each cultivar and 50 seeds, and in the case of traditional cultivars the evaluation was also done for seeds without husks. Using 200 mL distilled water, after 24 h electrical conductivity of exudates was measured with conductometer (Elmetron CC-551, Zabrze, Poland).

Drought stress induction. In the second stage of the experiment, seeds of the studied cultivars were placed in Petri dishes and expose to PEG solutions at three concentrations: -1, -1.5 and -2 MPa at 5 °C. At the same time, control seeds (without initial induction under drought conditions) were sown onto a substrate with water. After 5-d incubation the seeds were removed from dishes, rinsed with water and transferred to plate germinators of the 'Szmal' type which were placed under optimal conditions, i.e. full availability of water, 20 °C and photoperiod 16:8 h. During a period of consecutive 15 d the frequency of first leaves of seedlings outgrowing the germinator was evaluated, which made it possible to determine seedling growth rate (SR) and average seedling growth time (AST). On the last day the numbers of normally developed seedlings and abnormally developed seedlings, as well as the numbers of molding and rotting, and healthy non-germinating seeds were determined. At the same time biometric measurements were made: length of the first leaf and the longest root. In addition fresh and dry weights of seedlings were determined. Three replicates of 100 seeds each were used.

Statistical analysis

Two- and three-factor ANOVA (independent variables) were done, in which the testing was performed according to the regular model. For statistical analysis the values expressed in percentage terms were transformed into Bliss's angle values, according to the formula $y = arcsin\sqrt{x}$. The zero or alternative hypotheses were accepted on the basis of Tukey's test at p = 0.05 and p = 0.01. In order to estimate the contribution of the specified sources of variability to the total variability of the investigated characteristics, the components of variance were estimated (Searle et al., 2006) and their percentages were given. The correlations between the characteristics were evaluated on the basis of the Pearson correlation coefficient or linear regression. For statistical calculations and diagrams Statistica 12 (Statistica, Tulsa, Oklahoma, USA) was used.

RESULTS AND DISCUSSION

Germination under drought conditions

Drought is the most significant environmental stress in agriculture worldwide and improving yield under drought is a major goal of plant breeding (Cattivelli et al., 2008). New oat cultivars with genetically conditioned nakedness in relation to the ideotype concentrated on achieving proper germination parameters and next, optimal emergence, may be an alternative to traditional cultivars.

Three-factor ANOVA carried out for the parameters of germination under varied thermal conditions showed that the highest percentage contribution (> 67%) to the total variability of the investigated germination characteristics was that of substrates with varied water availability (Table 1). Temperature and cultivars accounted for 6.5% and 9% of the total variance, respectively, and interactions between the analyzed sources of variability did not exceed 15%. Water plays a key role in the regulation of germination (Moustafa et al., 2014). In naked oat cultivars access to water enabling effective distribution of nutrients to the tissues of the developing embryo is easier, quicker and more efficient as compared with husked forms. Temperature is the main factor breaking the dormancy, especially in grasses of temperate climate, and influencing germination after imbibition (Lambers et al., 2008). Finch-Savage and Bassel (2015) stress the significant effect of this factor as regards regulation of dormancy, which is the state of physiological sleep of the embryo. In the studies carried out on substrate with water, more than 97% germination capacity of all the cultivars was observed, irrespective of the applied temperature (Table 2). Only under drought conditions different responses of genotypes to varied thermal conditions were observed. On the substrate with PEG -1.5 MPa and at cool temperature (10 °C) germination was observed only in naked cultivars: Abel, Avenuda, Izak, Pikant, Polar and Saul, although the values of this parameter did not exceed 3%. This indicates a decrease in the permeability of cell membranes and an increase in the activity of osmoprotectants, among which, according to Ashraf and Foolad (2007), there are proline, soluble sugars, soluble proteins and other osmolytes. An increase in temperature of further 5 °C resulted in an average increase of 25% in germination capacity in that botanical form. Under the most favorable thermal conditions (20 °C) germination frequency ranged from 6% in 'Bullion' to nearly 80% in 'Abel'. At the same time the cumulative and absolute effect of physical barriers, i.e. husks was noted as in both traditional cultivars – Cwał and Stoper, on the substrate with PEG -1.5 MPa no normally germinating seeds at none of the applied temperatures were observed. However, under drought conditions a large increase in the number of healthy non-germinating seeds was noted which in 'Bullion' averaged 86% and in both husked cultivars was almost 99% (Table 2). Such inhibition of catabolic processes indicates a severe drought stress, although in other species (Rodríguez Pérez et al., 2007) even at greater osmotic potentials the transition to the anabolic phase was observed, abnormally germinating or dead seeds being in the majority. Germination rate of naked cultivars on the substrate with water, irrespective of thermal conditions, ranged from 29 to 55 and was on average 36% higher as compared with husked cultivars (Figure 1). At the same time, in both botanical oat forms, at higher temperatures of 15 and 20 °C the values of the analyzed parameter increased by 40% and 51%, respectively, as compared with seeds kept at 10 ºC. In the naked form, drought simulated by PEG -1.5 MPa affected an average 85% decrease in GR as compared with the control. Thus, in the case of limited access to water, naked cultivars seem to be better adapted to

