Genotype by environment interaction for main winter triticale varieties characteristics at two levels of technology using additive main effects and multiplicative interaction model

Jan Bocianowski · Anna Tratwal · Kamila Nowosad

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Abstract The aim of this study was to assess genotype by environment interaction for grain yield, plant height and thousand-grain weight in winter triticale cultivars by the additive main effects and multiplicative interaction (AMMI) model. The study comprised of ten winter triticale varieties i.e.: Algoso, Baltiko, Grenado, Magnat, Moderato, Pawo, Todan, Trimester, Trismart and Witon. Field trials were performed at seven locations in three years (21 environments) in a randomized complete block design, with two replicates at two levels of cultivation technology (standard – A1 and intensive – A2). Field experiments were carried out as part of Post Registration Variety Trials in Wielkopolska region. AMMI analyses revealed significant genotype and

environmental effects as well as genotype by environmental interaction with respect to all three observed traits in both levels of cultivation intensity. The cultivars Algoso, Baltiko and Trimester are recommended for further inclusion in the breeding programs because of their stability and good average values of observed traits.

Keywords Adaptability · AMMI · Biplot · Level of technology · Stability · Winter triticale

Introduction

Every year, several new varieties are entered in the National List of Registered Agricultural Plant Varieties admitted to use in Poland. In many works in the fields of agronomy, agriculture and biology, there is a need to study the impact of variety, agricultural technology, and the locations on the yield of plants. Such studies in Poland allow Post-Registering Variety Trials (PDO) experiments (Weber et al. 2017). Research conducted in the PDO system is focused on the needs of agricultural practice (Bujak et al. 2013). The main goal of PDO research is to help farmers correctly select the most valuable varieties for cultivation, adapted to local conditions (Padarewski and Rodrigues 2014; Derejko et al. 2016).

J. Bocianowski (✉)
Department of Mathematical and Statistical Methods,
Poznań University of Life Sciences, Wojska Polskiego 28,
60-637 Poznań, Poland
e-mail: jan.bocianowski@up.poznan.pl

A. Tratwal
Poland Department of Pests Methods Forecasting and
Economy of Plant Control, Institute of Plant Protection –
National Research Institute Poznan, Władysława Wegorka
20, 60-318 Poznań, Poland

K. Nowosad
Department of Genetics, Plant Breeding and Seed
Production, Wrocław University of Environmental and
Life Sciences, Grunwaldzki 24A, 53-363 Wrocław,
Poland

The area of winter triticale cultivation is about 3.5 million ha in the world, of which in Poland this cereal covers about 1.2 million ha, which is 1/3 of the total area of the world's crops. This makes our country the largest producer of triticale in the world. The share of winter triticale in Poland in the structure of crops of cereals with cereal mixtures was approximately 18%. Winter triticale is primarily a forage grain and its main advantages are high yield potential and very high forage value. An additional advantage is the possibility of sowing on weaker soils. Triticale is one of the tolerant plants the soil abundance in minerals and acidification. The spring thermal requirements of this cereal are greater than that of rye. Winter triticale later start with vegetation and has a slower growth dynamics in early spring than winter wheat. In the critical period (shooting—heading), the optimum temperature is 6–8 °C, and during the formation of grain—16–18 °C. Most important diseases and pest occurred on triticale are *Fusarium* spp., *Blumeria graminis*, *Pyrenophora tritici-repentis*, *Puccinia recondita*, and *Phaeosphaeria nodorum*. Most important pests

occurred on triticale are Aphidoidea, *Oulema* spp., *Oscinella frit* and Agromyzidae.

In field crop trials, the response of quantitative traits to varied environmental conditions is determined by the additive main effects of genotype (G) and environmental conditions (E), as well as by non-additive effects of genotype-by-environment interactions (GEI). These interactions are well described by the additive main effects and multiplicative interaction (AMMI) model (Zobel et al. 1988). The AMMI model combines the analysis of variance (ANOVA) with additive parameters and the principal component analysis (PCA) with multiplicative parameters in a single analysis. AMMI model is most useful when multiplicative GE terms have agricultural interpretability (Ghaed-Rahimi et al. 2015; Shahriari 2018; Bocianowski et al. 2019b; Singh et al. 2019). The AMMI is, therefore, also known as interaction PCA (Gauch and Zobel 1990).

The aim of this paper was to assess genotype by environment interaction for three traits (grain yield, plant height and thousand-grain weight) in winter

Fig. 1 Meteorological conditions (mean temperature and precipitation) in Bobrowniki from 2008 to 2010

triticale cultivars at two levels of cultivation intensity grown in 21 environments by the AMMI model.

Material and methods

Field experiments

Field experiments were conducted at seven locations (Wielkopolska region, Poland) of different soil and weather conditions. Soil conditions locations were varied, soils were included in the bonitation classes from II to IVa, e.g.: Kościelna Wieś – bonitation class IIIa, Bobrowniki –IVa, Śrem –IIIb, Nowa Wieś Ujska –IVa, Borowo – II, Choryń –IIIa, Winna Góra –IIIa. The experiments were carried out during three vegetation seasons (2007/08, 2008/09, 2009/2010) using ten winter triticale varieties (Algozo, Baltiko, Grenado, Magnat, Moderato, Pawo, Todan, Trimester, Trismart and Witon) accepted for research as part of PDO trials in a randomized complete block design, with two replicates. Ten winter triticale cultivars

analyzed in paper were on official list of Variety Protected By National Plant Breeders' Right (PBR) in years of field experiments. Only variety Trimester was not registered at the Polish National List, in PDO trials variety was tested as a variety registered at the Common catalogue of varieties of agricultural plant species (CCA). The research material selected for the experiments is determined at the annual meetings of the PDO team for each voivodeship. The cultivar selection criteria are factors such as the cultivation acreage of a given cultivar, resistance, and yielding. Two levels of technology were used: standard (A1) and intensive (A2). Intensive technology is characterized by increased nitrogen fertilization, foliar multi-component preparations, protection against lodging and pests. In experiment we observed three quantitative traits: grain yield [in $t\ ha^{-1}$], plant height [in cm] and thousand-grain weight [in g].

