AGRICULTURAL SCIENCE AND TECHNOLOGY, VOL. 14, No 2, pp 12-26, 2022
Published by Faculty of Agriculture, Trakia University, Bulgaria
ISSN 1313-8820 (print)
ISSN 1314-412X (online)
http://www.agriscitech.eu
DOI: 10.15547/ast.2022.02.015

Genetics and Breeding

Evaluation of heritability and genetic advance of some quality parameters in common wheat (Triticum aestivum L.) under genotype by environmental interaction

N. Tsenov[1], T. Gubatov[1], I. Yanchev[2]

[1]Department of Wheat Breeding and Technology, Agronom Breeding Company, 9300 Dobrich, Bulgaria

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

(Manuscript received 12 January 2022; accepted for publication 31 May 2022)

Abstract. *Growing conditions play a significant role in the yield and grain quality of winter wheat. Global climate changes and in particular in the meteorological situation in the regions typical for the crop presuppose conducting research on the newly created breeding materials for grain quality. The aim of the study is to determine the nature and magnitude of the change in important parameters of grain quality, under the influence of typical environmental conditions for growing common wheat. The working hypothesis suggests that most of the parameters have a good genetic basis that would allow the selection to lead to their increase. In a multi environmental field experiment involving five test locations over three consecutive years, changes in eight grain quality parameters were investigated reflecting different aspects of the end-use quality. The study involved 40 samples of wheat developed by the breeding company "Agronom" in the last 20 years. With the help of modern methods for statistical analysis, the effect of the main breeding factors "location", "year" and "genotype", the limits of variation and the correlations between them have been established. The real possibilities for selection and breeding of each parameter have been analyzed, against the background of the rest of the group. Quality parameters change significantly from the three factors studied. The interaction "genotype x year" has the strongest influence on each of them. The "location x genotype" interaction is not a factor that affects the parameters. Only Deformation energy shows a significant share of the genotype, while the other two factors have a negligible influence on it. Each of the studied parameters, without exception, changes both adequately (linearly, IPC1) and inadequately (nonlinearly, IPC2) when the conditions change during the studied seasons. This nature of change is the reason for the relatively weak positive correlations between the parameters, as well as for their low heritability coefficients in a broad sense. Against the background of the data, the values of Genetic advance are indicated, with which each of them can be increased by selection. There are both positive and negative correlations between the parameters, the direction and value of which must be taken into account in the attempt to change them. An effective selection can be made on the parameters Extensibility index, Deformation energy and P/L ratio which have the strongest genetic control (H2> 0.60), which against the background of the strong influence of the environment ("location", "year", "location x year") can lead to genetic advantage with 12% (Extensibility index), 17% (Deformation energy), 51% (P/L) of their present value. A selection based on PC or Wet gluten content parameters that have a direct effect on overall quality can also be effective (H2 =0.58-0.63). Instead, it would be more prudent to monitor, not so much their quantitative, but their qualitative composition, the accumulation of known or new alleles of glutenins (Glu) and gliadins (Gli), for which there is specific information that they are directly related to high grain quality.*

Keywords: wheat, end-use quality, correlations, broad sense heritability, genetic progress

*e-mail: nick.tsenov@gmail.com

Introduction

Grain quality in common wheat is important because it is directly related to human food (Békés, 2012; Wieser et al., 2020; Motta-Romero et al., 2021). Wheat provides about 21% of the protein needed by humans, on a planetary scale (Mc Fall and Fowler, 2009) According to the level of grain quality in different continents and growing conditions, various traditional food products are prepared that have entered people's lives for thousands of years (Shewry, 2009; Bilgin et al., 2016). The breeding of new varieties is aimed primarily at the gradual increase in yield, which inevitably changes the quality of the grain (Békés, 2012; Johansson et al., 2020). These changes are associated with a decrease in the values of a number of parameters related to protein in the grain, which in turn causes a deterioration in the baking qualities of the grain as a whole (Hristov et al., 2010b; Bornhofen et al., 2017; D'Amico et al., 2021). For this reason, it is necessary to monitor the changes in the parameters related to the accumulation of protein in the grain or to apply parallel breeding on some of them, which change more strongly in a negative direction (Kaya and Akcura, 2014). Then grain yield and quality could be progressively increased (Jernigan et al., 2018; Maich et al., 2020).

The analysis in the process of breeding of various aspects of grain quality is imperative to apply systematically for the following several main reasons: *First*: Wheat is a crop in which grain quality always matters, regardless of the products for which it is intended. For bread and bakery products, the quality should be high, for biscuits and their derivatives - low quality is preferable (Bushuk, 1998; Shewry, 2009; Békés, 2012). *Second*: The factors that influence the variation of each parameter are determined. Research in this direction shows that the growing conditions of the location and the year have a tangible effect, not only on the size, but on the change of each quality indicator (Johansson et al., 2020; Peterson et al., 1992; Williams et al., 2008; Mutwali, 2015). Agronomy practices, such as tillage (Studnicki et al., 2018), effect of the predecessor (Ivanova et al., 2013), nitrogen fertilization and crop density, also significantly affect the variation of quality characteristics (Zecevic et al., 2010; Bhatta et al., 2018; Gagliardi et al., 2020; Silva et al., 2019). *Third*: Specific information is collected on the magnitude and direction of change of individual parameters of quality (Harshwardhan et al., 2016; Nazarenko et al., 2020; Valdés et al., 2020). *Fourth*: The magnitude and direction of the correlations between the individual parameters are monitored, as well as the change in environmental conditions (Gut and Bichoński, 2007; Gómez-Becerra et al., 2009). *Fifth*: The degree of genetic control of each parameter of end-use quality is determined by its influence on the conditions, which is important for conducting a systematic and effective selection (Gómez-Becerra et al., 2009; Harshwardhan et al., 2016; Taneva et al., 2019; Mirosavljević et al., 2020). *Sixth*: The efficiency of the breeding is monitored according to a given indicator, independently and in direct connection with the others, as well as against the quantitative traits determining the productivity (Kiszonas and Morris 2018; Nehe et al., 2019). *Seventh*: The breeding applied is as effective as possible to increase yield and quality in parallel (Helguera et al., 2020; Hristov et al., 2010b). *Eighth*: The influence of biotic and abiotic factors on grain quality is taken into account, which is always palpable, especially in the context of ongoing climate change (Nuttall et al., 2017; Thungo et al., 2020). The strong influence of abiotic stress on quality can be positive or negative for its individual parameters (Li et al., 2013; Tsenov et al., 2015; Guzmán et al., 2016; Fleitas et al., 2020). *Ninth*: Wheat is a crop of the microclimate, which is a prerequisite for different variation of yield and grain quality in specific environmental conditions, which implies breeding for certain regions or areas (Kaya and Akcura, 2014; Kaplan et al., 2020; Tsenov et al., 2010b).

All these aspects are important and the information from them develops a proper breeding strategy in the direction of improving the quality of the grain (Taneva et al., 2019), provided that sustained efforts are made to progressively increase productivity (Akçura, 2009; Balkan, 2018). It is necessary to study the stability and adaptability of parameters that have a trade-off between yield and grain quality (Baenziger et al., 2001; Tsenov et al., 2021). They are extremely important for the production of more and better grain (Thungo et al., 2020; Tsenov et al., 2013), as well as for selection as genetic sources for breeding to certain traits or parameters (Chamurliyski et al., 2016; Jernigan et al., 2018; Zhang et al., 2020).

The aim of the study is to analyze as fully as possible the nature and magnitude of the change in parameters important for grain end-use quality, under the influence of typical for the country locations and climatic conditions for growing common winter wheat. The working hypothesis is that the parameters of grain quality are genetically determined and change within limits that allow their increase through breeding individually and in groups.

Material and methods

General statement

Forty (40) varieties of winter common wheat, created in the Agronom 1 Holding breeding company during the last 20 years, were studied in two factor trails (Table 1.1).

The varieties are selected mainly by grain yield, but also differ significantly in their quality. The manifestation and changes of their yield and grain quality have been studied. The field experiments were conducted in three consecutive years 2017, 2018 and 2019. The group of varieties was studied in three growing locations, as follows: village of Paskalevo-Dobrich region with designation (A), village of Trastenik-Russe with designation (B), and the Straldzha-Yambol region, with designation (C) (Table 1.2). They were chosen deliberately due to a significant difference in temperatures and precipitation in them. During the specific period of the experiment the conditions for growing common wheat in the locations can be characterized as follows: optimal in Dobrich, semi-dry in Trastenik, and dry and hot in Straldzha. The seasons during the study in terms of meteorology were significantly different without exception in the combination between their specific temperatures and precipitation during important sub periods for the vegetation (Figure 1).

Agronomy practices

In each of these selected locations, the varieties are grown in plots of 10 m^2. In each separate location the requirement for ensuring equal conditions for each variety participating in the scheme is strictly observed. Sowing is carried out in the optimal time (October 5-15), every year. Fertilization includes 250 kg/ha DAP (18% N, 46% P) before sowing, and 600 kg/ha ammonium nitrate, applied three times in spring. Care throughout the growing season includes plant protection throughout the period to ensure uniform conditions for growth and development of all genotypes. The important parameters of grain quality from breeding point of view related to the production of bakery products have been analyzed (Table 1.3). The results also include data on grain yield, to establish whether there are correlations between it and quality, which would complicate or help the selection to increase grain yield and quality, simultaneously.

