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Genotype by Environment Interaction (GEI) Effect for Potato Tuber Yield and Their Quality Traits in Organic Multi-Environment Domains in Poland

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Abstract: Potatoes (*Solanum tuberosum* L.) are an important plant crop, whose yield may vary significantly depending on pedo-climatic conditions and genotype. Therefore, the analysis of the genotype × environment interaction (GEI) is mandatory for the setup of high-yielding and stable potato genotypes. This research evaluated the tuber yield (t ha^{-1}) and yield characteristic of nine potato cultivars over 3 years and 4 organic farms in Poland by additive main effects and multiplicative interactions (AMMIs) and genotype plus genotype environment interaction (GGE) biplot analyses. The results of these analyses indicated significant differentiation of tuber yield among genotypes in individual environments. It was found that the environment (E, where E = L (localization) × Y (year)), genotype (G) and GEI, but not replication, significantly affected tuber yield. The AMMI analysis showed that the environment factor explained the most considerable part of tuber yield variations (52.3%), while the GEI and G factors explained a much lower part of the variations. The AMMI and GGE analyses identified five cvs.: Twister (46.4 t ha^{-1}), Alouette (35.8 t ha^{-1}), Kokra (34.8 t ha^{-1}), Levante (33.1 t ha^{-1}), and Gardena (30.4 t ha^{-1}), as leading cultivars in the studied organic farms due to their high productivity coupled with yield stability. The statistical measure Kang (YS_i) showed that these cvs. can be considered as adaptable to a wide range of organic environments. In the case of morphological traits of tubers (tuber shape and depth of tuber eyes), the most important factor influencing both these traits was genotype (G). Influence of other factors, like localization (L), year (Y), and all interactions (double and triple), were much less significant or insignificant. In case of taste and non-darkening of tuber flesh, the main effects which significantly affected the values of these traits were genotype (G) and localization (L). We observed that cooking type can vary depending on the year (Y) and the localization (L).

Keywords: organic crop; potato; GEI; AMMI model; GGE biplot; stable cultivars

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1. Introduction

The pandemic has caused rapid changes in life priorities for most citizens of developed countries. Taking care of your life and that of your loved ones has become the most important priority. In the last decade, the production and consumption of organic food has increased systematically worldwide. In recent years, several countries, including Germany, France, Estonia, Finland, Sweden, and Slovenia, have set goals of achieving 20% of their area under organic farming. In Austria, in 2019, already 26% of their area was already under organic farming, and over 20% in Estonia and Sweden. The report prepared by the Agricultural and Food Quality Inspection shows that in 2022, the total area of agricultural land on which organic production methods were used increased by 3.5% (22,882 ha). It can be safely emphasized that organic farming is a global trend—this was clearly stated by the European Commission. The most important goals of the EU strategy include reducing the use of pesticides, antibiotics, and fertilizers, and achieving a higher share of organic farming area by 2030, which on average for the entire European Union should amount to 25%. According to experts, a realistic goal for Poland is to achieve 7% of such uses. Potato (*Solanum tuberosum* L.) is an important staple food in Poland and is deeply rooted in Polish cultural traditions since it can be produced in most parts of the country. Organic production can be unpredictable due to environmental factors (e.g., climate and disease pressure), which can cause large fluctuations in quantity and quality. Producers of organic potato tubers are looking for productive cultivars, suited to their local climatic and soil conditions, that are not susceptible to diseases and pest attack. Organic agriculture standards recommend the cultivation of site-adapted crop cultivars [1]. Before commercial potato seeds are produced for organic farmers, the most suitable cultivars must be chosen [2,3]. The organic-farming growing conditions require adaptability and stability of potato cultivars [1]. The most important quality traits for suitable cultivars in organic farming are (a) early canopy closure under low N for good weed suppression; (b) early tuber setting and tuber bulking to be less exposed to late blight season; (c) well established root system for efficient nutrient uptake; (d) resilience to irregular water availability; (e) stability of yielding; (f) good morphological traits, good and stable taste; (g) durable resistance to main diseases [4,5]. The quality traits of potato tubers are well known to be closely affected by genotype (G) and environment (E) (i.e., soil properties, rainfall, temperature, and agricultural management) [6–9]. The environment is usually highly variable over seasons and specific locations, thus representing the main factor affecting phenotypic behaviour. Knowledge of the GEI index can be useful in developing widely adaptable and stable genotypes in different environments. It also allows for improving the quality characteristics of existing cultivars or breeding lines, thus meeting the quality standards required on the domestic and international market. In such studies, multi-environment trials (METs) are often conducted to better understand the performance of genotypes in different environments by examining their stability [10,11]. The AMMI analysis combines the ANOVA with the PCA [12], while the GGE analysis removes the E and integrates the G with the GEI effect [13]. The AMMI and the GGE biplot analysis can be effectively integrated to visualize the GEI, identify representative environments, and delineate mega-environments, detecting the ability of test environments to discriminate and identify stable genotypes in METs [14].

