Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture
Open Access

The Variability of Quantitative Traits Parameters of Facultative Wheat Affected by Sowing Time

Ionuț RACZ[1,2*], Ioana Virginia BERINDEAN[1], Rozalia KADAR[2], Diana HIRIȘCĂU[2], Adina VARADI[2], Darius MORAR[1,2], Beniamin ANDRAȘ[1,3]

[1] *Faculty of Agriculture, University of Agricultural Science and Veterinary Medicine Calea Manastur 3-5, Cluj-Napoca, 400372, Romania*
[2] *Agricultural Research and Development Station, Agriculturii 27, Turda, 401100, Romania*
[3] *Agricultural Research and Development Station, Baia Mare 7, Livada, 447180, Romania*
**Corresponding author: I. Racz email: ionut.racz@usamvcluj.ro*

RESEARCH ARTICLE

Abstract

Facultative wheat can be an appropriate alternative for maintained high grain yield and quality in these changing conditions. Three alternative wheat genotypes were tested in a field condition for their agronomic traits- spike length, spike weight, number of grains/spike and weight of grains/spike, qualitative indices- grain protein content, wet gluten content and Zeleny index; and rheological parameters- dough extensibility, dough tenacity, deformation energy, as effect of different sowing date, autumn sowing respectively spring sowing conditions. The reaction of studied genotypes to different sowing date regarding the morphological traits shows that genotype and genotype- sowing date interaction has a significant influence on the studied traits. Regarding the reaction of individual genotype, the variability coefficient having low and medium values (6.54 % by Ciprian variety to 15.5 % for Taisa, in spring sowing conditions) in case of spike length trait, respectively medium and high values for the other characters studied, significant differences being observed between genotypes. Superior values for qualitative and rheological indices were recorded under spring sowing conditions for all genotypes, which means that the accumulation of biochemical compounds is favored. Also, the spring sowing conditions has a positive effect on relationship between the main yield components of studied facultative wheat.

Keywords: Facultative wheat; quantitative traits; sowing date.

Received: 06 February 2024
Accepted: 01 November 2024
Published: 15 November 2024

DOI:
10.15835/buasvmcn-agr:
2024.0001

INTRODUCTION

Wheat (Triticum aestivum L.) is a staple food cereal for an estimated 35% of world population (Grote et al., 2021). Climatic changes are expected to affect more the wheat production cause to the heat and drought stresses (Rezaei et al., 2023). One of the genetic mechanisms for avoided these abiotic stresses are the use of an appropriate biologic material for minimize the effect of stress factors. Facultative wheat can be a viable alternative for mitigate the effect of unfavorable conditions on wheat grain yield. Generally, the grain yield of wheat is determined the genes directly controlling yield and yield components, but also by the genes controlling plant development and maturity (Chen et al., 2013; Slafer, 2003). Hexaploid wheat (2n=6x=42) has a triple genome AABBDD resulted from the wild hybridization of a Triticum urartu (A genome) and Aegilops speltoides (B genome) (Feldman and Levy, 2023). The wild emmer (Triticum dicocoides) a subspecies of tetraploid wheat (Triticum turgidum L., genomes AABB) was crossed with diploid Aegilops tauschii (genome DD) (Wang et al. 2013; Huang et al., 2002) from which has resulted the bread wheat. Its polyploid nature facilitated wheat adaptation to a wide range of environments as it spread westward into Europe and eastward into Asia (Dubcovsky and Dvorak, 2007).

