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Environmental influence on grain quality stability of common wheat cultivars

Nikolay TSENOV[1], Todor GUBATOV[1], Ivan YANCHEV[2]

[1]Agronom Breeding Company, Department of Wheat Breeding and Technology
9300 Dobrich, Bulgaria
E-mail: nick.tsenov@gmail.com

[2]Agricultural University, Faculty of Agronomy
4000 Plovdiv, Bulgaria

Abstract

The purpose of the study was to determine the stability of winter wheat (*Triticum aestivum* L.) cultivars according to the quality indices: deformation energy (W), alveograph P (dough tenacity) to L (dough extensibility) ratio (P:L), and dough extensibility (swelling) index (IE). The data were collected from four locations with different climatic conditions, in three consecutive years. The evaluation of the cultivar stability was made for each index using the statistical software PBSTAT specialised for this purpose. The information from its 16 different parameters is combined into a parameter stab16, by which the cultivars are compared for stability. The indices studied are influenced to varying degrees by the environmental (E) conditions. As a result of a reliable genotype and environment interaction (G × E), the stability ranking of cultivars according to the ranks of each of the parameters was very different. The level of stability of the cultivar in the studied different aspects of its grain quality is related to different levels of the indices. For the IE index, many of the studied cultivars are unstable in performance, which excludes its use for stability assessment. A limited number of cultivars combine a high and stable quality in different environmental conditions (c6 and c7). The W and P:L indices can be used independently to evaluate the stability of the cultivar as an additional characteristic of its quality. The estimation of cultivar stability by averaging the ranks of parameters (stab16) proved to be an effective approach due to its proven high and positive correlations with most of the 16 parameters. The applied analogical approach for the simultaneous assessment of quality stability does not provide correct information for the individual cultivar due to a significant discrepancy when comparing the information from each of the three indices.

Keywords: *Triticum aestivum*, genotype and environment interaction, stability statistics, grain quality, baking strength.

Introduction

The interaction between the growing conditions and the cultivar largely determines the variation of each trait (Kang, 2020). These changes also affect the stability of the cultivar, which is its unique characteristic. It is directly related to the breeding practice due to the differences that are found for each individual trait, index, or property in the created huge number of cultivars in cereal crops (Gubatov et al., 2017; Mohammadi et al., 2023). Each single quantitative trait or qualitative index changes specifically, which makes it very difficult to collect all possible information about the genotype. The quality of the grain in this regard is no exception – its many aspects, which are represented by dozens of indicators or indices, are generally poorly researched. Much of the research on the topic of stability is primarily focused on determining specific changes in given indices because of study environments (Kaplan et al., 2020; Vida et al., 2022). The significant influence of conditions on various aspects of grain quality has been proven many times (Johansson et al., 2020; Tsenov et al., 2022a).

Varietal quality stability was studied by groups or single indices, which are popular and routine for this kind of research, usually in combination with grain yield (Bosi et al., 2022; Kyratzis et al., 2022) or in cases where progress in breeding is analysed (Bornhofen et al., 2017; Nehe et al., 2019; Ilin et al., 2022). For each cultivar, after its development, information is collected on various aspects of its quality, but relatively little is known about its stability in different environmental conditions (Kyratzis et al., 2022; Liu et al., 2022). There are a limited number of studies, in which an attempt is made to compare cultivars simultaneously on several traits or indices (Mut et al., 2018; Studnicki et al., 2018; Öztürk, 2022). This is what is important for breeding,

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as it provides additional valuable information about the cultivar in terms of realising its genetic potential under changing environmental conditions. Global climate change has been felt for a long time, which means that the impact on quality indices will continue to be relevant (Georgieva et al., 2022; Fradgley et al., 2023).

The variation in the values of each quality index is unique to the cultivar and should be studied under characteristic target environments. Particular attention should be paid to indices that have a direct relationship with the selection in the breeding activities and on which there is established progress (Sanchez-Garcia et al., 2015; Mirosavljević et al., 2020). Stability quality index is also an object of attention, because it is as important as wheat productivity (Khazratkulova et al., 2015; Bosi et al., 2022).

The indices that are the subject of this study are no exception. They were selected for application and research due to the availability of sufficient information about their significance in the characterisation of wheat quality (Mikulikova et al., 2009; Kaplan et al. 2020; Tsenov et al., 2022a). They reflect different aspects of the quality of the grain, which is important to obtain a more complete picture of its stability in the unpredictable environmental conditions in the seasons. The study of cultivars with a different genetic potential for quality is also a challenge for breeding, because, in principle, they change in different ways. The new cultivars carry genetics from the old ones, but will their response to the conditions be like the ancient varieties, whose stability is high (Bosi et al., 2022; Liu et al., 2022)? These fundamental questions constantly require finding answers. They are also related to specific indices, some of which are analysed in the present study.

The listed particularities suggest that the quality assessment of the cultivar in a real environment should be carried out in several fundamental aspects: 1) to determine the stability of the cultivars according to each single index; 2) to establish whether the cultivar has a similar stability across the range of indices; 3) to establish experimentally whether there is a relationship between the mean and stability in qualitative indices, similar to the situation in productivity; 4) upon proving the previous hypothesis, to establish a model for a compromise combination of size and stability in one genotype; 5) to specify a parameter or a set of evaluation parameters that most strongly reflect the stability of the cultivar regardless of its quality mean.

So, the purpose of the study was to determine the stability of each cultivar of the studied group according to three indices representative of the quality of the grain under a significant influence of the environment on them. The working hypothesis was directly related to establishing the probability of combining a high level with stability in each of the indices. Particular attention was paid to those cultivars, whose individual index values were higher than the average for the studied group.

