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Original article

Morpho-agronomic characterization and genotype-environment interaction analysis in potato cultivars

Caracterización morfo-agronómica y análisis de interacción genotipo-ambiente en cultivares de papa

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ABSTRACT: The study of genotype-environment interaction is one of the determining factors in the selection and recommendation of cultivars, which allows increasing the efficiency of genetic improvement. With the objective of morpho-agronomically evaluating and analyzing the interactive effects of 16 potato cultivars with the environment, these were evaluated in three localities of the country during two years, considering 2015-2016 and 2016-2017 agricultural seasons. From the Analysis of Variance performed and the study of the interactive effects of the traits with the environment, the existence of significant differences between cultivars was determined and the stability analysis was proceeded, using the AMMI model and the Biplot GGE graph. Variability was found in the behavior of the qualitative and quantitative traits evaluated, allowing the detection of the greatest interactions between the latter and the environment. In this regard, the most stable cultivars in the environments evaluated for each quantitative trait were identified, as well as those with the greatest specific adaptations to the environments studied. Due to its significance, for the first time in Cuba, information on this subject is available, which could be used not only in the breeding programs developed in the country, but also as a criterion to outline strategies for crop diversification by the associated ministries.

Key words: *Solanum tuberosum* L., adaptation, stability, genetic improvement, selection.

RESUMEN: El estudio de la interacción genotipo-ambiente es uno de los factores determinantes en la selección y recomendación de cultivares, lo que permite incrementar la eficiencia del mejoramiento genético. Con el objetivo de evaluar morfo-agronómicamente y analizar los efectos interactivos de 16 cultivares de papa con el ambiente, éstos se evaluaron en tres localidades del país durante dos años, considerando las campañas agrícolas 2015-2016 y 2016-2017. A partir de los Análisis de Varianza efectuados y del estudio de los efectos interactivos de los caracteres con el ambiente, se determinó la existencia de diferencias significativas entre los cultivares y se procedió al análisis de estabilidad, utilizando el modelo AMMI y el gráfico Biplot GGE. Se constató variabilidad en el comportamiento de los caracteres cualitativos evaluados, así como en los cuantitativos, detectando en estos últimos las mayores interacciones con el ambiente. Al respecto, fueron identificados los cultivares más estables en los ambientes evaluados para cada carácter cuantitativo, así como aquellos con mayores adaptaciones específicas a los ambientes estudiados. Por su significación, se cuenta por primera vez para Cuba, con información al respecto, lo que podrá ser utilizado no sólo en los programas de mejora que se desarrollan en el país, sino como criterio para trazar estrategias de diversificación del cultivo.

Palabras clave: *Solanum tuberosum*, adaptación, estabilidad, mejoramiento genético, selección.

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INTRODUCTION

Solanum tuberosum L. (Family Solanaceae, Section Petota) (1) comes from wild species found north of Lake Titicaca, southern Peru (2). It is one of the most important food crops in the world (3). In terms of production and nutritional importance, potato ranks fourth after rice, wheat and maize (4). Annual world production totals approximately 370 million tons and covers about 17 million hectares with an average yield of 21.4 t ha^{-1} (5). The need to satisfy the food demand at world level is increasing every day, in this sense; the use of genetic improvement of crops is oriented to obtain genetic materials with characteristics according to the productive demands (6).

In Cuba, potato occupies the first place among roots and tubers and about 6600 ha are planted each year in six provinces (Artemisas, Mayabeque, Matanzas, Cienfuegos, Villa Clara and Ciego de Avila) with an average yield between 18 and 25 t ha^{-1} and an annual production of between 200,000 and 300,000 t. There are 16 Cuban potato cultivars; however, the production of the crop is based on a varietal spectrum with foreign cultivars, approximately 30 cultivars in generalization and extension (7).

In the final stage of genetic improvement, the study of genotype-environment interaction is a relevant topic, being one of the determining factors in the selection and recommendation of cultivars (8).