Table 1. Significance of differentiation and the percentage share of components in the total variance of germination parameters.

Source of variability	Degrees of freedom	Germination capacity	Non-germinating seeds	Germination rate	Average germination time
Substrate (A)	1	82.2**	67.4**	82.2**	89.9**
Temperature (B)	2	2.0**	1.6**	6.5**	2.7**
Cultivars (C)	9	8.4**	9.0**	2.7**	3.3**
A × B	2	1.2**	3.9**	6.1**	0.1**
A × C	9	2.3**	14.7**	1.3**	2.0**
B × C	18	1.4**	0.2^{ns}	0.4**	0.4**
A × B × C	18	1.4**	0.0^{ns}	0.1^{ns}	1.1**
Error	120	1	3.3	0.6	0.5

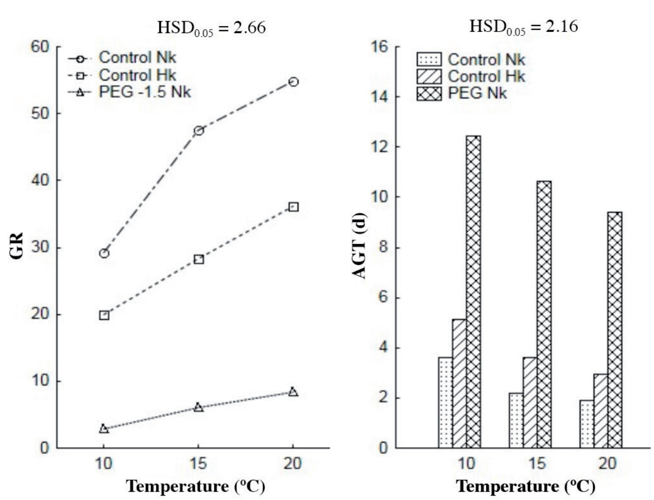
*, **Significant at the 0.05 and 0.01 probability levels; ns: nonsignificant.

Table 2. Percentage of germination frequency and healthy non-germinating seeds under control conditions and under the action of polyethylene glycol (PEG) -1.5 MPa.

Conditions	Cultivars	Germination capacity at: 10 ºC	15 ºC	20 ºC	Non-germinating seeds (difference)
Control	Mean	98.0	98.0	97.9	1.2
$HSD_{(\alpha=0.05)}$			2.6		
Drought-stress	Abel	1.2	73.6	79.2	19.0
(PEG -1.5 MPa)	Avenuda	1.2	39.9	50.1	30.4
	Bullion	0.0	3.7	6.6	86.1
	Cacko	0.0	23.0	42.5	48.2
	Izak	0.5	22.2	54.8	42.8
	Pikant	2.2	12.5	53.3	40.6
	Polar	1.0	16.2	52.7	45.5
	Saul	2.6	36.9	71.5	31.0
	Mean	0.9	22.8	41.1	42.9
	Cwał	0.0	0.0	0.0	98.3
	Stoper	0.0	0.0	0.0	98.9
	Mean	0.0	0.0	0.0	98.6
$HSD_{(\alpha=0.05)}$			8.2		

HSD: Tukey's honest significant difference.