In the present study, nine potato cultivars were evaluated (eight table and one starch).The experiments were conducted in four organic farms during three growing seasons to (1) estimate the GEI of potato tuber yield by using the AMMI and the GGE biplot analysis, (2) find out stable cultivars suitable for organic production with low levels of GEI, and (3) recognize cultivars with good morphological traits and high cooking quality in all tested environments.

2. Materials and Methods

2.1. Plant Material

In each location, nine potato cultivars (Alouette, Carolus, Otolia, Twister, Twinner, Levante, Kokra, Bzura, Gardena) were planted in three replications (Table 1). In each of the three blocks (=replications), the cultivars were planted in 10-hill plots. The spacing of plants in individual locations was as follows: in Tuligłowy 65 cm × 35 cm; in Połomia 67.5 cm × 35 cm; in Grabów 70 cm × 40 cm; in Jadwisin 75 cm × 33 cm. The tuber yield (t ha^{-1}) and the morphological traits, depth of eyes and regularity of tuber shape, were evaluated after harvest. Cooking quality (taste, texture, and discoloration of tuber flesh) was carried out over two years of experiments. The cultivars evaluated in the study were selected from a group of 65 European potato cultivars intended for organic farming, characterized within the Ecobreed project (https://ecobreed.eu (accessed on 11 September 2024)). The chosen cvs. were evaluated within the farmer-participatory breeding framework in contrasting pedoclimatic zones. These cvs. stood out from the rest with a good set of morphological features and a high level of resistance to *P. infestans*.

Table 1. List of potato cultivars used in this work.

Cultivar [(1)]	Type	Maturity Group	Resistance to PVY	Resistance to *Phytophtora infestans* (Leaflets)	Flesh Colour	Cooking Type [(2)]
Alouette (NL)	table	early	8	9/9	yellow	AB
Carolus (NL)	table	early	7	9/9	yellow	BC
Twinner (NL)	table	early	7	8/9	yellow	AB
Levante (NL)	table	early	6	8.5/7.5	light yellow	B
Gardena (PL)	table	mid early	7	8/8	yellow	B-BC
Twister (NL)	table	mid early	8	9/9	light yellow	AB
Otolia (DE)	table	mid early	7	7/4.5	yellow	B
Kokra (SL)	table	mid early	8	8	cream	AB
Bzura (PL)	starch	late	9	8/4	light yellow	C

[(1)] The cultivar description according to catalogue data; Country of origin: NL—Netherlands; PL—Poland; DE—Germany; SL—Slovenia; [(2)] Cooking types: Type A—salad, tubers remain whole after boiling, firm, easy to cut out with fine structure, suitable for salad; Type B—multi—purpose for salad, mashing, French fries, flesh slightly mealy, slightly moist with fairy fine structure; Type C—mealy for mashing and baking.

2.2. Cultivation Practices

Field experiments were carried out over three growing seasons: 2020, 2021, and 2022 across four organic locations. Two of these locations were on fields belonging to individual farmers from Podkarpackie Voivodeship: Połomia and Tuligłowy. Another two were located in the Mazowieckie Voivodeship: Jadwisin and Grabów (Figure 1). The geographic, soil, fertilization, and fore crops data for field experiments are presented in Supplementary Table S1. The tubers were planted at the end of April and harvested approximately after 130 days (Supplementary Table S2). Meteorological conditions ((rainfall (mm) and air temperature (°C)) for each growing season and for each localization are presented in the Supplementary Figures (Figures S1–S4).

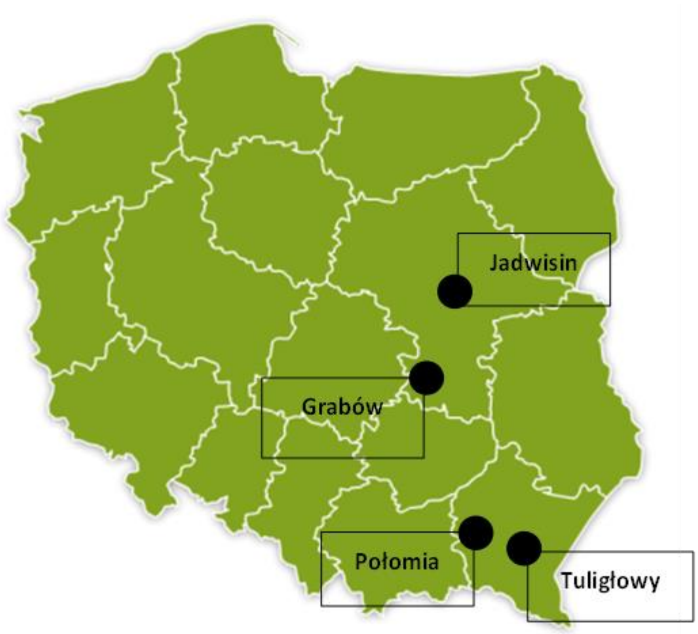

Figure 1. Map of Poland with location of organic farms.

