Genotype by environment interaction for seeds yield in pea (*Pisum sativum* L.) using additive main effects and multiplicative interaction model

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Abstract The objective of this study was to evaluate the genotype by environment interaction using the additive main effects and multiplicative interaction model for seeds yield of pea cultivars grown in Poland. Twelve pea (*Pisum sativum* L.) cultivars: Bohun, Boruta, Cysterski, Ezop, Kavalir, Lasso, Medal, Santana, Tarchalska, Terno, Wenus and Zekon were evaluated in 20 environments (ten locations in 2 years). The experiment was laid out as randomized complete block design with three replicates. Seeds yield ranged from 26.10 dt ha⁻¹ (for Wenus in Radostowo 2011) to 79.73 dt ha⁻¹ (for Lasso in Słupia 2010), with an average of 50.70 dt ha⁻¹. AMMI analyses revealed significant genotype and environmental effects as well as genotype-by-environment interaction with respect to seeds yield. In the

analysis of variance, 89.19% of the total seeds yield variation was explained by environment, 1.65% by differences between genotypes, and 8.33% by GE interaction. The cultivar Terno is the highest stability. The cultivar Tarchalska is recommended for further inclusion in the breeding program because its stability and the highest averages of seeds yield.

Keywords *Pisum sativum* L. · Seeds yield · AMMI · Stability

Introduction

Poland has favourable agro-ecological conditions for the cultivation of peas for seeds. This species is characterized by high fertility, but at the same time significant variability of yield level. It also has a high protein content in seeds and the ability to bind atmospheric nitrogen, which is of both ecological and economic importance. Peas also play an important role in crop rotation as a plant that interrupts the frequent succession of cereals. Due to its short growing season it is a valuable forecrop for winter plant species. The relatively deep root system of peas and the large mass of post-harvest residues enrich the soil with nitrogen and organic matter. Peas also play an important role in the plant production systems where chemicals are not used or only used to a limited

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extent. Pea seeds can be used as human food and animal feed. In some countries, pea seeds are almost entirely used as a component of the human diet or are mainly used as a raw material for the production of high-protein concentrates. According to Bilalis et al. (2015), Davidsson et al. (2001), due to their nutritional value, peas may be considered as an alternative source of protein for soya in the countries where it is not a natural species or where soya beans of that species cannot be used due to allergic reactions or intolerance. Pea seeds contain about 22–24% total protein, 1.5% fat, 55% nitrogen-free extract compounds, and 6–8% crude fibre. They are an important source of lysine amino acid, whose content in 1 kg of seeds is 3–4 times higher than in cereal grains.

Pea is often described as a species adapted to a wide type of environmental conditions (e.g., Annicchiarico and Iannucci 2002) many studies have showed a significant influence of environment and genotype-by-environment (GE) interaction on phenotypic performance of seeds yield and other agronomically important traits (Moot and McNeil 1995; Acikgoz et al. 2009; Tolessa et al. 2013). An important goal of pea breeding has always been to maximize productivity by increasing seed yield. Obtaining as much knowledge as possible about the inheritance of the seed yield will allow acceleration of the genetic progress of this species. This trait is very complex and its expression depends on factors such as: genetics, environment and GE (Tan et al. 2012). The genotype response to diverse environmental conditions during the growing season determines the seed yield.

Among the main methods used to evaluate GE interaction, the following can be highlighted: (1) Eberhart–Russel (1966); (2) additive main effects and multiplicative interaction (AMMI) (Gollob 1968; Gabriel 1971; Mandel 1971; Gauch 1988, 2006; Zobel et al. 1988; van Eeuwijk 1995; Dias and Krzanowski 2003); and (3) mixed model (Henderson 1975; Smith et al. 2005; Resende 2007; Piepho et al. 2008). The literature shows several studies on the use of these three methods to assess GE interaction in different crops (Piepho 1994; Annicchiarico 1997; Yang et al. 2009; Malosetti et al. 2013).

The objective of this study was to assess genotype by environment interaction for seeds yield in pea (*Pisum sativum* L.) grown in Poland by the AMMI model. The AMMI method combines the traditional analysis of variance for the main effects of genotype

and environment as well as the principal component analysis (PCA) with multiplicative parameters into single analysis (Zobel et al. 1988).