Material and methods

Settings of the field trail. Twenty-four modern cultivars of winter wheat (*Triticum aestivum* L.) were tested over a three-year (2017–2019) period in four climatically different locations of Bulgaria (Table 1). The technology of growing the cultivars was the same for each location according to the specifics of the region. Sowing was carried out in optimal terms for the region (October 5–20) with the difference between individual sites being 1–2 days. Fertilisation was the same for all locations and seasons and included the basic fertilisation with 30% of nitrogen and the entire amount of phosphorus and potassium in rates of $N_{160}P_{100}K_{100}$ kg ha^{-1} (in active substance). The remaining amount of nitrogen (70%) was applied twice in spring, the first at the end of the tillering stage and the second after twenty days (stem elongation). Plant protection included the mandatory application of herbicide and two treatments with fungicide in the phase of the beginning of spindles and before the emergence during the three years without exception. The cultivars were tested in a randomised block, in which all 24 cultivars were included in three replicates. The size of the area of each plot was 10 m^2. The plots were harvested at full maturity when a standard moisture content of the grain was below 14%. Quality indices were analysed from an average grain sample obtained from the three replications of the field experiment.

Table 1. Information about the conducted field experiment during the experimental years (2017–2019)

Location	Coordinates		Altitude
	N	E	m
Dobrich, Northern Bulgaria	43°38′47″	27°48′40″	248
Plovdiv, Southern Bulgaria	42°08′13″	24°48′22″	155
Trastenik Village, Rousse, Northern Bulgaria	43°37′40″	25°51′37″	170
Veliko Tarnovo, Northern Bulgaria	43°36′30″	25°30′02″	110

Cultivars studied were selected in such a way that the group had representatives of all levels of grain quality such as genetic potential. The ranking was in a descending order from c1 to c22 according to their preliminary quality data with the first six (c1–c6) being the highest quality and the last six (c16–c22) being productive cultivars with low grain quality genetics (Table 3). About two-thirds of the cultivars studied were developed in the last five to six years, and no information has been collected about their grain quality under different growing conditions. Due to the unforeseen loss of grain samples of two cultivars, the total number analysed was 22 instead of the originally selected.

Analysis of grain quality. Three popular quality indices were investigated as follows: deformation energy (W), alveograph P (dough tenacity) to L (dough extensibility) ratio (P:L), and dough extensibility (swelling) index (IE). Grain samples were analysed using a Chopin AlveoLink NG 6741 (KPM Analytics, France) according to the requirements of ISO 27971:2015 standard (Determination of alveograph properties of dough at constant hydration from commercial or test flours and test milling methodology). The grain samples were ground into flour with a laboratory mill Perten model 3310 (Perten Instruments AB, Sweden). The values of each index were obtained from a duplicate analysis of two samples by the Chopin AlveoLink NG according to the requirements of the standard ISO 27971:2015.

Statistical analysis. The stability of each cultivar was determined using the statistical software PBSTAT (Suwarno et al., 2008) specialised for this purpose. It includes all the necessary digital and graphical tools for establishing the G × E and the correct assessment of the stability of the cultivar. The program provides a complete assessment of cultivar stability through a set of 16 single stability statistics. The large numbers of 16 parameters (parametric and non-parametric) provide different stability information, which is misleading when a sample of them is used. These significant differences are the reason why researchers recommend averaging their ranks for the cultivar as a compromise solution to the problem (Pour-Aboughadareh et al., 2019; Gubatov, Delibaltova, 2020). For this purpose, a parameter stab16 obtained by averaging the ranks of all single parameters was applied. To identify those of the cultivars that have the combination of high levels of performance and stability together for each index, several figures obtained by applying the statistical program JMP 14 were built. In a similar way, the combinations of the three indices were compared for all the investigated cultivars to achieve their direct combination according to grain quality. For brevity, these visual data were presented as part of the overall Figure 4.

The ranking of cultivars was determined by the program used: the most stable is 1 and the most variable is 22. The correlations between the parameters were made using the statistical module XLSTAT, version 2014. The analysis of variance was done in two ways: by separating the main from the additional components of variation using the AMMI (additive main effect and multiplicative interaction analysis) model from the GEA-R program (Pacheco et al., 2015) and by the traditional analysis of variance (ANOVA) of all studied factors and interactions between them by the software Statgraphics, version 18 (Statgraphics Technologies, Inc., USA).

Results

The direct influence and interactions between the studied factors determine the levels of the three indices to different degrees (Table 2). The conditions of the location and the genetic characteristics of the cultivar significantly influence the change of the three indicators. The year and the year × location had an effect only on the extensibility index (IE) at the lowest level of confidence. For the other two indices, those same effects were unreliable. The effect of the location and the genotype × location were shown to be high for all three indices without exception. In general, the variation of the studied indices was due to the conditions of the location, the genetic potentialities of the cultivar, and the direct interaction between them. The year × location affected only the variation of the IE index to some extent.