2.3. Assessment of Morphological Characteristics of Potato Tubers

The most important characteristic for assessing the morphological features of tubers are regularity of tuber shape and depth of eyes. The evaluated samples of potato tubers were previously cleaned from the rest of the soil and washed. Regularity of tuber shape depends on the depth of indentations at the rose and heel ends and on all other deviations from ideal shape. The regularity of the tuber shape was evaluated on a 9-grade scale, where 1 = the highly malformed tuber shape and 9 = the perfect tuber shape (almost all tubers of one type of shape). The depth of eyes is a trait especially important for cultivars for table and processing use. The depth of eyes was evaluated on a 9-grade scale, where 1 = very deep eyes, tubers not suitable for table use; 9 = eyes impalpable under finger [15].

2.4. Cooking Quality Traits

The cooking quality of the potato tubers was assessed in two growing seasons: 2020 and 2021. In potato breeding, cooking quality is evaluated mainly by using tubers boiled in water. The objective is to evaluate the suitability of fresh tubers for the preparation of dishes. Ten main characteristics of potato after cooking quality may be distinguished: surface colour of flesh, uniformity of colour of cut surface, disintegration, consistency, mealiness, moisture, structure, taste, stickiness, and cooking type. In Europe, the assessment of cooking quality has been standardized by the European Association for Potato Research (EAPR) and designed as the so-called European method [16]. According to this method, potatoes are classified into four cooking types: (1) Type A—salad, tubers remain whole after boiling, firm, easy to cut out with fine structure, suitable for salad; (2) Type B—multi–purpose for salad, mashing, French fries, flesh slightly mealy, slightly moist with fairly fine structure; (3) Type C—mealy, for mashing and baking; and (4) Type D—very mealy, has limited consumption use, for dry and coarse purée, and for baking. The classification is based on the textural characteristics of the tuber flesh. These features have been expressed into five main characteristics, which are scored on a 4-grade scale: disintegration (of tuber cortex), consistency, mealiness, moistness, and structure. There was also a separate characteristic for flavour. Besides the characteristics, the potatoes are evaluated for (1) flesh colour; (2) discoloration of cooked tubers, which is rated twice (10 min and 24 h after cooking) on scale ranging from 1 to 9 (the colour range is controlled by colour chart); (3) discoloration of potato flesh in raw state, which is evaluated on a lengthwise cut of tubers 4 h after cutting, rating system as above.

2.5. Statistical Analyses

The additive main effects and multiplicative interaction (AMMI) model was used to assess the stability and yielding level of nine potato cultivars in four organic localizations over three years. The environment in the AMMI analyses was a combination of year and localization. The AMMI model is based on the number axes of the main components, and it is displayed graphically in the form of GGE biplots. The ANOVA test was used for comparison data from the morphological and cooking quality traits. All statistical analyses were performed with the use of Statistica 13 software (version 13, StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Tuber Yield

Statistical analyses were performed by using the AMMI model. The analysis of genotype by environment interaction (GEI) was performed for 9 cultivars evaluated in 12 environments. In this research, we treated each location in each year as individual environment.

The GGE biplots analysis based on the AMMI model for the performance of 9 potato cultivars was constructed based on the values of the first two interactions' principal component scores (IPC1 and IPC2), which explained 68.7% of the potato yield variation due to G and GEI (Table 2, Figure 2). Figure 2 shows the association or relationship between the different environments and cultivars. Environments which are located at larger distances from the centre of the biplot contributed the most to GEI. Environments with small vector angles tend to have closer similarity, and those with wide vector angles show minimum association. The greatest contribution in this interaction was observed for environments: Grabów 2021, Tuligłowy 2020 and 2021, while the smallest one for: Jadwisin 2021 and 2022, Grabów 2022, Połomia 2020, and 2021 (Figure 2). Cultivars and environments on the right side of the figure have higher tuber yields than average, while cultivars and environments on the left side have tuber yields below average (Figure 2). Cultivars yielding better than environmental average were Twister, Otolia, Alouette, Kokra, and Levante, while weaker than environmental average: Bzura, Twinner, Carolus, and Gardena (Figure 2, Table 3, and Supplementary Tables S3 and S4). Cultivars and environments relative to first IPC1 are presented in Figure 3. The distance from the IPC1 controls the extent of GEI. Cultivars and environments which are located near axis IPC1 (with small effects of GEI) characterized small participation in interactive variability. These cultivars and environments can be classified as stable (Figure 3). The GGE biplot analysis shown that Twister, Alouette, Kokra, Levante, and Gardena were the most stable cultivars in tuber yield in all 12 environments and can be considered as adaptable to all the environments in Poland (Figure 3). Cultivars Otolia, Twinner, Carolus, and Bzura were far from axis IPC1, hence they are more sensitive to the GEI and therefore specifically adapted to environments (Figure 3).