Materials and methods

Material for the studies covered 12 pea (*Pisum sativum* L.) cultivars: Bohun, Boruta, Cysterski, Ezop, Kavalir, Lasso, Medal, Santana, Tarchalska, Terno, Wenus and Zekon. All 12 cultivars were in the official catalogue of varieties—The Polish National List (NLI) published by The Research Centre for Cultivar Testing (COBORU) at 2011. Field experiments were carried out over two years: 2010–2011 at ten locations: Bezek (51° 12' 06" N, 23° 16' 06" E), Chrzastowo (53° 09' 52" N, 17° 35' 02" E), Cicibór Duży (52° 04' 39" N 23° 06' 48" E), Głębokie (52° 38' 41" N, 18° 26' 18" E), Kawęczyn (52° 10' 09" N, 20° 20' 45" E), Krzyżewo (53° 01' 34" N, 22° 45' 29" E), Pawłowice (50° 27' 14" N, 18° 29' 28" E), Słupia (50° 36' 03" N, 19° 58' 28" E), Sulejów (51° 21' 10" N, 19° 53' 05" E) and Radostowo (53° 59' 27" N, 18° 43' 59" E). During each year, the experiment with genotypes (cultivars) was carried out in a randomized block design, with three replications. Peas were most frequently sown in the first decade of April. Harvesting took place in the last decade of July. The pH of soil, depending on the year and the experimental station, ranged from 6.2 to 7.2 pH. Cereals (winter or spring wheat) were the most common pre-crop. The seeds were treated with fungicide and Nitragin before sowing. In all experiments, after sowing, the soil herbicide was sprayed, and in case of weeds, a second spraying on dicotyledonous or monocotyledonous weeds was applied. Two insecticide sprays were used in all pest control experiments, and in case of pest occurrence, a third spraying was performed. The following fertilizers were applied: P₂O₅—from 30 to 60 kg ha⁻¹, K₂O— from 70 to 110 kg ha⁻¹, N—from 20 to 30 kg ha⁻¹. The meteorological conditions in Bezek, Cicibór duży, Chrzastowo, Głębokie, Kawęczyn, Krzyżewo, Pawłowice, Radostowo, Słupia and Sulejów during the vegetation season of pea in 2010, 2011 and over an extended period were presented in Table 1.

A two-way fixed effect model was fitted to determine the magnitude of the main effects of variation and their interaction on seeds yield. Least-squares means were simultaneously produced for the AMMI

Table 1 Meteorological conditions in Bezek, Cicibór Duży, Chrzastowo, Głębokie, Kawęczyn, Krzyżewo, Pawłowice, Radostowo, Słupia and Sulejów during the vegetation seasons of pea in 2010, 2011 and over an extended period

Cultivar	Year	Rainfall (mm)				Total (IV–VII)	Average temperature				Average (IV–VII)
		Month					Month				
		IV	V	VI	VII		IV	V	VI	VII	
Bezek	2010	18.9	72.4	94.4	156.3	342.0	9	14.5	17.6	21.6	15.7
	2011	30.6	40.8	80	178.9	330.3	9.9	14.6	18.3	19.4	15.6
Cicibór Duży	2010	23	126.8	67.7	48.2	265.7	8.7	14.5	17.9	21.6	15.7
	2011	37.6	61	65.4	201.6	365.6	9.5	13.7	18.4	18.1	14.9
Chrzastowo	2010	35.4	119.7	9.5	147.9	312.5	7.8	11.3	16.6	21.7	14.4
	2011	9	38.4	39.7	115.5	202.6	10.9	13.7	18.6	17.8	15.3
Głębokie	2010	32.4	35.4	27.2	162.4	257.4	8.3	12.5	16.8	21.5	14.8
	2011	6.4	39.7	87.5	95.2	228.8	11.2	14.7	18.1	18	15.5
Kawęczyn	2010	15.1	155.5	37	67.4	275.0	8.9	13.4	17.1	21.5	15.2
	2011	40.2	31.5	51.4	179.8	302.9	10.6	14.3	18.6	18.8	15.6
Krzyżewo	2010	29.8	148	74.1	87	338.9	8	14	17.2	21.3	15.1
	2011	42.5	66.4	44.6	218	371.5	9.8	13.3	18	19.2	15.1
Pawłowice	2010	54.3	214.6	61.2	97.6	427.7	8.7	12.3	17.1	21.1	14.8
	2011	21.4	57.4	42.8	111	232.6	10.4	13.4	19.3	17.7	15.2
Radostowo	2010	7.9	92.4	41.8	77.3	219.4	7.2	11.5	15.3	19.7	13.4
	2011	17.2	32.1	36.2	114.3	199.8	9.3	12.4	16.8	18.2	14.2
Słupia	2010	40.8	197.8	78.5	168.9	486.0	8.1	12.8	16.5	20.1	14.4
	2011	29.4	49.7	25.6	166.9	271.6	9.7	13.9	18.4	17.5	14.9
Sulejów	2010	25.5	136.9	58.3	86.7	307.4	8.3	12.8	16.9	20.7	14.7
	2011	21.6	49.8	22.6	175.5	269.5	9.8	13.5	18.1	18.2	14.9

