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ANALYSIS OF GENOTYPE X ENVIRONMENT INTERACTION IN TRITICALE LINES WITH AMMI AND PCA

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Abstract

In order to determine to what degree the different conditions affected the stability of certain triticale genotypes and to what extent they determined the effect of the genotype x environment interaction, 12 lines of winter hexaploid triticale were studied under contrasting growing periods. The results from the AMMI-analysis showed that the GxE interaction accounted for 14.8% of the total variation of yield, while four significant principal components could explain 96% of its variance. The PCA analysis demonstrate that the first component related to the action of the meteorological conditions during 2015/2016 and 2019/2020 growing periods, and had the highest effect on the interaction. The AMMI-based biplot graphs revealed that the behavior of the local check Kolorit and lines G2 and G7 was the most stable according to the different periods affecting the genotype x environment interaction, while G1, G6 and G11 also had lower interaction with the conditions of the environment, but only during certain periods. Such characteristics allowed involving these lines in testing under the varied soil and climatic conditions of Bulgaria.

***Key words**: genotype x environment interaction, triticale, stability.*

INTRODUCTION

The main purpose of plant breeding is developing genotypes of cultivated plants that would meet certain food and industrial requirements. This is related to the constantly increasing demand for quality plant raw materials in accordance with the growing world population and the increasingly higher requirements of the agricultural producers. In this respect, the yield as a resultant value from a given plant production becomes a major breeding goal aiming qualitative and quantitative improvement.

There are various concepts for increasing the values of the yield from crops. Some of them include thorough analysis on the yield related traits, other focus entirely on the yield and its behavior under variable environments (Stoyanov, 2021). One of the most widely used methods for evaluation of the yield performance under a certain combination of soil and climatic conditions is to determine its stability. According to the definition of Mariotti et al. (1976), stability is the ability of the genotype to realize predictable values under different conditions of the environment. At the same time, Becker and Leon (1988) defined two types of stability: static (biological) - the genotype is stable if its yield varies insignificantly under variable environments, and dynamic - stable is considered a genotype with yield, which is similar to the averaged expression of a set of genotypes, i.e. the genotype x environment interaction approaches zero. A most commonly used dynamic model for determining the stability of the yield from a group of studied genotypes is the AMMI analysis. A peculiarity of this model is that it allows by nature to combine additive and multiplicative parameters into a single analysis (Gauch, 1992), since it uses simultaneously the advantages of the ANOVA and the principal components analysis (PCA).

In the recent years, a great variation in the conditions for growing of winter cereals is being observed in Bulgaria and in the region of South Dobrudzha, in particular; the greater part of these conditions can be described as extremely unfavorable. During 2015/2016, rather untypical high amounts of rainfalls were observed in June, and in 2019/2020 extreme levels of drought were registered during the active vegetative growth of such crops as wheat and triticale. At the same time, 2014/2015 and 2016/2017 were characterized as exceptionally favorable for the growing of these crops. Such peculiarities and the continuous meteorological variations of the environmental conditions were a prerequisite for great differences in the behavior of certain genotypes during the separate growing periods. In a crop as triticale, which is amphidiploid by nature, the genotype x environment interaction is rather important because the more complex genotypes interact in a significantly more complex manner with the conditions of the environment (Stoyanov, 2021). This implies that the multiplicative parameters are much more important for determining of the yield value. Such a dependency makes the use of AMMI in triticale an efficient tool for ranking of a certain investigated set of genotypes. The researches of Gelalcha et al. (2007), Kendal et al. (2016), Kendal et al. (2019), Oral (2018), Lule et al. (2014), as well as our own studies (Stoyanov et al., 2017; Stoyanov, 2018) confirm the high efficiency of the method for identifying genotypes, which are valuable from a breeding point of view. On the other hand, such researches often do not focus on the effect of the environmental conditions during the separate periods on the stability of a given genotype. Motzo et al. (2001) pointed out that the genotype x environment interaction with regard to yield is influenced by certain conditions of the environment. On the other hand, different researchers have observed different stability depending on the specific periods of study. Such peculiarities require detailed investigation on the genotype x environment interaction determined on the basis of AMMI.

The aim of this study was to determine the degree to which the different conditions of the environment affect the stability of certain triticale genotypes and the degree to which they determine the genotype x environment effect.

MATERIALS AND METHODS

To realize the above aim, the data on the yield from twelve breeding lines described in detail in Stoyanov and Baychev (2021) were used. The studied lines were grown as whole area crop in 10 m^2 experimental plots in four replications according to a standard block design within a competitive varietal trial. Sowing was mechanized and was done within the standard dates for triticale, at crop density of 550 seeds per m^2. Besides the above cultivars, the experiment involved the triticale local checks AD-7291, Vihren and Rakita. The plots were harvested at full maturity, reading the yield from each of them separately.