Fig. 2 Meteorological conditions (mean temperature and precipitation) in Borowo from 2008 to 2010

Fig. 3 Meteorological conditions (mean temperature and precipitation) in Choryń from 2008 to 2010

Statistical analysis

Obtained data were analysed using AMMI model (Gauch and Zobel 1990) for each trait and for two levels of technology, independently. The AMMI model first fits additive effects for the main effects of genotypes (G) and environments (E) followed by multiplicative effects for GEI by PCA. Environments were defined as combinations of locations and years. Results of AMMI analysis were presented by biplot graphs. The AMMI model (Nowosad et al. 2016) is given by:

$$y_{ge} = \mu + \alpha_g + \beta_e + \sum_{n=1}^N \lambda_n \gamma_{gn} \delta_{en} + Q_{ge}$$

where y_{ge} is the trait mean of genotype g in environment e , μ is the grand mean, α_g is the genotypic mean

deviations, β_e is the environmental mean deviations, N is the number of PCA axis retained in the adjusted model, λ_n is the eigenvalue of the PCA axis n , γ_{gn} is the genotype score for PCA axis n , δ_{en} is the score eigenvector for PCA axis n , Q_{ge} is the residual, including AMMI noise and pooled experimental error. The AMMI stability value (ASV) was used to compare the stability of genotype as described by Purchase et al. (2000):

$$ASV = \sqrt{\left[\frac{SS_{IPCA1}}{SS_{IPCA2}} (IPCA_1) \right]^2 + (IPCA_2)^2}$$

where SS_{IPCA1} is the sum of squares for IPCA1, SS_{IPCA2} – the sum of squares for IPCA2, the $IPCA_1$ and $IPCA_2$ scores are the genotypic scores in the

Fig. 4 Meteorological conditions (mean temperature and precipitation) in Kościelna Wieś from 2008 to 2010

AMMI model. Lower ASV score indicate a more stable genotype across environments (Nowosad et al. 2017).

Genotype selection index (GSI) was calculated for each cultivar which incorporates both mean of trait and ASV index in single criteria (GSI_i) as (Farshadfar and Sutka 2003)

$$GSI_i = RM_i + RA_i$$

where RM_i is rank of trait mean (from maximal to minimal for grain yield and thousand-grain weight, and from minimal to maximal for plant height) for i -th cultivar, RA_i is rank of the ASV for the i -th cultivar. Finally, total genotype selection index (TGSI) was

calculated for each cultivar as sum of GSIs for all five traits of study, independently for A1 and A2 as well as for both levels of cultivation intensity.

The relationships between the particular traits (grain yield, plant height and thousand-grain weight) observed in different environments independently for two levels of cultivation technology (standard – A1 and intensive – A2) were assessed based on Pearson's correlation coefficients. These relationships were presented in the form of heatmaps. All the analyses were conducted using the GenStat v. 18 statistical software package.

Fig. 5 Meteorological conditions (mean temperature and precipitation) in Nowa Wieś Ujska from 2008 to 2010

Results

Grain yield

A1

The three sources of variation were highly significant. In the analysis of variance, the sum of squares for environment main effect represented 21.20% of the total grain yield (in A1) variation. Environmental factors like weather, mainly temperature, rainfall influenced the condition of plants, and thus their susceptibility to diseases or pests occurrence. During the years of experiments, there were favorable meteorological conditions for the development of triticale.

The variability of the yield and the weight of a thousand grains was determined by the variety genotype (Figs. 1, 2, 3, 4, 5, 6, 7). The differences between genotypes explained 3.20% of the total grain yield variation, while the effects of GE interaction explained 71.0% (Table 1). Values for the three principal components were also highly significant and accounted jointly for 75.45% of the whole effect it had on the variation of grain yield. The first principal component (IPCA 1) accounted for 47.50% of the variation caused by interaction, while IPCA 2 and IPCA 3 accounted for 18.04 and 9.91%, respectively. Grain yield of the tested genotypes varied from 2.60 (for Grenado in E18) to 15.15 t ha⁻¹ (for Pawo in E17) throughout the 21 environments, with an average of

Fig. 6 Meteorological conditions (mean temperature and precipitation) in Šrem from 2008 to 2010

12.20 t ha⁻¹ (Table 2). The cultivar Trimester had the highest average grain yield (10.53 t ha⁻¹), and the Grenado had the lowest (9.01 t ha⁻¹). The average grain yield per environments also varied from 6.65 t ha⁻¹ in E06, to 13.36 t ha⁻¹ E21 (Table 2). Genotype stability is considered as non significant reaction to changing environmental conditions, agronomic factors, weather conditions, biotic and abiotic stresses. In this study, climatic conditions were the source of this variation component. The stability of tested cultivars can be evaluated according to biplot for grain yield (Fig. 8). Winter triticale cultivars interacted differently with climate conditions in the observed environments. The cultivars Magnat, Tristan and Witon interacted positively with the E03 and E06 environ-

ments, but negatively with the E09, E14 and E17 (Fig. 8). The cultivars Moderato, Todan and Trimester interacted positively with the E09, E14 and E17 environments, but negatively with the E01, E03 and E09. The analysis showed that some cultivars have high adaptation; however, most of them have specific adaptability. AMMI stability values (ASV) revealed variations in grain yield stability among the ten cultivars (Table 2). According to Purchase et al. (2000), a stable variety is defined as one with ASV value close to zero. Consequently, the cultivars Algozo and Baltiko with ASV of, respectively, 0.419 and 0.451, were the most stable, while the cultivars Grenado (8.224) and Trismart (2.347) were the least stable (Table 2). The cultivars Algozo and Trimester

Fig. 7 Meteorological conditions (mean temperature and precipitation) in Winna Góra from 2008 to 2010

with high average grain yield (10.41 and 10.53 t ha⁻¹, respectively) and ASV equal to, respectively, 0.419 and 0.900 are cultivars with the best genotype selection index (4).

A2

The sum of squares for environment main effect represented 83.78% of the grain yield variation. The differences between cultivars explained 1.18% of the grain yield variation, while the effects of GE interaction explained 12.51% (Table 1). Values for the three principal components were also highly significant and accounted jointly for 68.81% of the whole effect it had

on the variation of grain yield (in A2). The IPCA 1 accounted for 34.41% of the variation caused by interaction, while IPCA 2 and IPCA 3 accounted for 19.35 and 15.05%, respectively. Grain yield of the tested cultivars varied from 5.60 (for Grenado in E03) to 17.75 t ha⁻¹ (for Witon in E18) throughout the 21 environments, with an average of 12.20 t ha⁻¹ (Table 3). The Algosio the highest average grain yield (12.75 t ha⁻¹), and the cultivar Grenado had the lowest (11.45 t ha⁻¹). The average grain yield per environments also varied from 8.54 t ha⁻¹ in E01, to 16.88 t ha⁻¹ in E18. The cultivars Tristan and Witon interacted positively with the E02, E06 and E12 environments, but negatively with the E16 and E21 (Fig. 9).