Wheat adaptation to different areas and planting dates is mainly associated with natural variation in the photoperiod gene PPD1 that promotes flowering under long days (Beales et al., 2007; Diaz et al., 2009; Diaz et al., 2012) and in the vernalization genes VRN that modulates the requirement of long exposures to cold temperatures (vernalization) to induce flowering (Yan et al., 2003; Danyluk et al., 2003, Muterko et al., 2016). The vernalization requirement determines the need for a prolonged exposure to low temperature in order for plants to transition to the reproductive phase of development (Muterko et al., 2016) The VRN genes interact epistatically (Muterko et al., 2015). The vernalization requirement and growth habit in wheat is largely controlled by four major loci, which are also critical in determining flowering and maturity times: these include VRN1, VRN2, VRN3 and VRN4 (Yan et al., 2003; Yan et al., 2004; Yan et al., 2006; Kippes et al., 2015). According to their response to vernalization, wheat plants can be categorized as winter (strong vernalization sensitivity), spring (not sensitive to vernalization), or facultative types (intermediate growth habit).

Aims: the aims of this study were to investigate the behavior of three facultative wheat varieties regarding the yield components, grain quality and rheological parameters as a result of genotype x environment interaction.

MATERIALS AND METHODS

Three facultative wheat varieties- two Romanian wheat varieties (Taisa and Ciprian) and one foreign variety (Lennox) was used as biologic material being sown in autumn and spring field condition at Agricultural Research and Development Station (ARDS) Turda in 2022/2023. The sowing rate of field plots was 550 grains sqm-1 also for autumn and spring crop in a single experimental plot of 30 sqm. Basic fertilization was applied for both sowing date in 50 kg ha-1 s.a. NPK. The experiment was realized in randomized complete block design in three replications in Wheat Breeding Department of ARDS Turda. The sample plants for analysis (30 plants) were harvested randomized at physiological maturity and analyzed in a laboratory condition for morpho-productive and quality traits. Quantitative traits were analyzed (length of spike- SL; weight of spike-WS; number of grain/spikes- NGS; weight of grains/spike, weight of grains/spike-WGS) alongside by grain quality traits (protein content, wet gluten content, Zeleny index) and rheological parameters (dough extensibility- L, dough tenacity- P; L/P ratio, deformation energy- W). The quality traits were determinate using NIR Inframatic 9500 grain analyzer (Perten Instruments), respectively a Tango spectrometer (Bruker,Germany) for rheological parameters.

The climatic conditions of experimental year are presented in Figure 1 as a Selyaninov coefficient, which is calculated based on the formula: $k = P*10 / \Sigma t$; - where: P - total precipitation (mm) for a decade and Σt - sum of average daily air temperature (> 0 °C) for the decade (Chmist-Sikorska et al., 2022).

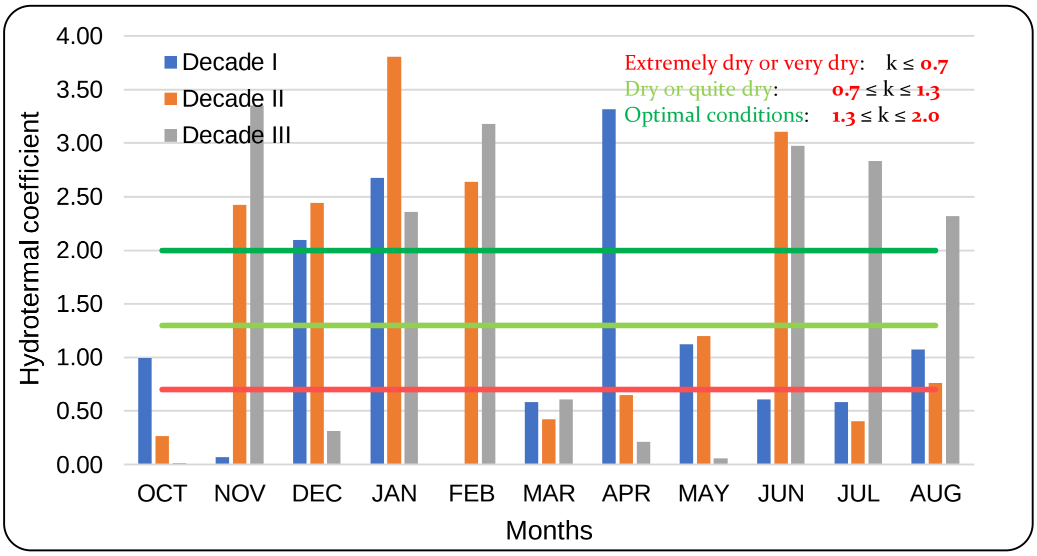


Figure 1. The hydrothermal coefficient of experimental period.