Figure 1. Germination rate (GR) and the average germination time (AGT) determined for seedlings of naked (Nk) and husked (Hk) oat cultivars under varied temperature conditions during drought simulated by polyethylene glycol (PEG) -1.5 MPa.



these unfavorable conditions and during germination they are able to make even better use of the available resources than other crops with naked seeds, such as wheat or barley (Kolasinska, 2009). It is also confirmed by the average germination time, which in the case of full moistening at 20 °C was 2 d in naked cultivars and 3 d in husked cultivars (Figure 1). Under drought conditions, in naked cultivars, in spite of an average 76% increase in AGT, an increase in temperature from 10 to 20 °C caused an almost 25% reduction in the decrease in the value of the analyzed factor. Oat is a cold-loving grass (Copeland and McDonald, 2012) and its germination may occur even at 3 °C, however the results obtained show that thermal adaptation in naked seeds plays a key role in the tolerance to drought.

Vigor evaluation – electrical conductivity of exudates

Evaluation of germination not always reflects the possibility of obtaining complete and uniform emergence over an entire field (Shipley, 2010). That is why vigor is a sharper and more reliable criterion for the reproductive value (Powell, 2009). Vigor of naked and husked oat cultivars, initially established by measuring the electrical conductivity of seed leachates, was more than 94% determined by variability of cultivars. Conductometric values for naked cultivars did not exceed 15 μS cm^{-1} and, compared with husked cultivars, they were on average 60% lower (Figure 2). The significantly lowest concentration of exudates was found for 'Izak', 'Pikant' and 'Polar' (≤ 10 μS cm^{-1}), while the highest concentration was observed for 'Cwał' (33 μS cm^{-1}). Measurements made after removing them by hand showed 26% higher, on average, but insignificant values as compared with the naked cultivars.

Vigor after drought stress induction

Vigor evaluated after 120-h induction of drought stress simulated by PEG at three concentrations, expressed by the number of normally developed seedlings, length of the first leaf, and dry weight of seedlings was determined to the greatest extent by variability of cultivars (> 37%) (Table 3). Substrate was the factor with the highest percentage values (> 30%) in the evaluation of seedling growth rate (SR), average seedling growth time (AST), fresh weight of seedlings and length of the longest root. No interactions between genotypes and the substrate used were found only for AST, length of the longest root and dry weight of seedlings.

The high vigor, determined on the basis of frequency of seedlings (> 90%), noted under the conditions of full access to water (Table 4), was probably the result of proper conditions during maturation of seeds and harvest made after full physiological maturity, with simultaneous optimally high dry weight obtained (Copeland and McDonald, 2012). Thus, rapid drying after harvest, resulting in mechanical damage to embryos during threshing and loss of vitality, was avoided. Besides, as Belgacem et al. (2006) report non-aged seeds generally show high emergence dynamics. The significantly decreased percentage of normally developed seedlings

Figure 2. Electrical conductivity of exudates of naked and husked oat cultivars.

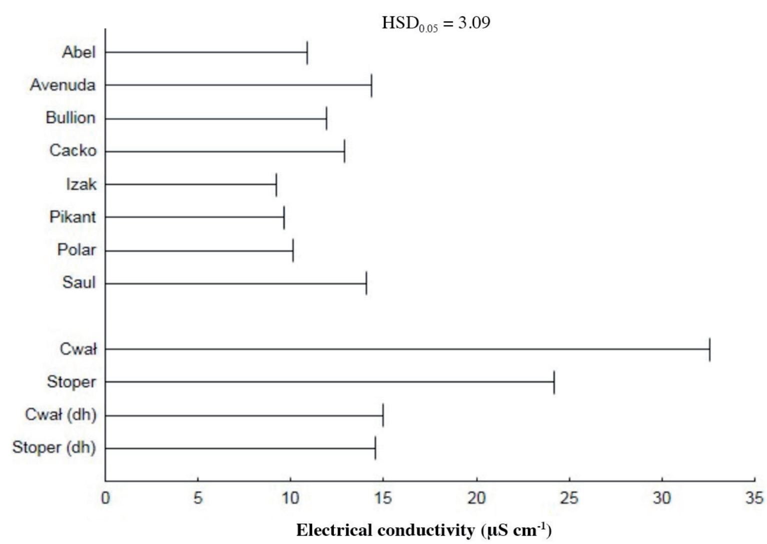


Table 3. Significance of differentiation and the percentage share of components in the total variance of vigor parameters.