Table 2. Multivariate analysis of variance for the field experiment during the experimental years (2017–2019)

Source	DF	W	P:L	IE
Location (factor A)	2	***	***	*
Year (factor B)	3	ns	ns	*
Cultivar (factor C)	21	***	**	**
A × B	6	ns	ns	*
A × C	42	***	**	*
B × C	63	ns	ns	ns

DF – degree of freedom; W – deformation energy; P:L – alveograph P to L ratio; IE – extensibility index; *, **, and *** – level of significance; alpha = 5.0; 1.0, and 0.1, respectively; ns – not significant

The influence of environmental conditions has been proven for the three investigated indices (Table 3). The characteristic of the IE is the low unreliable influence of environmental conditions as the main factor (4.2%). The influence that it exerts is an interaction with the genotype (G × E), which accounts for about 1/3 of all variation. The latter has a significant share of the total variation in the other two indices, also P:L 21.4% and W 41.6%. The proportion of variation that the genotype causes on individual indices is very different. In the W and P:L indices, it is 21.1% and 29.8%, respectively. For the G index, the influence of the genotype in its change is very strong (62.7%). The direction of the fundamental change of a group of cultivars is also different for individual indices. For two of them – W and IE – the values of PC1 are around 70%, which means that the cultivars in the group change mostly adequately (linearly) when the conditions in the locations change. However, in both there is the proven presence of non-linear change expressed by the relatively high values of PC2 and PC3. For the P:L index, this share is a little over 50%, which, against the background of 42% (IPC2+3), means the presence of a cross-type of G × E.

The differences between the main influencing factors in the field experiment are presented in Table 4. The weakest is the influence of the season (year), which is proven only for the IE index. The P:L index had the greatest similarity between the values at the different experimental locations, while the differences between them are statistically proven for the other two. G × E at the whole-group level was incomplete in terms of individual cultivar performance.

Substantial differences in the values of the indices were also found in the studied cultivars. Their change due to the interaction with conditions (G × E) was different. There is almost no cultivar that shows a credible G × E on all three indices. Exceptions are the cultivars c8, c15, c19, and c21, which are proven to be affected by the conditions in all three indices. Cultivar c9 showed a complete lack of interaction in all three indices, which can be considered an exception. All other cultivars interact directly with the environmental conditions, which directly affects their specific change. It is expressed by the change in the ranks of the cultivars for the individual indices. For example, the high-quality cultivar c5 has high ranks in W and IE indices. The cultivar c21, whose quality is average, also shows differences in ranks: low 1-(W), medium 8-(IE), and high 18-(P:L). There are similar discrepancies in other cultivars. This is a proof of

Table 3. ANOVA by site regression analysis according to GGE during the experimental years (2017–2019)

Statistics	Environment (E)	Genotype (G)	G × E	PC1	PC2	PC3
			Deformation energy (W)			
Sum Sq	123671.49	209774.39	267857.58	206248.21	47893.27	13716.08
Mean Sq	41223.83	9989.25	4251.70	8967.31	2280.63	721.89
F value	119.75	2.35	12.53	26.43	6.72	2.13
PV%	38.3	20.1	41.6	67.2	21.3	8.7
Pr(>F)	*0.000*	*0.005*	*0.000*	*0.000*	*0.000*	*0.006*
			Alveograph P to L ratio (P:L)			
Sum Sq	0.036	8.40	9.26	4.66	3.01	1.58
Mean Sq	0.012	0.40	0.14	0.20	0.14	0.08
F value	0.10	2.72	5.40	7.44	5.28	3.07
PV%	48.7	29.8	21.4	53.1	25.0	17.0
Pr(>F)	*0.000*	*0.0012*	*0.0000*	*0.0000*	*0.0000*	*0.0001*
			Extensibility index (IE)			
Sum Sq	61.86	926.60	489.24	244.09	156.31	88.84
Mean Sq	20.62	44.12	7.76	10.61	7.44	4.67
F value	3.43	5.68	6.51	8.91	6.25	3.92
PV%	4.2	62.7	33.1	70.4	15.0	9.0
Pr(>F)	*0.0723*	*0.0000*	*0.0000*	*0.0000*	*0.0000*	*0.0000*
DF	3	21	63	23	21	19

GGE – genotype (G) main effect plus genotype by environment (G × E) model by GEA-R (Pacheco et al., 2015); PV% – proportion of total variation; *Pr(>F)* = *p*-value; DF – degree of freedom; PC(1–3) – principal component analysis (1–3-ordinal factor)

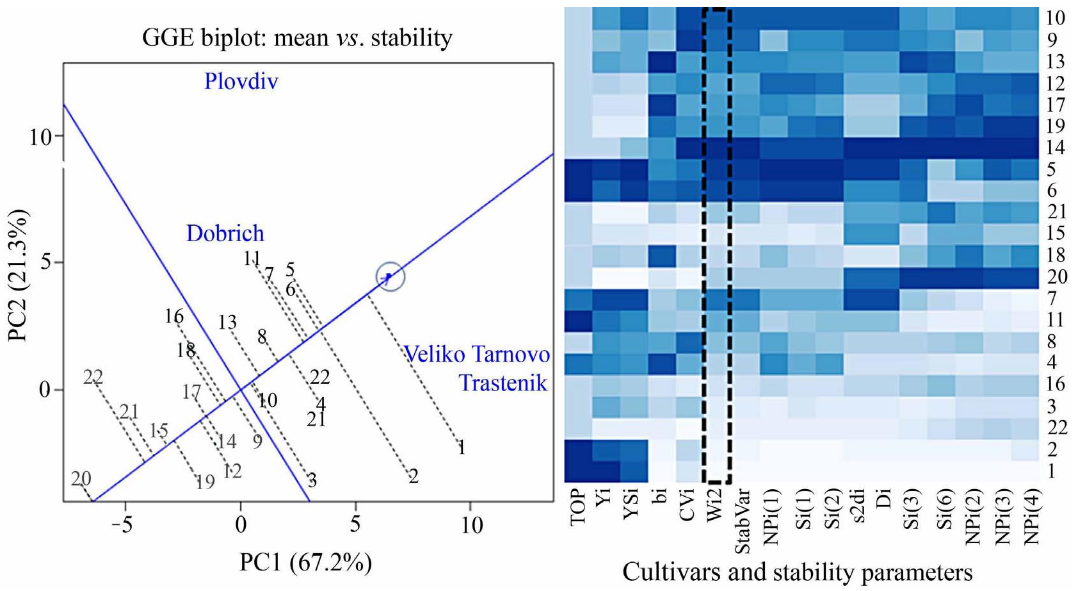
Table 4. Means and ranks of quality parameters and differences between 22 winter wheat cultivars in the locations during the experimental years (2017–2019)