Table 1 Analysis of variance of main effects and interactions for observed traits in winter triticale cultivars and variability explained (ve, in %)

Source of variation	d.f	Grain yield [t ha ⁻¹]			Plant height [cm]			Thousand-grain weight [g]		
		A1		A2	A1		A2	A1		A2
		m.s	ve	m.s	m.s	ve	m.s	m.s	ve	m.s
Treatments	209	12.24***	95.40	17.34***	418.5***	91.58	382.4***	173.3***	97.32	196.1***
Genotypes, G	9	9.55***	3.20	4.93***	5033***	47.43	3842.4***	711.7***	17.21	721.2***
Environments, E	20	95.15***	71.00	155.7***	83.78	31.66	1742.8***	1205***	64.75	1424***
GE Interactions	180	3.16***	21.20	2.58***	12.51	12.49	58.3***	31.8***	15.36	33.3***
IPCA 1	28	9.64***	47.50	5.72***	34.41	38.87	172.9***	91.8***	44.94	79.3***
IPCA 2	26	3.94***	18.04	3.48***	19.35	28.57	66***	36.6***	16.66	47.6***
IPCA 3	24	2.35***	9.91	2.92***	15.05	10.34	44***	29***	12.17	47.6***
Residuals	102	1.37***		1.41***	26		28.2***	14.7***		13.7***
Error	189	0.41		0.4	33		15.3	4.6		4.7

*** P < 0.001; d.f. – number of degrees of freedom; m.s. – mean squares

The cultivars Baltiko, Magnat, Moderato, Todan and Trimester interacted positively with the E07, E09, E14, E16, E18 and E21 environments, but negatively with the E02 and E14. The cultivar Grenado interacted positively with the E08, E19 and E20 environments, but negatively with the E03 and E15. The cultivars Magnat and Trimester with ASV of, respectively, 0.578 and 0.643, were the most stable, while the cultivars Grenado (4.847) and Witon (1.923) were the least stable (Table 3). The cultivars Algos and Todan with the average grain yield equal to 12.75 and 12.34 t ha⁻¹, respectively, and ASV equal to 0.832 and 0.710, respectively, are cultivars with the best genotype selection index (6).

Plant height

A1

The three sources of variation were highly significant. In the analysis of variance, the sum of squares for environment main effect represented 31.66% of the total plant height variation. The differences between genotypes explained 47.43% of the total plant height variation, while the effects of GE interaction explained 12.49% (Table 1). Values for the first two principal components were also highly significant and accounted jointly for 67.44% of the whole effect it had on the variation of plant height. The first principal component (IPCA 1) accounted for 38.87% of the variation caused by interaction, while IPCA 2 accounted for 28.57%. Plant height of the tested cultivars varied from 79 (for Grenado in E15) to 156 cm (for Witon in E11) throughout the 21 environments, with an average of 115.1 cm (Table 4). The cultivar Moderato had the highest average plant height (126.3 cm), and the cultivar Baltiko had the lowest (97 cm). The average plant height per environments also varied from 101.2 cm in E15, to 130.8 cm in E10. The stability of tested cultivars can be evaluated according to biplot for plant height (Fig. 10). Winter triticale cultivars interacted differently with climate conditions in the observed environments. The cultivars Baltiko, Grenado and Trimester interacted positively with the E02 and E10 environments, but negatively with the E09, E12 and E18 (Fig. 10). The cultivars Moderato, Pawo and Todan interacted positively with the E06, E09, E12 and E18 environments, but negatively with the E02.

Table 2 Average grain yield ($t\ ha^{-1}$), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from maximal to minimal), and genotype selection index (GSI) of tested winter triticale cultivars at standard level of technology (A1)

Location	Year	Code	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
Bobrowniki (52°49'N, 17°18'E)	2008	E01	7.20	8.25	7.25	6.65	7.00	7.10	7.60	6.85	9.45	7.15	7.45	-0.176	0.701
	2009	E02	9.00	8.30	7.80	8.10	8.00	7.80	8.90	9.00	9.00	9.20	8.51	-0.053	0.340
	2010	E03	7.70	7.20	5.20	10.03	6.00	8.20	9.00	7.60	8.80	7.90	7.76	0.598	0.877
Borowo (52°07'12"N, 16°47'19"E)	2008	E04	8.50	7.70	7.75	7.90	7.45	8.10	7.65	7.30	7.45	7.35	7.71	-0.349	0.295
	2009	E05	10.00	7.60	7.55	7.00	10.50	10.50	10.00	9.75	8.55	7.80	8.93	0.034	-0.868
Choryń (52°02'26"N, 16°46'59"E)	2010	E06	7.25	5.75	3.95	6.55	5.25	7.85	6.55	8.05	7.35	7.90	6.65	0.598	0.517
	2008	E07	9.75	7.10	9.05	8.90	10.00	9.55	9.15	9.20	8.95	9.00	9.06	-0.291	-0.176
	2009	E08	7.90	7.75	9.65	7.75	7.75	7.80	6.85	8.85	7.05	6.65	7.8	-0.947	0.118
Kościelna Wieś (51°47'08"N, 18°00'34"E)	2010	E09	8.00	6.45	6.05	6.75	8.60	7.90	9.00	7.45	8.05	7.35	7.56	0.179	-0.308
	2008	E10	12.40	13.60	12.95	12.25	12.35	13.00	10.80	12.65	11.05	13.10	12.41	-0.535	0.336
Nowa Wieś Ujska (53°01'59"N, 16°44'56"E)	2009	E11	13.55	12.05	13.65	11.55	12.25	13.15	13.75	12.30	13.00	13.35	12.86	-0.485	0.270
	2010	E12	9.15	8.80	6.55	10.03	9.25	12.10	12.15	11.70	9.70	10.90	10.03	0.883	-0.102
	2008	E13	12.85	11.10	13.25	12.65	12.00	11.00	12.00	11.80	11.85	11.30	11.98	-0.722	0.235
Śrem (52°05'19"N, 17°00'53"E)	2009	E14	11.95	10.40	8.90	9.95	13.90	8.40	12.90	12.90	9.05	10.90	10.93	0.137	-1.485
	2010	E15	12.40	12.00	4.80	12.50	12.50	12.00	12.00	11.55	11.15	12.20	11.31	1.604	-0.244
	2008	E16	13.20	14.20	13.55	11.55	12.50	11.95	11.95	13.35	11.25	12.90	12.64	-0.699	0.084
Winna Góra (52°12'17"N, 17°26'48"E)	2009	E17	12.60	12.30	15.00	12.30	14.80	15.15	14.30	14.35	9.70	11.60	13.21	-0.978	-1.151
	2010	E18	8.70	9.65	2.60	8.80	10.55	11.20	10.35	10.55	11.10	11.15	9.47	1.890	-0.115
	2008	E19	8.95	9.05	10.05	9.20	8.05	10.05	9.50	9.65	9.75	10.80	9.51	-0.338	0.759
Mean	2009	E20	12.99	10.71	11.77	10.21	11.76	12.23	12.35	12.16	11.73	10.06	11.6	-0.429	-0.263
	2010	E21	14.61	13.58	11.82	14.53	12.43	13.52	13.76	14.05	12.09	13.22	13.36	0.080	0.180
			10.41	9.69	9.01	9.77	10.14	10.41	10.5	10.53	9.81	10.08	10.04		
IPCAg1			-0.130	0.	-3.122	0.386	0.104	0.	0.541	0.219	0.755	0.764			
IPCAg2			-0.242	0.	0.335	0.771	-1.785	0.039	-0.755	-0.690	1.248	0.639			
ASV			0.419	0.451	8.224	1.	1.806	1.175	1.613	0.9	2.347	2.109			