Source of variability	Normally developed seedlings	Seedlings growth rate	Average seedlings growth	Length of first leaf	Length of the longest root	Fresh weights of seedlings	Dry weights of seedlings
Substrate (A)	13.3**	61.3**	67.4**	30.8**	51.6**	37.6**	6.3**
Cultivars (B)	50.4**	23.2**	12.8**	37.6**	29.0**	29.7**	75.6**
A × B	21.8**	7.2**	3.1^{ns}	18.9**	0.5^{ns}	18.8**	3.3^{ns}
Error	14.5	8.3	16.8	12.8	18.8	13.9	14.9

*, **Significant at the 0.05 and 0.01 probability levels; ns: nonsignificant.

Table 4. Percentage of normally and abnormally developed seedlings and non-germinating seeds under control conditions and under the action of polyethylene glycol (PEG) -1.5 MPa.

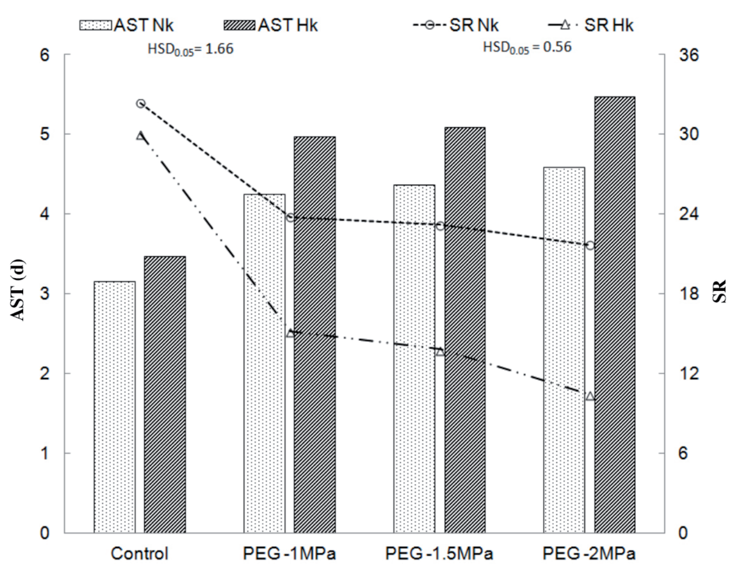
	Developed seedlings (%)					
	Normally					
Cultivars	Control	-1 MPa	-1.5 MPa	-2 MPa	Abnormally (difference)	Non-germinating seeds (difference)
Abel	99.3	98.0	95.3	92.7	2.3	0.6
Avenuda	100.0	96.7	94.0	96.0	2.6	0.3
Bullion	99.3	95.3	96.7	95.3	2.9	0.2
Cacko	100.0	94.0	98.7	95.3	2.3	0.8
Izak	98.0	90.7	94.7	95.3	9.0	0.7
Pikant	97.3	99.3	100.0	91.3	0.4	0.4
Polar	100.0	94.7	98.0	93.3	0.7	0.4
Saul	98.7	91.3	95.3	88.7	3.0	0.5
Mean	99.1	95.0	96.6	93.5	2.9	0.5
Cwał	97.3	66.7	68.7	56.0	4.3	22.0
Stoper	97.3	72.0	61.3	47.3	7.7	27.4
Mean	97.3	69.3	65.0	51.7	6.0	24.7
$HSD_{(\alpha=0.05)}$		9.51			4.12	2.99

HSD: Tukey's honest significant difference.

(89%) among naked genotypes was noted only after using PEG -2MPa and only in one cultivar – Saul (Table 4). Lesser tolerance to short-term drought during hydration or imbibition of seeds, the process that is strategic for seedling development, was observed in husked cultivars. As the access to water was decreased by 0.5 MPa, these cultivars showed, on average, more than a 15% decrease in the analyzed parameter which at the lowest osmotic potential reached 51%. In consequence, a 6% increase in the number of abnormally developed seedlings and an almost 25% increase in the number of healthy non-germinating seeds occurred. Reduction in mitotic activity, observed during the evaluation of both vigor and germination as an after-effect of drought, seems to be the main mechanism for maintaining the viability of diaspores in both the botanical forms of oat. Inversion of the physical stress factor to the biochemical one in the first phase leads to loss of water in the cells constituting the basic pathway of signal transduction at that level (Farooq et al., 2009). The mechanism underlying it is the activity of genes responsible for inducing osmosensory activity, synthesis of abscisic acid, accumulation of osmolytes or repair proteins, initiation of reactive forms of oxygen with simultaneous inhibition of the development of plant organs, or non-development of plant organs under water deficit conditions (Huang et al., 2012). Most probably, as a result of these processes, together with an increase in osmotic potential in the substrate, in traditional cultivars a 34% decrease in SR was noted. In naked cultivars, between the substrates -1 and -1.5 MPa no changes in that parameter were found, and its values were, on average, 35% higher in all the variants (Figure 3).