Knowing the magnitude of the genotype-environment interaction allows evaluating the stability of cultivars in the range of environments, in which they are to be introduced, as well as their productive potentials and limitations in the localities (9).

Based on the above, the objective of this work is to characterize morpho-agronomically and analyze the effects of genotype-environment interaction of 16 potato (*Solanum tuberosum* L.) cultivars in six environments of the country.

MATERIALS AND METHODS

Plant material

The potato cultivars (*Solanum tuberosum* L.) used in this study were: Melanto, Burren, Faluka, Panamera, Santana, Rudolph, Ultra, Dirosso, Zinared, Spunta, Taisiya, Romano, Electra, Passion, Barna, La Perla. It should be noted that they were introduced from Netherlands.

Methodology

With the objective of analyzing the interactive effects of cultivars with the environment, the experiment was carried out in three locations in the country. 1) Experimental area of "Las Papas" Farm, National Institute of Agricultural Sciences (INCA), of San José de Las Lajas municipality, Mayabeque province. 2) "Máximo Gómez" Agricultural Enterprise, Perico municipality, Matanzas province and 3) "La Cuba" Various Crops Enterprise, Ciego Avila municipality, Ciego de Avila province.

In each locality, the experiments were carried out during two years, considering the 2015-2016 and 2016-2017 agricultural campaigns. The planting date in each locality was between December 12-17, 2015 and 2016, respectively.

In all locations, the experiments were conducted in a randomized complete block design with four replications. Each plot measured 2.25 x 1.8 m with two furrows spaced 90 cm apart and 25 cm between plants, with 20 plants per plot. In all cases, the recommended cultural practices for crop management were adopted (7).

Morpho-agronomic evaluation of cultivars

At the harvest time, the morphological evaluation of the cultivars was carried out, evaluating the qualitative and quantitative characters of the plant (Tables 1 and 2), detailing for each case its evaluation form according to the corresponding descriptors. The description and evaluation form of the qualitative characters were taken from what was previously described in the literature (10).

Considering the importance for the crop of its behavior against different pests, traits related to the response of cultivars to *Streptomyces scabies* (common scab) and *Alternaria solani* (Ellis and Martin) Jones and Grout (early blight) were also evaluated.

The evaluation of foliage damage by the fungus Alternaria solani (Ellis and Martin) Jones and Grout (early blight) was carried out 65 days after planting. The nine-grade scale proposed by Horsfall and Barrat (11) was used for this purpose. However, the evaluation of *Streptomyces*

Table 1. Description and evaluation form of qualitative characteristics

Qualitative characteristics		
CpT	Color of tuber skin	**(Rs),** pink **(R),** red **(A),** yellow
FT	Tuber shape:	**(Rd),** round **(Ov),** oval **(Al),** elongated **(O),** oblong **(Ob),** oval-oblong
PoT	Depth of tuber eyes:	**(S),** Superficial **(M),** Medium **(P),** Deep

Table 2. Quantitative characteristics evaluated. Description, unit of measurement and method of calculation

Quantitative characteristics		
NTp	Number of tubers per plant (Unit)	Number of tubers on a plant of a cultivar
NP	Number of Plants (Unit)	Number of plants evaluated per cultivar
NTT	Total number of tubers (Unit)	Number of tubers on all evaluated plants of a cultivar $\mathrm{NTT} = \sum NtTp_1 + NtTp_2 + \ldots NtTp_{20}$
NtTP	Total number of tubers per plant (Unit)	$NtTP = \frac{\mathrm{NTT}}{NP}$
MTT	Total mass of tubers (Kg)	Total mass of tubers in all evaluated plants of a cultivar $\mathrm{MTT} = \sum MtTp_1 + MtTp_2 + \ldots MtTp_{20}$
MpT	Average tuber mass (kg)	$MpT = \frac{\mathrm{MTT}}{\mathrm{NTT}}$
RTpP	Total yield per plant (kg plant^{-1})	$RTpP = \frac{\mathrm{MTT}}{\mathrm{NP}}$
Rha	Yield per hectare (g ha^{-1})	$Rpha = RTpP{*}44444plants$

scabies (common scab) on the tuber was performed after harvest (3 days), according to the six-grade scale proposed (12).