		W				P:L				IE			
	Factor	mean	HG			mean	HG			mean	HG		
	Year		ns				ns				*		
	2017	246	a			1.12	a			20.1	a		
	2018	243	a			1.16	a			20.5	b		
	2019	246	a			1.25	a			20.8	b		
	Location		**				*				***		
	Dobrich	268	c			1.19	b			20.7	c		
	Plovdiv	252	b			1.17	ab			20.3	b		
	Trastenik	250	b			1.13	a			21.1	d		
	Veliko Tarnovo	209	a			1.19	b			19.8	a		
	Genotype		***				***				***		
	Cultivar name			R	G × E			R	G × E			R	G × E
c1	Tervel	295	j	1	***	1.37	ij	3	***	24.3	k	1	ns
c2	ABC Alfio	277	i	4	***	1.20	fg	7	***	23.2	j	4	ns
c3	ABC Kolino	249	fg	11	***	1.46	j	2	ns	23.7	jk	3	ns
c4	Apogej	270	hi	7	***	1.74	k	1	***	23.8	jk	2	ns
c5	ABC Navo	281	ij	2	ns	1.12	bcde	14	ns	21.6	hi	6	***
c6	ABC Lombardia	276	i	5	*	1.35	hij	4	ns	22.1	i	5	ns
c7	ABC Zigmund	277	i	3	ns	1.16	def	11	ns	21.1	h	7	**
c8	ABC Aldo	255	gh	8	***	1.17	ef	10	**	21.0	gh	8	***
c9	ABC Grosso	243	efg	12	ns	1.18	ef	8	ns	18.5	abc	20	ns
c10	ABC Clover	251	fg	9	ns	1.23	fgh	6	ns	19.6	def	12	**
c11	ARO Redmat	273	i	6	**	1.15	cdef	12	ns	20.3	fg	9	***
c12	Neven	230	cde	15	**	1.32	ghi	5	ns	18.1	a	22	ns
c13	Ognyana	251	fg	10	**	1.14	cdef	13	ns	19.2	cde	16	*
c14	Riana	230	cde	16	ns	1.17	ef	9	ns	19.7	def	11	***
c15	ARO Sankti	220	bc	18	*	1.03	abcd	19	***	18.9	bcd	19	**
c16	ABC Klauzius	237	def	13	***	1.00	ab	20	ns	19.3	de	14	***
c17	ABC Veto	225	cd	17	***	0.93	a	22	***	19.1	cd	17	ns
c18	ARO Romans	231	cde	14	***	0.98	a	21	ns	19.5	def	13	*
c19	ABC Speri	219	bc	19	**	1.03	abcd	18	*	19.0	cd	18	**
c20	Faktor	181	a	22	ns	1.03	abcd	17	ns	19.3	cde	15	***
c21	Vyara	208	b	21	**	1.11	bcde	15	***	20.0	ef	10	**
c22	Aneta	210	b	20	***	1.06	abcd	16	ns	18.1	ab	21	ns
	Location × genotype[1]		***				***				***		

Note. W – deformation energy, P:L – alveograph P to L ratio, IE – extensibility index; HG – homogeneous groups by 95.0% LSD; R – rank (the highest value 22, the lowest one 1); G × E – genotype and environment interaction; [1] – two-way ANOVA: * – $p \leq 0.05$, ** – $p \leq 0.01$, *** – $p \leq 0.01$; ns – not significant; different letters (a–k) denote significant differences between the cultivars.

the complex and multi-layered picture of the stability of a single cultivar when it is determined by different indices. High positive correlations exist between the indices studied (Tsenov et al., 2022a). However, the cultivar changes differently regardless of the overall group change, and this change is unique to each index. The variation of the cultivars is sufficiently well expressed to proceed to an objective assessment of their stability according to the studied indices.

The cultivars showed a different stability according to the W index (Figure 1). According to the arrangement of the cultivars on the left side of the figure, the stability level was not related to the index mean. The highly variable cultivars c1, c2, and c3, c16 and c19, and c22 were of a high, medium, and low grain quality, respectively. Only a few cultivars (c4, c5, c6, c8, and c10) show a compromise combination between a high value and stability. This is usually confirmed by the intensity of staining in the Figure 1 on the right. Varietal stability, expressed by the parameter Wi^2 (a black dashed line), almost completely matches the information, both for stable and highly variable cultivars (left). The arrangement of cultivars in the two parts of Figure 1 proves that any cultivar can be stable regardless of its mean value of the W index. On the straight line (lower left to upper right) there is the point called AEC (average environmental coordination). The closer the cultivar is to it, the higher its value and stability. The most valuable are the cultivars c5 and c6, which are closest to the zone of this point.