Table 1.1. Information on soil and coordinates of the test locations, during the period 2017-2019.

Location	Type of Soil	Coordinates		Year of study
		N	E	
Paskalevo-Dobrich region	Leached chernozem	$43^{0}38'47''$	$27^{0}48'40''$	2017
Trastenik-Ruse region	Leached chernozem	$43^{0}37'40''$	$25^{0}51'37''$	2018
Straldzha-Yambol region	Chernozem	$42^{0}24'33''$	$26^{0}37'33''$	2019

Table 1.2. Information on the studied varieties

Groups of varieties	Number	Designation of genotypes
Used in production	11	Aneta, Apogej, Presiana, Ognyana, Alisa, Bilyana, Viyara, Neven, Ralitsa, Tervel, Faktor
New developed	8	Riana, ABC Alfio, ABC Lombardia, ABC Klauzius, ABC Speri, ABC Zigmund, ABC Kolino, ABC Navo
Candidate varieties	11	A 68/64, A 48/716, A 18/74, ACR 48/615, A 27/320, ABC 27/512, ABC 28/313, A 37/215, ABC 48/716, A 47/415, ABC 37/716
Advanced lines	7	R_A 1-4-5, 06/198-21, 06/137-22, 1/54-84, 04/255-92-2, 05/48-22-1, 05/48-22-8
Check varieties	3	Pryaspa, LG Avenue, LG Anapurna
Total number	40	Aneta, Apogej, Presiana, Ognyana, Alisa, Bilyana, Viyara, Neven, Ralitsa, Tervel, Faktor

Table 1.3. Information on the laboratory methods for evaluation of the quality by groups

Wheat flour parameters	Code	Method
Test Weight (kg)	TW	(BSS 7971-2: 2000) *
Protein content (%)	PC	NIR method, INFRAMATIC, 8600 Perten
Wet gluten, (%)	WGC	ICC no. 155 – determination of wet gluten quantity and quality
Gluten index (GI)	GI	ISO 3093:2009 - Wheat, rye and their flours, durum wheat and durum wheat semolina - Determination of the falling number according to Hagberg-Perten
Falling number (sec)	FN	
Deformation energy (W, 104 J/g)	W	ISO 27971:2015 - cereals and cereal products - Common wheat (*Triticum aestivum* L.) - Determination of alveograph properties of dough a constant hydration from commercial or test flours and test milling methodology
P/L ratio	P/L	
Extensibility index	G	

* Standard method in Bulgaria

Meteorological conditions

In Bulgaria, wheat is grown annually for about 250-270 days (8-9 months). This long growing season covers all four climatic seasons, which are characterized by large differences in terms of the two main factors - temperature and precipitation.

The average air temperature shows significant differences in the period of active vegetation (April - June) for both environmental factors. In Dobrich the temperature is a prerequisite for obtaining the maximum possible yields (10.4 - 19.8˚C), in Trastenik the conditions are less optimal (11.0 - 21.0˚C), and in Straldzha - there are conditions for drought due to higher temperatures (13.0 - 22.0˚C), which accelerates the vegetation and reduces grain yield. The years of research also differ, with the coldest being in 2017 (15.8˚C) and the hottest in 2019 (18.5˚C).

The amount of precipitation in our country is the limiting factor that most strongly affects the yield and quality of grain. The three locations selected in the study differ significantly in the amount of precipitation in them throughout the growing season. The largest and sufficient amount of precipitation is in Dobrich (amount of 528 mm/m^2 = 100%), followed by Trastenik (amount of 462 mm/m^2 = 85%), and the scarcest precipitation is in Straldzha, (sum of 346 mm/m^2 = 65%). During each of the seasonal periods there is a significant difference between them. When considering precipitation from the point of view of the test years, the differences are also statistically proven. The wettest year is 2017 (amount of 539 mm/m^2), the driest is 2019 (amount of 339 mm/m^2), 2018 occupies an intermediate place (amount of 457 mm/m^2).

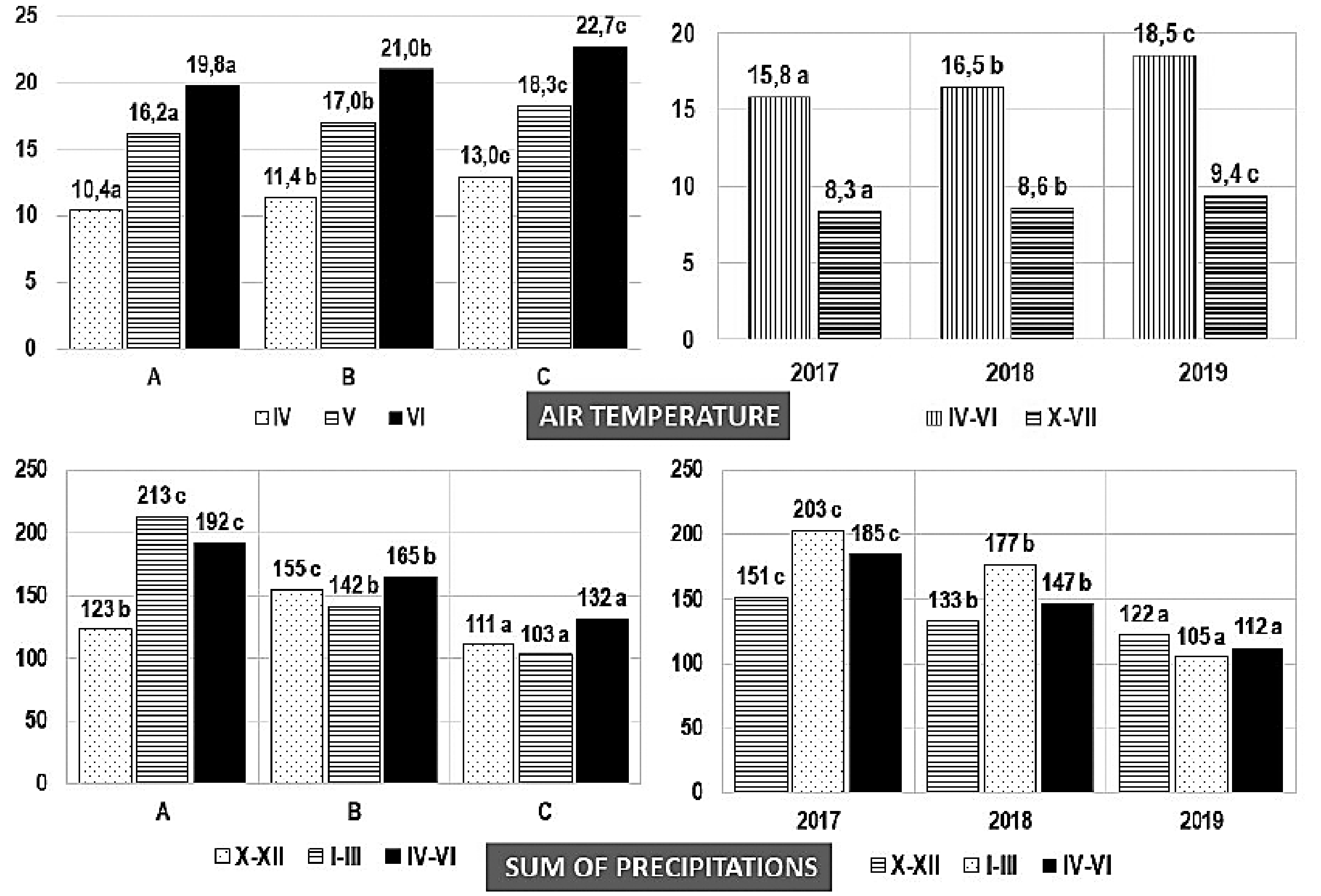

Figure 1. Average air temperature and amount of precipitation (mm/m^2), during the main vegetation periods, according to the location and year of the study, the significant differences (a, b, c) between the main factors of research are according to Duncan test, at the level of significance = 0.05

Statistical analyses

The genetic and phenotypic parameters of the studied indexes were calculated according to the formulas for each of them presented in Table 2. In order to test the hypothesis, the collected data were subjected to various statistical analyses, aiming to accumulate information on various aspects of the topic. Descriptive statistics, analysis of variants, correlation analysis, principal component analysis and analyses related to the inheritance and genetic progress of each indicator participating in the study were applied. All of them were implemented using the following several statistical packages XLStat 2019, Past 4, Statgraphics XVIII, PBstat GE2.9, IBM SPSS 23.