Table 2 continued

Location	Year	Code	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
RA			1	2	10	5	7	4	6	3	9	8			
RM			3	9	10	8	5	4	2	1	7	6			
GSI			4	11	20	13	12	8	8	4	16	14			

The cultivar Witon interacted positively with the E11 environment. AMMI stability values (ASV) revealed variations in plant height stability among the ten cultivars (Table 4). The cultivars Algoso and Trismart with ASV of 0.957 and 1.919, respectively, were the most stable, while the cultivars Witon (7.860) and Moderato (4.283) were the least stable (Table 4). The cultivar Baltiko with the lowest average plant height (97 cm) and ASV equal to 1.928 is genotype with the best genotype selection index (4) (Table 4).

A2

The three sources of variation for the plant height were highly significant. In the ANOVA, the sum of squares for environment main effect represented 41.17% of the total plant height variation. The differences between genotypes explained 40.85% of the total plant height variation, while the effects of GE interaction explained 12.39% (Table 1). Values for the three principal components were also highly significant and accounted jointly for 72.59% of the whole effect it had on the variation of plant height. The first principal component (IPCA 1) accounted for 46.16% of the variation caused by interaction, while IPCA 2 and IPCA 3 accounted for 16.35 and 10.07%, respectively. Plant height of the tested cultivars varied from 76 (for Baltiko and Grenado in E15) to 137 cm (for Moderato in E09 and E12 as well as for Trismart in E16) throughout the 21 environments, with an average of 110.3 cm (Table 5). The cultivar Moderato had the highest average plant height (122 cm), and the cultivar Baltiko had the lowest (95.1 cm). The average plant height per environments also varied from 89.9 cm in E15, to 124.5 cm in E10. The stability of tested cultivars can be evaluated according to biplot for plant height (Fig. 11). The cultivars Moderato and Todan interacted positively with the E03, E12 and E21 environments, but negatively with the E02, and E08 (Fig. 11). The cultivars Baltiko and Magnat interacted positively with the E01 and E08 environments, whereas Trimester and Witon with the E11 and E14. The cultivar Algoso with ASV of 1.039, was the most stable, while the cultivars 11.238 (11.238) and Todan (9.048) were the least stable (Table 5). The cultivar Witon with low average plant height (108.7 cm) and ASV equal to 2.276 is cultivar with the best genotype selection index (7).

Fig. 8 Biplot for genotype by environment interaction of grain yield in winter triticale cultivars at standard level of technology (A1) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

Thousand-grain weight

A1

In the ANOVA, the sum of squares for cultivars main effect represented 17.21% of the total, and this factor had the highest effect on the thousand-grain weight. The differences between environments explained 64.75% of the thousand-grain weight variation, while the effects of GE interaction explained 15.36% (Table 1). Values for the three principal components were also highly significant. The three principal components of GE interaction accounted jointly for 73.77% of the whole effect it had on the variation of thousand-grain weight. The first principal component

(IPCA 1) accounted for 44.94% of the variation caused by interaction, IPCA 2 accounted for 16.66% while IPCA 3 accounted for 12.17% (Fig. 12). Thousand-grain weight of the tested cultivars varied from 19.45 (for Grenado in E03) to 60.07 g (for Todan in E14) throughout the 21 environments, with an average of 39.21 g (Table 6). The Todan had the highest average thousand-grain weight (43.87 g), and the Grenado had the lowest (32.49 g). The average thousand-grain weight per environments also varied from 22.20 g in E01 to 49.27 g in E08. The stability of tested lines can be evaluated according to biplot for thousand-grain weight (Fig. 12). The cultivar Trimester interacted positively with the E06 (Fig. 12). The cultivars Baltiko and Magnat interacted positively with the

Table 3 Average grain yield ($t\ ha^{-1}$), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from maximal to minimal), and genotype selection index (GSI) of tested winter triticale cultivars at intensive level of technology (A2)

Env	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
E01	9.05	9.65	8.70	7.90	7.60	7.75	8.30	7.65	10.20	8.55	8.54	-0.236	-0.393
E02	8.20	9.30	8.70	9.35	6.90	9.20	9.00	9.70	10.60	12.80	9.38	0.161	-1.279
E03	9.50	8.50	5.60	12.20	8.50	9.30	9.70	8.10	9.60	9.20	9.02	0.953	0.219
E04	9.50	8.70	8.85	9.30	8.35	8.85	8.40	8.55	8.20	8.65	8.73	-0.311	0.047
E05	13.45	11.55	10.60	10.85	12.10	12.95	11.70	10.00	11.50	11.75	11.64	0.233	-0.028
E06	10.85	10.50	8.15	10.30	7.90	10.35	8.65	9.75	10.45	11.40	9.83	0.442	-0.674
E07	11.00	9.65	9.65	10.55	10.35	10.15	9.50	10.05	9.60	9.80	10.03	-0.167	0.200
E08	8.95	8.10	10.50	8.60	8.65	8.60	8.15	9.50	8.25	7.90	8.72	-0.976	0.080
E09	9.90	10.75	7.60	10.75	10.80	9.80	10.95	10.40	11.20	10.10	10.23	0.568	0.453
E10	12.80	15.05	14.40	13.45	12.80	13.60	14.00	14.05	13.05	14.45	13.76	-0.517	-0.022
E11	17.30	15.40	15.25	14.85	15.35	15.00	17.10	15.00	17.25	17.15	15.96	0.147	-0.568
E12	16.95	12.65	12.40	12.20	13.10	14.95	14.05	13.90	14.30	16.80	14.13	0.585	-1.022
E13	14.05	12.40	14.00	13.95	13.35	12.10	12.80	14.20	12.50	12.50	13.18	-0.685	0.307
E14	13.00	12.45	10.80	11.55	15.15	12.80	14.15	13.10	11.55	12.50	12.71	0.259	0.982
E15	14.85	13.75	6.55	13.15	13.00	13.65	13.20	12.75	13.50	13.25	12.77	1.889	0.459
E16	14.65	15.55	14.85	14.50	15.00	13.05	13.90	15.05	12.70	14.60	14.38	-0.572	0.580
E17	16.60	17.15	16.75	16.15	17.15	17.15	17.60	16.65	15.50	16.70	16.74	-0.322	0.412
E18	15.05	17.35	15.10	17.05	17.25	16.95	17.55	17.50	17.30	17.75	16.88	0.285	0.246
E19	9.70	9.65	11.50	11.10	9.55	10.80	10.00	10.30	10.85	9.85	10.33	-0.670	-0.232
E20	15.53	11.84	15.34	13.53	12.88	14.07	14.24	12.97	15.14	12.64	13.82	-0.683	-0.552
E21	16.78	17.66	15.19	15.66	14.48	13.99	16.27	15.92	14.11	13.91	15.4	-0.382	0.785
Mean	12.75	12.27	11.45	12.24	11.91	12.15	12.34	12.15	12.25	12.49	12.2		
IPCAg1	0.455	0.165	-2.721	0.210	0.106	0.485	0.284	-0.275	0.535	0.757			
IPCAg2	-0.210	0.737	-0.543	0.444	1.425	-0.302	0.502	0.420	-1.094	-1.378			
ASV	0.832	0.793	4.847	0.578	1.437	0.91	0.71	0.643	1.447	1.923			
RA	5	4	10	1	7	6	3	2	8	9			
RM	1	4	10	6	9	8	3	7	5	2			
GSI	6	8	20	7	16	14	6	9	13	11