Statistical analysis

Analysis of qualitative traits

For the qualitative traits tuber skin color (CpT), tuber shape (FT) and tuber eye depth (PoT), a frequency analysis was performed using the IBM SPSS package version 21.0 (13), representing the values for each cycle in a mosaic graph with the use of *Microsoft Excel*.

Analysis of quantitative characteristics

For the quantitative traits of average tuber mass (MpT), total yield per plant (RTpP), yield per hectare (Rha), tuber damage by *Streptomyces scabies* (Ss) and foliage damage by *Alternaria solani* (As) were carried out an analysis of variance (ANOVA) of one factor and a mean comparison test. It was in order to describe the variability existing in these characters in the cultivars evaluated and to determine the existence or not of differences in their behavior, using the Student-Newman-Keuls test (p≤0.05), using the IBM SPSS version 21.0 package (13).

Analysis of the genotype-environment interaction

To determine if there was a significant difference in the case of genotype-environment interaction for the quantitative characters of average tuber mass (MpT), total yield per plant (RTpP), yield per hectare (Rha), tuber damage by *Streptomyces scabies* (Ss) and leaf damage by *Alternaria solani* (As) a two-factor analysis of variance (ANOVA) was performed. The factors taken into account were genotype and environment (composed in this case by the combination of locations and years). The IBM SPSS 21 statistical package was used for this purpose.

Once the presence of the genotype-environment interaction was detected, the stability analysis was carried out using the Additive Main Effects and Multiplicative Interactions (AMMI) model and the GGE Biplot graph (15,16). The formula representing this model is shown below (14):

$$AMMI_M : E\left(y_{ijk}\right) = \mu + \alpha_i + \beta_j + \sum_{m=1}^{M} {}_m u_{mi} v_{mj}$$

where:

μ : mean of the analyzed values

α_i : main effect for rows

β_j : main effect for the columns

m : corresponds to the singular value of order m of Z'Z

u_{mi} : i-th coordinate of the singular vector of ZZ' associated to λ_m

v_{mj} : j-th coordinate of the singular vector of Z'Z associated to λ_m

RESULTS AND DISCUSSION

Analysis of qualitative characteristics for morpho-agronomic evaluation

From the frequency analysis carried out for the qualitative characters used in the characterization of the evaluated cultivars, it was observed that the most abundant color for tuber skin (CpT); in the case of these 16 cultivars, is yellow (75 %), while red and pink colors are equal in 12.5 % (Figure 1).

Considering the divergence in criteria of various authors, it is considered that the results on the dominance of yellow color may be due to the greater preference of breeders to select and include in their breeding programs in favor of these colors. This can be corroborated by the results of breeding programs in Cuba (15) and other programs carried out worldwide (16).

In the case of tuber shape (Figure 2), it is known that at present, the boom in the potato processing industry at the international level is demanding varieties with round shapes for chips and elongated shapes for sticks (17). This fact may be determining that cultivars with oblong shape occupy the highest frequencies of production by companies producing crop seed for fresh consumption and for satisfy the market demanding. Similar results were considered by researches in Italy, in order to reduce production costs (18).

In the case of tuber eye depth (Figure 3), the results are due, largely, to the fact that breeding programs try to obtain cultivars with shallow eyes, with the objective of responding to the market. It is suggested that this is a characteristic that influences the final quality of the product, making tuber peeling easier and reducing the loss of raw material, either for fresh consumption or for industrial processing (19).