Table 2. Genetic parameters and formulas for their respective calculation*

Symbol	Meaning
$\sigma^2_g = (MS_g - MS_{gy})/y$	Genotypic variance
$\sigma^2_{gy} = (MS_{gy} - MS_e)/r$	Variance of interaction between G and Y
$\sigma^2_e = MS_e$	Variance of environments
$\sigma^2_{ph} = \sigma^2_g + \sigma^2_{gy}/y + \sigma^2_e)/r$	Phenotypic variance
$H^2_{BS} = (\sigma^2_g / \sigma^2_{ph}) *100$	Broad sense heritability
$GA = K * (\sigma^2_{ph})^{0.5} * H^2_{BS}$	Genetic advance, K - selection intensity – 2.06 %
$GAM = GA/\overline{GM}*100$	Genetic advance in %
$CV_p = \sqrt{\sigma^2_{ph}} / (\bar{x}* 100)$	Phenotypic coefficient of variation
$CV_g = \sqrt{\sigma^2_g} /(\bar{x}* 100)$	Genotypic coefficient of variation
GM	Grand mean
MS_g	Mean squares of genotype (g)
MS_{gy}	Mean squares of interaction (g*y)
MS_e	Mean squares of error
y	Number of locations
r	Number of replications

* Variance components were estimated according to Snedecor and Cochran, 1980.

Results

The studied parameters show different magnitude of change depending on the conditions. TW, PC parameters vary phenotypically within 10%, which is relatively weak, assuming that the grain yield that is most strongly affected has a variation of 18.33% (Table 3). The parameters WGC, GI, G and FN show a variation of about 10-12%, which we assume conditionally as being average in size. The most variable parameters are W (19.81%) and P/L (36.68%). In general, the genetic coefficient of variation of almost all parameters is about 50% of the phenotypic variation (VCg), with the exception of WGC (62%) and P/L (66%). This is indicative of the serious interference of environmental factors on the manifestation of each of the parameters and grain yield, too.

Table 3. Main Descriptive statistics of grain quality traits investigated

Parameter*	Min	Max	Mean	Variance	St. deviation	VC_p	VC_g
GY	4.16	11.02	6.85	2.17	1.47	18.33	9.66
TW	70.10	84.2	76.95	9.93	3.15	1.34	0.69
PC	8.80	16.6	12.23	2.47	1.57	6.25	3.61
WGC	12.30	36.9	24.01	28.66	5.35	11.41	7.19
GI	8	100	83.6	541	23.3	10.79	4.30
G	10.20	25.60	16.24	11.06	3.33	10.70	5.48
W	49	440	176.5	5013	70.8	19.81	8.06
P/L	0.36	5.76	2.03	1.30	1.14	36.68	24.80
FN	62	669	366.5	17174	131.0	9.83	3.07

* (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index, (FN)-Falling number, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (G)-Extensibility index

Table 4. Combined ANOVA with AMMI analysis (MS)

Trait/parameter	Genotype	Environments	G x E	IPC1	IPC2
GY	0.934 ***	279.9 ***	0.603 ***	6.778 **	2.333 **
TW	10.61 ***	360.4 ***	2.58 ***	3.386 **	1.738 **
PC	4.34 ***	63.3 ***	0.897 ***	1.052 **	0.734 **
WGC	59.9 ***	612.3 ***	10.41 ***	14.85 **	5.74 **
GI	1890.8 ***	2458.5 ***	124.6 ***	137.38 **	111.66 88**
G	28.36 ***	28.23 ***	7.41 ***	8.271 **	6.52 **
W	16124.3 ***	8874.7 ***	2410.1 ***	3145.9 **	1637.2 **
P/L	4.96 ***	6.93 ***	0.742 ***	0.843 **	0.641 **
FN	18767.3 ***	704660 ***	4177.34 ***	5146.03 **	3150.52 *
df	39	8	312		

(GY)- Grain Yield, (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index, (G)-Extensibility index, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (FN)-Falling number, The analysis of variances shows the presence of a significant influence of environmental factors on the manifestation of quality parameters and grain yield (Table 4). In the G and P/L parameters, the genotype and the environment have almost similar values. For the other parameters, the influence of the conditions is significantly stronger than that of the genotype. The highest share of genotype is in the indicator W, which is the only one in the entire group of studied parameters. The interaction of the genotype with the conditions according to the two main components of PCA is essential. The magnitude of their reliable values shows the complex linear and nonlinear nature of the interactions. The parameters could be conditionally divided into groups, according to the comparison between IPC_1 and IPC_2. There are three parameters in which the two components have almost similar weights (GI, G and P/L). In all others, including grain yield, the first component is significantly higher.

Table 5. Analysis of Variance for GY and all quality parameters *(p-values)* *

Source	A:LOC	B:YEAR	C:GEN	AxB	AxC	BxC
GY	0.000	0.000	0.000	0.000	0.011	0.011
TW	0.000	0.000	0.000	0.000	0.882	0.038
PC	0.000	0.000	0.000	0.000	0.967	0.371
WGC	0.000	0.000	0.000	0.000	0.982	0.222
GI	0.000	0.000	0.000	0.000	0.572	0.000
G	0.004	0.000	0.000	0.000	0.203	0.004
W	0.291	0.267	0.000	0.000	0.922	0.000
P/L	0.000	0.026	0.000	0.000	0.314	0.000
FN	0.000	0.000	0.000	0.022	0.529	0.000
df	2	2	39	4	78	78

* Type III Sums of Squares; * (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index, (FN)-Falling number, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (G)-Extensibility index,

The studied three factors directly and independently affect some of the parameters (Table 5). They interact in the following several combinations: A x B, for all parameters; A x C, only in grain yield and B x C, in GY and almost all parameters except PC and WGC. The W has a special performance, in which only the genotype (A), its interaction with the year (B x C) and the interaction between the other two factors (A x B) have a tangible effect. According to these data, we can assume that the conditions of the year have the most significant impact, alone or by combining with the other two factors with which they interact. For all quality parameters examined, the conditions of location (A) do not interact with genotype (C).

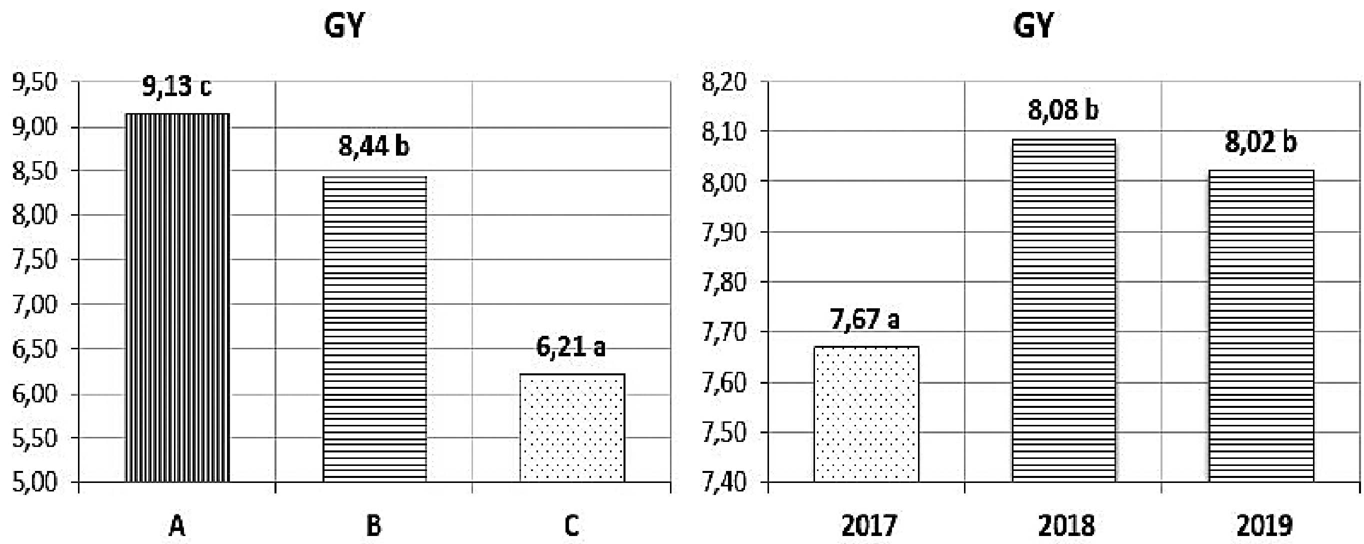

Figure 2. Different effects of environmental factors on the performance of Grain Yield