Hydrothermal coefficient (Selyaninov coefficient) determines the relationship between precipitation and evaporation and it characterizes the moisture conditions for plants growing. Based on the value of the coefficient, the periods were classified in 4 groups after Kuklik et al. (2016):

- extremely dry or very dry – k ≤ 0.7
- dry or quite dry – 0.7 < k ≤ 1.3

- optimal or quite moist – $1.3 < k \leq 2.0$
- humid, very humid or extremely humid – $k > 2.0$.

Analyzing the values of Selyaninov coefficient during the experimental period (Figure 1) can be observed that the autumn sowing condition can be characterized as optimal for the studied genotypes ($k > 1.3$), respectively in the early vegetative stages the plants had favorable conditions for development, except third and first decade of October respectively November. For the spring sowing conditions, the Selyaninov coefficient has low values offering extremely dry or very dry conditions ($k < 0.7$ for March, second and third decade of April) that coincides with hostility conditions for plant development in the early stages. Also, extremely dry or very dry conditions was observed in the third decade of May, respectively first decade of June, and dry and quite dry conditions ($0.7 < k < 1.3$) characterized the first and second decade of May during the main vegetative and generative stages for both sowing plant conditions. Generally, the growing season for both sowing conditions can be characterized as unfavorable.

RESULTS AND DISCUSSIONS

The ANOVA analysis shows that the sowing date, genotype and interaction between sowing date and genotype has a significant influence on the spike length, while for the other analyzed traits the A factor has unsignificant influence (Table 1). The genotype and the interaction between environment conditions and genotype exhibit a significant influence on the studied yield traits.

Table 1. ANOVA for yield components as a result of sowing date, genotype and interaction between them

Analyzed traits	**A (sowing date)**		**B (genotype)**		**A x B**	
	M.S.	F value	M.S.	F value	M.S.	F value
SL	31.249	37.101**	127.447	85.404**	53.700	35.985**
WS	0.052	0.397	3.902	12.798**	3.492	11.453**
NGS	764.672	0.892	3745.733	2.038	78.978	0.043
WGS	0.026	0.362	0.743	3.958**	2.686	14.315**

The results show that the sowing time has a different effect, depending on the sowing time and genotype, on wheat agronomic trait (Table 2). In the autumn sowing date conditions, the Taisa genotype (Control) exhibit the highest spike length (9,49 cm) with more than 18% than Ciprian and Lennox genotypes. Regarding the interaction between spike length and climatic conditions the Lennox genotype show a superior stability (6.83%) especially compared with the Ciprian genotype (10.53%). The spring sowing conditions has a positive effect on mean spike length both for Lennox and Taisa genotypes (9.97 cm, respectively 9.91 cm). Compared with the autumn sowing the Lennox genotypes has the highest range for spike length (from 7.64 cm when is sowing in autumn to 9.97 cm for spring sowing) which means this genotype exhibit a better development for this trait in spring sowing conditions.

The weight of spike, as a closer trait related to grain yield has a medium and high variability, also for autumn and spring sowing conditions, stress condition having a significant role during the grain filling period (Zhao et al., 2022). The climatic conditions have determined a specific reaction for this trait for each genotype. The Lennox genotype exhibit high value for this trait when it is sown in spring conditions, comparatively with Ciprian and Taisa genotypes which shows superior values for weight of spike in condition of autumn sowing.