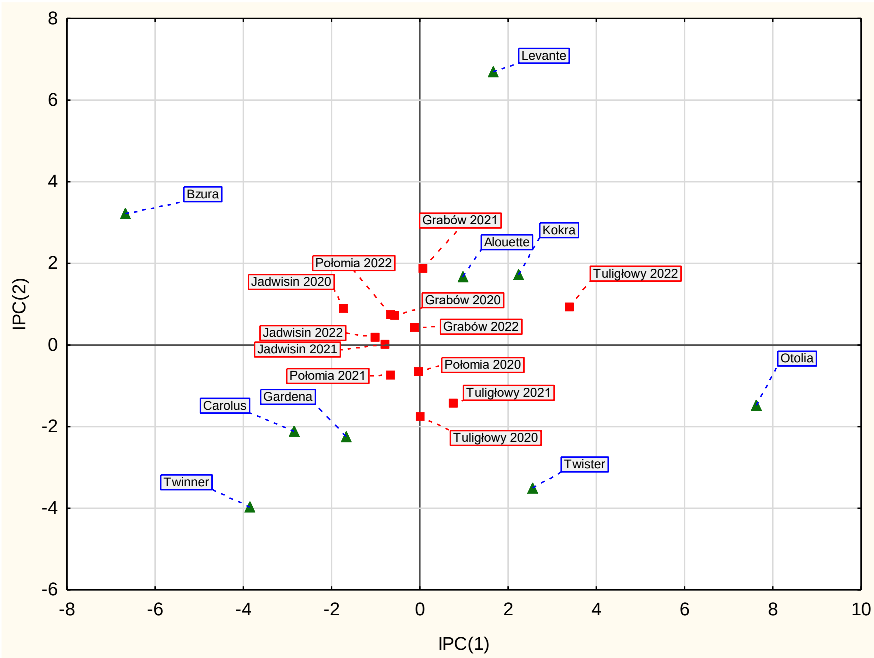

Figure 2. Biplot analysis of GGE for first two IPC scores (IPC1 vs. IPC2) for tuber yield (2020–2022).

Table 2. AMMI analysis of the variance of tuber yield of potato cultivars evaluated in 12 environments (2020–2022).

Source of Variation	DF [(1)]	Sum of Square	Mean Square	Variability %	GEI Explained %	F Statistic
Total	251	59530.8	237.2	100.0		
Environment (L × Y = E) [(2)]	11	31132.6	2830.2	52.3		45.987 **
Replication (R)	16	984.7	61.5	1.7		1.634
Genotype (G)	8	8534.3	1066.8	14.3		28.325 **
Genotype × Environment (GEI)	88	14058.5	159.8	23.6		4.242 **
IPC 1	18	6484.7	360.3	10.9	46.1	4.242 **
IPC 2	16	3182.8	198.9	5.3	22.6	2.873 **
IPC 3	14	1482.5	105.9	2.5	10.5	2.159 **
IPC 4	12	1225.2	102.1	2.1	8.7	1.931 **

Table 2. *Cont.*

Source of Variation	DF [1]	Sum of Square	Mean Square	Variability %	GEI Explained %	F Statistic
IPC 5	10	700.0	70.0	1.2	5.0	1.596 **
IPC 6	8	556.8	69.6	0.9	4.0	1.451
IPC 7	6	306.5	51.1	0.5	2.2	1.133
IPC 8	4	120.0	30.0	0.2	0.9	0.797
Error	128	4820.7	37.7	8.1		

(1) DF—degrees of freedom; (2) L × Y = E—Localization × Year = Environment; GEI—interaction G × E; IPC—interaction principal component; ** $p < 0.01$.

Table 3. Measures of wide adaptation for 9 potato cultivars for tuber yield (2020–2022).

Cultivar	Mean Tuber Yield t ha^{-1} (1)	SD (2)	Measure of Yield Superiority	Measure of Yield of Advantage of the *i*-th Cultivar (R_i)	Measure Kang (YS_i)
Alouette	35.8 $_{(3)}$	±14.3	86 $_{(2)}$	0.75 $_{(2)}$	8 $_{(2)}$
Bzura	33.4 $_{(6)}$	±9.5	183 $_{(6)}$	0.58 $_{(4)}$	0 $_{(7)}$
Carolus	27.8 $_{(8)}$	±10.8	249 $_{(8)}$	0.08 $_{(7)}$	0 $_{(7)}$
Gardena	30.4 $_{(7)}$	±10.4	188 $_{(7)}$	0.33 $_{(6)}$	2 $_{(5)}$
Kokra	34.8 $_{(4)}$	±15.8	101 $_{(4)}$	0.75 $_{(2)}$	7 $_{(3)}$
Levante	33.1 $_{(5)}$	±15.1	160 $_{(5)}$	0.50 $_{(5)}$	3 $_{(4)}$
Otolia	37.2 $_{(2)}$	±21.2	94 $_{(3)}$	0.67 $_{(3)}$	1 $_{(6)}$
Twinner	24.7 $_{(9)}$	±11.6	347 $_{(9)}$	0.08 $_{(7)}$	−1 $_{(8)}$
Twister	46.4 $_{(1)}$	±17.5	13 $_{(1)}$	0.92 $_{(1)}$	12 $_{(1)}$

(1) mean value for tuber yield from 12 environments; (2) SD—standard deviation.