Fig. 9 Biplot for genotype by environment interaction of grain yield in winter triticale cultivars at intensive level of technology (A2) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

E03, E13 and E21, but negatively with the E14, E17 and E18. The cultivars Algoso, Grenado and Moderato interacted positively with the E001, E02 and E10, but negatively with the E109, E12 and E18. The cultivar Witon with ASV of 2.014 was were the most stable, while the cultivars such as Todan (9.223) and Grenado (8.928) were the smallest stable (Table 6). A cultivar Algoso with averages of thousand-grain weight equal to 41.74 g and and good ASV (2.231) had the best

genotype selection index (6). However, the Grenado has the worst genotype selection index (19).

A2

The three sources of variation for the thousand-grain weight were highly significant. In the ANOVA, the sum of squares for environment main effect represented 67.81% of the total thousand-grain weight variation. The differences between genotypes

Table 4 Average plant height (cm), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from minimal to maximal), and genotype selection index (GSI) of tested winter triticale cultivars at standard level of technology (A1)

Env	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
E01	112	89	87	104	103	116.5	109	92	121	107	104	-0.246	0.843
E02	104	91	100.5	101	104	96	100.5	113	106.5	108.5	102.5	-2.945	3.328
E03	119	90.5	95.5	115.1	129	124	137	113.5	128	119.5	117.1	0.869	-0.622
E04	125	100	107.5	120	127.5	115	127.5	112.5	127.5	119	118.1	-0.360	1.146
E05	127.5	102.5	102.5	120	137.5	127.5	132.5	112.5	135	120	121.8	1.031	-0.270
E06	122.5	100	97.5	120	140	130	132.5	112.5	130	117.5	120.2	1.513	-0.691
E07	132.5	100	107.5	122.5	132.5	130	135	120	137.5	120	123.8	0.864	0.711
E08	112.5	92.5	95	100	117.5	115	115	97.5	120	110	107.5	-0.219	0.159
E09	130.5	97	100.5	113.5	143	128	136	107.5	134	120	121	1.627	-1.762
E10	137	118.5	117.5	138	135.5	133	135	120.5	136.5	136.5	130.8	-1.114	1.161
E11	120	90.5	97.5	103.5	128	116	115.5	102	118	156	114.7	-4.810	-3.926
E12	131.5	103	96	115.1	143.5	125	134	111.5	135	122	121.7	1.360	-1.541
E13	117	96.5	95.5	111.5	118	119	127	101	124	119	112.8	-0.245	-0.052
E14	115	89	91	100.5	118	115	117.5	98	117	112	107.3	-0.139	-0.466
E15	110	80	79	96	108	107.5	113	103	111	104	101.2	0.057	0.242
E16	129	104.5	111	126.5	135.5	127	131	121	141	126	125.3	-0.061	0.845
E17	124.5	107	102.5	116	126	123	124	111	126.5	119.5	118	-0.344	0.871
E18	136	108	102.5	123	151.5	130	133.5	113.5	131	123.5	125.2	1.344	-1.377
E19	110	90	87.5	96.5	115	111	120	102.5	120	107.5	106	0.263	0.157
E20	115	87.5	89.5	97.5	112.5	107.5	112.5	99	110	105	103.6	-0.276	0.536
E21	124.5	99	95	118.5	126.8	121	129.2	105	126.5	106.8	115.2	1.831	0.709
Mean	121.7	97	98	112.3	126.3	119.9	124.6	108	125.5	118.1	115.1		
IPCAg1	0.630	-0.485	-2.041	0.601	2.101	1.413	2.499	-0.868	1.405	-5.254			
IPCAg2	-0.425	1.812	2.410	1.804	-3.189	-0.916	-0.897	2.499	0.167	-3.264			
ASV	0.957	1.928	3.678	1.981	4.283	2.13	3.517	2.764	1.919	7.86			
RA	1	3	8	4	9	5	7	6	2	10			
RM	7	1	2	4	10	6	8	3	9	5			
GSI	8	4	10	8	19	11	15	9	11	15

Fig. 10 Biplot for genotype by environment interaction of plant height in winter triticale cultivars at standard level of technology (A1) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

explained 15.45% of the total thousand-grain weight variation, while the effects of GE interaction explained 14.29% (Table 1). Values for the three principal components were also highly significant and accounted jointly for 76.64% of the whole effect it had on the variation of thousand-grain weight. The first principal component (IPCA 1) accounted for 36.99% of the variation caused by interaction, while IPCA 2 and IPCA 3 accounted for 20.61 and 19.04%, respectively. Thousand-grain weight of the tested cultivars varied from 15.95 (for Grenado in E03) to 64.79 g (for Trismart in E18) throughout the 21 environments, with an average of 40.92 g (Table 7). The Trismart had the highest average thousand-grain weight (47.72 g), and the Grenado had the lowest (34.01 g). The average thousand-grain weight per environments also varied

from 21.72 g in E01, to 52.63 g in E17. The stability of tested cultivars can be evaluated according to biplot for thousand-grain weight (Fig. 13). The cultivars Todan and Trimester interacted positively with the E12 and E21 environments, but negatively with the E03 and E06 (Fig. 13). The cultivar Trismart interacted positively with the E09 and E18, but negatively with the E14 and E17. The cultivar Magnat interacted positively with the E03 and E06. The cultivar Pawo with ASV of 0.568 was the most stable, while the Algoso (5.288) and Trismart (5.020) were the least stable (Table 7). The cultivar Pawo with medium average thousand-grain weight (40.22 g) and the best ASV (0.568) is cultivar with the best genotype selection index (7). The Grenado has the worst genotype selection index (15).