model. The model first fits additive effects for the main effects of genotypes (G) and environments (E) followed by multiplicative effects for GE interaction by principal component analysis. The AMMI model (Gauch and Zobel 1990; 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 seeds yield 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. Expected distribution of Q_{ge} is normal.

The AMMI stability value (ASV) was used to compare the stability of genotypes as described by Purchase et al. (2000) as follows:

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

where SS is the sum of squares, $IPCA_1$ and $IPCA_2$ are the first and the second interaction principal component axes, respectively; and the $IPCA_1$ and $IPCA_2$ scores were the genotypic scores in the AMMI model. ASV is the distance from zero in a two-dimensional scatterplot of $IPCA_1$ scores against $IPCA_2$ scores. Since the $IPCA_1$ score contributes more to GE sum of square, it has to be weighted by the proportional difference between $IPCA_1$ and $IPCA_2$ scores to compensate for the relative contribution of $IPCA_1$ and $IPCA_2$ total GE sum of squares. The higher the $IPCA$ score, either negative or positive, the more

specifically adapted a genotype is to certain environments. Lower ASV score indicate a more stable genotype across environments.

Genotype selection index (GSI) was calculated for each genotype which incorporates both mean seeds yield and ASV index in single criteria (GSI_i) as (Farshadfar and Sutka 2003; Bocianowski et al. 2019a)

$$GSI_i = RY_i + RASV_i,$$

where GSI_i is genotype selection index for i th genotype, RY_i is rank of mean seeds yield for i th genotype, $RASV_i$ is rank for the AMMI stability value for the i th genotype.

The relationships between the seeds yield observed in different environments were assessed based on Pearson's correlation coefficients. All the analyses were conducted using the GenStat v. 18 statistical software package.

Results

In the analysis of variance, the sum of squares for environments main effect represented 89.19% of the total, and this factor had the highest effect on seeds yield. The differences between genotypes explained 1.65% of the total seeds yield variation, while the effects of GE interaction explained 8.33% (Table 2). Values for the three principal components were also highly significant (Table 2). The three principal

components of GE interaction accounted jointly for 68.99% of the whole effect it had on the variation of seeds yield. The first principal component (IPCA 1) accounted for 35.39% of the variation caused by interaction, IPCA 2 accounted for 18.03% while IPCA 3 accounted for 15.57% (Fig. 1 and Table 2).

The results of field trials demonstrated the impact of weather conditions, environment and genotypes on the seeds yield of pea genotypes. The seeds yield of the tested genotypes varied from 26.10 dt ha⁻¹ (for Wenus in Radostowo 2011) to 79.73 dt ha⁻¹ (for Lasso in Słupia 2010), throughout the 20 environments, with an average of 50.70 dt ha⁻¹ (Table 3). The reason of low yields in Radostowo in the 2011 was small amount of rainfall in June (36.2 mm) and theirs very unproportionate spread as well as high amount of precipitation in July (114 mm) what caused strong lodging of pea's cultivars. Very profitable rainfall was observed in period of vegetation in Słupia at 2010 (V—197.8 mm, VI—78.5 mm, VII—166.9 mm) as well as they profitable distribution (Table 1). The cultivar Tarchalska had the highest average seeds yield (54.10 dt ha⁻¹), and the cultivar Zekon had the lowest (48.82 dt ha⁻¹). The average seeds yield per environment also varied from 33.73 dt ha⁻¹ in Radostowo 2011, to 73.80 dt ha⁻¹ in Słupia 2010.