Table 2. The main statistical parameters of facultative wheat plants affected by sowing date

Morphological traits		Autumn sowing time			Spring sowing time		
		Lennox	Ciprian	Taisa (Ck.)	Lennox	Ciprian	Taisa (Ck)
Spike length (cm)	Min	6.3	6.5	7.5	8.0	6.5	6.9
	Max	8.8	9.0	10.5	11.9	8.5	12
	Mean	7.64^{000}	7.77^{000}	9.49	9.97	7.52^{000}	9.91
	CV	6.83	10.53	8.17	10.36	6.54	15.50
DL (p 5%) = 0.44 DL (p 1%) = 0.58 DL (p 0.1%) = 0.75							

Weight of spike (g)	Min	0.9	0.77	1.26	1.19	1.03	0.82
	Max	2.42	2.6	3.08	2.83	2.21	2.68
	Mean	1.71^{000}	1.71^{000}	2.15	2.05^{*}	1.57^{00}	1.84
	CV	19.41	29.00	20.88	18.75	18.47	30.55
DL (p 5%) = 0.20 DL (p 1%) = 0.26 DL (p 0.1%) = 0.34							
Number of grains/spike	Min	16	18	28	25	20	15
	Max	49	51	55	54	45	55
	Mean	33.10	33.10	40.07	40.30	30.73	35.63
	CV	21.28	24.43	14.90	19.18	21.09	31.22
DL (p 5%) = 15.50 DL (p 1%) = 20.52 DL (p 0.1%) = 26.41							
Weight of grain/spike (g)	Min	0.7	0.56	0.92	0.9	0.76	0.57
	Max	1.81	1.99	2.44	2.2	1.96	1.8
	Mean	1.30^{00}	1.23^{000}	1.56	1.52^{***}	1.29	1.2
	CV	21.38	29.91	21.73	21.25	20.59	32.19
DL (p 5%) = 0.16 DL (p 1%) = 0.21 DL (p 0.1%) = 0.27							

Number of grains per spike, respectively weight of grains per spike are two most important yield elements, highly correlated with grain yield. In case of number of grains per spike the variability of this traits is high for all studied genotypes both in autumn and spring sowing conditions. Regarding the phenotypic expressiveness of number of grains per spike, the Taisa genotype show the highest value for this trait in autumn sown conditions (40,07 grains/spike), while in spring sown conditions the highest value was observed for Lennox genotype (40,3 grains/spike). Also, genotype specific reaction can be observed in case of number of grains/spike stability trait, respectively Lennox and Ciprian genotypes shows a relatively low stability in spring sown conditions (19,18 % for Lennox and 21,09% for Ciprian) compared to autumn sown conditions (21,28% for Lennox, respectively 24,43% for Ciprian), while Taisa genotype has an opposite reaction to the other two genotypes (medium stability when is sown in autumn condition- 14.90%, low stability when is sown in spring conditions- 31,22%).

When is sown in spring conditions the average of the weight of grains per spike of the three varieties (1,56 g/spike) was superior to autumn sowing conditions (1,36 g/spike). Koppensteiner et al. (2022) founded that Lennox genotype exhibit superior quantitative traits in autumn sowing conditions that in spring conditions. Similar behavior regarding the weight of grains per spike can be observed in case of Taisa genotype, which has a different reaction, the highest value for weight of grains/spike trait being register in autumn sowing conditions (1,56 g/spike). Regarding the variability of this trait, high variability can be observed in both sowing conditions (CV>20), which means that weight of grains/spike is a very complex trait.

Taisa and Lennox varieties has a significant reaction on grain quality parameters when they are sown in spring compared to autumn sowing (Table 3). Generally, there is known that the quality of spring wheat varieties is superior to winter wheat varieties, and it seems that the same trend is maintained when it comes to alternative varieties. Thus, when are sowing in autumn the genotypes accumulate in grains low protein content (10,18% for Lennox, 10,61% for Ciprian, respectively 10,42% for Taisa) comparative to spring sowing (12,32 % for Lennox, 11,03% for Ciprian, respectively 12,59% for Taisa). On average, the use of genotype as spring wheat varieties improves the grain protein content with more than 13 %, the highest grain protein content improvement being observed for Taisa and Lennox varieties, the increase of grain protein content being over 2%. The same reaction can be observed also for wet gluten content, respectively Zeleny index, the two genotypes having a similar reaction, the spring sowing favoring the improvement of this qualitative traits.