Table 1. Lines used during the period of study

No.	Name	Pedigree
1	AD-7291	Local check
2	Vihren	Local check
3	Rakita	Local check
4	Kolorit	Local check
5	G1	5741-43 / 2853-1044
6	G2	46/96-244 / 129/98
7	G3	115/96-238 / 129/98-81
8	G4	161/98-133 / Respekt
9	G5	18/95-159 / Akord
10	G6	Akord / Respekt
11	G7	Akord / Respekt
12	G8	49/97-142 / 18/95-89
13	G9	Akord / 54/03
14	G10	61/97-215 /88/96-222
15	G11	Respekt / Kolorit
16	G12	Respekt / 110/03

The data were obtained within six consecutive harvest years - 2014/2015, 2015/2016, 2016/2017, 2017/2018, 2018/2019, 2019/2020. Concerning the mean monthly temperature and the sum of precipitation, the studied period can be characterized as rather contrasting. Extremely unfavorable meteorological processes were observed during certain periods. These were respective highly intensive and long-lasting rainfalls in May (2015/2016), untypical daily rainfalls in July (2017/2018) and severe droughts during February-March (2018/2019). Highly unfavorable for growing of triticale was 2019/2020 due to the rather long drought during March-April. At the same time, most favorable for growing of triticale were the conditions in 2014/2015, when the lowest number of negative events were observed during the vegetative growth of the plants.

The data used were processed through AMMI-analysis. Based on the obtained IPCA values and factors, biplots were constructed, with the mean yields on the abscissa, and the respective IPCA values up to the highest significant IPC on the ordinate. Based on the yield means, the values of the interaction were calculated according to Gauch (1992), where $\theta_{ge} = \overline{Y}_{ge} - \overline{Y}_g - \overline{Y}_e + \overline{Y}$,

where:

θ_{ge} - effect of the environment x genotype interaction;

Y_{ge} - mean yield from the gth genotype at the eth conditions of the environment;

Y_g - mean yield from the gth genotype;

Y_e - mean yield from the eth conditions of the environment;

Y - mean yield from all genotypes and conditions of the environment.

PCA analysis was performed by θ_{ge} values to determine the principal components in the formation of the interaction. Varimax rotation was applied for better interpretation of the data (Manly and Alberto, 2017). Based on the rotated varimax correlation matrix, the conditions of the environment, which were most important for the formation of the genotype x environment interaction, were specified. To summarize the data and calculate the θ_{ge} values, MS Office Excel, 2003 was used, to carry out AMMI analysis -AMMISOFT, and for the analysis of the principal components – IBM SPSS Statistics, v. 19.

RESULTS AND DISCUSSIONS

The applied AMMI analysis (Table 2) allowed following the effect of the separate factors, which influenced the yield values and determining their effect on its variation. The environment accounted for the largest percent from the total variation in the investigated cultivars and contrasting conditions - 45.026% from the total variation in the experiment. Such high values are typical for such a crop as triticale, as well as other cereals. The researches of Dogan et al. (2009) and Kendal et al. (2019) confirm these results in triticale. Significant was the effect of the genotype on the variation of yield - 23.369%. In our previous studies (Stoyanov & Baychev, 2016; Stoyanov, 2018; Stoyanov, 2020), the genotype accounted for 11-13% of the variation. Such a behavior shows that in this investigation the genotypes differed significantly and clear differences were observed between the separate lines and checks subjected to study. In fact, in our previous research (Stoyanov & Baychev, 2021), the results from the investigated cultivars undoubtedly demonstrated that the lines were with much higher productivity in comparison to the local and world checks. Such values have been rarely reported on the triticale genotypes; they often vary between 1 and 10% from the total variation (Gelalcha et al., 2007; Dogan et al., 2011; Kaya & Ozer, 2014; Kendal et al., 2019), while the effect of the environment may reach up to 98% (Kendal et al., 2019). Obuchowski et al. (2010) and Grzesiak et al. (2012) have also reported a high effect of the genotype on the yield from triticale.

Table 2. AMMI analysis of the variance in the studied triticale lines

Source	df	SS	MS	Sig.	SS%
Treatments	95	4808062.977	50611.189	0.000	84.290
Genotypes	15	1333015.914	88867.728	0.000	23.369
Environments	5	2568390.961	513678.192	0.000	45.026
GxE	75	906656.102	12088.748	0.000	15.895
IPC1	19	447628.364	23559.388	0.000	49.371
IPC2	17	230772.220	13574.837	0.000	25.453
IPC3	15	134073.135	8938.209	0.000	14.788
IPC4	13	58408.113	4492.932	0.001	6.442
Residual	11	35774.270	3252.206	0.045	3.946
Error	288	896139.125	3111.594		
Total	383	5704202.102	14893.478		

The genotype x environment interaction accounted for 15.895% of the total variation in our experiment and was significant. The researches of different authors (Gelalcha et al., 2007; Akbarian et al., 2011; Dogan et al., 2011; Lule et al., 2014; Kaya & Ozer, 2014; Kendal & Sayar, 2016; Kendal et al., 2019; Bocianowski et al., 2021) confirm the significance of the interaction in various studied genotypes and conditions of the environment. Only the results of Dogan et al. (2009) did not show significant effect in the triticale lines they investigated both of the genotype and the genotype x environment interaction with regard to yield. A peculiarity of the genotypes we studied was their differing genetic basis, which was a prerequisite for the different ranking of the yield values under contrasting growing conditions. Only lines G6 and G7 were with origin from the same cross but their behavior was not identical as evident from the data on their yield during the separate periods of growing (Stoyanov & Baychev, 2021).