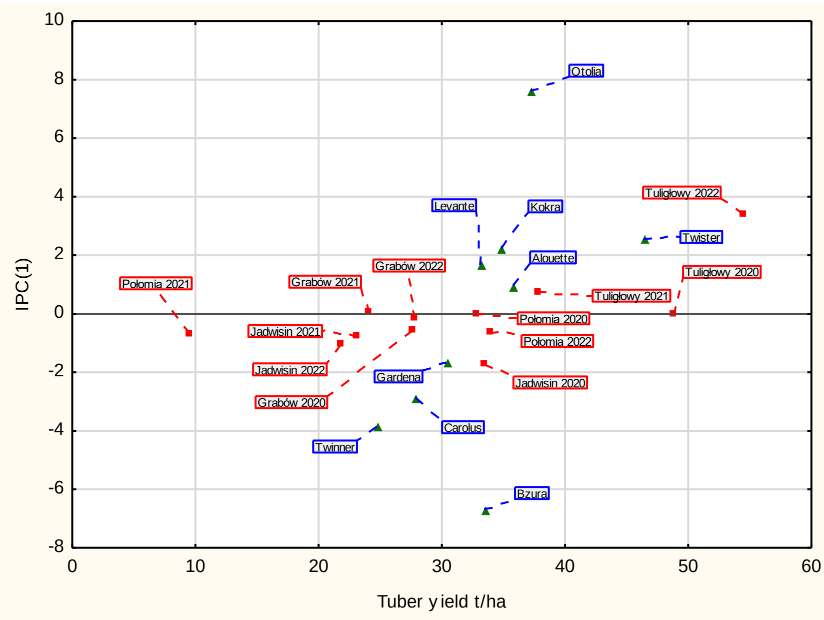

Figure 3. Biplot analysis of GGE for the IPC1 scores and tuber yield of 9 potato cultivars across 12 environments (2020–2022).

The statistical results (Table 2) indicate significant differentiation of tuber yield among genotypes in individual environments. It was found that the environment (E, where E = L × Y), genotype (G), and GEI were the main effects, which significantly affected the tuber yield. The contribution of factor genotype (G) to explaining the observed variability was 14.3%, environment (E)—52.3% and GEI—23.6%. This shows that the environment had the greatest influence on the variability of tuber yield, the interaction GEI had a smaller influence and the genotype had the least variability (Table 4). In the AMMI analysis, the sum of squares deviations for GEI has been divided on the sum of squares deviations for interaction principal components (IPCs). The first five IPCs were statistically significant. IPC1 was responsible for 46.1% and IPC2 for 22.6% sum of squares for GEI. IPC1 and IPC2 were used for further statistical analyses (Table 2).

Table 4. Mean values and standard deviations for depth of eyes and regularity of tuber shape in individual years (2020–2022).

Year	Depth of Eyes (Scale 1–9)		Regularity of Tuber Shape (Scale 1–9)	
	Mean	SD [(1)]	Mean	SD [(1)]
2020	7.4	±0.06	7.0	±0.08
2021	7.3	±0.11	6.8	±0.13
2022	7.3	±0.08	7.0	±0.09

[(1)] SD—standard deviation.

In next step, cultivars with broad adaptation to various environments were distinguished. In Table 3, the following statistics are presented: mean values of tuber yield (t ha^{-1}), standard deviation (SD), index for ranks for mean, measure of yield of advantage of the *i-th* cultivar (R_i), and measure Kang (YS_i). The highest tuber yield was noted for cvs. Twister (46.4 t ha^{-1}), Otolia (37.2 t ha^{-1}), Alouette (35.8 t ha^{-1}), and Kokra (34.8 t ha^{-1}). The analysis of cultivars in terms of measures of broad adaptation showed that cvs. Twister, Alouette, Kokra, and Otolia have a higher degree of adaptation in a broad sense, while cvs. Bzura, Twinner, Carolus, Gardena, and Levante have a lower degree of adaptation in a broad sense. Cultivars with R_i closer to 1 always yield means above environmental (Table 3). Measure Kang (YS_i) showed that cultivars Twister, Alouette, Kokra, and Levante were characterized by a relatively higher (compared to other cultivars) degree of wide adaptation. A different response of potato cultivars to environmental factors suggests that there is a need to select potato cultivars in various locations and years.

3.2. Morphological Assessment of Tubers: Regularity of Tuber Shape and Depth of Eyes

Potato tubers followed by three years of experiments had good regularity of tuber shape and shallow depth of eyes (Tables 4 and 5, and Supplementary Tables S3 and S4). In Table 5, the following data are presented: mean values for depth of eyes and regularity of tuber shape, standard deviation (SD), and rank for mean values. Analysis of variance for regularity of tuber shape and depth of eyes are presented in Table 6. It was found that genotype (G), localization (L), year (Y), and all interactions (double and triple) were significantly affected by regularity of tuber shape. Analysis of variance for depth of eyes showed highly statistically significant differences for genotype (G) and interactions (G × L), (G × Y), and (G × L × Y) (Table 6).

Table 5. Result for mean values, standard deviation, index for ranks for mean values for depth of eyes and regularity of tuber shape (2020–2022).