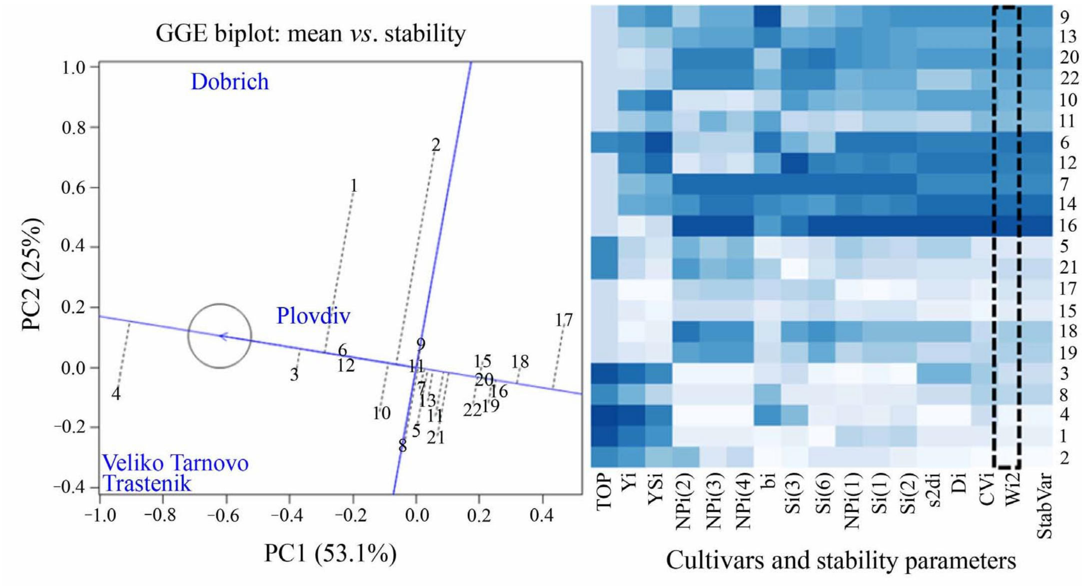
Note. The numbers of the cultivars studied are vertically on the right, the names are in Table 4.

Figure 1. Deformation energy (W) index: GGE biplot of means *vs.* stability (left) and the heat map of winter wheat cultivars and the stability parameters (right)

The values of the P:L index had no relationship with the stability level of the cultivar (Figure 2). The cultivars c3, c5 c6, and c9 with high values as well as those with relatively low values – c17 and c21 – are stable in terms of performance. For that index, it is noticeable that a larger number of cultivars with a higher stability prevail in the group compared to the other two indices. The likely reason for this is the absence of a significant direct G × E in most cultivars numbering 14 (Table 3). On the other hand, the established low stability of cultivars c1, c2, c4, and c17 against the background of their strong G × E can be considered as an acceptable compromise. Relatively the most stable were the cultivars c9, c10, c11, and c14, whose index mean values were around the average for the group. The closest to AEC were the cultivars c3, c4, c6, and c12, which against the background of the others can also be considered among the valuable cultivars according to this indicator due to the excellent compromise between value and stability. Depending on the minimal differences between cultivars, differences in stability can be accepted as a varietal characteristic. According to the criteria for this index, any cultivar with a value of P:L > 0.7 falls into the strong wheat flour group (Serna-Saldivar, 2012).

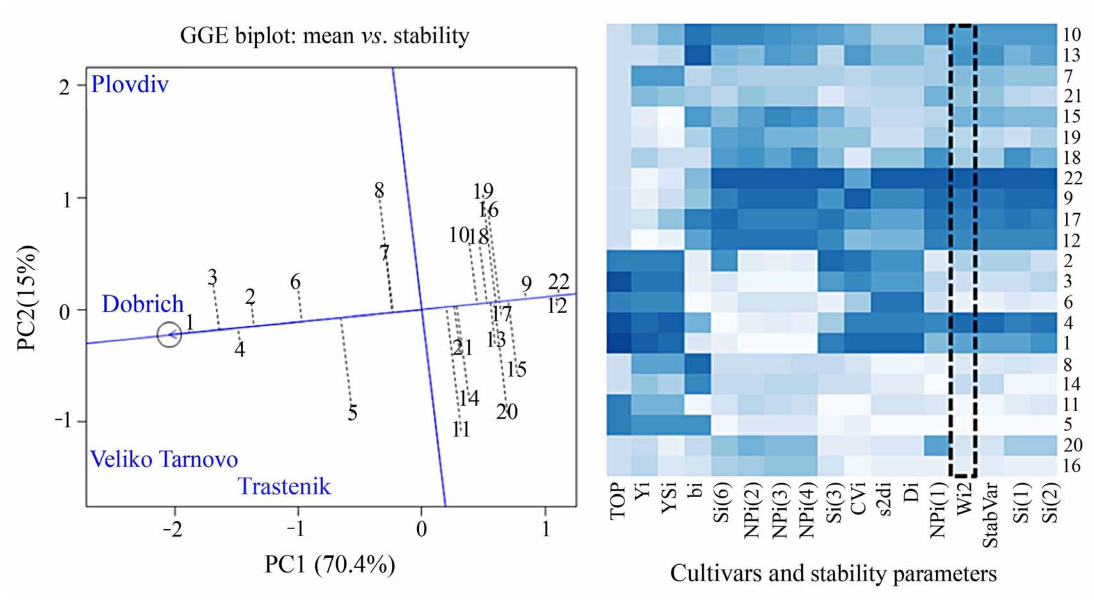
For the IE index, the stability of the cultivars was also different (Figure 3). The lowest variability was shown by the cultivars c1, c2, c3, c5, c7, c12, c17, and c22, whose points are located close to the line of the average stability of the group. Two of them (c5 and c7) can be considered stable enough, because they also exhibit a credible G × E (Table 3). The stability of the remaining four was likely related to the strong adequate change in the trait found (Table 2). The strong variation of the cultivars (c11, c19, and c20) could, without exception, be related to their reliably high G × E, which means the performance of a non-linear change of the index in them. The cultivar change information (right) corresponds to that on the left. The colouring of the parameter Wi^2 fully matches the changes that the cultivars show in this experiment.