The results from the AMMI analysis showed that the genotype x environment interaction was determined by four components, which formed 95% of the total variation. It is interesting to mention that the first component (IPC1) accounted for only 49% of the interaction. Such a behavior showed that the formation of the yield under such contrasting conditions of the environment is of rather complex and not unambiguous nature. At the same time, the first and second components accounted for almost 75% of the interaction, but even this was not sufficient to explain the behavior of the yield and its stability in the experiment we carried out. According to Gauch and Zobel (by Lule et al., 2014), the first two components were sufficient to obtain a precise model of the interaction. This thesis, however, was later modified, the number of the components that would explain the model largely depending on the crop, as well as on the accessions used and the conditions of the environment (Lule et al., 2014).

In the experiment we conducted, significant were four components, which further confirmed the complexity of the interaction. Four significant components were also reported by Gelalcha et al. (2007) when investigating twenty-two spring forms of triticale under the conditions of Ethiopia.

Although the AMMI analysis showed that the interaction was of complex nature, its components could not explain the exact reason for such a behavior of the yield. The principal components analysis on the values of the interaction θ_{ge} (Table 3) showed the actual presence of four principal components related to the variation of the yield values. The results also revealed a fifth component with rather low eigenvalues. Such values could not relate it significantly to the effect of a specific factor on the interaction.

The rotated varimax correlation matrix (Table 4) linked each of the contrasting periods in the investigation to a certain component of the interaction. The first component was in highest correlation with the θ_{ge} values for 2015/2016 and 2019/2020. This indicated that the conditions of the environment during these two growing periods had the highest effect on the variation of the values of the genotype x environment interaction. These two periods were characterized by extremely unfavorable and untypical conditions of the environment for growing of triticale. In 2015/2016, the intensive rainfalls in May and June were the reason for the lower seed set, but also for the considerably more difficult grain filling. The rather severe drought in 2019/2020, on the other hand, was the reason for the radically different performance of the crop - high number of grains in spike for which sufficient grain filling could not be provided. This was the reason also for the opposite signs of the correlation coefficient values of the two periods according to the first component.

Table 3. Principal component analysis on the studied triticale cultivars during economic year 2014/2015

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.492	41.535	41.535	2.492	41.535	41.535	1.331	22.188	22.188
2	1.847	30.787	72.322	1.847	30.787	72.322	1.194	19.898	42.086
3	0.869	14.481	86.803	0.869	14.481	86.803	1.192	19.860	61.947
4	0.500	8.334	95.137	0.500	8.334	95.137	1.155	19.247	81.194
5	0.292	4.863	100.000	0.292	4.863	100.000	1.128	18.805	99.999
6	0.000	0.000	100.000	0.000	0.000	100.000	0.000	0.001	100.000

Table 4. Rotated varimax correlation matrix by values of interaction during the separate investigated periods

	Component					
	1	2	3	4	5	6
2014/2015	-0.232	0.166	-0.265	0.913	-0.120	0.000
2015/2016	-0.699	-0.498	-0.476	-0.056	-0.186	0.007
2016/2017	0.100	0.923	-0.141	0.156	-0.307	0.000
2017/2018	0.208	-0.132	0.923	-0.291	0.055	0.000
2018/2019	-0.067	-0.222	0.063	-0.080	0.967	0.000
2019/2020	0.855	0.009	0.140	-0.450	-0.215	0.003

Table 5. AMMI analysis of the variance of the investigated triticale lines according to the effects of the separate periods of study

Source	df	SS	MS	Sig.	SS%
Treatments	95	4808062.977	50611.189	0.000	84.290
Genotypes	15	1333015.914	88867.728	0.000	23.369
Environments	5	2568390.961	513678.192	0.000	45.026
GxE	75	906656.102	12088.748	0.000	15.895
IPC1 (2015/2016 + 2019/2020)	19	447628.364	23559.388	0.000	49.371
IPC2 (2016/2017)	17	230772.220	13574.837	0.000	25.453
IPC3 (2017/2018)	15	134073.135	8938.209	0.000	14.788
IPC4 (2014/2015)	13	58408.113	4492.932	0.001	6.442
Residual (2018/2019)	11	35774.270	3252.206	0.045	3.946
Error	288	896139.125	3111.594		
Total	383	5704202.102	14893.478		

The second component was in high correlation with the values of the genotype x environment interaction in 2016/2017 growing period. This was related to the highly different values of the yield during this period according to other favorable periods leading to different ranking of the investigated genotypes. Therefore, the second component accounted for over 30% of the variation of θ_{ge}.