Cultivar	Depth of Eyes (Scale 1–9)			Regularity of Tuber Shape (Scale 1–9)		
	Mean	SD [(1)]	Rank	Mean	SD [(1)]	Rank
Alouette	7.8	±0.34	1	7.6	±0.49	1
Bzura	6.1	±0.61	6	5.8	±0.94	8
Carolus	7.6	±0.46	2	7.4	±0.54	2
Gardena	7.3	±0.44	4	6.6	±0.66	6
Kokra	6.6	±0.46	5	6.5	±0.49	7
Levante	7.8	±0.39	1	7.1	±0.74	5
Otolia	7.4	±0.57	3	7.1	±0.69	5
Twinner	7.6	±0.52	2	7.3	±0.57	3
Twister	7.6	±0.44	2	7.2	±0.58	4

[(1)] SD—standard deviation.

Table 6. ANOVA results for the morphological traits (2020–2022).

Sources of Variation	ANOVA (Two–Way)			
	Sum of Squares	DF [1]	Mean Square	F Statistic
	ANOVA results for regularity of tuber shape			
Genotype (G)	60.91	8	7.61	65.13 ***
Localization (L)	3.97	3	1.32	11.32 ***
Year (Y)	1.36	2	0.68	5.82 **
(G) × (L)	10.78	24	0.45	3.84 ***
(G) × (Y)	8.25	16	0.52	4.41 ***
(L) × (Y)	2.45	6	0.41	3.49 **
(G) × (L) × (Y)	10.90	48	0.23	1.94 ***
Error	16.83	144	0.12	
	ANOVA results for depth of eyes			
Genotype (G)	61.225	8	7.653	33.91 ***
Localization (L)	1.471	3	0.490	2.17
Year (Y)	1.280	2	0.640	2.84
(G) × (L)	23.721	24	0.988	4.38 ***
(G) × (Y)	14.728	16	0.920	4.08 ***
(L) × (Y)	2.590	6	0.432	1.91
(G) × (L) × (Y)	21.424	48	0.446	1.98 ***
Error	32.500	144	0.226	

[1] DF—degrees of freedom; *** significant at $p < 0.001$; ** significant at $p < 0.01$.

3.3. Cooking Quality Traits

Potato tubers from four organic farms were characterized by a two-year experiment (2021 and 2022) in terms of cooking quality and cooking types. The statistical analysis showed that genotype (G) and year (Y) were the main effects, which significantly affected the values obtained for cooking type (Table 7 and Table 9).

Table 7. Cooking type (2021–2022).

Cultivar	Cooking Type [1]							
	Year 2021				Year 2022			
	Tuligłowy	Połomia	Grabów	Jadwisin	Tuligłowy	Połomia	Grabów	Jadwisin
Alouette	BC	BC	BC	BC	B	A	BC	C
Carolus	B	BC	AB	AB	B	A	A	AB
Levante	BC	BC	BC	AB	B	AB	B	BC
Twinner	BC	AB	B	AB/C	AB	AB	BC	AB
Twister	BC	BC	C	B	BC	AB	AB	AB
Otolia	BC	BC	BC	AB	AB	AB	BC	B
Kokra	BC	BC	BC	BC	BC	B	C	BC
Bzura	CD	CD	BC	CD	C	AB	CD	C
Gardena	BC	BC	BC	BC	BC	BC	BC	BC

[1] Cooking types: Type A—salad; Type B—multi-purpose; Type C—mealy for mashing and baking; Type D—very mealy for purée and baking.

All tested cultivars were characterized in individual year and localization by good taste and non-darkening of tuber flesh, both raw and cooked. Mean values, standard deviation, and rank for taste and non-darkening of tuber flesh are presented in Table 8. Statistical analysis showed that genotype (G) and localization (L) were the main effects that significantly affected the values obtained for the taste and non-darkening of flesh tubers, both raw and cooked (Table 9). By two-year experiments, the potato tubers harvested from four organic localization were characterized as having a very good and stable taste (Figure 4).