Analysis of quantitative traits

The analysis of variance for the quantitative traits of average tuber mass, total yield per plant, yield per hectare, tuber damage by *Streptomyces scabies* and foliage damage by *Alternaria solani* showed highly significant differences in the behavior of these traits in all the evaluations carried out (Table 3).

In this regard, when comparing the means for these traits using the Student-Newman-Keuls test (Table 4), differential behavior was observed among cultivars.

For the average tuber mass trait, the cultivars Burren, Faluka, Santana, Rudolph, Ultra, Electra and Passion showed the best performance, with average values ranging from 0.106 to 0.116 kg.

However, for the traits total yield per plant and yield per hectare, the Rudolph cultivar showed the highest values (0.7767 kg plant^{-1} and 34.52 kg ha^{-1} respectively). Melanto, however, showed the lowest values for these traits (0.356 kg plant^{-1} and 15.95 kg ha^{-1}), as well as the greatest damage to the tuber by *Streptomyces scabies* and to the foliage by *Alternaria solani*. The rest of the cultivars showed differential values for these traits.

Al respecto, al comparar las medias para estos caracteres mediante la Prueba de Student-Newman-Keuls (Tabla 4), se observó un comportamiento diferencial entre los cultivares.

Analysis of genotype-environment interaction

From the bifactorial analysis of variance (ANOVA) carried out for the quantitative traits studied, significant differences were observed for the means in each of the quantitative variables analyzed with the environments in which the cultivars were planted (Table 5).

Starting with the quantitative traits that showed interaction with the environment, the stability analysis was carried out using the AMMI model and the Biplot graph. In this regard, considering the positive correlation structure between the traits total yield per plant and yield per hectare, the AMMI model was only performed for the total yield per plant trait (Figure 4).

In similar studies using the AMMI, they affirm that the closer the genotypes are located to the center of the graph, the less they respond to environmental variations and therefore, the more stable they are (20,21). Meanwhile, those farthest from the center are considered to be those that contribute the most to the interaction; that is, those that respond the most to environmental stimuli.

For this reason, other authors who have carried out studies in this same crop (potato), consider that this technique is useful for genetic improvement, since it allows knowing the stability of the genotypes, according to the proximity to the origin of coordinates, as well as the genotypes responsible for the significant interaction (22-24). On the other hand, it is said that the most stable genotypes, i.e., those that show low values of markers in PC1, have high means for the traits in question (25).

From a study developed in different potato crosses, some authors consider that this fact could be indicating that these

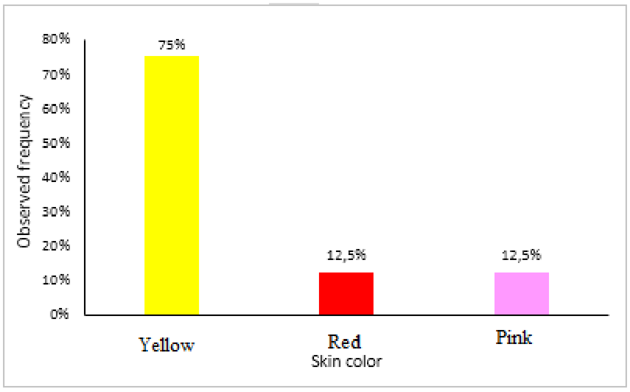

Figure 1. Graphical representation of the frequencies observed for the qualitative characteristic tuber skin color (CpT) in the cultivars analyzed

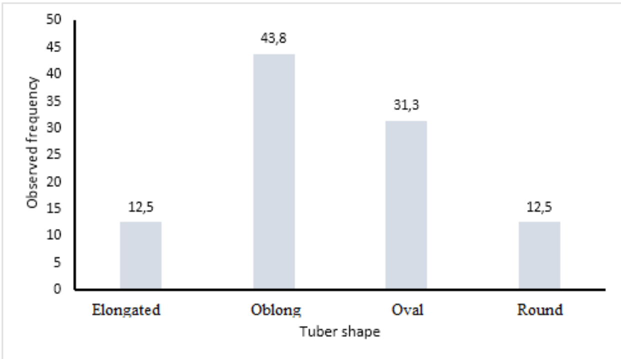

Figure 2. Graphical representation of the frequencies observed for the qualitative characteristic tuber shape (TF) in the cultivars analyzed