The third component, on its part, correlated with the interaction values of 2017/2018 growing period. In this period, the late and long-lasting rainfalls in July contributed to the decrease of the yields and of such traits as 1000 kernel weight and test weight (Stoyanov, 2020). Lower yields were obtained from the studied lines in comparison to the periods favorable for growing of triticale, and the ranking of the genotypes was also different. It should be emphasized, however, that the yield decrease was not as high as in 2015/2016 and 2019/2020, and therefore the effect of this factor was considerably lower - 14.481%.

Concerning the fourth component, it was in highest correlation with the values of θ_{ge} for economic year 2014/2015. Although this was the most favorable period for growing of triticale in the study, the results from the investigated lines revealed different behavior with regard to their ranking according to most of the periods. Nevertheless, the effect of this component was comparatively low - 8.334%, confirming the fact that the favorable conditions of the environment influenced the genotype x environment interaction to a lesser degree than the unfavorable ones.

The fifth component accounted for less than 5% of the θ_{ge} variation, which was insignificant according to the total effect of the other factors and can rather be considered a residual effect. Nevertheless, this component was in highest correlation with the values of the interaction of 2018/2019.

To summarize the presented results: the meteorological conditions of 2015/2016 and 2019/2020 had the highest effect on the genotype x environment interaction. This means that during these two periods the individual lines significantly changed their behavior with regard to yield and their stability was affected to a highest degree. On the other hand, the favorable meteorological conditions during economic year 2014/2015 had a significantly lower effect on the environment x genotype interaction and were less important for the stability of the yield. In this respect, the results from Table 2 become considerably clearer when presented as Table 5.

In spite of the possibility to determine the effect of each contrasting condition of the environment on the genotype x environment interaction itself, it is highly important for the practice to assess to what degree the individual periods influence the stability of the studied genotypes. Different researchers have used AMMI1 biplot to compare the mean yields to IPCA1 values, and AMMI2 biplot to compare IPCA1 and IPCA2 values as a result from a conventional AMMI analysis.

An example in this respect are the researches on triticale of Lozano del Rio et al. (2009) and Lule et al. (2014). When, however, each of the IPC components can be related to the effect of the meteorological conditions during a certain period, the IPCA values of each component may be compared in a biplot to the mean yield thus determining a tendency in the stability according to the specific conditions of the environment. Figure 1 presents an AMMI1 biplot comparing the mean values of the yield to the values of IPCA1.

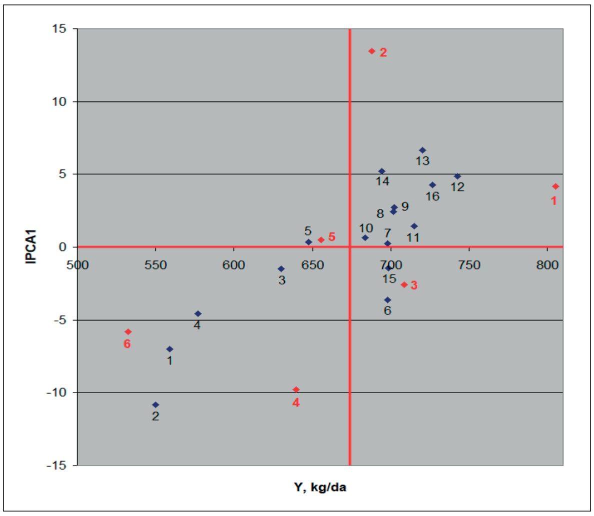

Figure 1. AMMI1 biplot of investigated triticale lines
Genotypes: 1-AD-7291, 2-Vihren, 3-Rakita, 4-Kolorit, 5-G1, 6-G2, 7-G3, 8-G4, 9-G5, 10-G6, 11-G7, 12-G8, 13-G9, 14-G10, 15-G11, 16-G12

According to the graph, lines G1, G2, G6, G7 and G11 were in lowest interaction with the environment, as well as the standard Rakita. Nevertheless, the results from the PCA analysis showed that the stability demonstrated above refers rather to the conditions of the two extremely unfavorable economic years 2015/2016 and 2019/2020. Figures 2, 3 and 4 present biplots showing significant differences with regard to the stability of the genotypes.

With regard to Figure 2, genotypes Kolorit, G2, G7 and G12 were in the lowest interaction with the conditions of the environment during 2016/2017. On the other hand, Figure 3 shows that lines G5, G6, G7 and G10, as well as the local checks AD-7291 and Kolorit were in low interaction with the conditions of economic year 2017/2018. Furthermore, the results on Figure 4 determine lines G1, G2, G7, G8, G9 and G11, as well as the local check Kolorit, as the genotypes with the weakest interaction with the environment during the favorable year 2014/2015.