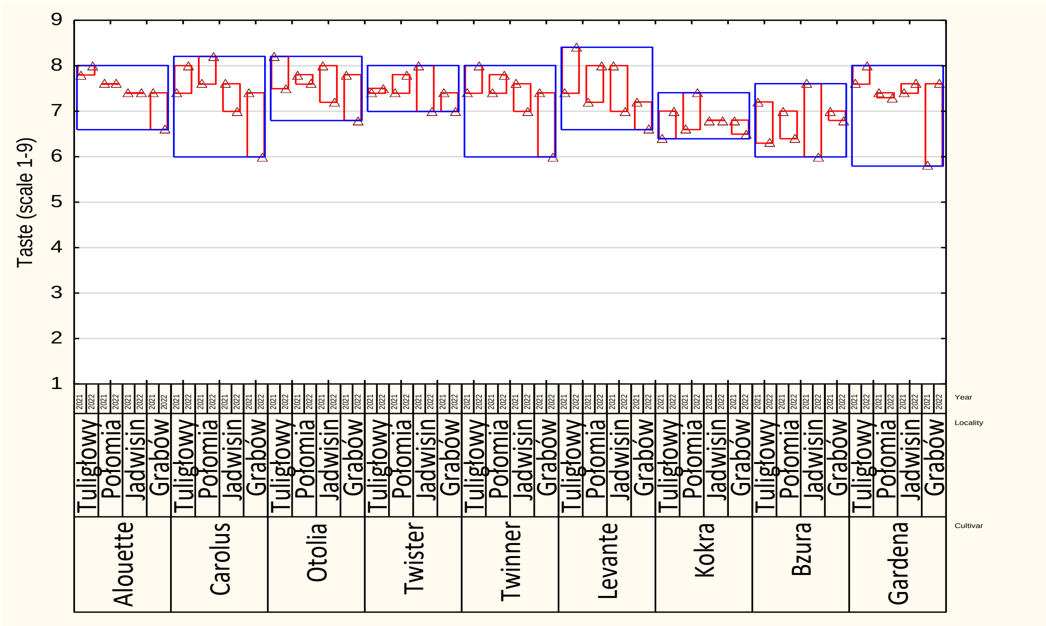

Figure 4. Taste of potato cultivars (2020–2021).

Table 8. Result for mean values, standard deviation, index for ranks for mean values of taste and darkening of potato tubers 10 min. and 24 h after cooking and darkening of potato flesh 4 h after cutting raw state (2021–2022).

Cultivar	Taste (Scale 1–9)			Darkening 10 min. after Cooking (Scale 1–9)			Darkening 24 h after Cooking (Scale 1–9)			Darkening 4 h after Cutting Raw State (Scale 1–9)		
	Mean	SD [(1)]	Rank	Mean	SD[1)]	Rank	Mean	SD [(1)]	Rank	Mean	SD [(1)]	Rank
Alouette	7.5	±0.41	2	8.2	±0.37	2	7.8	±0.35	1	8.1	±0.92	1
Bzura	6.8	±0.52	5	7.3	±0.26	6	7.0	±0.49	5	7.0	±0.46	6
Carolus	7.4	±0.68	3	8.1	±0.50	3	7.8	±0.60	1	7.5	±0.83	3
Gardena	7.3	±0.66	4	7.8	±0.46	5	7.5	±0.49	4	7.7	±0.78	2
Kokra	6.8	±0.31	5	7.0	±0.00	7	6.4	±0.30	6	7.5	±0.75	3
Levante	7.5	±0.60	2	8.2	±0.80	2	7.7	±0.89	2	7.3	±0.53	5
Otolia	7.6	±0.45	1	8.3	±0.53	1	7.8	±0.53	1	7.5	±0.71	3
Twinner	7.3	±0.61	4	7.8	±0.53	5	7.6	±0.60	3	7.3	±0.66	5
Twister	7.4	±0.35	3	7.9	±0.50	4	7.5	±0.75	4	7.4	±0.55	4

[(1)] SD—standard deviation.

Table 9. ANOVA results for darkening and taste of potato tubers (2021–2022).

Sources of Variation	ANOVA			
	Sum of Squares	**DF (1)**	**Mean Square**	**F Statistic**
Darkening of potato tubers 10 min after cooking				
Genotype (G)	12.069	8	1.509	8.53 ***
Year (Y)	0.500	1	0.500	2.83
Localization (L)	3.819	3	1.273	7.20 ***
Darkening of potato tubers 24 h after cooking				
Genotype (G)	13.780	8	1.723	7.54 ***
Year (Y)	0.073	1	0.073	0.32
Localization (L)	7.856	3	2.619	11.46 ***
Darkening of potato flesh 4 h after cutting raw state				
Genotype (G)	5.537	8	0.692	2.26 *
Year (Y)	0.002	1	0.002	0.01
Localization (L)	13.121	3	4.374	14.30 ***
Taste				
Genotype (G)	5.718	8	0.715	3.32 *
Year (Y)	0.451	1	0.451	2.09
Localization (L)	4.296	3	1.432	6.64 ***
Cooking type				
Genotype (G)	24.611	8	3.076	2.39 ***
Year (Y)	16.056	1	16.056	12.48 ***
Localization (L)	0.056	3	0.019	0.01

(1) DF—degrees of freedom; * significant at $p < 0.05$; *** significant at $p < 0.001$.

4. Discussion

Under organic production, potatoes are subjected to different pests, diseases, and limited available nutrients, consequently producing lower tuber yield compared to the conventionally grown potatoes. The evidence suggests that organic arable cropping systems generally produce lower, more variable yields than systems employing synthetic fertilizers and chemical crop protection measures [17]. Reviews by De Ponti et al. [18] and Seufuret et al. [19] concluded that organic arable yields average 80% and 75% of conventional production, respectively. Djaman et al. [20] and Zarzyńska et al. [21] also report large differences in yield depending on the production system.

Cultivation in organic conditions requires adaptability and greater stability of varieties [1]. The requirement for stable genotypes that perform well in a wide range of environments is becoming increasingly important, as farmers need reliable cultivars [14]. The performance of a genotype is determined by three factors: genotypic main effect (G), environmental main effect (E), and their interaction (GEI) [10]. Therefore, the aim of our research was to estimate the GEI of organic potato tuber yield by using the AMMI and the GGE biplot analysis and to find stable cultivars suitable for organic production with a low level of GEI and with good morphological traits and high cooking quality in all tested environments.