At the same time higher values of the AST were noted – in naked cultivars they were 26% higher, and

Figure 3. Seedling growth rate (SR) and average seedling growth time (AST) of naked (Nk) and husked (Hk) oat cultivars under drought conditions simulated by PEG at various concentrations.



in husked cultivars they were 30% higher as compared with the control, which means a change of 29 and 41 h, respectively. High sensitivity of the dynamics and seedling growth time indices confirms the possibility of using them for the evaluation of cereal seed vigor not only under drought conditions, which was proposed in earlier works (Geravandi et al., 2011). Lesser differentiation was found for indices determined on the basis of measurements of the basic parameters of plant organs (Table 5). The length of first seedling leaves in the control, in traditional cultivars, reached 11.7 cm and was, on average, 9% longer compared with naked cultivars. This parameter in both oat forms was similarly significantly decreased, by less than 10%, as an after-effect of 5-d drought, however only with PEG -2 MPa. Franco (2011) shows that inhibition of shoot growth may be more intensely manifested under water deficit conditions as compared with root growth disorders. Under such conditions the survival mechanism should consist in inhibition of the elongation of cell walls resulting in decreased cell size and hence the decreased surface area of the developing organ. The carried out evaluation of root length in all the genotypes showed that in spite of lack of differentiation under control conditions (≈ 7.5 cm), when the access to water was gradually limited, its values increased in naked and husked cultivars on average by 15% and 18%, respectively. An increase in root growth is an indicator of the ability of plants to withstand water stress, as well as it makes it possible to screen plant cultivars for drought tolerance. Most probably, the lack of mechanical resistance of the substrate, the factor which can limit the root growth in soil by more than 50% (Bengough et al., 2011), in the case of the substrate with PEG contributed to more intense growth of these organs, enabling more effective penetration of the substrate so as to limit the stressor action. In short periods of water deficit the hydraulic activity of roots is modified by increased activity and regulation of aquaporins which control the accumulation of polysaccharides in cell walls (Hrmova and Fincher, 2009), changing their weight. Consequently, greater differentiation of the two botanical forms of oat was observed for fresh weight of seedlings which under control and drought conditions in traditional cultivars, compared with naked cultivars, was 12% and 17% lower, respectively. The usefulness of this index for the evaluation of vigor was reported earlier for other crops with naked seeds (Du et al., 2011; Tamiru and Ashagre, 2014). As regards dry weight of seedlings, no changes affected by drought stress were noted; however, the values of this parameter in all the variants of PEG-saturated substrate were more than 21% higher in traditional cultivars. It seems obvious considering heterotrophic nutrition of the embryo, which in husked seeds is additionally connected with delayed hydration and decomposition of starch colloids during imbibition, and next, slower redistribution of substrates and delay in seedling growth processes (Bewley and Black, 2012).

Table 5. The basic parameters of seedlings of naked and husked oat cultivars obtained in plate germinators of the 'Szmal' type.

Cultivars	Length of first leaf	Length of the longest root	Fresh weights of seedlings	Dry weights of seedlings
	cm		g	
Abel	11.50	8.83	9.31	0.85
Avenuda	11.30	7.73	9.25	0.90
Bullion	9.13	7.07	10.01	0.93
Cacko	11.27	7.33	9.17	0.87
Izak	9.37	6.67	8.46	0.84
Pikant	10.73	7.27	8.69	0.79
Polar	10.30	7.40	8.69	0.83
Saul	11.67	6.03	8.30	0.82
Cwał	12.13	8.10	7.73	1.11
Stoper	10.87	7.90	7.26	1.16
$HSD_{(\alpha=0.05)}$	0.517	0.216	0.668	0.047
Naked				
Control	10.66	7.29	7.99	0.85
-1 MPa	10.45	8.49	8.78	0.90
-1.5 MPa	10.46	8.55	9.07	0.81
-2 MPa	9.83	8.54	8.93	0.84
Husked				
Control	11.65	7.63	7.03	1.13
-1 MPa	11.50	9.40	7.48	1.18
-1.5 MPa	11.35	9.73	7.52	1.07
-2 MPa	10.52	8.88	7.35	1.16
$HSD_{(\alpha=0.05)}$	0.327	0.353	0.423	0.03

HSD: Tukey's honest significant difference.