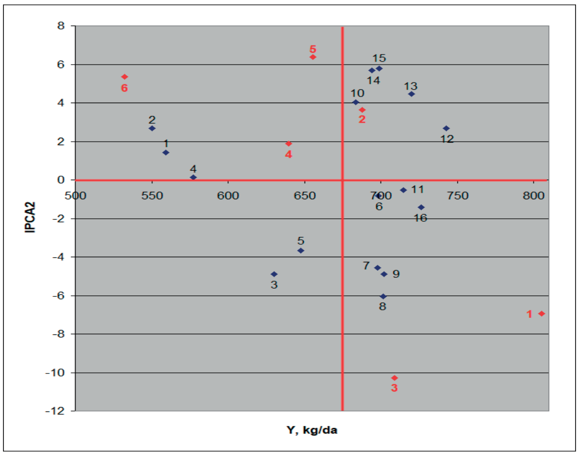

Figure 2. AMMI biplot for IPC2 of investigated triticale lines
Genotypes: 1-АД-7291, 2-Vihren, 3-Rakita, 4-Kolorit, 5-G1, 6-G2, 7-G3, 8-G4, 9-G5, 10-G6, 11-G7, 12-G8, 13-G9, 14-G10, 15-G11, 16-G12

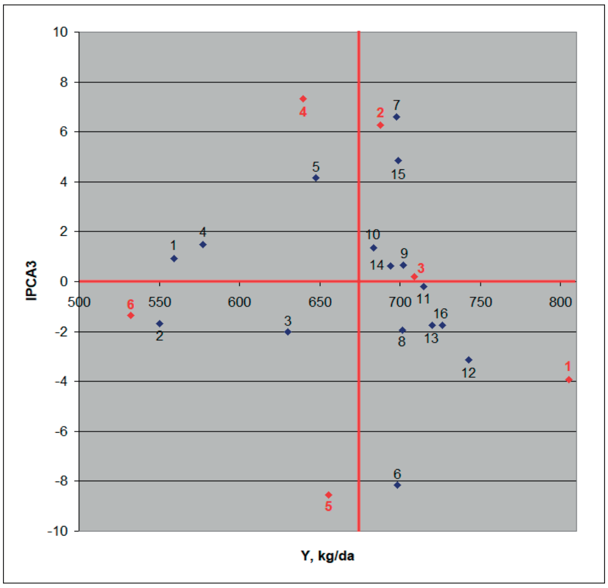

Figure 3. AMMI biplot for IPC3 of investigated triticale lines
Genotypes: 1-АД-7291, 2-Vihren, 3-Rakita, 4-Kolorit, 5-G1, 6-G2, 7-G3, 8-G4, 9-G5, 10-G6, 11-G7, 12-G8, 13-G9, 14-G10, 15-G11, 16-G12

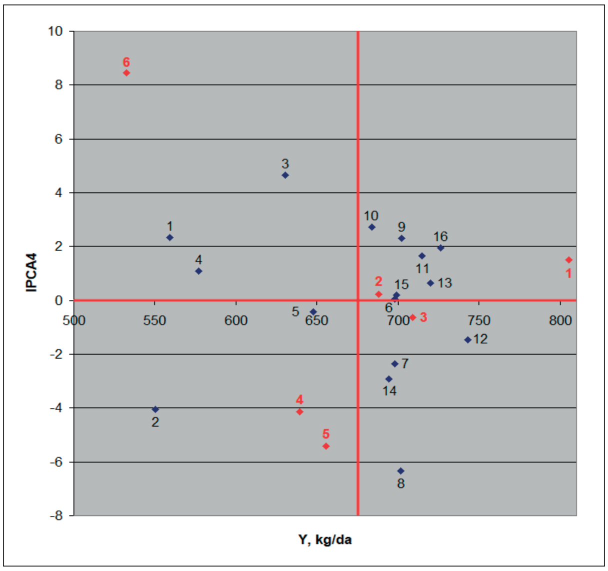

Figure 4. AMMI biplot for IPC4 of investigated triticale lines
Genotypes: 1-AD-7291, 2-Vihren, 3-Rakita, 4-Kolorit, 5-G1, 6-G2, 7-G3, 8-G4, 9-G5, 10-G6, 11-G7, 12-G8, 13-G9, 14-G10, 15-G11, 16-G12

The results from the biplot graphs demonstrated that according to the different periods, which influenced the genotype x environment interaction, the standard Kolorit and lines G2 and G7 were with the most stable behavior. Lines G1, G6 and G11 also demonstrated lower interaction with the conditions of the environment but only with regard to certain periods. This indicated that from the point of view of adaptability, G2 and G7 were most adapted to a wide range of environments, while the rest of the lines were with comparatively specific adaptability. Such a behavior is typical since these genotypes were developed through purposeful multiple individual selection under contrasting environments, one of the main criterion being high productivity.