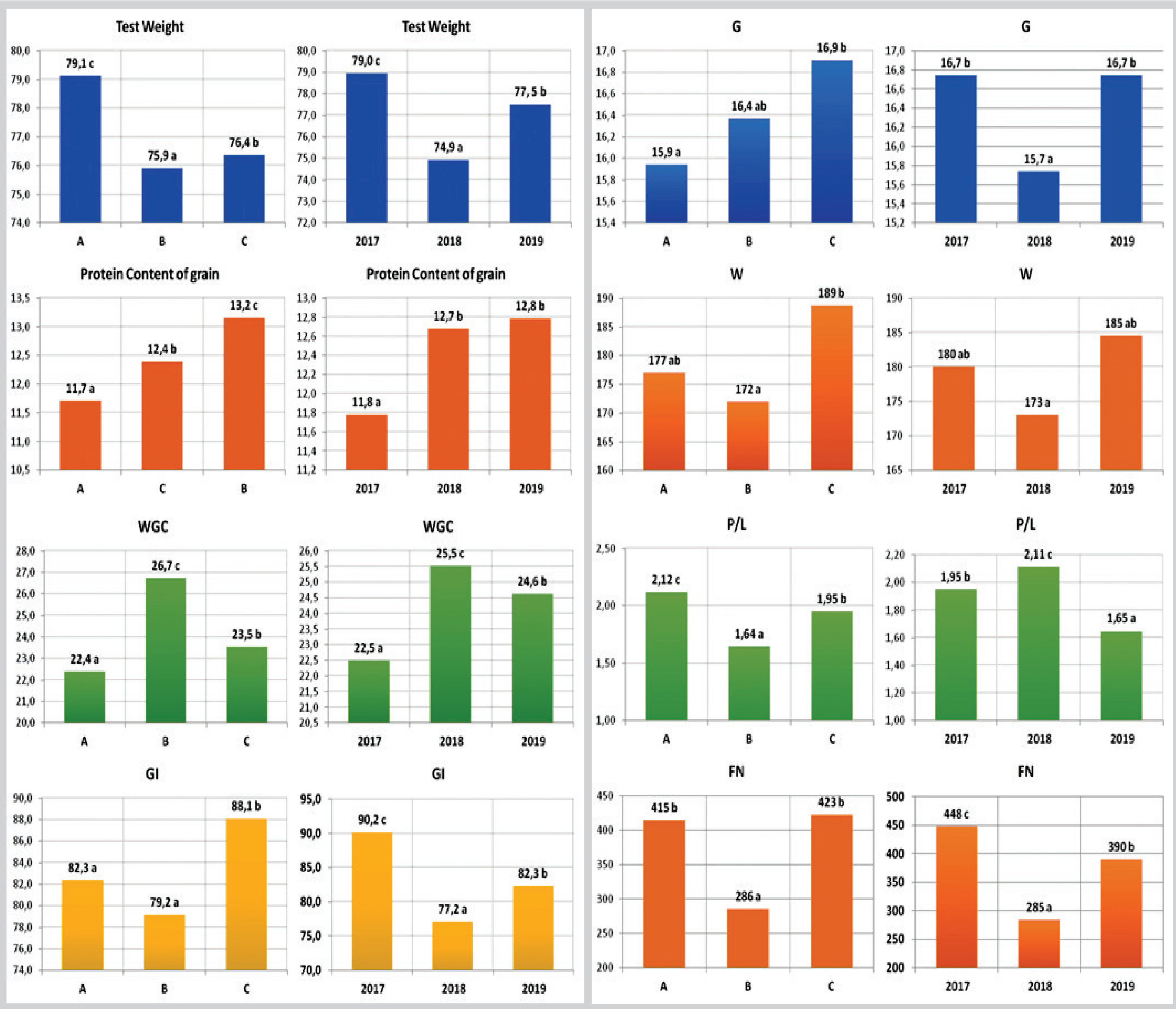

Figure 3. Different effects of environmental factors on the performance of the parameters (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index; (G)-Extensibility index, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (FN)-Falling number

How does the interaction of the genotype with the conditions change the values of the studied parameters in the specific context of the field experiment? The conditions of the locations cause in the same varieties different performance of grain yield, which is well emphasized (Figure 2). The differences between the individual locations reach 10-30%. The conditions of the year also model the values, but to a lesser extent, that is why in 2018 and 2019 GY has similar values.

The quality parameters are strongly influenced to the extent that there are significant differences in their manifestation compared to the two studied environmental factors (Figure 3). The effect of the location is especially strong. For all parameters in the figure, without exception, the values are different, except for indicator G, in which there is no significant difference in the manifestation between the two locations (A and B). The conditions of the year also have their significant impact on the parameters. In the three years they have significant differences, which are different for each indicator, compared to different seasons. An exception to this statement is the PC indicator, the values of which in 2018 and 2019 are completely identical.

In the second group of quality parameters, the growing conditions show a similar effect on their levels (Figure 3). The differences between some of the variants of the two main factors are lower and belong to the same reliability group or the differences are small (ab). Such is the case with FN, with respect to point G, according to the year factor. The W, where the values have a difference, changes relatively the least, but it is reliable at the lowest possible statistical level. In a sense, this means that these parameters should be genetically more stable, which in turn reduces the degree of interaction with the conditions of the locations and the year.

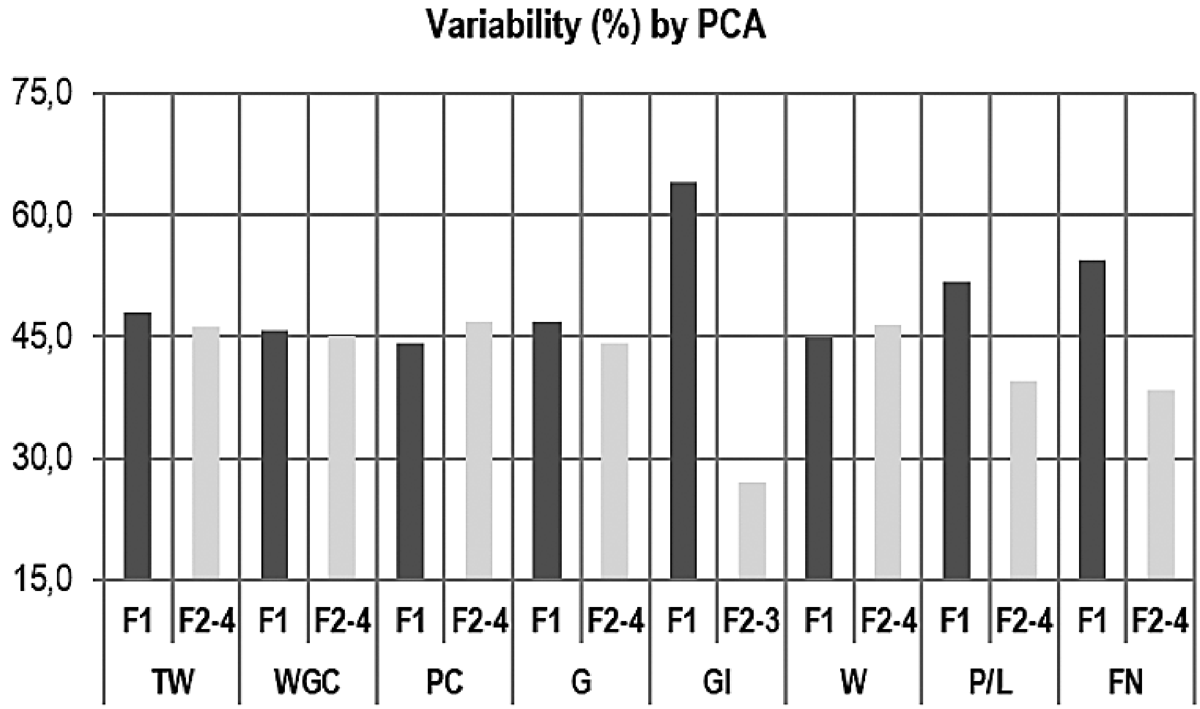

Figure 4. Linear (F1) and nonlinear (F2-4) variability of Components of PCA for the parameters; (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index; (G)-Extensibility index, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (FN)-Falling number

The group of studied parameters shows a strong interaction with the environmental conditions (Figure 4) which in this experiment reaches four main components, according to the eigenvalues of the components (Eigenvalue > 1) and only for the GI indicator - they are three. Each of the parameters changes to a different degree and direction, which could be difficult to analyze in details. The reliable main components determine over 90% of the total variation in each indicator. Of the eight parameters, only in three (G, P/L, FN) the nonlinear nature of interaction with the conditions is weaker than the linear one (F_1), and in all others they are almost similar in value, as in PC and W they are even slightly higher. This is an indication that the individual parameters in the group of varieties change in different directions regardless of the direction of change of the conditions for their realization.

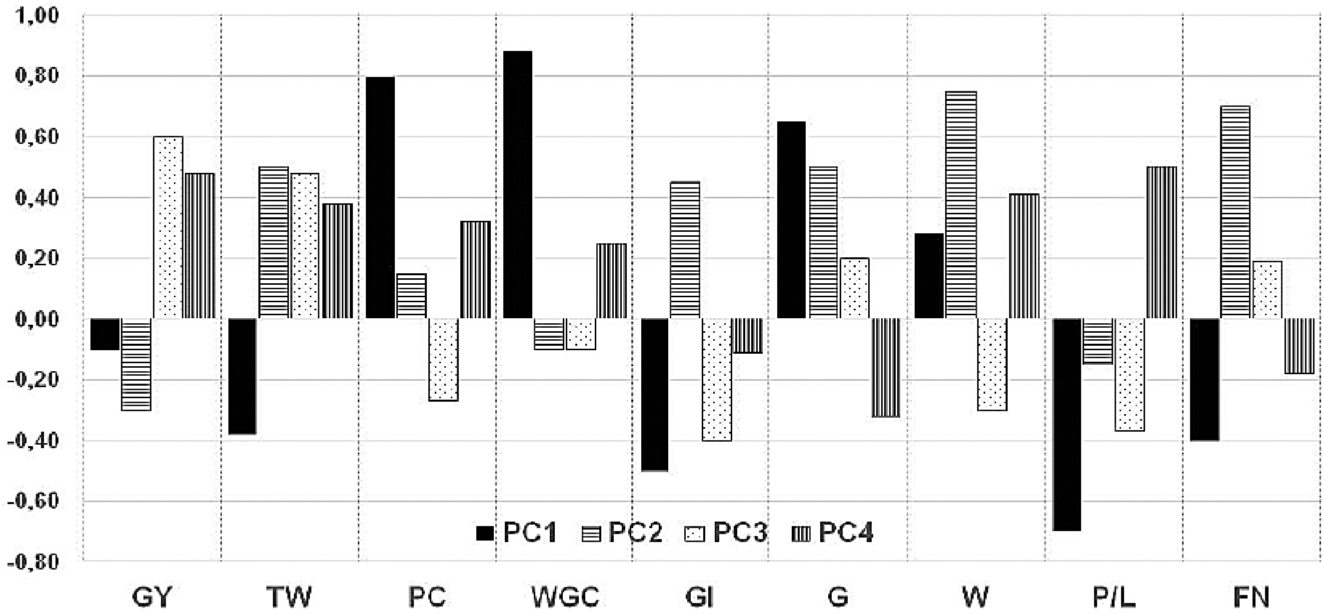

Figure 5. Loading plots of correlations between the principal components and traits (Past 4); (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index; (G)-Extensibility index, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (FN)-Falling number