Table 3. Qualitative indices of studied facultative wheat grains

Quality traits	Autumn sowing time			Spring sowing time		
	Lennox	Ciprian	Taisa	Lennox	Ciprian	Taisa
Protein content (%)	10.18	10.61	10.42	12.32	11.03	12.59
Wet gluten content (%)	21.67	24.17	22.33	27.87	24.17	28.93
Zeleny index	35.33	34.33	40.67	46.67	37.00	54.00

The rheological parameters have the same behavior as the other qualitative traits, respectively the sowing in spring conditions improve these dough parameters (Table 4). In case of dough extensibility (L), spring sowing conditions have improved this parameter with more than 1/3 in case of Lennox and Taisa genotypes. For Ciprian variety as a poor improvement of dough extensibility was observed in case of spring sowing conditions comparative with autumn sowing conditions, which means that these rheological traits are quite stable.

Regarding the dough tenacity (P) the sowing conditions (autumn or spring) has a low influence, the range of these traits being quite reduced between two sowing systems. Also, a low increasing value can be observed for the ratio P/L between the two periods of sowing date.

Table 4. Rheological indices of studied facultative wheat grains

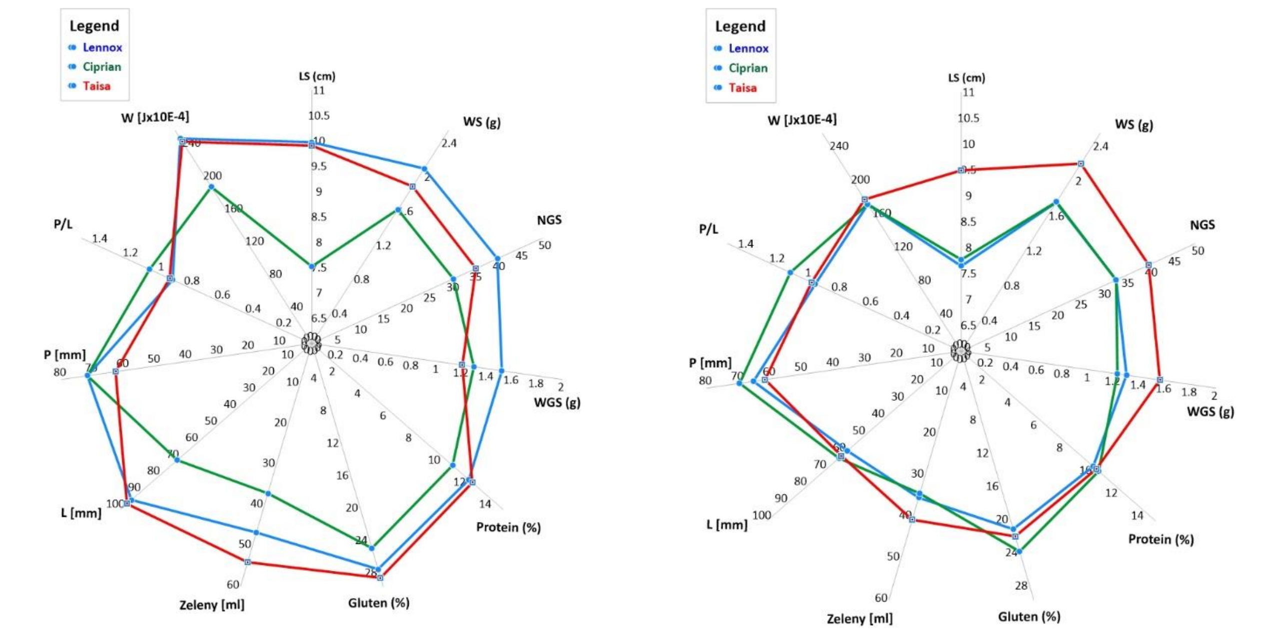
Rheological traits	Autumn sowing time			Spring sowing time		
	Lennox	Ciprian	Taisa	Lennox	Ciprian	Taisa
L (mm)	58.67	63	61.67	94.33	70.33	96.67
P (mm)	65.33	69.67	61.67	71.67	71.67	62.67
P/L	0.91	1.10	0.96	0.94	1.06	0.93
W (J x $10E^{-4}$)	175	175.3	181	250	191	246.3