On the other hand, the presence of separate values related to the possibility of grouping the lines did not allow comparing the individual genotypes. This was even impossible, if comparing graphically the individual IPCA values (Figure 5). In order to determine the tendencies in the response of a group of genotypes under certain conditions of the environment, the IPCA values were transformed based on the absolute mean values of each genotype from all principal components and values of all genotypes for a specific principal component. The transformation was carried out according to formula 1 (Stoyanov, 2021):

$$AIPCAX_i = \sqrt{\frac{\sum_{i=1}^{G} |IPCAX_i|}{G} . \frac{\sum_{X=1}^{N} |IPCAX_i|}{N}} \qquad (1)$$

where:
$IPCAX_i$ - IPCA values of the ith genotype and the Xth principal component of the interaction;
G - number of investigated genotypes;
N - number of determined principal components of the interaction;
$AIPCAX_i$ - transformed IPCA value of the ith genotype and the Xth principal component of the interaction.

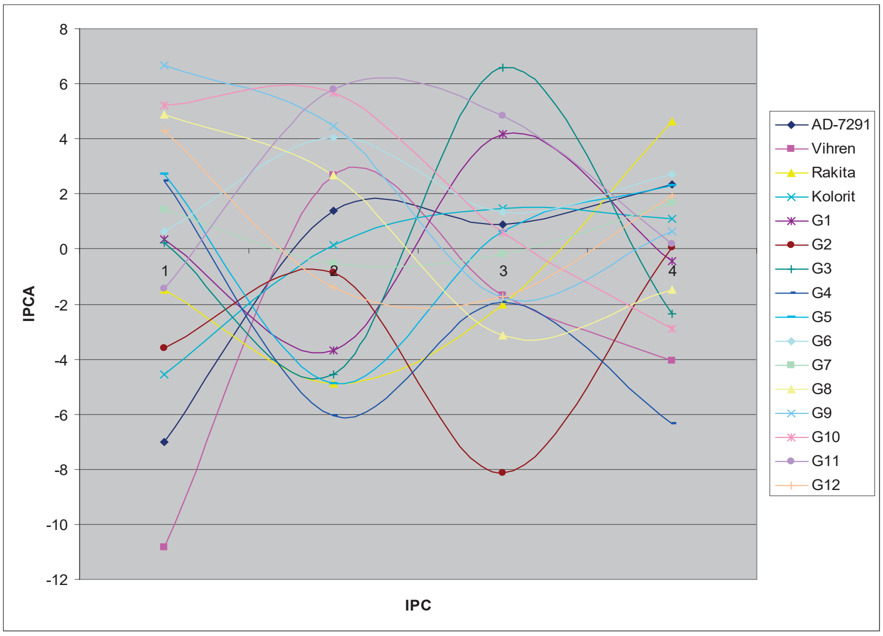

Figure 5. IPCA values of the investigated genotypes over principal components

The obtained results (Figure 6) allowed dividing the cultivars into clearly outlined groups by their stability under contrasting environments according to the separate principal components of the interaction, which were determined. The AIPCA values allowed considering the stability as a tendency, not as a value. The lower the curve of a genotype was positioned, the more stable reaction to the changeable environment this genotype realized; respectively the higher the curve on the graph, the stronger the interaction of the genotype with the environment was, i.e. its yield stability was lower. On the other hand, the curves with greater inclination indicated higher interaction with unfavorable environments.

The obtained results placed the local check Kolorit lower on the graph, while the other two checks - AD-7291 and Vihren, were characterized by the highest values of the interaction. This was an indication that Kolorit demonstrated the weakest reaction as a result from the contrasting conditions of the environment, i.e. it was the most stable cultivar. At the same time, AD-7291 and Vihren interacted strongly with the environmental conditions. Cultivar Rakita, on the other hand, demonstrated higher stability and productivity than these two standards, which makes it a considerably more valuable genotype from a breeding point of view. Different researches of ours define cultivar Rakita as a significantly more stable check cultivar (Stoyanov et al., 2017; Stoyanov & Baychev, 2018). Lines G3, G9 and G10 were positioned between Rakita and Vihren. They were characterized by good productivity (Stoyanov & Baychev, 2021), which, however, was rather different during the individual periods of the study.

A tendency toward lower interaction with the conditions of the environment than that of Rakita was found in genotypes G1, G2, G4, G5, G8 and G12. Lines G6 and G11 interacted with the conditions of the environment in an almost similar way. G7 demonstrated a tendency toward the highest stability among all investigated lines; at the same time, this line responded with a comparatively lower reaction to the unfavorable conditions of the environment. Such ranking of the lines according to their reaction of stability and interaction to conditions unfavorable for the crop development allowed evaluating their breeding value. Although responding weakly to contrasting environments, cultivars such as Kolorit were characterized by lower productivity (Figures 1-4).