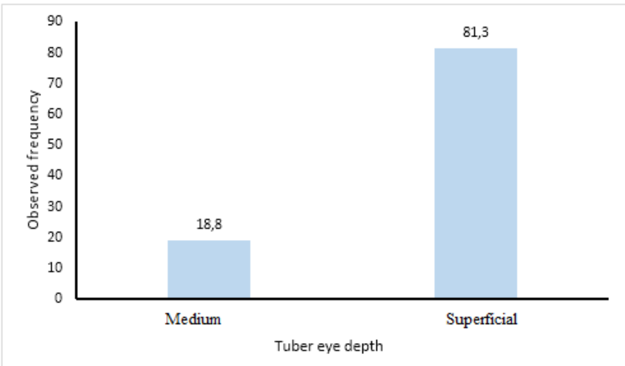

Figure 3. Graphical representation of frequencies observed for the qualitative characteristic depth of tuber eyes (PoT) in the cultivars analyzed

Table 3. A factor analysis of variance for the quantitative traits evaluated

		Square sum	gl	Quadratic mean	F	Sig.
MpT	Inter-groups	.068	15	.005	5.192	.000
	Intra- groups	.239	272	.001		
	Total	.307	287			
RTpP	Inter- groups	4.325	15	.288	11.140	.000
	Intra- groups	7.039	272	.026		
	Total	11.364	287			
Rha	Inter- groups	8541.755	15	569.450	11.141	,000
	Intra- groups	13903.095	272	51.114		
	Total	22444.850	287			
As	Inter- groups	114.986	15	7.666	6.683	.000
	Intra-grupos	312.000	272	1.147		
	Total	426.986	287			
Ss	Inter- groups	57.691	15	3.846	6.647	.000
	Intra- groups	157.389	272	.579		
	Total	215.080	287			

(p≤0,05)

Average tuber mass -MpT-; total yield per plant -RTpP-; yield per hectare -Rha-; *Alternaria solani* -As- and *Streptomyces scabies* -Ss- damage in the foliage and *Streptomyces scabies* -Ss- damage in the tuber

Table 4. Student-Newman-Keuls test for comparison of means for the quantitative traits evaluated

	Cultivar name	MpT (kg)	RTpP	Rha	Ss	As
1	Melanto	0.065c	.3589g	15.95g	2.72a	5.11a
2	Burren	0.108a	.5789cde	25.73cde	1.67cd	3.28cde
3	Faluka	0.111a	.7456ab	33.14ab	1.50cd	3.00e
4	Panamera	0.087abc	.4444defg	19.75efg	1.28d	3.72bcde
5	Santana	0.113a	.6633abc	29.48abc	1.89bcd	3.89bcde
6	Rudolph	0.110a	.7767a	34.52a	1.44d	4.33abc
7	Ultra	0.109a	.6961abc	30.94abc	1.28d	3.72bcde
8	Dirosso	0.088abc	.4461defg	19.83efg	1.83bcd	3.33cde
9	Zinared	0.091abc	.5344cdef	23.75def	1.11d	3.28cde
10	Spunta	0.100ab	.5706cde	25.36 cde	1.67cd	3.50cde
11	Taisiya	0.092abc	.6294abc	27.98abc	1.56cd	3.61cde
12	Romano	0.071bc	.4283efg	19.04efg	1.17d	4.22abcd
13	Electra	0.116a	.6783abc	30.15abc	1.67cd	3.11de
14	Passion	0.106a	.5978bcd	26.57bcd	1.83bcd	4.11abcde
15	Barna	0.094abc	.5611cde	24.94 cde	2.50ab	4.94a
16	La Perla	0.074bc	.4000fg	17.78fg	2.28abc	4.72ab

(p=0,05)

Average tuber mass -MpT-, total yield per plant -RTpP-, yield per hectare -Rha-, tuber damage by *Streptomyces scabies* -Ss- and foliage damage by *Alternaria solani* -As-.

genotypes carry stability genes, which may be present, regardless of the breeding program that gives rise to them (free pollination, hybrids) (24).