Water stress induced by PEG solutions is an alternative approach to screening the germplasm (Rai et al., 2011), which under *in situ* conditions may be quite difficult because of the interaction with other unfavorable factors (Rauf et al., 2008). The analysis of the indices used in this work shows that considering naked cultivars, the greatest sensitivity to drought conditions was shown by 'Bullion' seeds, the cultivar that showed low susceptibility to mechanical damage or sprouting in earlier studies (Zieliński et al., 2014). Seeds of this cultivar, characterized by the highest values of basic parameters (such as weight of 100 seeds, seed density or seed length) under drought stress conditions showed in this research the lowest germination frequency and the lowest length of first seedling leaves.

Interrelationship of the tested parameters

The coefficients of correlation calculated for germination and vigor parameters determined under drought conditions showed that the strongest linear relationship was between dry weight of seedlings and the rate of germination and average germination time evaluated in both experiments (r from -0.880** to 0.942**) (Table 6). High values of the linear relationship for methodically separate tests were found between vigor determined on the basis of electrical conductivity of exudates and all the parameters evaluated in the two tests (r from -0.919 to 0.828**). In addition, vigor evaluated by conductometric method showed high linear but negative correlation with fresh weight of seedlings (r = -0.666*) and positive correlation with dry weight of seedlings (r = 0.896**) and length of the first seedling leaf (r = 0.692*).

Table 6. Matrix of the coefficients of correlation between selected parameters of germination and vigor of oat seeds (n = 20).

Correlated features	GR[1]	AGT[1]	NDS[2]	SGR[2]	AST[2]	LFL[2]	LLR[2]	FWS[2]	DWS[2]	EE[3]
Germination capacity	0.937**	-0.934**	0.827**	0.905**	-0.915**	-0.185ns	0.178ns	0.508ns	-0.880**	-0.784**
Germination rate (GR[1])		-0.991**	0.962**	0.989**	-0.955**	-0.355ns	0.155ns	0.720**	-0.934**	-0.874**
Average germination time (AGT[1])			-0.968**	-0.978**	0.932**	0.405ns	-0.191ns	-0.737**	0.942**	0.901**
Normally developed seedlings (NDS[2])				0.969**	-0.897**	-0.521ns	0.105ns	0.823**	-0.934**	-0.919**
Seedlings growth rate (SGR[2])					-0.971**	-0.425ns	0.148ns	0.761**	-0.913**	-0.901**
Average seedlings growth (AST[2])						0.291ns	-0.164ns	-0.685*	0.858**	0.828**
Length of the first leaf (LFL[2])							0.126ns	-0.400ns	0.483ns	0.692*
Length of the longest root (LLR[2])								0.251ns	0.019ns	-0.195ns
Fresh weights of seedlings (FWS[2])									-0.593*	-0.666*
Dry weights of seedlings (DWS[2])										0.896**

[1]Evaluation of germination at Petri dishes.
[2]Evaluation of vigor at Szmal's germinator plate.
EE: Electrical conductivity of exudates.
*, **Significant at the 0.05 and 0.01 probability levels; ns: nonsignificant.

CONCLUSIONS

Considering the protection of crop production, aimed at adaptation to climate changes, searching for or developing genotypes resistant to water deficit is a challenge for modern agriculture and a strategic goal of plant breeding. The carried out ANOVA showed a varied effect of drought stress on germination and vigor parameters in naked and husked oat cultivars, which indicates their high sowing value specified by the current standards. In naked oat cultivars the effects of permanent drought were modified by temperature, an increase from 10 to 20 °C resulted in an increase in germination capacity and germination dynamics, with simultaneous limitation of the average time of this parameter. The husked cultivars were characterized by absolute sensitivity to drought and showed no symptoms of germination during constant water deficit. They also showed a decrease in vigor parameters when the substrate osmotic potential was decreased by 25%. The after-effect of 5-d induction of drought stress, in the case of naked cultivars resulted in fewer differences between most of the analyzed seed vigor indices, indicating better use of the available water resources at the initial germination phase. The greatest tolerance to drought, determined on the basis of the majority of the analyzed indices, was found for 'Abel'. The coefficients of correlation indicate that the strongest linear relationship occurs between dry weight of seedlings and the rate of germination and average germination time evaluated in both the experiments.

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