Table 5 Average plant height (cm), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from minimal to maximal), and genotype selection index (GSI) of tested winter triticale cultivars at intensive level of technology (A2)

Env	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPC Ae1	IPC Ae2
E01	105	85	85	98.5	98	107	103	77	114	92	96.5	0.298	3.361
E02	101	81	94.5	93	93.5	84.5	89	104.5	100.5	99.5	94.1	4.138	-2.349
E03	115.5	89	89.5	110.3	126	125.5	133	111	126	117.5	114.3	-2.198	-0.744
E04	127.5	101	102.5	115	135	122.5	122.5	112.5	130	112.5	118.1	-0.383	-0.209
E05	117.5	100	105	117.5	127.5	125	125	107.5	125	115	116.5	0.024	0.800
E06	110	92.5	97.5	107.5	127.5	115	117.5	102.5	117.5	105	109.2	-0.324	0.038
E07	127.5	107.5	107.5	127.5	125	127.5	127.5	120	130	115	121.5	0.956	0.941
E08	102.5	100	100	107.5	107.5	100	105	97.5	110	100	103	2.817	1.396
E09	120.5	100	103.5	115	137	128	131.5	111.5	124.5	114	118.6	-1.138	-0.091
E10	127	112.5	113	125	133.5	129	131	118.5	130	125.5	124.5	0.808	0.276
E11	117.5	86.5	94.5	99	114.5	114	111	99	109.5	108	105.4	0.278	-0.896
E12	122	93	85	110.3	137	119	125	105.5	127	116	114	-2.549	-0.863
E13	112.5	100	98.5	108	118.5	116.5	111.5	109.5	119	107.5	110.1	1.230	0.117
E14	111.5	90	94	100	122	109.5	107.5	102	110	107.5	105.4	0.477	-1.324
E15	99	76	76	86	104	92	96.5	86.5	96.5	86	89.9	0.207	-0.592
E16	124.5	113	98	121.5	130.5	124	129	116	137	112.5	120.6	-0.268	1.503
E17	118	99.5	92	112.5	122.5	115.5	112.5	104.5	116.5	118.5	111.2	0.424	-0.347
E18	118	102	93.5	113.5	135	119.5	125	107.5	123	106.5	114.3	-1.173	0.467
E19	120	92.5	92.5	100	123.5	116	123	112.5	123	107.5	111	-0.814	-1.405
E20	112.5	82.5	87.5	95	110	110	112.5	95	115	97.5	101.8	-0.534	0.156
E21	124.2	94.5	93.2	116.2	134.8	118.2	136	106	129.5	118.2	117.1	-2.275	-0.235
Mean	115.9	95.1	95.4	108.5	122	115.2	117.8	105.1	119.7	108.7	110.3		
IPC Ag1	-0.249	2.300	3.982	0.952	-3.034	-1.842	-3.203	1.743	-1.023	0.374			
IPC Ag2	-0.765	2.033	0.087	2.029	-1.465	1.355	0.404	-3.160	1.500	-2.016			
ASV	1.039	6.801	11.238	3.366	8.688	5.373	9.048	5.848	3.253	2.276			
RA	1	7	10	4	8	5	9	6	3	2			
RM	7	1	2	4	10	6	8	3	9	5			
GSI	8	8	12	8	18	11	17	9	12	7

Fig. 11 Biplot for genotype by environment interaction of plant height in winter triticale cultivars at intensive level of technology (A2) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

Total genotype selection index

The best total genotype selection index we observed for cultivar Algos (TGSI = 46), while the worst – Grenado (TGSI = 96). For A1 level of cultivation intensity cultivar Algos was the best TGSI (18), however for A2 – Magnat (TGSI = 25). Cultivar Grenado was the worst in both level of cultivation intensity (49 for A1 nad 47 for A2). The cultivars Algos, Baltiko and Trimester are recommended for further inclusion in the breeding programs because of their stability and good average values of observed traits.

Relationships for observed traits between environments

The negative statistically significant ($\alpha = 0.05$) correlation coefficients for grain yield were observed for following pair of environments at both (standard and intensive) levels of technology: E08-E15, E08-E18 (Figs. 14 and 15). Additionally, positively correlation coefficients at A1 were observed for: E03-E06, E03-E12, E05-E07, E05-E09, E05-E20, E06-E12, E06-E15, E06-E18, E10-E16, E12-E15, E12-E18 and E15-E18 (Fig. 14). However, negative for pairs: E01-E17, E03-E16, E09-E10 and E13-E18 (Fig. 14). The positively correlation coefficients at A2 were observed for

Table 6 Average thousand-grain weight (g), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from maximal to minimal), and genotype selection index (GSI) of tested winter triticale cultivars at standard level of technology (A1)