Evidence for such a statement can be found if the data on the correlations between the eigenvalues of the parameters and the four components of variation identified are traced in detail (Figure 5). Each indicator changes extremely uniquely against the background of changes in conditions in direction and magnitude. It is generally accepted that it is normal for each successive component to decrease in value within a given indicator or attribute. The performance of the parameters PC, WGC and G is similar, while for the others it is more of an exception. An example of such an imbalance are the parameters TW, G, P/L, FN, and GY in which PC_1 has significantly lower values than the other three. The data on the correlations between the components and the values unequivocally prove that the interaction with the environmental conditions is complex, multi-layered and essential for the variation of each of them.

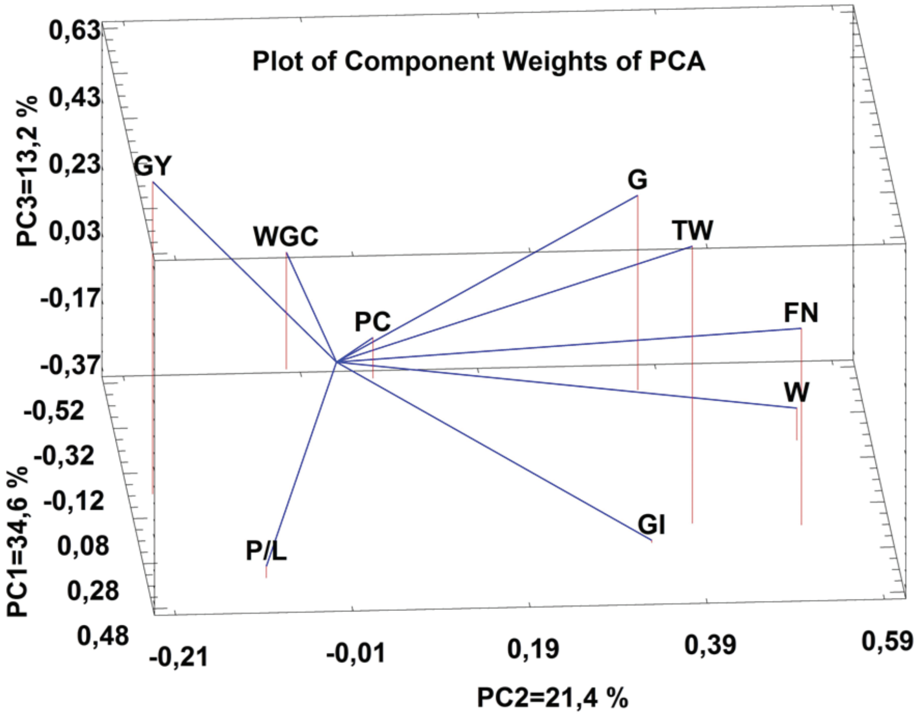

Figure 6. Principal component analysis of grain yield (GY) and investigated parameters of grain quality; (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index; (G)-Extensibility index, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (FN)-Falling number

There are no reliable correlations between grain yield and quality parameters (Figure 6). Relatively the highest, compared to other parameters, are the correlations GY-WGC and GY-PC, but within r = 0.12–0.14, (data not provided for brevity), which is practically absent of interdependence. This is an indication that each of the traits could be increased without adversely affecting grain yield. The vectors of the parameters of the figure make angles with each other, and the sharper it is, the higher the correlation between them and vice versa. This is a good idea of the complex relationships between the groups of parameters between them. Numerical data on the correlations of the quality parameters are provided in Table 6.

Table 6. Pearson Correlations between the parameters of grain quality

Indicator	W	TW	PC	WGC	GI	G	P/L	FN
TW	0.186	*0.0004*	*0.0000*	*0.0000*	*0.0000*	*0.0000*	*0.6312*	*0.0000*
PC	0.419	-0.195	*0.0002*	*0.0000*	*0.0120*	*0.6011*	*0.0002*	*0.0000*
WGC	0.247	-0.213	0.863	*0.0000*	*0.0000*	*0.0000*	*0.0000*	*0.0000*
GI	0.328	0.132	-0.318	-0541	*0.0000*	*0.0000*	*0.0000*	*0.0000*
G	0.424	-0.028	0.391	0.491	-0.080	*0.1281*	*0.0000*	*0.0000*
P/L	-0.025	0.192	-0.330	-0.469	0.268	-0.784	*0.0000*	*0.1027*
FN	0.212	0.557	-0.295	-0.341	0.245	0.086	0.088	*0.0964*

Values of the correlation coefficient (below the diagonal), above the diagonal - reliability at 0, 05% (*p-value*); (TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index, (FN)-Falling number, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (G)-Extensibility index.

There are correlations between the different parameters with different values and directions (Table 7). The W is the only one that has reliable correlations with all others, except the P/L ratio. The highest correlation is between PC and WGC (r = 0.863). The extensibility index (G) has positive correlations (r = 0.424, W; r = 0.391, PC; r = 0.491, WGC) with most of the parameters, high negative correlation with P/L (r = -0.784), and with parameters TW and GI the values are close to zero and show no correlations. The gluten index (GI) has a negative correlation with the PC (r = -0.318) WGC (r = -0.541). The number of falls FN is an indicator which correlates with the others very differently, positive (W, r = 0.212; TW, r = 0.557; GI, r = 0.245), negative (PI, r = -0.295; WGC, r = -0.341) or no correlation with G, (r = 0.086; and FN, (r = 0.088).

Table 7. Component of variance (σ^2), broad-sense heritability (H^2) and genetic advance (GA)

Parameters	Variances						H^2	GA	GAM
	GM	σ^2_g	σ^2_{gy}	σ^2_e	σ^2_g / σ^2_e	σ^2_{ph}			
GY	6.85	0.04	0.07	0.22	0.19	0.13	0.57	0.42	6.09
TW	76.95	0.29	0.86	1.92	0.15	1.070	0.42	1.10	1.43
PC	12.23	0.19	0.31	1.01	0.19	0.584	0.58	0.91	7.44
WGC	24.0	2.98	4.79	11.19	0.27	7.508	0.63	3.56	14.83
GI	83.6	13.0	190.1	110.6	0.12	81.52	0.40	7.42	8.88
G	16.2	0.79	4.89	4.24	0.19	3.021	0.63	1.83	11.30
W	176	202.8	1365.1	2379.1	0.09	1223.3	0.71	29.33	16.66
P/L	2.03	0.25	0.96	0.42	0.60	0.556	0.68	1.04	51.23
FN	366	127.0	1636.8	2695.6	0.05	1298.2	0.31	23.21	6.34

(TW)-Test Weight, (PC)-Protein content, (WGC)-Wet gluten content, (GI)-Gluten index, (FN)-Falling number, (W)-Deformation energy, (P/L)-Alveograph P/L ratio, (G)-Extensibility index

The genotype variants (σ^2_g) are significantly lower than those of the medium (σ^2_e) in grain yield and all parameters, without exception (Table 7). Significantly lower than zero ratios between the two variants (σ^2_g/σ^2_e) are in the direction of this statement. Strong variation as a result of combining the effects of the genotype with the conditions is the reason why the values of the inheritance coefficient (H^2) in the individual parameters are moderately high. According to them, the parameters of quality could be divided into three groups: low values (FN = 0.31; GI = 0.40; TW = 0.42), medium high (GY = 0.57; PC = 0.58; WGC = 0.63; G = 0.63) and relatively high (P/L = 0.68 and W = 0.71). The values of this ratio largely determine the effectiveness of the breeding in each indicator, regardless of the potential GA's ability to do so. This is the reason for the large differences in the values of relative genetic progress (GAM in %). According to them, the parameters could be grouped again as follows, 1- with very high genetic progress (P/L, 51.33%), 2- with high potential for progress (W, 16.66%; WGC, 14, 83%; G = 11.30%), 3- with low potential for increase (GY, 6.09%; PC, 7.44%, GI, 8.88%) and 4- with negligible potential for improvement- TW, 1.43%).