Deformation energy (W) is a dough trait which react positively to sowing time, the rage of these parameter is between 175.3 to 191 (J x 10E-4) in case of Ciprian variety which has the lowest amplitude, compared to Lennox and Taisa varieties whose amplitude vas more than 70 units (J x 10E-4).

Based on the radar area of each genotype used in a different sowing time, the use of biologic material as winter or spring variety has a positive effect on the most studied traits (Figure 2). Thus, the sowing in spring conditions (Figure 2a) reveal that for morphological traits (LS, WS, NGS and WGS) the highest value can be observed at Lennox variety. Regarding the grain quality indices (Protein content, Gluten content and Zeleny index) the highest value was registered at Taisa genotype, while for rheological proprieties the two varieties have a similar performance. The radar area of studied genotypes in spring sowing conditions suggest that the most performances genotypes are Lennox and Taisa which exhibit the highest values for morphological traits and rheological parameters, respectively for grain quality indices.

The use of the studied genotypes as winter wheat genotypes with autumn sowing has an inhibitory effect on the phenotypic manifestation of studied traits especially in case of Lennox and Ciprian varieties (Figure 2b). Also, in autumn sown conditions the Taisa genotype show a superior value for morphological traits (LS, WS, NGS and WGS) alongside by Zeleny test and deformation energy (W). The other two studied genotypes - Lennox and Ciprian- has most similar behavior for morphological traits, respectively for quality and rheological parameters. In autumn sowing conditions the Ciprian variety shows superior values for rheological indices respectively L, P and P/L ratio. Analyzing the radar surface, it can be ascertained that Taisa genotype has the biggest area which means that between studied genotypes this variety manifest superior adaptability to winter specific environmental conditions.

Regarding the correlation between morphological traits of studied genotypes, the spring sowing conditions determine a tightly relationship between yield components compared to the autumn sowing conditions (Table 5). The strength relationship can be determined by the short vegetation period of the wheat plants, respectively by high interaction between environments conditions and genotype requirements.



(a) (b)

Figure 2. Morphological, quality and rheological traits of facultative wheat affected by time sowing (a- sown in spring; b- sown in autumn).

Even the spring sowing conditions have a positive effect on the relationship between yield elements, the intensity of relationship for genotypes is specific. In case of autumn sowing conditions, the tightest relationship can be observed in case of Taisa genotype followed by Lennox respectively Ciprian variety. For the spring sowing conditions, the intensity of relationship between morphological traits are more tightly for all studied traits in case of Lennox genotype, except the relationship between number of grains/spike and weight of grains/spike which is kept at the same level (0.92). Also, the Ciprian variety has the same behavior regarding the intensity relationship between studied traits, except the relation between weight of spike and weight of grains/spike. In case of Taisa variety, the intensity of relationship between weight of spike and number of grains/spike, respectively weight of spike and weight of grains/spike, alongside by number of grains/spike and weight of grains/spike has a low value in spring sowing conditions compared to autumn sowing conditions.