The stability of genotypes, environments, and specific GE interactions were showed in the AMMI1 biplot (Fig. 1). Among the tested genotypes, cultivar Santanta had the highest IPCA1 value of 1.860, while the smallest value of IPCA1 was – 2.578 for cultivar

Table 2 Analysis of variance of main effects and interactions for pea (*Pisum sativum* L.) cultivars seeds yield

Source of variation	d.f.	Sum of squares	Mean squares	F-statistic	Variability explained (%)
Total	719	103,188	143.5		
Treatments	239	102,324	428.1	1915.85***	99.16
Genotypes, G	11	1700	154.5	691.47***	1.65
Environments, E	19	92,029	4843.6	252.97***	89.19
Block	40	766	19.1	85.68***	0.74
GE interactions	209	8596	41.1	184.04***	8.33
IPCA 1	29	3042	104.9	469.37***	35.39
IPCA 2	27	1550	57.4	256.97***	18.03
IPCA 3	25	1338	53.5	239.41***	15.57
Residuals	128	2666	20.8	93.2***	
Error	440	98	0.2		

*** $P < 0.001$; IPCA principal component of interaction

Fig. 1 Biplot for genotype by environment interaction of pea (*Pisum sativum* L.) cultivars in 20 environments, showing the effects of primary and secondary components (IPCA1 and

IPCA2, respectively); *Be* Bezek, *Ch* Chrzastowo, *Ci* Cicibór Duży, *Gł* Głębokie, *Ka* Kawęczyn, *Kr* Krzyżewo, *Pa* Pawłowice, *Śł* Słupia, *Su* Sulejów, *Ra* Radostowo

Wenus (Fig. 1). Among the tested environments, the smallest IPCA1 value was observed in Głębokie 2011 (-4.582), while the highest value of IPCA1 was 1.604 in Radostowo 2011 (Fig. 1 and Table 3). The reaction to environmental changes as weather conditions, agronomic factors as well as stress has been described as the stability of the genotype. In the conducted research, the variability of this component resulted from climatic conditions.

The stability of tested genotypes can be evaluated according to biplot for seeds yield (Fig. 2). The cultivars Cysterski and Santanta interacted positively with the Głębokie 2010, Pawłowice 2010 and Cicibór Duży 2010, but negatively with the Głębokie 2011 and Słupia 2010 (Figs. 1, 2). The cultivars Bohun, Ezop, Tarchalska, Terno and Wenus interacted positively with the Głębokie 2011 and Radostowo 2010, but negatively with the Radostowo 2011 and Pawłowice 2011. The analysis showed that some genotypes have high adaptation; however, most of them have specific

adaptability. AMMI stability values (ASV) revealed variations in seeds yield stability among the 12 genotypes (Table 3). A stable variety is defined as one with ASV value close to zero. Consequently, the cultivars Terno and Zekon with ASV of, respectively, 0.494 and 0.959 were the most stable, while the cultivar Wenus ($ASV = 5.061$) was the least stable (Table 3). Cultivar Kavalir, with average seeds yield of 50.63 dt ha^{-1} very close to the general mean of 50.70 dt ha^{-1} , is distinguished on the biplot (Fig. 2). Generally, all cultivars were average seeds yield close to general mean, but with different adaptations (Figs. 1, 2): Bohun, Ezop, Tarchalska and Wenus showed specific adaptation to the conditions in Głębokie 2011, and Boruta, Cystersko, Kavalir, Lasso, Medal and Santana showed specific adaptation to the conditions in Pawłowice (both years), Zekon showed specific adaptation to the conditions in Bezek 2011, and Terno shows the highest stability. The cultivar Tarchalska has the best genotype selection index,

Table 3 Average seeds yield (dt ha^{-1}), for genotypes and environments, principal component analysis values of tested pea (*Pisum sativum* L.) cultivars, AMMI stability value (ASV) and genotype selection index (GSI)