In the evaluation of specific cultivar stability, all researchers encounter the dilemma: which of the available parameters to use for this purpose (Pour-Aboughadareh et al., 2022; Tsenov et al., 2022b). Averaging the ranks of all applied parameters is the approach by which the problem is successfully circumvented (Pour-Aboughadareh et al., 2019; Gubatov, Delibaltova, 2020). The correlation between the rank of the indicator means



Note. The numbers of the cultivars studied are vertically on the right, the names are in Table 4.

Figure 2. Alveograph P to L ratio (P:L) index: GGE biplot of means *vs.* stability (left) and the heat map of cultivars and the stability parameters (right)



Note. The numbers of the cultivars studied are vertically on the right, the names are in Table 4.

Figure 3. Extensibility index (IE): GGE biplot of means *vs.* stability (left) and the heat map of winter wheat cultivars and the stability parameters (right)

and the ranks of the individual evaluation parameters values was different even contrasting in magnitude and value (Tsenov et al., 2022b). The only objective way to solve this case study is to calculate an average rank (stab16) from all parameters. This rank is suitable for evaluating the stability of the cultivar (Table 5). The cultivar ranking approach by parameter stab16 was applicable due to its high correlations with 14 (88%) of the single parameters. Only the parameters that have a strong positive correlation with the value rank (bi, YSi, and TOP) were not related to it. For a large proportion of the stability statistics (9 out of 14), the correlations were valid for most of the measurement set (R^2 = 0.50–0.94).

The strongest and most stable relationship is between the stab16 and the parameter Wi^2 followed by NPi(3), and the weakest is with respect to the parameter Ysi. Positive correlation values were associated with low R^2 values, so they cannot be considered valid. The existence of strong correlations between the parameters stab16 and Wi^2 were the evidence that the stability assessment can be made regardless of the rank of the index mean (no correlation).

Information from all similar studies (Vaezi et al., 2019; Tsenov et al., 2022c) point to this parameter as the strongest and most stable exponent of general stability compared to all others. This is a sufficient argument for this index to be used as an independent criterion for differences in the stability of cultivars. This is done and illustrated in the right part of Figures 1, 2, and 3. The stability of the cultivar expressed by spatial comparison is not always completely correct. This is evident in a direct comparison between the total variation (left) and the

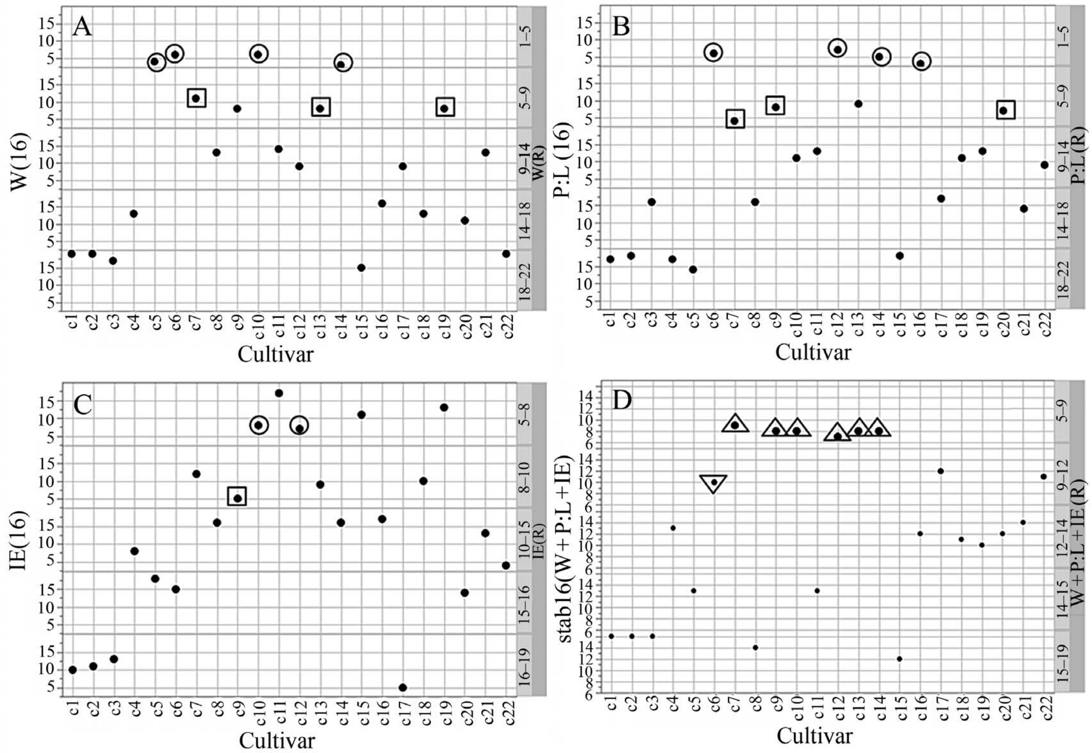
Table 5. Spearman rank correlations between each single parameter and the averaged parameter (stab16)