Discussion

The most variable of all parameters in this study were GY, and W which are important in the breeding efforts to combine the highest possible levels of yield and end-use quality. Each of them is the result of a main or combined effect of different factors.

Grain yield (GY) is influenced by all factors and their several combinations. Its absolute values and its change are strongly related to the specific locations, the meteorological conditions of the years, as well as the choice of specific varieties for research. Similar data from other studies in wheat (Chenu et al., 2011; Eltaher et al., 2021) are an indication of the need to collect data for specific varieties and test locations. This is where the need for at least a 3-year study arises, which will provide significantly more objective information about the effect of the “year” factor. Therefore, a number of authors consider it quite logical to make a selection of productivity for specific regions (locations) (Kaya and Akcura, 2014). The absence of reliable negative genetic correlations with grain quality parameters is a prerequisite for grain yield to be gradually increased (Herrera et al., 2020; Tsenov et al., 2020), and the level of quality to be maintained or increased by parallel breeding (Khazratkulova et al., 2015; Nazarenko et al., 2020), or by technological means in cultivation (density, early maturity or fertilization) (Bhatta et al., 2018; Horvat et al., 2021).

With the indicator W, which is the most widely used to assess the quality of grain even in its trade, the studied factors have very different influences. *First*: the varieties were selected so as to differ as much as possible on this indicator (Tsenov et al., 2021). *Second*: the factors location and year do not have a direct effect on its change. Only the genotype influences its values. In it, the interactions (A x B and B x C) have a direct impact. This combined effect causes differences in the values of the indicator in the group of varieties by locations and years, which, however, are slightly reliable. Probably these differences are small as a result of the fact that the interaction between the factors causes strong variation. With the indicator W there is a significantly stronger nonlinear interaction with the environmental factors, although the broad-sense heritability of the indicator is high. This is the main reason why Sanchez-Garcia et al., (2015) found significant progress in the breeding of this parameter in Spain, and Bornhofen et al. (2017) - in Brazil. Kaplan et al. (2020) are of the opinion that it is quite possible to conduct a successful selection on several basic quality parameters (W, WGC, GI) against the background of efforts to increase grain yield.

The values of the ratio of tenancy to extensibility (P/L) show an aspect of quality and are important for breeding. Sanchez-Garcia et al. (2015) studied the changes in the quality of grain and flour in Spain during the period 1930-2000. In modern varieties, there is a tendency for the P/L ratio to increase because tenancy increases (P) and extensibility decreases (L). This indicator is the most variable of all. Similar are the results reported by Li et al. (2013), when growing wheat in drought and high temperature. Its values are strongly influenced by each factor, as well as by the combination between them, with the exception of (location x genotype). This interaction with the factors has a pronounced nonlinear character, which is the reason why the genetics of the variety has the smallest share in its variation. Given that this indicator has negative correlations with the content of protein and gluten, it means that it is also quantified by them. According to Mirosavljević et al. (2020) in the process of breeding by yield there is a tendency for a significant decrease in PC and WGC, which in turn explains why the value of P/L increases in the most modern varieties (Sanchez-Garcia et al., 2015). In this regard, Maich et al. (2020) found that the reduction of PC in the grain does not adversely affect its quality. The opinions of Kaya and Akcura (2014) and Hristov et al. (2010b) were similar, especially if the known high-molecular alleles for high grain quality are monitored and selected in the breeding. Guzmán et al. (2016) believe that with a balance in P/L values, in drought conditions, durum wheat grain, in addition to pasta, could be used successfully for bakery products.

The parameters WGC, G, GI and FN showed a medium degree of variation in this experiment. With the exception of WGC, all others are influenced in a similar way by the studied factors. WGC alone is not affected by the interaction between the genotype with the location and the genotype with the year.

According to the change in the values in the experiment, these four parameters could be divided into two groups: *first*: WGC and G and *second*: GI and FN. The first two parameters have a higher coefficient of broad-sense heritability (0.63), which is a prerequisite for the possibility of breeding increase by more than 10% of the current level. The combination (location x year) has a significant influence on them, which is a prerequisite for effective selection, as other factors influence independently, but complicate the picture, and the linear component of PCA is almost as much as all the others. As a result of long-term breeding in order to combine high yield and maintaining high grain quality, there is a tendency for a significant decrease in WGC (Hristov et al., 2010a; Mirosavljević et al., 2020; Tsenov et al., 2010b). The amount of gluten in the grain is increasingly losing its importance as a selection value, because it has been replaced by an assessment of the qualitative composition of gluten through its various allelic states (Atanasova et al., 2009; Baenziger et al., 2001; De Santis et al., 2017). Tracking and accumulation of alleles that are associated with improving gluten quality has become a priority in selection to combine quality with yield (Thungo et al., 2020; Tsenov et al., 2010a). From this point of view, the amount of gluten no longer plays a significant role in the grain quality selection process, although it shows a positive correlation with a number of quality parameters (Denčić et al., 2011). On the other hand, tracking the accumulation of high-quality alleles of high and low molecular weight glutenins is already routine for breeding and shows good and stable results (Bonafede et al., 2015; Mirosavljević et al., 2020; Nehe et al., 2019).

Balkan (2018) showed that the tracking of WGC can lead to an effective increase in grain quality due to a coefficient of broad-sense heritability, the value of which is high enough, quite similar to those here.

The second group of parameters (GI and FN) has very low influence of the genotype, which is reflected in their low heritability rates. In both parameters, this is accompanied by significantly higher effects of the nonlinear (PC_2, PC_3 and PC_4) components. Their values could theoretically be increased by 6-8%, but this will negatively affect the efforts to increase the protein and gluten content, due to the strong negative correlations with the PC and WGC. On the other hand, Kaplan et al. (2020) and Balkan (2018) showed that selection on these two parameters can be effective if used in combination with other parameters such as W and sedimentation value. It follows that the breeding of grain quality (end-use) must include a number of its parameters that reflect various aspects of it in order to make progress, especially in efforts to combine high productivity (Johansson et al., 2020; Kiszonas and Morris, 2018).

The most stable values against the background of the simultaneous impact of the three factors are the indexes TW and PC. These are parameters that have a relatively positive relationship with grain yield, but according to Yabwalo et al. (2018) depend mainly on environmental conditions (90%). At the same time, the correlation between them is negative, but weak, which means that a selection on both grounds is meaningless. In addition, the TW index is associated with variable conditions, usually in the last stage of grain filling, (Taneva et al., 2019; Yabwalo et al., 2018), or weather with significant precipitation or dry wind. At the same time, the amount of protein is extremely important for its level of quality when it is as high as possible (Gut and Bichoński, 2007; Kaplan et al., 2020; Williams et al., 2008;). Based on the above, selection, especially on both parameters, is meaningless and difficult to achieve. Indeed, there are a number of studies that show a tendency to increase PC with prolonged breeding not directly but indirectly due to the weak negative correlation with yield or lack of significant relationship between them (Williams et al., 2008; Khazratkulova et al., 2015; Eichi et al., 2020). Other studies show that the amount of protein decreases with increasing grain yield (Hristov et al., 2010a; Bhatta et al., 2018), and its level could be adjusted by optimizing nitrogen fertilization (Gagliardi et al., 2020; Horvat et al., 2021; Valdés et al., 2020).

Conclusion

All quality parameters studied here are significantly affected by environmental conditions. The interactions between the factors "location x year" and "genotype x year" affect the variation of the parameters. The only exceptions in this respect are the PC and WGC, for which this interaction is not reliable. The interaction between "location x genotype" does not affect the manifestation of the parameters, but it does affect the grain yield. There is no strong correlation between grain yield and each individual quality indicator, which is not an obstacle to its breeding increase. There are both positive and negative correlations between the quality parameters, which the selection must comply with in order not to disturb the balance between them. The parameter W strongly depends on the genetics of the variety (genotype), it is not influenced by the independent action of the factors "location" and "year", but is strongly influenced by the interaction between them. In this study, it has a unique performance that differs from that of each of the other parameters. Despite the significant influence of the conditions on it, W could be increased after a selection by more than 15%. It is followed by the efficiency parameters of P/L and G, the values of which must be monitored according to the specific selection objectives. The P/L ratio is significantly affected by the presence of stress during grain formation and yet its selection increase is the most effective compared to the rest of this group (+ 50%). The WGC parameter and the inextricably linked PC could also make easy progress, but account must be taken of the fact that its increase leads to an overall reduction in grain yield, which is unacceptable from the point of view of wheat selection objectives. Instead of the amount of protein and gluten, their qualitative composition should be monitored due to the dynamic change of the gliadin/glutenin ratio, which is important from the point of view of yield formation and grain quality in variable grain filling conditions, annually.