Table 5. Pearson coefficient of correlation between morphological traits of facultative wheat

Autumn sowing time	**Spring sowing time**			
	LS	**WS**	**NG**	**WG**
		Lennox		
LS	-	0.85**	0.75**	0.77**
WS	0.76**	-	0.84**	0.93**
NG	0.64**	0.80**	-	0.92**
WG	0.63**	0.90**	0.92**	-
		Ciprian		
LS	-	0.76**	0.64**	0.63**
WS	0.71**	-	0.80**	0.90**
NG	0.62**	0.77**	-	0.92**
WG	0.52**	0.91**	0.84	-

Taisa				
LS	-	0.92**	0.83**	0.77**
WS	0.82**	-	0.83**	0.89**
NG	0.75**	0.89**	-	0.89**
WG	0.72**	0.96**	0.90**	-

CONCLUSION

Regarding the agronomic performances of studied genotypes, the Lennox genotype exhibit superior traits in spring sowing conditions followed by Taisa genotype, while in autumn sowing conditions Taisa has a superior phenotypic expression for morphological traits. Also, grain quality and rheological parameters have low variability for studied genotypes in autumn sowing conditions, while in spring sowing conditions these parameters are more specificity. The spring sowing conditions has a positive effect on relationship between the main yield components of studied facultative wheat. The use of facultative wheat has a major advantage for farmers due to the shifting the sowing time. The accumulation of assimilates in wheat grains can be different according to the specific genotype adaptability.

Author Contributions: I.R., I.V.B., R.K. Conceived and designed the analysis; D.H. Collected the data; I.R.; A.V.; D.M.; B.A., Contributed data or analysis tools; I.R. Performed the analysis; A.B.; D.M. Wrote the paper.

Acknowledgments

This work was supported by a grant of the Ministry of Agriculture and Rural Development-Romania, project number ADER 1.1.2./2023-2026: "Development of breeding program of facultative and spring wheat".

Conflicts of Interest

The authors declare that they do not have any conflict of interest.

REFERENCES

1. Beales J, Turner A, Griffiths S, Snape JW, Laurie DA. A pseudo-response regulator is misexpressed in the photoperiod insensitive Ppd-D1a mutant of wheat (Triticum aestivum L.). Theor Appl Genet. 2007; 115, 721–733.
2. Chen F, Gao M, Zhang J, Zuo A, Shang X, Cui D. Molecular characterization of vernalization and response genes in bread wheat from the Yellow and Huai Valley of China. BMC Plant Biol. 2013; 5;13:199. doi: 10.1186/1471-2229-13-199. PMID: 24314021; PMCID: PMC4029403.
3. Chmist-Sikorska J, Kępińska-Kasprzak M, Struzik P. Agricultural drought assessment on the base of Hydro-thermal Coefficient of Selyaninov in Poland, Italian Journal of Agrometeorology. 2022; (1): 3-12. doi: 10.36253/ijam-1530
4. Danyluk J, Kane NA, Breton G, Limin AE, Fowler DB, Sarhan F. TaVRT-1, a putative transcription factor associated with vegetative to reproductive transition in cereals. Plant Physiol. 2003; 132(4):1849-60. doi: 10.1104/pp.103.023523. PMID: 12913142; PMCID: PMC181271.
5. Díaz A, Zikhali M, Turner AS, Isaac P, Laurie DA. Copy number variation affecting the Photoperiod-B1 and Vernalization-A1 genes is associated with altered flowering time in wheat (Triticum aestivum). PLoS One 7. 2012; e33234.
6. Dubcovsky J, Dvorak J. Genome plasticity a key factor in the success of polyploid wheat under domestication. Science. 2007; 316, 1862–1866.
7. Feldman M, Levy AA. Triticum L. In: Wheat Evolution and Domestication. Springer, Cham. 2023; https://doi.org/10.1007/978-3-031-30175-9_10.
8. Grote U, Fasse A, Nguyen TT and Erenstein O. Food Security and the Dynamics of Wheat and Maize Value Chains in Africa and Asia. Front. Sustain. Food Syst. 2021; 4:617009. doi: 10.3389/fsufs.2020.617009
9. Huang S, Sirikhachornkit A, Su X, Faris J, Gill B, Haselkorn R, Gornicki P. Genes encoding plastid acetyl-CoA carboxylase and 3-phosphoglycerate kinase of the Triticum/Aegilops complex and the evolutionary history of polyploid wheat. Proc Natl Acad Sci USA. 2002; 11; 99(12):8133-8. doi: 10.1073/pnas.072223799. PMID: 12060759; PMCID: PMC123033.