On the other hand, the lines with high yield potential as G8, G9 and G12 reacted rather strongly under sharp changes in the conditions of the environment, which impeded its proper realization. The lines in the middle of the graph, G1, G2, G4, G5, G8 and G12, demonstrated moderate reaction to the conditions of the environment, being also characterized by high productivity, with the exception of G1.

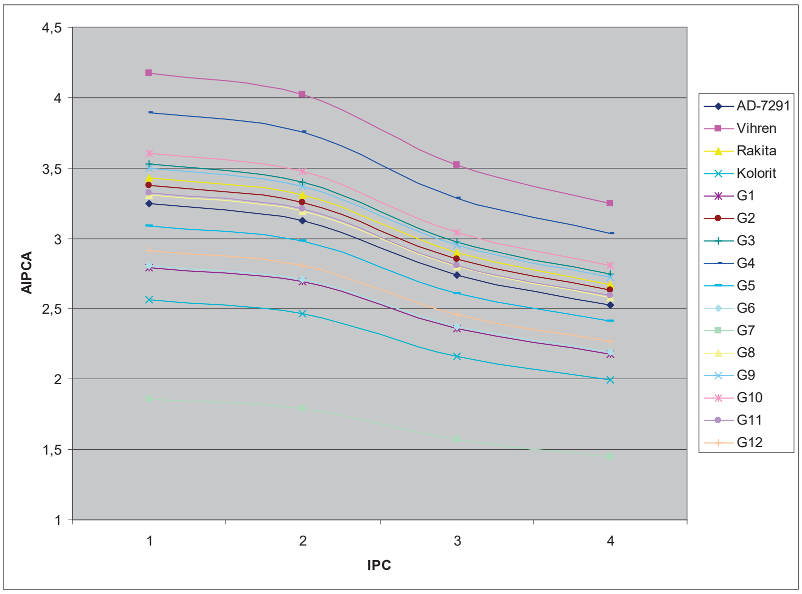

Figure 6. Transformed IPCA values (AIPCA) of the investigated genotyeps over principal components

This makes them significantly valuable both as breeding material and as production prospect. At the same time, such lines as G7 and G11 possess both high stability (their interaction with the conditions of the environment is very low, and their interaction with the unfavorable conditions is considerably lower), but they were characterized by good productivity. This makes them exceptionally valuable for introduction in the agricultural practice of Bulgaria

CONCLUSIONS

Based on the results presented above, the following conclusions could be made:

1. The genotype x environment interaction accounted for 14.8 % of the total yield variation in the lines investigated under contrasting growing environments, and was significant.
2. Four significant interaction principal components were identified based on the AMMI-analysis carried out, which accounted for 96% of the interaction's variance.
3. The PCA analysis performed on the values of the interaction θ_{ge} and the varimax rotated correlation matrix revealed that the first component of the interaction was related to the action of the meteorological conditions during 2015/2016 and 2019/2020, and had the highest effect on the genotype x environment interaction, while the conditions of the favorable year 2014/2015 had the lowest effect on the values of the interaction.
4. The biplot graphs based on AMMI showed that according to the different periods, which influenced the genotype x environment interaction, the check cultivar Kolorit and lines G2 and G7 had the most stable behavior, while lines G1, G6 and G11 were in lowest interaction with the conditions of the environment, but only in certain periods.
5. The best tendency towards stability, regardless of the conditions of the environment, was determined in the local check Kolorit and line G7. On the other hand, lines G2, G4, G5, G8 and G12 demonstrated moderate reaction to the environments, being characterized also by high productivity. This makes them valuable breeding material with good prospects for production.

REFERENCES

Akbarian, A., Arzani, A., Salehi, M., & Salehi, M. (2011). Evaluation of triticale genotypes for terminal drought tolerance using physiological traits. *Indian Journal of Agricultural Sciences, 81*(12), 1110-1115.

Becker, H. C., & Leon, J. (1988). Stability Analysis in Plant Breeding. *Plant Breeding*, *101*, 1-23.

Bocianowski, J., Tratwal, A., & Nowosad, K. (2021). Genotype by environment interaction for main winter triticale varieties characteristics at two levels of technology using additive main effects and multiplicative interaction model. *Euphytica*, *217*, 26. https://doi.org/10.1007/s10681-020-02756-x.

Dogan, R., Kacar, O., Coplu, N., & Azkan, N. (2009). Characteristics of new breeding lines of triticale. *African Journal of Agricultural Research*, *4*(2), 133-138.

Dogan, R., Kacar, O., Goksu, E., & Azkan, N. (2011). Evaluation of triticale genotypes in terms of yield stability for the Southern Marmara Region. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *39*(2), 249-253.