The results of performed statistical analyses indicated a significant differentiation of tuber yield among tested cultivars in 12 environments. A significant ($p < 0.01^{**}$) influence of environment (E), genotype (G), and GEI on potato yield was found. The highest influence on determining the variability of tuber yields had environment, a smaller interaction GEI, while the genotype had the least effect. It should be emphasized that all the varieties we tested in organic cultivation showed a high level of yield. The highest tuber yield was noted for cvs. Twister ($mean_{2020–2022}$ = 46.4 t ha^{-1}), Otolia ($mean_{2020–2022}$ = 37.2 t ha^{-1}), Alouette ($mean_{2020–2022}$ = 35.8 t ha^{-1}), and Levante ($mean_{2020–2022}$ = 33.1 t ha^{-1}). Cultivars Twister, Alouette, Kokra, Levante, and Gardena are characterized by a relatively higher (compared to other cultivars) degree of wide adaptation. The main effects influencing on potato yield variability were the environmental factors (E) and GEI. The environment was responsible for 52.3% of the effects of variability in total yield, while the GEI had less impact and was responsible for 23.6% of variability. The obtained results showed that GEI is a very important measure that helps the breeder to select the desirable cultivars in the process of evaluation and increases the efficiency of selection. Kim et al. [22], who investigated the genotype and environment interaction (GEI) using the AMMI and the GGE, also concluded that potato yield is highly related to environment and GEI factors. Moreover, GEI was the main environmental factor that affected the qualitative characteristics of other assessed cultivated species. Overall, the results obtained in the GGE biplots are in line with the Kang's measures (YS_i), highlighting cvs. Twister, Alouette, Kokra, Levante, and Gardena as the superior genotypes for potato production throughout the studied environments. These cvs. can be considered suitable for adaptation to all organic farms in Poland. An ideal genotype has high performance coupled with high stability across environments [13,23]. In our research, the most suitable cultivar to organic farming was Twister, which showed the highest and most stable tuber yield in all environments. AMMI analysis is increasingly used for the evaluation of genotypes in multi-environmental trials, often reporting specific adaptations, as in the present study [24–33].

By three years of experiments, the potato tubers were characterized by a good regularity of tuber shape and shallow depth of eyes. It was found that genotype (G), localization (L), year (Y), and all interactions (double and triple) were significantly affected by the regularity of tuber shape. Depth of eyes showed highly statistically significant differences for genotype (G) and interactions (G × L), (G × Y), and (G × L × Y). By two years of experiments, the potato tubers characterized a very good taste and non-darkening of flesh tubers both raw and cooked. The observed variability between cultivars in these traits was influenced by genotype (G) and localization (L). The best taste was observed for the cvs. Otolia, Alouette, and Levante. A large variability was observed in the cooking type of tubers from individual organic farms. Variability was observed for both years and locations. Only cv Gardena did not change cooking type. The classification of cooking type is based on the textural characteristics of the tuber flesh. In our previous research, tuber texture was also influenced by the effects of genotype, location, and their interaction, which resulted in the cooking type changing depending on the environment [34] and for some cultivars, the cooking type was different than in the catalogue description. Similar observation can be found in research by Thybo et al. [35], which investigated the effects of six different organic treatments on the chemical, rheological, and sensory quality of cooked potatoes. Organic environments had a significant effect on most of the characteristics creating a cooking type.

It should be noted that all tested cultivars were characterized in individual years and localizations by good taste and non-darkening of tuber flesh, both raw and cooked. This is due to the fact that potatoes from organic production are generally characterized by better taste and less darkening of the flesh due to the lower amount of nitrogen [20].

Tuber yields analysis using the AMMI and the GGE allowed us to find the best cultivars across different locations. Cultivars Twister, Alouette, Kokra, Levante, and Gardena can be selected for organic farming due to their higher tuber yield at final harvest. For successful organic farming, it is essential to know the potato genotypes response to different environment over the years. An important aspect for selecting cultivars for organic farming is also the characterization of traits related to tuber morphology and cooking quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14091591/s1, Figure S1: Rainfall (monthly total in mm) and temperature (average in monthly °C) during the potato growing seasons 2020–2022 in Jadwisin; Figure S2: Rainfall (monthly total in mm) and temperature (average in monthly °C) during the potato growing seasons 2020–2022 in Grabów; Figure S3: Rainfall (monthly total in mm) and temperature (average in monthly °C) during the potato growing seasons 2020–2022 in Tuligłowy; Figure S4: Rainfall (monthly total in mm) and temperature (average in monthly °C) during the potato growing seasons 2020–2022 in Połomia; Table S1:Geographic, soil, fertilization and fore crops data for field experiments; Table S2: Data for planting and harvested potato cultivars in four organic farms; Table S3: Mean values of potato tubers yield (t ha−1) and morphological of tubers from 9 cultivars grown in field experiments in 2020, 2021 and 2022; Table S4: Mean values of potato tubers yield (t ha−1) and morphological of tubers from 9 cultivars grown in Tuligłowy, Połomia, Jadwisin and Grabów in 2020, 2021 and 2022.

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