Stability statistics (according to PBSTAT)	W		P:L		IE	
	stab16	R^2	stab16	R^2	stab16	R^2
Relevant index (W, P:L, or IE)	−0.03	0.00	0.05	0.00	**−0.43**	0.18
Coefficient of variation (CVi)	**0.80**	**0.65**	**0.93**	**0.87**	**0.74**	0.55
Regression coefficient (bi)	**0.69**	0.47	**0.72**	**0.51**	0.30	0.09
Deviation from regression (s^2di)	**0.79**	**0.63**	**0.94**	**0.88**	**0.72**	**0.52**
Wricke ecovalence (Wi^2)	**0.94**	**0.89**	**0.96**	**0.92**	**0.95**	**0.91**
Hanson's genotypic stability parameter (Di)	**0.79**	**0.63**	**0.94**	**0.88**	**0.72**	**0.52**
Shukla's stability variance (StabVar = $\sigma^2 i$)	**0.94**	**0.89**	**0.96**	**0.92**	**0.95**	**0.91**
Kang's yield and stability index (YSi)	0.15	0.02	0.30	0.09	−0.15	0.02
1st Huehn's stability parameter (Si(1))	**0.95**	**0.91**	**0.95**	**0.89**	**0.97**	**0.93**
2nd Huehn's stability parameter (Si(2))	**0.94**	**0.89**	**0.94**	**0.89**	**0.95**	**0.91**
3rd Huehn's stability parameter (Si(3))	**0.89**	**0.80**	**0.82**	**0.68**	**0.81**	**0.66**
6th Huehn's stability parameter (Si(6))	**0.65**	0.43	**0.83**	**0.69**	**0.67**	0.45
Fox's TOP	−0.13	0.02	**−0.51**	0.26	−0.21	0.04
1st Thennarasu's stability parameter (NPi(1))	**0.90**	**0.81**	**0.93**	**0.86**	**0.88**	**0.77**
2nd Thennarasu's stability parameter (NPi(2))	**0.70**	0.48	**0.60**	**0.36**	**0.56**	0.32
3rd Thennarasu's stability parameter (NPi(3))	**0.76**	**0.57**	**0.74**	0.54	**0.58**	0.34
4th Thennarasu's stability parameter (NPi(4))	**0.72**	**0.52**	**0.68**	**0.47**	**0.57**	0.33

Note. W – deformation energy, P:L – alveograph P to L ratio, IE – extensibility index; stab16 – average rank of all (16) stability parameters analysed; values in bold are different from 0 with a significance level alpha = 0.05; R^2 – coefficient of determination.

stability estimate (right). However, the visual assessment should be close to correct since the comparison of cultivars in space (mean *vs.* stability) is based on the full interaction denoted as GGE (G + GE). However, a detailed comparison of the data for the cultivar by indices reveals a discrepancy in the set of cultivars with a different stability.

A direct visual comparison of the value and stability ranks of each index provides further insight into this (Figure 4). Stable and at the same time realised high values were the cultivars that showed a rank below the average (11) for the group according to the indices: c5, c6, c9, c10, c13, c14, and c19 for W, c6, c7, c9, c12, c13, c14, c16, and c20 for P:L, and c9, c10, c12, c13, and c18 for IE. The stability of the cultivar according to one index was rarely combined with that of another. Although rare, such combinations are possible in the following several cultivars: for the three indices – c9 and c13, and for two of the indices – c6, c10, c12, and c14. Precisely the cultivars c9 and c13 showed a different interaction with the environmental conditions (Table 4). One of them (c9) showed no interaction (GE ns), which



Note. 1–5, 5–9, 9–14, 14–18, and 18–22 were the values of the ranks of the corresponding quality index, which were generated by the statistical program JMP 14.

Figure 4. Scatter plot of winter wheat cultivars as quality ranks ~(R) *vs.* their stability ranks ~(stab16) for the deformation energy (W) (A), alveograph ratio P:L (B), extensibility index (IE) (C), and average stability rank of the three quality indices stab(16) *vs.* their average respect ranks (R) (D)

means that it changes mostly linearly, and c13 linearly and non-linearly (G × E**). In the other cultivars listed, stability was probably the result of no such interaction with conditions (G × E ns).

About 1/3 of the cultivars c6, c7, c9, c10, c12, c13, and c14 have a good combination of high and stable quality (average of the three indices) (Figure 4D). Two of them (c6 and c7) have the highest quality of this group, but its stability is relatively lower. Cultivars with an average level of quality indices realise their quality most stably. Combining the rank scores of the three indices successfully marks cultivars with the selection desired combination of high levels of the index stability. This approach should be carefully applied and, if possible, the differences between cultivars should be determined at the index level, which is significantly more correct.

Discussion

Establishing the stability of the cultivar in aspects of its quality is important for enriching its individual characteristics. The indices selected for analysis are related to different aspects of grain quality. From this point, they provide complex information on the set goal. In this group, cultivars possess the entire palette of quality levels expressed through each of the indices. Special attention is paid to the quality cultivars in terms of the combination between the mean value and its stability.

The parameter deformation energy (W) represents the energy required to inflate the dough bubble until it bursts. It is known as deformation energy, or alveograph W value, the strength of flour or dough. It is used to determine flour strength in different wheat samples (Abuhammad et al., 2012; Jødal, Larsen, 2021). Its relation to the strength of flour (dough) defines it as a criterion for a high bakery quality (Stoeva, Ivanova, 2009; Tsenov et al., 2022a).