References

Akçura M, 2009. Genetic variability and interrelationship among grain yield and some quality traits in Turkish winter durum wheat landraces. Turkish Journal of Agriculture and Forestry, 33, 547-556. https://doi.org/10.3906/tar-0903-5

Atanasova D, Tsenov N, Todorov I and Ivanova I, 2009. Glutenin composition of winter wheat varieties bred in Dobrudzha agricultural institute. Bulgarian Journal of Agricultural Science, 15, 9-19. http://www.agrojournal.org/15/01-02.htm

Baenziger PS, Shelton DR, Shipman MJ and Graybosch RA, 2001. Breeding for end-use quality: Reflections on the Nebraska experience. Euphytica, 119, 95-100. https://doi.org/10.1023/A:1017583514424

Balkan A, 2018. Genetic variability, heritability and genetic advance for yield and quality traits in M 2-4 generations of bread wheat (*Triticum aestivum* L.) genotypes. Turkish Journal of Field Crops, 23, 173-179. https://doi.org/10.7557/tjfc.485605

Békés F, 2012. New aspects in quality related wheat research: II. New methodologies for better quality wheat. Cereal Research Communications, 40, 307-333. https://doi.org/10.1556/CRC.2012.0003

Bhatta M, Regassa T, Rose DJ, Baenziger S, Eskridge P, Santra KD and Poudel R, 2018. Genotype, environment, seeding rate, and top-dressed nitrogen effects on end-use quality of modern Nebraska winter wheat. Journal of the Science of Food and Agriculture, 98, 2830. https://doi.org/10.1002/jsfa.8916

Bilgin OG, Guzmán C, Başer I, Crossa J and Korkut KZ, 2016. Evaluation of grain yield and quality traits of bread wheat genotypes cultivated in Northwest Turkey. Crop Science, 56, 73-84. https://doi.org/10.2135/cropsci2015.03.0148

Bonafede MD, Tranquilli G, Pflüger LA, Peña RJ and Dubcovsky J, 2015. Effect of allelic variation at the Glu-3/Gli-1 loci on breadmaking quality parameters in hexaploid wheat (*Triticum aestivum* L.). Journal of Cereal Science, 62, 143-150. https://doi.org/10.1016/j.jcs.2015.02.001

Bornhofen E, Benin G, Storck L, Marchioro VS, Meneguzzii C, Miliolii AS and Trevizani DM, 2017. Environmental effect on genetic gains and its impact on bread-making quality traits in Brazilian spring wheat. Chilean Journal of Agricultural Research, 77, 27-34. https://doi.org/10.4067/s0718-58392017000100003

Brancovic G, Dodig D, Pajic V, Kandic V, Knezevic D, Đuric N and Živanovic T, 2018. Genetic parameters of *Triticum aestivum* and *Triticum durum* for technological quality properties in Serbia. Zemdirbyste-Agriculture, 105, 39-48. http://dx.doi.org/10.13080/z-a.2018.105.006

Bushuk W, 1998. Wheat breeding for end-product use. Euphytica, 100, 137-145. https://doi.org/10.1023/A:1018368316547

Chamurliyski P, Tsenov N, Stoeva I, Doneva S and Penchev E, 2016. Quality of grain and flour of foreign bread wheat cultivars (*Triticum aestivum* L.), under the conditions of South Dobrudzha region. Agricultural Science and Technology, 8, 283-288. http://dx.doi.org/10.15547/ast.2016.04.054

Chenu K, Cooper M, Hammer GL, Mathews KL, Dreccer MF and Chapman S, 2011. Environment characterization as an aid to wheat improvement: interpreting genotype–environment interactions by modelling water-deficit patterns in North-Eastern Australia. Journal of Experimental Botany, 62, 1743-1755. https://doi.org/10.1093/jxb/erq459

D'Amico I, Silva M, Moriconi JI, Santa-María GE, Bainotti CT and Tabbita F, 2021. Grain mineral composition of Argentinean-adapted wheat cultivars: a case study. Crop and Pasture Science, 72, 113-124. https://doi.org/10.1071/CP20380

De Santis MA, Giuliani MM, Giuzio L, De Vita P, Lovegrove A, Shewry PR and Flagella Z, 2017. Differences in gluten protein composition between old and modern durum wheat genotypes in relation to 20th century breeding in Italy. European Journal of Agronomy, 87, 19-29. https://doi.org/10.1016/j.eja.2017.04.003

Denčić S, Mladenov N and Kobiljski B, 2011. Effects of genotype and environment on breadmaking quality in wheat. International Journal of Plant Production 5, 71-81. www.ijpp.info

Eichi VR, Okamoto M, Garnett T, Eckermann P, Darrier B, Riboni M and Langridge P, 2020. Strengths and weaknesses of national variety trial data for multi-environment analysis: a case study on grain yield and protein content. Agronomy, 10, 753. https://doi.org/10.3390/agronomy10050753

Eltaher S, Baenziger PS, Belamkar V, Emara HA, Nower AA, Salem FM, Alqudah AM and Sallam A, 2021. GWAS revealed effect of genotype × environment interactions for grain yield of Nebraska winter wheat. BMC Genomics, 22, 2. https://doi.org/10.1186/s12864-020-07308

Fleitas MC, Mondal S, Gerard GS, Hernández-Espinosa N, Singh RP, Crossa J and Guzmán C, 2020. Identification of CIMMYT spring bread wheat germplasm maintaining superior grain yield and quality under heat-stress. Journal of Cereal Science, 93, 102981. https://doi.org/10.1016/j.jcs.2020.102981

Gagliardi A, Carucci F, Masci S, Flagella Z, Gatta G and Giuliani M, 2020. Effects of genotype, growing season and nitrogen level on gluten protein assembly of durum wheat grown under Mediterranean conditions. Agronomy, 10, 755. https://doi.org/10.3390/agronomy10050755

Gómez-Becerra HF, Abugalieva A, Morgounov A, Abdullayev K, Bekenova L, Yessimbekova M, Sereda, G, Shpigun S, Tsygankov V, Zelenskiy Y, Peña RJ and Cakmak I, 2009. Phenotypic correlations, G × E interactions and broad sense heritability analysis of grain and flour quality characteristics in high latitude spring bread wheats from Kazakhstan and Siberia. Euphytica, 171, 23-38. https://doi.org/10.1007/s10681-009-9984-6

Gut M and Bichoński A, 2007. Technological quality and yield's components of winter wheat lines under Polish climatic conditions. Cereal Research Communications, 35, 151-161. https://doi.org/10.1556/CRC.35.2007.1.17

Guzmán C, Autrique JE, Mondal S, Singh RP, Govindan V, Morales-Dorantes A, Posadas-Romano G, Crossa J, Ammar K and Peña RJ, 2016. Response to drought and heat stress on wheat quality, with special emphasis on bread-making quality, in durum wheat. Field Crops Research, 186, 157-165. https://doi.org/10.1016/j.fcr.2015.12.002

Harshwardhan H, Kumar A, Kumar A and Prasad B, 2016. Study of variance, heritability and genetic advance for various yield contributing and quality traits in spring wheat (*Triticum aestivum* L.). Journal of Applied and Natural Science, 8, 1811-1814. https://doi.org/10.31018/jans.v8i4.1045

Helguera M, Abugalieva A, Battenfield S, Békés F, Branlard G, Cuniberti M, Hüsken A, Johansson E, Morris CF, Nurit E, Sissons M and Vazquez D, 2020. Grain Quality in Breeding. In: Igrejas G., Ikeda T., Guzmán C. (eds) Wheat quality for improving processing