Environment	Code	Genotype														Mean	IPC Ae1	IPC Ae2
		Bohun	Boruta	Cysterski	Ezop	Kavalir	Lasso	Medal	Santana	Tarchalska	Temo	Wenus	Zekon					
Bezek	2010	Be10	56.00	50.70	55.60	62.40	55.70	62.40	56.70	49.00	60.40	60.80	53.30	57.50	56.71	– 0.542	– 0.518	
	2010	Ch10	46.20	46.10	46.40	42.00	47.10	43.80	45.10	43.30	46.60	42.30	43.00	40.00	44.33	0.454	0.587	
	2010	Ci10	46.33	43.40	51.20	45.30	44.30	44.77	47.70	47.50	49.40	48.17	47.70	43.80	46.63	0.166	1.609	
Duży	2010	Gł10	39.90	41.80	50.50	40.20	42.90	41.60	39.20	43.70	45.43	42.20	39.90	44.33	42.64	1.103	1.981	
	2010	Ka10	52.30	51.40	45.00	49.30	47.40	52.53	52.50	49.00	55.60	44.30	51.10	49.57	50.00	– 0.394	– 0.467	
	2010	Kr10	78.17	70.00	73.40	73.50	72.00	71.40	72.00	75.70	76.60	73.50	71.40	70.30	73.16	– 0.312	1.344	
Pawłowie	2010	Pa10	50.00	48.70	57.00	47.20	52.40	57.20	55.00	53.40	61.70	46.30	50.40	49.30	52.38	0.980	0.921	
	2010	Śl10	75.60	75.10	66.90	76.70	73.10	79.73	69.40	68.40	78.50	72.30	77.20	72.67	73.80	– 1.148	– 1.115	
	2010	Su10	51.60	58.00	56.00	54.70	56.80	59.40	60.80	52.00	60.50	53.50	53.30	49.20	55.48	0.754	– 0.682	
Sulejów	2010	Ra10	49.60	46.20	44.40	45.90	45.20	43.70	47.50	44.20	49.70	46.50	46.70	45.60	46.27	– 0.514	0.546	
	2011	Be11	46.40	48.30	50.10	53.40	51.10	45.50	41.90	44.40	45.70	47.70	43.00	52.00	47.46	0.318	0.718	
	2011	Ch11	33.60	37.70	33.40	34.10	34.00	35.50	36.80	34.50	37.70	33.80	35.30	32.60	34.92	0.267	– 0.018	
Chrzastowo	2011	Ci11	37.60	42.20	39.00	44.80	40.30	43.70	40.20	37.90	44.20	44.70	43.60	36.40	41.22	– 0.386	– 0.389	
	2011	Gł11	57.50	38.20	40.90	57.50	41.50	43.50	41.40	39.00	59.50	44.00	59.70	41.80	47.04	– 4.582	0.876	
	2011	Ka11	42.10	41.50	37.20	43.80	39.10	48.00	49.70	38.00	44.40	38.00	39.20	32.80	41.15	– 0.034	– 1.617	
Kawęczyn	2011	Kr11	57.40	62.00	62.30	58.60	63.70	66.20	62.50	66.10	65.70	61.20	63.80	61.10	62.55	1.016	0.366	
	2011	Pa11	50.80	52.70	53.60	48.30	51.90	61.13	55.20	57.60	56.13	51.20	52.20	53.60	53.70	1.343	0.058	
	2011	Śl11	66.20	72.97	62.60	71.40	75.10	72.50	71.10	65.90	67.50	65.10	73.50	66.10	69.16	– 0.001	– 1.729	
Radostowo	2011	Su11	43.20	41.60	34.80	41.20	42.70	47.90	44.50	33.27	42.50	42.80	38.90	46.60	41.66	– 0.093	– 1.735	
	2011	Ra11	30.10	34.30	35.40	36.40	36.40	44.90	31.00	35.10	34.20	29.70	26.10	31.20	33.73	1.604	– 0.735	
	Mean	50.53	50.14	49.79	51.34	50.63	53.27	51.01	48.90	54.10	49.40	50.47	48.82	50.70				
IPCAg1		– 2.377	1.257	1.858	– 2.210	1.103	1.336	0.914	1.860	– 1.444	– 0.185	– 2.578	0.465					
IPCAg2		0.565	– 1.297	2.801	– 0.757	– 0.632	– 2.538	– 1.390	1.622	0.826	0.335	0.171	0.295					
Stability (ASV)		4.697	2.786	4.597	4.4	2.254	3.649	2.269	3.994	2.95	0.494	5.061	0.959					
GSI		17	13	19	12	8	9	8	19	7	11	19	14

Fig. 2 Biplot for the primary component of interaction (IPCA1) and average pea (*Pisum sativum* L.) seeds yield (dt ha^{-1}). Vertical line at the centre of biplot is the general grand mean

equal to 7 (Table 3). However, the cultivars Cysterski, Santana and Wenus have the worst genotype selection index (19).