Env	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
E01	23.9	21.2	21.35	22.75	19.65	21.5	26.85	21.2	24.05	19.55	22.2	0.997	1.050
E02	22.1	21.3	25.3	23.1	20.8	20.1	22.15	22.1	20.35	26.3	22.36	2.087	0.686
E03	26.05	23.8	19.45	39.21	20.65	24.4	26.65	25	26.1	21.65	25.3	1.297	-1.096
E04	42.1	37.2	33.95	45.45	37.8	36.6	49.05	40.75	45.35	36	40.42	0.115	0.588
E05	44.95	34.5	36.25	41.45	35.6	41.45	46.1	45.6	48.35	33.55	40.78	-0.324	0.345
E06	36.9	35.8	25	45.4	28.9	41.3	41.3	54.5	43.4	32.5	38.5	-1.363	-2.969
E07	42.85	35.75	32.7	42.6	37.8	38.3	46.55	43.05	40.7	35	39.53	0.021	0.463
E08	54.4	44.45	43.5	50.95	44.45	50.35	52.85	53.8	55.45	42.55	49.27	-0.092	0.055
E09	42	36.85	24.25	39.4	34	45.4	53.2	49.3	52.2	39.75	41.64	-2.563	-0.296
E10	38.15	36.9	35.9	38.55	36.2	35.05	37.05	33.75	42.2	30.1	36.38	1.474	0.589
E11	53.3	43.55	37.95	48.5	40.4	49.05	47.15	48.9	52.5	37.7	45.9	0.038	-0.278
E12	35.1	37.8	31.5	39.21	33.25	44.3	49.75	49.35	46.45	37.6	40.43	-1.485	-0.560
E13	43.83	43.54	41.63	48.43	42.37	45.06	45.86	50.02	47.77	37.16	44.57	0.627	-0.672
E14	52.43	42.25	34.7	42.05	43.62	49.61	60.07	49.35	47.97	40.85	46.29	-1.515	1.774
E15	36.19	34.3	24.45	39.2	32.56	35.08	37.68	38.81	35.86	32.57	34.67	0.169	-0.685
E16	39.25	34.35	33.45	36.8	33.3	36.25	39.85	38.2	37.25	32.7	36.14	0.705	0.603
E17	55.59	38.69	40.87	50.19	45.36	48.98	58.86	54.09	53.07	38.2	48.39	-1.046	1.012
E18	39.31	32.51	26.21	37.19	37.5	41.36	55.58	47.3	46.5	36.45	39.99	-2.387	0.847
E19	48.25	39.15	38.8	46.7	35.2	34.35	34.95	42	40.3	40.6	40.03	2.335	-0.587
E20	55.5	45.09	41.05	47.48	41.57	43.73	49.01	47.12	54.86	40.58	46.6	0.527	0.522
E21	44.45	45.2	33.95	44.75	47.85	40.5	40.7	50.75	53.95	38.4	44.05	0.384	-1.392
Mean	41.74	36.39	32.49	41.4	35.66	39.18	43.87	43.09	43.55	34.75	39.21		
IPCAg1	0.653	1.315	3.270	1.479	0.830	-1.479	-3.298	-2.156	-1.362	0.747			
IPCAg2	1.367	-0.902	1.385	-2.101	0.887	-0.147	2.435	-2.401	-0.553	0.029			
ASV	2.231	3.661	8.928	4.51	2.409	3.992	9.223	6.292	3.715	2.014			
RA	2	4	9	7	3	6	10	8	5	1			
RM	4	7	10	5	8	6	1	3	2	9			
GSI	6	11	19	12	11	12	11	11	7	10

Fig. 12 Biplot for genotype by environment interaction of thousand-grain weight in winter triticale cultivars at standard level of technology (A1) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

pairs of environments: E02-E06, E03-E09, E03-E15, E04-E07, E08-E13, E09-E15, E09-E18 and E11-E12 (Fig. 15), however negative for pairs: E03-E08, E04-E18, E07-E10, E08-E09 and E14-E19 (Fig. 15).

For plant height we observed significant correlation coefficients for all pairs of environments except E02 with all environments at both (standard and intensive) levels of technology (Figs. 16 and 17), and E11-E01, E03, E04, E05, E06, E07, E08, E09, E15, E16, E17, E18, E19, E20 and E21 as well as E17-E18 at standart level of technology (Fig. 16), and pairs: E01-E14, E01-E19, E03-E08, E08-E11, E08-E12, E08-E13, E08-E14, E08-E15, E08-E17, E08-E19 and E08-E20 at intensive level of technology (Fig. 17).

For thousand-grain weight we observed 101 from 210 significant correlation coefficient at standard level of technology (Fig. 18) and 102 from 201 at intensive level of technology (Fig. 19).

Discussion

Field experiments carried out under PDO system are a valuable source of information for farmers in terms of selection of varieties for cultivation. Every year, several new varieties entered into the National Register of Varieties of Agricultural Plants are admitted for using in Poland. In addition, after Poland's accession to the structures of the European Union, legal regulations at the EU level, allow the placing on the market of plant varieties registered in any Community country. The result is that the farmer has the option of choosing up to several dozen varieties of crops, e.g. triticale 1000. This can cause serious difficulties in choosing the right variety even for the best growers in its specific soil and climate conditions. PDO system on the base of an extensive system of post-registration

Table 7 Average thousand-grain weight (g), for genotypes and environments, principal component analysis values, AMMI stability value (ASV), rank of the AMMI stability value (RA), rank of trait mean (RM, from maximal to minimal), and genotype selection index (GSI) of tested winter triticale cultivars at intensive level of technology (A2)

Env	Algoso	Baltiko	Grenado	Magnat	Moderato	Pawo	Todan	Trimester	Trismart	Witon	Mean	IPCAe1	IPCAe2
E01	24.65	20.55	20.15	26.1	17.4	20.3	23.7	19.6	26.45	18.35	21.72	0.861	-0.078
E02	24.25	22.45	28.25	24.35	21.15	22.2	23.45	28.7	24.95	30.7	25.04	0.681	0.569
E03	22.95	22.35	15.95	40.93	18.8	21.35	22.75	21	24.5	20.15	23.07	1.362	-2.328
E04	47.05	40.15	33.95	46.65	37.9	41.4	47.35	42.6	44	39.5	42.05	0.501	0.398
E05	48.1	44	35.25	50.2	40.25	42.05	45.7	39.2	52.95	37.7	43.54	0.539	-0.821
E06	47.8	46.5	36.6	51	38.9	43	37.2	34.2	55.8	36.6	42.76	1.178	-1.974
E07	42.45	37.3	31.1	42.65	34.2	35.85	41.6	37.35	40.1	32.75	37.53	0.763	0.161
E08	54.5	46.1	46.05	53	44.5	50.95	53.95	53.35	55.45	42.35	50.02	0.322	0.887
E09	37.45	45.2	26.8	49	33.2	40.55	48	47.3	57.5	41.35	42.63	-2.340	-1.693
E10	40.9	37.5	36.5	43.1	39.65	36.8	41.85	40.1	44.2	36.3	39.69	0.644	0.052
E11	53.3	43.55	37.95	48.5	40.4	49.05	47.15	48.9	52.5	37.7	45.9	0.390	0.786
E12	42.4	46.3	39.8	40.93	40.3	49.35	56.25	53.65	59.35	48.5	47.68	-2.461	0.987
E13	42.89	43.65	39.98	46.73	41.9	42.81	43.34	45.13	49.39	35.09	43.09	0.437	-0.207
E14	51.2	45.92	40.72	44.68	45.06	49.59	54.88	50	54.63	41.13	47.78	-0.409	1.446
E15	39.04	36.52	24.81	40.43	35.04	37.48	35.07	36.34	35.29	36.08	35.61	0.839	-0.290
E16	43.5	38.1	36.3	40.5	36.45	38.65	43.1	41.35	42.7	33.6	39.43	0.576	0.900
E17	63.89	44.69	41.72	54.01	46.78	52.4	61.59	55.67	60.37	45.19	52.63	-0.088	1.872
E18	35.18	48.61	34.19	49.42	38.03	45.4	56.5	55.66	64.79	46.89	47.47	-3.633	-1.262
E19	42.15	41.7	37.75	43.45	36.95	38.2	38.65	41.45	47.7	39.5	40.75	0.421	-0.451
E20	51.99	44.15	37.9	48.19	43.38	43.38	45.89	47.39	55.84	39.77	45.79	0.257	0.180
E21	53.2	48.8	34.3	44.05	33.75	43.8	49.8	49.85	53.7	41.1	45.23	-0.838	0.868
Mean	43.28	40.19	34.1	44.18	36.38	40.22	43.7	42.32	47.72	37.16	40.92		
IPCAg1	2.689	-0.357	1.987	1.683	1.614	0.003	-2.082	-2.072	-2.719	-0.745			
IPCAg2	2.161	-1.512	0.799	-3.271	0.070	0.568	1.592	1.395	-1.173	-0.628			
ASV	5.288	1.642	3.654	4.452	2.898	0.568	4.062	3.972	5.02	1.477			
RA	10	3	5	8	4	1	7	6	9	2			
RM	4	7	10	2	9	6	3	5	1	8			
GSI	14	10	15	10	13	7	10	11	10	10