and human health. Springer, Cham., pp. 273-307. https://doi.org/10.1007/978-3-030-34163-3_12
Herrera JM, Häner L, Mascher F, Hiltbrunner J, Fossati D, Brabant C, Charles R and Pellet D, 2020. Lessons from 20 years of studies of wheat genotypes in multiple environments and under contrasting production systems. Frontiers in Plant Science, 10. https://doi.org/10.3389/fpls.2019.01745
Horvat D, Šimić G, Dvojkovic K, Ivic M, Plavšin I and Novoselovic D, 2021. Gluten protein compositional changes in response to nitrogen application rate. Agronomy, 11, 325. https://doi.org/10.3390/agronomy11020325
Hristov N, Mladenov N, Djuric V, Kondic-Spika A and Marjanovic-Jeromela A, 2010a. Genotype by environment interactions in wheat quality breeding programs in southeast Europe. Euphytica, 174, 315-324. https://doi.org/10.1007/s10681-009-0100-8
Hristov N, Mladenov N, Djuric V, Kondic-Spika A and Marjanovic-Jeromela A, 2010b. Improvement of wheat quality in cultivars released in Serbia during the 20 century. Cereal Research Communications, 38, 111-121. https://doi.org/10.1556/crc.37.2009.4.9
Ivanova A, Tsenov N and Stoeva I, 2013. Grain quality of common wheat according to variety and growing conditions in the region of Dobrudzha. Bulgarian Journal of Agricultural Science, 19, 523-329. http://agrojournal.org/ARH.htm
Jernigan KL, Godoy JV, Huang MZY, Morris CF, Garland-Campbell KA, Zhang Z and Carter AH, 2018. Genetic dissection of end-use quality traits in adapted soft white winter wheat. Frontiers in Plant Science, 9, 271. https://doi.org/10.3389/fpls.2018.00271
Johansson E, Branlard G, Cuniberti M, Flagella Z, Hüsken A, Nurit E, Peña RJ, Sissons M and Vazquez D, 2020. Genotypic and environmental effects on wheat technological and nutritional quality. In: Igrejas, G., Ikeda, T. M. and Guzmán C. (Eds), Wheat quality for improving processing and human health. Springer, pp. 171-204. https://doi.org/10.1007/978-3-030-34163-3
Kaplan EA, Pehlivan A, Sanal T, Salantur A, Kilic G, Dugan G, Boyaci IH and Koksel H, 2020. Utilization potential of glutograph in wheat breeding programs and the influence of genotype and environment on bread wheat quality. Cereal Chemistry, 97, 634-641. https://doi.org/10.1002/cche.10279
Kaya Y and Akcura M, 2014. Effects of genotype and environment on grain yield and quality traits in bread wheat (*T. aestivum* L.). Food Science and Technology, Campinas, 34, 386-393. https://doi.org/10.1590/fst.2014.0041
Khazratkulova S, Sharma RC, Amanov A, Ziyadullaev Z, Amanov O, Alikulov S, Ziyaev Z and Muzafarova D, 2015. Genotype × environment interaction and stability of grain yield and selected quality traits in winter wheat in Central Asia. Turkish Journal of Agriculture and Forestry, 39, 920-929. https://doi.org/10.3906/tar-1501-24
Kiszonas AM and Morris CF, 2018. Wheat breeding for quality: A historical review. Cereal Chemistry, 95, 17-34. https://doi.org/10.1094/CCHEM-05-17-0103-FI
Li Y, Wu Y, Hernandez-Espinosa N and Peña RJ, 2013. The influence of drought and heat stress on the expression of end-use quality parameters of common wheat. Journal of Cereal Science, 57, 73-78. https://doi.org/10.1016/j.jcs.2012.09.014
Maich RH, Manera GA, Londero WH, Vanzetti LS, Helguera M and Di Rienzo JA, 2020. Changes in yield determinants and quality traits in wheat after 12 cycles of recurrent selection. Cereal Research Communications, 48, 533-538. https://doi.org/10.1007/s42976-020-00053-w
Mc Fall LK and Fowler ME, 2009. Overview of wheat classification and trade. In: Carver, B.F. (Ed), Wheat: science and trade, Wiley-Blackwell, London, pp 439-454. http://dx.doi.org/10.1002%2F9780813818832.ch19
Mirosavljević M, Momčilović V, Živančev D, Aćin V, Jocković B, Mikić S, Takač V and Denčić S, 2020. Genetic improvement of grain yield and bread-making quality of winter wheat over the past 90 years under the Pannonian Plain conditions. Euphytica, 216, 184. https://doi.org/10.1007/s10681-020-02724-5
Motta-Romero H, Niyongira F, Boehm JD and Rose DJ, 2021. Effects of foliar fungicide on yield, micronutrients and cadmium in grains from historical and modern hard winter wheat genotypes. PLoS ONE, 16, e0247809. https://doi.org/10.1371/journal.pone.0247809
Mutwali NIA, Mustafa AI, Gorafi YSA and Mohamed AIA, 2015. Effect of environment and genotypes on the physicochemical quality of the grains of newly developed wheat inbred lines. Food Science and Nutrition, 4, 508-520. https://doi.org/10.1002/fsn3.313
Nazarenko M, Mykolenko S and Okhmat P, 2020. Variation in grain productivity and quality of modern winter wheat varieties in northern Ukrainian Steppe. Ukrainian Journal of Ecology, 10, 102-108. https://doi.org/10.15421/2020_175
Nehe A, Akin B, Sanal T, Evlice AK, Ünsal R, Dinçer N, Demir L, Geren H, Sevim I, Orhan Ş, Yaktubay S, Ezici A, Guzman C and Morgounov A, 2019. Genotype x environment interaction and genetic gain for grain yield and grain quality traits in Turkish spring wheat released between 1964 and 2010. PLOS ONE, 14, e0219432.

https://doi.org/10.1371/journal.pone.0219432
Nuttall JG, O'Leary GJ, Panozzo JF, Walker CK, Barlow KM and Fitzgerald GJ, 2017. Models of grain quality in wheat-A review. Field Crops Research, 202, 136-145. https://doi.org/10.1016/j.fcr.2015.12.011
Peterson CJ, Graybosch RA, Baenziger PS and Grombacher AW, 1992. Genotype and environment effects on quality characteristics of hard red winter wheat. Crop Science, 32, 98-103. https://doi.org/10.2135/cropsci1992.0011183X003200010022x
Sanchez-Garcia M, Álvaro F, Peremarti A, Martín-Sánchez JA and Royo C, 2015. Changes in bread-making quality attributes of bread wheat varieties cultivated in Spain during the 20th century. European Journal of Agronomy, 63, 79-88. https://doi.org/10.1016/j.eja.2014.11.006
Shewry PR, 2009. Wheat. Journal of Experimental Botany, 60, 1537-1553. https://doi.org/10.1093/jxb/erp058
Silva RR, Zucareli C, Fonseca ICB, Gazola D and Riede CR, 2019. Influence of nitrogen, environment, and cultivars on the industrial quality of wheat. Semina: Ciências Agrárias, 40, 2571. https://doi.org/10.5433/1679-0359.2019v40n6p257
Snedecor GW and Cochran WG, 1980. Statistical methods. 7th Edition, Iowa State University Press, pp. 593.
Studnicki M, Wijata M, Sobczyński G, Samborski S and Rozbicki J, 2018. Assessing grain yield and quality traits stability of spring wheat cultivars at different crop management levels. Cereal Research Communications, 46, 180-190. https://doi.org/10.1556/0806.45.2017.066
Taneva K, Bozhanova V and Petrova I, 2019. Variability, heritability and genetic advance of some grain quality traits and grain yield in durum wheat genotypes. Bulgarian Journal of Agricultural Science, 25, 288-295. https://journal.agrojournal.org/page/download.php?articleID=1759
Thungo Z, Shimelis H, Odindo A and Mashilo J, 2020. Genotype-by-environment effects on grain quality among heat and drought tolerant bread wheat (*Triticum aestivum* L.) genotypes. Journal of Plant Interactions, 15, 83-92. https://doi.org/10.1080/17429145.2020.1748732
Tsenov N, Atanasova D, Chamurliiski P and Stoeva I, 2013. Influence of extreme environmental changes on grain quality of winter common wheat (*Triticum aestivum* L.). Bulgarian Journal of Agricultural Science, 19, 685-690. https://journal.agrojournal.org/page/en/details.php?article_id=1502
Tsenov N, Atanasova D, Stoeva I and Tsenova E, 2015. Effect of drought on productivity and grain quality in winter wheat. Bulgarian Journal of Agricultural Science, 21, 589-595. https://journal.agrojournal.org/page/en/details.php?article_id=463
Tsenov N, Atanasova D, Todorov I, Ivanova I and Stoeva I, 2010a. Quality of winter common wheat advanced lines depending on allelic variation of *Glu-A3.* Cereal Research Communications, 38, 250-258. https://doi.org/10.1556/CRC.38.2010.2.11
Tsenov N, Gubatov T and Yanchev I, 2020. Correlations between grain yield and related traits in winter wheat under multi-environmental traits. Agricultural Science and Technology, 12, 295-300. DOI: 10.15547/ast.2020.04.047.
Tsenov N, Gubatov T and Yanchev I, 2021. Genotype selection for grain yield and quality based on multiple traits of common wheat (*Triticum aestivum* L.). Cereal Research Communications, 49, 119-124. https://doi.org/10.1007/s42976-020-00080-7
Tsenov N, Stoeva I and Atanasova D, 2010b. Breeding of end-use quality of winter wheat in Dobrudzha Agricultural Research Institute – present and prospects. Field Crop Studies, 6, 217-234 (Bg).
Valdés VC, Estrada-Campuzano G, Martinez-Rueda CG, Domínguez-López A, Solis-Moya E and Villanueva CA, 2020. Grain and flour wheat quality modified by genotype, availability of nitrogen, and growing season. International Journal of Agronomy, 1-9. https://doi.org/10.1155/2020/1974083
Wieser H, Koehler P and Scherf KA, 2020. The two faces of wheat. Frontiers in Nutrition, 7, 517313. https://doi.org/10.3389/fnut.2020.517313
Williams RM, O'Brien L, Eagles HA, Solah VA and Jayasena V, 2008. The influences of genotype, environment, and genotype×environment interaction on wheat quality. Australian Journal of Agricultural Research, 59, 95. https://doi.org/10.1071/ar07185
Yabwalo DN, Berzonsky WA, Brabec D, Pearson TK, Glover D and Jonathan LK, 2018. Impact of grain morphology and the genotype by environment interactions on test weight of spring and winter wheat (*Triticum aestivum* L.). Euphytica, 214, 125. https://doi.org/10.1007/s10681-018-2202-7
Zecevic V, Knezevic D, Boskovic J, Micanovic D and Dozet G, 2010. Effect of nitrogen fertilization on winter wheat quality. Cereal Research Communications, 38, 243-249. https://doi.org/10.1556/CRC.38.2010.2.10
Zhang G, Chen RY, Shao M, Bai G and Seabourn BW, 2020. Genetic analysis of end-use quality traits in wheat. Crop Science, 61, 1709-1723. https://doi.org/10.1002/csc2.20411