The positively statistically significant ($\alpha = 0.05$) correlation coefficients for seed yield were observed for following pair of environments: Sh10-Ka10 ($r = 0.60$), Su10-Ch10 (0.59), Su10-Pa10 (0.62), Ch11-Ka10 (0.67), Ch11-Su10 (0.78), Ci11-Sh10 (0.59), G111-Sh10 (0.63), G111-Ra10 (0.65), Ka10-Ka11 (0.61), Ka11-Su10 (0.78), Ka11-Ch11 (0.65), Pa10-Kr11 (0.76), Pa10-Pa11 (0.71), Pa11-Kr11 (0.81), and Be10-Su11 (0.61) (Fig. 3). However, negative correlation coefficients were observed for seed yield in Ci10 and Sh11 (-0.59) as well as G110 and Sh11 (-0.60) (Fig. 3).

Discussion

The seeds yield in pea (*Pisum sativum* L.) is a trait determined by multiple genes that cause change in the performance of genotypes depending on the

cultivation environment. The plant's morphological characteristics are influenced by abiotic environmental factors such as soil structure, availability of oxygen and nutrients, soil moisture, temperature, and biotic factors such as plant genetic features and occurring soil microorganisms (Hodge et al. 2001; Rich and Watt 2013). High diversity of fungal communities may be beneficial for crop production, especially high diversity of AM fungi may be an important factor in maintaining productivity and stability in sustainable agricultural ecosystems (Kjølner and Rosendahl 2001; Unterseher et al. 2011). In this study, the three sources of variation were highly significant. Similar results for seeds yield in pea obtained Krajewski et al. (2012) and Tolessa et al. (2013). Krajewski et al. (2012) obtained significant GE interaction for seeds yield of two populations of lines of the F_5 generation (110 and 101 lines, respectively) grown in Poznań and Wiatrowo, Poland. Tolessa et al. (2013) analysed 14 pea genotypes in 16 environments of Ethiopia. Boros and Sawicki (1997) showed that high yielding varieties are characterized by lower yield stability than

Fig. 3 Heatmap for linear Pearson's correlation coefficients between seeds yield observed in different environments (*Be* Bezek, *Ch* Chrzastowo, *Ci* Cicibór Duży, *Gł* Głębokie, *Ka* Kawęczyn, *Kr* Krzyżewo, *Pa* Pawłowice, *Sł* Słupia, *Su* Sulejów, *Ra* Radostowo, *10* 2010, *11* 2011); $r_{critical} = 0.576$

average. Dore et al. (1998) report that the yield of a narrow-leaved Solara variety in a relatively small area of France ranged from 3.07 to 7.09 t ha⁻¹ in 3 years of research. The basic cause of this state is considered to be variable humidity conditions prevailing during the growing season. They affect the cast and all elements of the yielding structure, the length of subsequent growing stages of vegetation, the height and lodging of plants. Multi-location experiments the AMMI biplot allows to visualize the main genotype effect in different environments (Bocianowski et al. 2019a). The AMMI model was used to study many species (Abakemal et al. 2016; Edwards 2016; Nowosad et al. 2017, 2018; Bocianowski et al. 2019d). Indicating GE's interaction and other interactions is possible using the AMMI model. This model ensures an increase in the correctness of estimation (Bocianowski et al. 2018, 2019b). The use of AMMI

allows the division of genotypes or other factors into groups based on similarity as well as characterization and detection of trends depending on the environment. It provides a very efficient tool for extracting genotypes or varieties that are characterized by greater efficiency in diverse environments. The use of such a strategy makes it possible to obtain more information from the GE interaction. The seeds yield expression in Poland is the most influenced trait by genotype and environment main effects as well as GE interaction. AMMI analyzes allowing for the estimation of the effect of genotype interaction in each environment, thus enable the identification of genotypes most accurately matched to the environmental conditions. Significant GE interaction of seeds yield was indicated with AMMI analysis application.

High genotypes stability is linked with the AMMI stability value. Determination of the main effect of the

genotype, the environment, and the most meaningful GE interactions could be assessed based on the AMMI results displayed on GE biplot. The AMMI models are able to measure the weight of the environments, the genotypes and their interactions using a value that measure genotype stability in all environments taking into account the seeds yield. The observation and analysis of GE interaction in multi-environment yield trials is very important for evaluation, selection and recommendation of crop cultivars. AMMI models are widely used in plant breeding of the most popular crops such as wheat (Sardouei-Nasab et al. 2019), maize (Branković-Radojčić et al. 2018; Bernardo Júnior et al. 2018; Bocianowski et al. 2019c), rice (Inabangan-Asilo et al. 2019), cassava (Fotso et al. 2018), peanuts (Patil et al. 2018), cotton (Riaz et al. 2019), and willow (Fabio et al. 2017).

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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