Gauch, H. G. (1992). Statistical Analysis of Regional Yield Trials: AMMI Analysis of Factorial Designs. Elsevier, New York, New York.

Gelalcha, S., Fantahun, B., Yaie, B., & Girma, B. (2007). Triticale (X *Triticosecale* wittmack) – A new addition to the Ethiopian cereals. *African Crop Science Conference Proceedings*, *8*, 1991-1995.

Grzesiak, M. T., Marcińska, I., Janowiak, F., Andrzej R., & Hura, T. (2012). The relationship between seedling growth and grain yield under drought conditions in maize and triticale genotypes. *Acta Physiol Plant*, *34*, 1757–1764. https://doi.org/10.1007/s11738-012-0973-3.

Kaya, Y., & Ozer, E. (2014). Parametric stability analyses of multi-environment yield trials in triticale (x*Triticosecale* Wittmack). *Genetika*, *46*(3), 705-718.

Kendal, E., & Sayar, M. S. (2016). The stability of some spring triticale genotypes using biplot analysis. *The Journal of Animal & Plant Sciences*, *26*(3), 754-756.

Kendal, E., Sayar, M. S., Tekdal, S., Aktas, H., & Karaman, M. (2016). Assessment of the impact of ecological factors on yield and quality parameters in triticale using GGE biplot and AMMI analysis. *Pakistan Journal of Botany*, *48*(5), 1903-1913.

Kendal, E., Tekdal, S., & Karaman, M. (2019). Proficiency of biplot methods (AMMI and GGE) for appraise Triticale genotypes across multiple environments. *Applied Ecolgy and Envirnmental Research*, *17*(3), 5995-6007.

Lozano-del Río, A. J., Zamora-Villa, V. M., Ibarra-Jiménez, L., Rodríguez-Herrera, S. A., de la Cruz-Lázaro, E., & de la Rosa-Ibarra, M. (2009). AMMI analysis of genotype-environment interaction and production potential of forage triticale (X *Triticosecale* Wittm.). *Universidad y Ciencia Tropico Humedo*, *25*(31): 81-92.

Lule, D., Tesfaye, K., & Mengistu, G. (2014). Genotype by environment interaction and grain yield stability analysis for advanced triticale (x. *Triticosecale* Wittmack) genotypes in Western Oromia, Ethiopia. *Ethiopian Journal of Science*, *37*(1), 63-68.

Manly, B. F. J. & Alberto, J. A. N. (2017). Multivariate statistical methods. A primer. 4th edition. CRC Press.

Mariotti, J. A., Oyarzabal, E. S., & Osa, J. M. (1976). Stability and adaptability analysis of sugarcane genotypes, 1: Interactions within and experimental site. *Revista Agronomica del Noroeste Argentino*, *13*(1-4), 105-127. (Es)

Motzo, R., Giunta, F., & Deidda, M. (2001). Factors affecting the genotype × environment interaction in spring triticale grown in a Mediterranean environment. *Euphytica*, *121*, 317–324. https://doi.org/10.1023/A:1012077701206.

Obuchowski, W., Banaszak, Z., Makowska, A. and Łuczak, M. (2010), Factors affecting usefulness of triticale grain for bioethanol production. *J. Sci. Food Agric.*, *90*: 2506-2511. https://doi.org/10.1002/jsfa.4113.

Oral, E. (2018). Effect of nitrogen fertilization levels on grain yield and yield components in triticale based on AMMI and GGE biplot analysis. *Applied Ecology and Environmental Research*, *16*(4): 4865-4878.

Stoyanov, H., & Baychev, V. (2016). Analysis on “Genotype x Environment” Interaction in Bulgarian Triticale (×*Triticosecale* Wittm.) Cultivars. *Scientific works of Institute of Agriculture - Karnobat*. (in press).

Stoyanov, H., Baychev, V., Petrova, T., & Mihova, G. (2017). Triticale cultivars suitable for growing under high level of abiotic stress. *Journal of Mountain Agriculture on the Balkans*, *20*(6): 223-242.

Stoyanov, H., & Baychev, V. (2018). Tendencies in the yield and its components of the Bulgarian varieties of triticale, grown under contrasting conditions of the environment. *Rastenievadni nauki*, *55*(3), 16-26 (Bg).

Stoyanov, H. (2018). Reacton of Triticale (xTriticosecale Wittm.) to Abiotic Stress. PhD Thesis, General Toshevo, Bulgaria (Bg).

Stoyanov, H. (2020). Analysis on test weight of Bulgarian triticale cultivars. *Rastenievadni nauki*, *57*(6), 3-16.

Stoyanov, H. (2021). Tendencies in the reaction of the yield of Bulgarian triticale cultivars under contrasting environments. *Rastenievadni nauki*, *58*(1), 14-25

Stoyanov, H., & Baychev, V. (2021). Triticale lines combining high productivity with stability and adaptability under contrasting environments. *Rasteniavadni nauki*, *58*(5), 3-15.