10. Kippes N, Debernardi JM, Vasquez-Gross HA, Akpinar BA, Budak H, Kato K et al. Identification of the VERNALIZATION 4 gene reveals the origin of spring growth habit in ancient wheats from South Asia. Proc Natl Acad Sci USA. 2015;112 (39):5401–10.
11. Koppensteiner L J, Kaul H-P, Piepho H-P, Barta N, Euteneuer P, Bernas J, Klimek-Kopyra A, Gronauer A, Neugschwandtner RW. Yield and yield components of facultative wheat are affected by sowing time, nitrogen fertilization and environment, European Journal of Agronomy. 2022; 140: 126591. https://doi.org/10.1016/j.eja.2022.126591.
12. Kulik M, Baryła R, Czarnecki Z, Bochniak A. Warunki hydrotermiczne w centralnej części rejonu kanału Wieprz-Krzna w 50-leciu (1966–2015). Ann. UMCS Sect. E Agric. 2016; LXXI, 1–12.
13. Muterko A, Kalendar R, Salina E. Novel alleles of the vernalisation 1 genes in wheat are associated with modulation of DNA curvature and flexibility in the promoter region. BMC Plant Biol. 2016; 16 (Suppl 1), 9. https://doi.org/10.1186/s12870-015-0691-2
14. Muterko AF, Balashova IA, Fayt VI, Sivolap YM. Molecular genetic mechanisms of regulation of growth habit in wheat. Tsitol Genet. 2015; 49(1):58–71.
15. Rezaei, E.E., Webber, H., Asseng, S. et al. Climate change impacts on crop yields. Nat Rev Earth Environ. 2023; https://doi.org/10.1038/s43017-023-00491-0
16. Slafer GA. Genetic basis of yield as viewed from a crop physiologist's perspective. Ann Appl Biol. 2003; 142: 117-128. 10.1111/j.1744-7348.2003.tb00237.x.
17. Trevaskis B, Bagnall DJ, Ellis MH, Peacock WJ, Dennis ES, MADS box genes control vernalization-induced flowering in cereals. Proc Natl Acad Sci USA. 2003;100, 13099–13104.
18. Wang J, Luo MC, Chen Z, You FM, Wei Y, Zheng Y, Dvorak J. Aegilops tauschii single nucleotide polymorphisms shed light on the origins of wheat D-genome genetic diversity and pinpoint the geographic origin of hexaploid wheat. New Phytol. 2013;198(3):925-937. doi: 10.1111/nph.12164. Epub 2013; PMID: 23374069.
19. Wilhelm EP, Turner AS, Laurie DA, Photoperiod insensitive Ppd-A1a mutations in tetraploid wheat (Triticum durum Desf.). Theor Appl Genet, 2009; 118, 285–294.
20. Yan L, Fu D, Li C, Blechl A, Tranquilli G, Bonafede M. The wheat and barley vernalization gene VRN3 is an orthologue of FT. Proc Natl Acad Sci USA. 2006; 103(51):19581–6.
21. Yan L, Loukoianov A, Blechl A, Tranquilli G, Ramakrishna W, SanMiguel P, et al. The wheat VRN2 gene is a flowering repressor down-regulated by vernalization. Science. 2004; 303(5664):1640–4.
22. Yan L, Loukoianov A, Tranquilli G, Helguera M, Fahima T, Dubcovsky J. Positional cloning of the wheat vernalization gene VRN1. Proc Natl Acad Sci USA. 2003; 100(10):6263–8.
23. 23. Zhao K, Tao Y, Liu M, Yang D, Zhu M, Ding J, Zhu X, Guo W, Zhou G, Li C, Does temporary heat stress or low temperature stress similarly affect yield, starch, and protein of winter wheat grain during grain filling? Journal of Cereal Science. 2022; 103, 103408. https://doi.org/10.1016/j.jcs.2021.1034