Fig. 13 Biplot for genotype by environment interaction of thousand-grain weight in winter triticale cultivars at intensive level of technology (A2) in 21 environments, showing the effects of primary and secondary components (IPCA 1 and IPCA 2, respectively)

experiments and recommendation of varieties for particular species of arable crops significantly facilitates the selection of the right variety for specific farming conditions, which is one of the requirements of integrated protection. Poland in the EU ranks third in terms of cereal sown area, and the world's first in triticale production. The growing interest in triticale and the ever-increasing selection of new, improved varieties, often focused on specific use in the food or feed industry, requires research to confirm their usefulness. The most important and the most valuable effect of research conducted in the PDO system for farmers is an annual "List of cultivars recommended

for cultivation in the area of the province". Research carried out in the system of PDO are directed directly at the needs of agricultural practice. Growers thanks to this type of research have continuous information about the value of varieties, including selection of the right varieties cultivated crop species.

The grain yield, plant height and thousand-grain weight in winter triticale are traits determined by multiple genes that cause change in the performance of genotypes depending on the cultivation environment. That is why the importance of GEIs in plant breeding programs have been a focus of attention for triticale breeders (Miedaner et al. 2001; Motzo et al. 2001;

Fig. 14 Heatmap for linear Pearson's correlation coefficients between grain yield observed in different environments (E01 – E21 – see Table 1) at standard level of technology (A1); $r_{critical} = 0.5760$

Santiveri et al. 2004; Oettler and Wahle 2008). GEI is an important and challenging issue for plant breeders especially in developing new improved varieties. Multi-environment trials are used to determine sites representing the target environment and can identify superior cultivars for recommendation to breeders (Goyal et al. 2011). Goyal et al. (2011) characterized of triticale genotypes for stability of yield and other quality traits, as well as GEI and adaptability,

constitute a starting point towards the development of new breeding populations for the improvement of yield, and quality traits in triticale for southern and central Alberta, Canada. These results provide impetus for using triticale feedstock in the biorefinery industry, and show that germplasm is available to enhance cultivar development. Data collected from such trials are needed for precise estimation of genotype value and yield stability (Yan and Hunt

Fig. 15 Heatmap for linear Pearson's correlation coefficients between grain yield observed in different environments (E01 – E21 – see Table 1) at intensive level of technology (A2); $r_{critical} = 0.5760$

2001). These trials facilitate quantification of the environment and GEIs. Differences in environmental conditions may cause large GEIs, especially under drought-prone environments (Bocianowski et al. 2019a).

The AMMI model was often used in study of many species (Branković-Radojčić et al. 2018; Fotso et al. 2018; Hassani et al. 2018; Bocianowski et al. 2019c). The AMMI model provides a useful tool in diagnosing

GEI patterns and improving the accuracy of response estimates. It enables clustering of genotypes based on similarity of response characteristics and identifying potential trends across environments (Bocianowski et al. 2018). The suggested strategy could extract more information from the GEI, thereby aiding researchers in identifying specific cultivars with competitive yields across diverse environments. The genotype and environment main effects as well as GEI had the

Fig. 16 Heatmap for linear Pearson's correlation coefficients between plant height observed in different environments (E01 – E21 – see Table 1) at standard level of technology (A1); $r_{critical} = 0.5760$

strongest effect on all three observed traits (grain yield, plant height and thousand-grain weight), in both levels of cultivation intensity (standard and intensive), expression in Wielkopolska region Poland. AMMI analyses permits estimation of interaction effect of a genotype in each environment and it helps to identify

cultivars best suited for specific environmental conditions. AMMI analyses revealed significant GE interaction with respect to all three traits in both levels of cultivation intensity. The AMMI stability value exposed high cultivars stability. Yang et al. (2009) reported that biplot, based on AMMI, is a useful

Fig. 17 Heatmap for linear Pearson's correlation coefficients between plant height observed in different environments (E01 – E21 – see Table 1) at intensive level of technology (A2); $r_{critical} = 0.5760$

visualization techniques to find similarity or dissimilarity among genotypes or environments. Yang et al. (2009) also cautions against the use of a biplot beyond a visual descriptive tool as the method utilizes only a sample of the full data set and does not involve any statistical hypothesis testing. The AMMI results displayed on the GE biplot enables determination of the main effect of the genotype, the environment, and the most meaningful GEIs.

In general, environments with scores near zero have little interaction across cultivars and provide low discrimination among cultivars (Anandan et al. 2009). In this study, these patterns were observed in E10, E13 and E20 environments (Figs. 8, 9, 10, 11, 12, 13). AMMI models are capable of measuring the weight of the environments, the genotypes and their interactions throughout a value that measures how stable a genotype is in all environments in terms of particular

Fig. 18 Heatmap for linear Pearson's correlation coefficients between thousand-grain weight observed in different environments (E01 – E21 – see Table 1) at standard level of technology (A1); $r_{critical} = 0.5760$

observed traits. The cultivars Algos, Baltiko and Trimester are recommended for further inclusion in the breeding programs because of their stability and good average values of observed traits. For these cultivars we obtained the best total (calculated for all three traits in both levels of cultivation intensity) genotype selection index (TGSI = 46, 52 and 53, respectively).

Conclusions

Obtained results show that genotypes, environments and GEI are highly significant indicating the existence of a wide range of variation between the cultivars, environments and their interactions. The existence of such significant GEI indicated possibility of selection of stable cultivars across the environments. Sources of genetic resistance used in cultivars Algos, Baltiko and Trimester breeding programs are recommended

Fig. 19 Heatmap for linear Pearson's correlation coefficients between thousand-grain weight observed in different environments (E01 – E21 – see Table 1) at intensive level of technology (A2); $r_{critical} = 0.5760$

for further inclusion in the breeding programs because of their stability and good average values of observed traits. For these cultivars we obtained the best total genotype selection index.

Compliance with ethical standards

Conflict of interest Authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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