The W index is a universal indicator of grain quality in general, because it shows high correlations with a wide range of indices (Stojceska, Butler, 2012; Tsenov et al., 2022a). The influence of environmental conditions on it has been proven to be significant. The influence of the genotype on its change has a share of about 20%, which defines it as weak against the background of the twice stronger influence of the environment (G × E). Similar data on the influence of conditions on this index are available in other studies of wheat (Branković et al., 2018; Öztürk, 2022). These are the main reason why cultivars with high quality genetics (c1 and c2) showed a low stability against the others. It is interesting to note that the cultivars with the lowest means (c19 and c22) also exhibited a low stability. According to several previous studies (Stoeva, Ivanova 2009; Öztürk, 2022), the lower the value of the cultivar index, the higher its stability and *vice versa*. Such regularity is not noticeable here. On the contrary, cultivars whose values were reliably different can be both stable (c6, c14, and c20) and unstable (c1, c16, and c20). This thesis is confirmed by a direct comparison of the mean value with stability (Figure 4). Therefore, the stability of cultivars according to the W index is not related to its mean value and should be taken as a varietal peculiarity (Szafrańska et al., 2023). In this case, this is extremely important, because there is no need to seek a compromise between the mean and its stability.

The P:L index is a ratio between two indicators: P, which expresses the tenacity strength of the dough, and L, which is the indicator that expresses the degree of extensibility of the dough. A high value of P:L indicates a stable and inextensible dough, while a low P:L value indicates a weak and extensible dough (Jødal, Larsen, 2021). Weak is flour with a low P value (gluten strength) and a long L value (extensibility), which is preferred for cakes, biscuits, and confectionery, while strong is that which has high P values and is preferred for bread and bakery products. Abuhammad et al. (2012) found that some alveograph parameters can effectively separate flours into groups according to their strength. This parameter could be used to evaluate and possibly predict the baking qualities of the grain (Rózylo, Laskowski, 2011).

In contrasting environmental conditions (E), Guzmán et al. (2016) found that in the presence of heat and drought, in spring wheat this index can be effectively used for selection in efforts to increase flour strength. The regularities established in it were the result of a strong direct influence of the environmental conditions (E), but a relatively weak interaction between them and the genotype (G × E). In a large proportion of cultivars, this interaction is absent despite the demonstrated cross-type interaction of the whole group (PC2–PC4) (Table 2). High stability is mainly shown by cultivars with medium and low index means (c12, c14, c18, and c22), while those with the highest means (c1 and c2) are the most unstable (Figure 4). The comparison of the cultivar ranks by mean and stability confirms this trend with the difference that two more cultivars (c6 and c7) can be added to the stable ones, whose means approach the high levels of the index. According to Kaya and Sahin (2015), it is possible to identify cultivars with a favourable combination of mean value and stability. The stability is not directly related to its index mean, but still the most stable cultivars have either a low or an average value.

The extensibility index (IE) is a measure of swelling, but it is related to the elasticity and tensile strength of the dough. Several studies over different periods have reported that alveograph parameters have positive correlations with each other and should be used as tests for a rapid assessment of cultivar quality (Rasper et al., 1986; Wang, Kovac, 2002; Jødal, Larsen, 2021). The IE value does not depend on the amount of protein but on its quality (strong correlation with W, P:L, and gluten index (GI)), which makes it a desirable parameter for further fine-tuning of the quality of cultivars, especially those with a higher quality than others (Jødal, Larsen, 2021; Tsenov et al., 2022a). In the studied group of cultivars, the differences between the index means were significant. Their performance was most strongly related to the genotype, while the environment had a direct symbolic influence (Table 3).

The index shows a stable genetic control where a large proportion of cultivars do not show any interaction with conditions (G × E) regardless of its magnitude. In addition, its change is mostly adequate (PC2 > 70%), which is an additional condition for preserving the existing differences between cultivars despite their variation (Table 3). Among the set of qualitative cultivars, only c5 and c7 showed a significant non-linear variation, while for those with low values, G × E was common (Table 4).

Unfortunately, stable cultivars had a low index mean (Figure 4). The index mean and its stability diverged strongly. Consequently, cultivars with high values may not be stable, which, given the strong genetic control, is somewhat surprising. Determining the specific variation of cultivars in the listed ways was also not unambiguous (Figures 3 and 4), which means that the index cannot group cultivars by stability. Apparently, this is an extremely rare phenomenon, because out of 45 investigated cultivars with a different genetic potential only one showed a good combination between the mean and stability (Mikulikova et al., 2009). The combined quality assessment represented by the stability of the three indices identified seven cultivars as stable (Figure 4D). Two of them (c6 and c7) belong to the group of quality genotypes, and the quality of the remaining five can be defined as average in size.

The discrepancy in the evaluation of the stability of the cultivars obtained after analysing each index separately and the integral of the three is obvious. The data clearly show that such an approach does not provide correct information about the individual cultivar. Stability as information specific to it must be determined by each single index.

Conclusions

1. Each of the investigated winter wheat quality indices: deformation energy (W), alveograph P to L ratio (P:L), and dough extensibility index (IE), changed significantly under the influence of the genotype and environment interaction (G × E).

2. Despite the significant interaction for the entire group of winter wheat cultivars, for each of the indices there was a set of cultivars where the changes were not related to G × E. The cultivar c9 showed a unique performance, because it was not affected by the conditions in all three indices. It was the most stable in quality, which was proven during analysis in several different ways.

3. The quality level of studied cultivars is a serious obstacle to its high stability. This applies to the highest degree to cultivars with a high genetic potential for quality. In the studied environments, the number of cultivars that combine a relatively high and stable quality was minimal (c6 and c7).

4. Using the average rank of the parameters (stab16) is an applicable and correct way to evaluate the stability of each cultivar, incomplete and regardless of the magnitude of its quality index.

5. The indices studied in the described way are a suitable tool for evaluating the stability of each cultivar. The rare combination of a high mean and stability in one genotype is an indication that stability as such should be taken as a varietal trait in relation to various aspects of grain quality.

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