CONCLUSIONS

- There is a diversity of color, shape and depth of eyes in the tubers of the 16 potato cultivars.
- There is differential behavior among potato cultivars for yield and average tuber mass.
- Cultivars Burren, Rudolph, Ultra, Dirosso, Zinared, Romano and La Perla are the most stable and with the best general adaptation for average mass in the six environments studied, while Passion, Santana, Panamera, Faluka, Barna and Spunta, express specific adaptation for each environment.
- Cultivars Melanto, Dirosso, La Perla, Ultra, Zinared, Rudolph, Romano and Panamera have better general adaptation in the studied environments for total yield per plant; however.
- Cultivars Faluka, Electra, Zinared, Burren, Dirosso are the least affected in their foliage (< 3.5 degrees) by *Alternaria solani* fungus.
- Cultivars Zinared, Romano, Ultra and Panamera are the least affected in tubers by *Streptomyces scabies* (< 1.2 degrees).

Table 5. Bifactorial analysis (ANOVA) of the genotype-environment interaction for the quantitative traits evaluated

	Square sum	df	Mean Square	F	Sig.
Average tuber mass-MpT- (kg)					
Genotype	.068	15	.005	7.238	.000
Environment	.006	5	.001	1.857	.104
Genotype * Environment	.118	75	.002	2.502	.000
Replica (Environment)	.001	12	.000	.192	.999
Error	.113	180	.001		
Total	2.958	288			
Total Corrected	.307	287			
Total yield per plant -RTpP- (kg $plant^{-1}$)					
Genotype	4.325	15	.288	46.158	.000
Environment	.037	5	.007	1.191	.315
Genotype * Environment	5.780	75	.077	12.339	.000
Replica (Environment)	.097	12	.008	1.300	.222
Error	1.124	180	.006		
Total	104.730	288			
Total Corrected	11.364	287			
Yield per hectares -Rha- (kg ha^{-1})					
Genotype	8541.755	15	569.450	46.154	.000
Environment	73.431	5	14.686	1.190	.316
Genotype * Ambiente	11416.145	75	152.215	12.337	.000
Replica (Environment)	192.678	12	16.056	1.301	.221
Error	2220.841	180	12.338		
Total	206873.257	288			
Total Corrected	22444.850	287			
Alternaria solani (As) foliage damage					
Genotype	114.986	15	7.666	9.818	.000
Environment	2.486	5	.497	.637	.672
Genotype * Environment	150.847	75	2.011	2.576	.000
Replica (Environment)	18.125	12	1.510	1.934	.033
Error	140.542	180	.781		
Total	4736.000	288			
Total Corrected	426.986	287			
Damage in the tyber by por *Streptomyces scabies* (Ss)					
Genotype	57.691	15	3.846	7.639	.000
Environment	4.601	5	.920	1.828	.110
Genotype * Environment	58.122	75	.775	1.539	.011
Replica (Environment)	4.042	12	.337	.669	.780
Error	90.625	180	.503		
Total	1059.000	288			
Total Corrected	215.080	287			
a. R^2= .901 (R^2 adjusted= .842)					

($p \leq 0,05$)

Average tuber mass (MpT), total yield per plant (RTpP), *yield per hectare (Rha), Alternaria solani (As) foliage damage and Streptomyces scabies* (Ss) tuber damage.

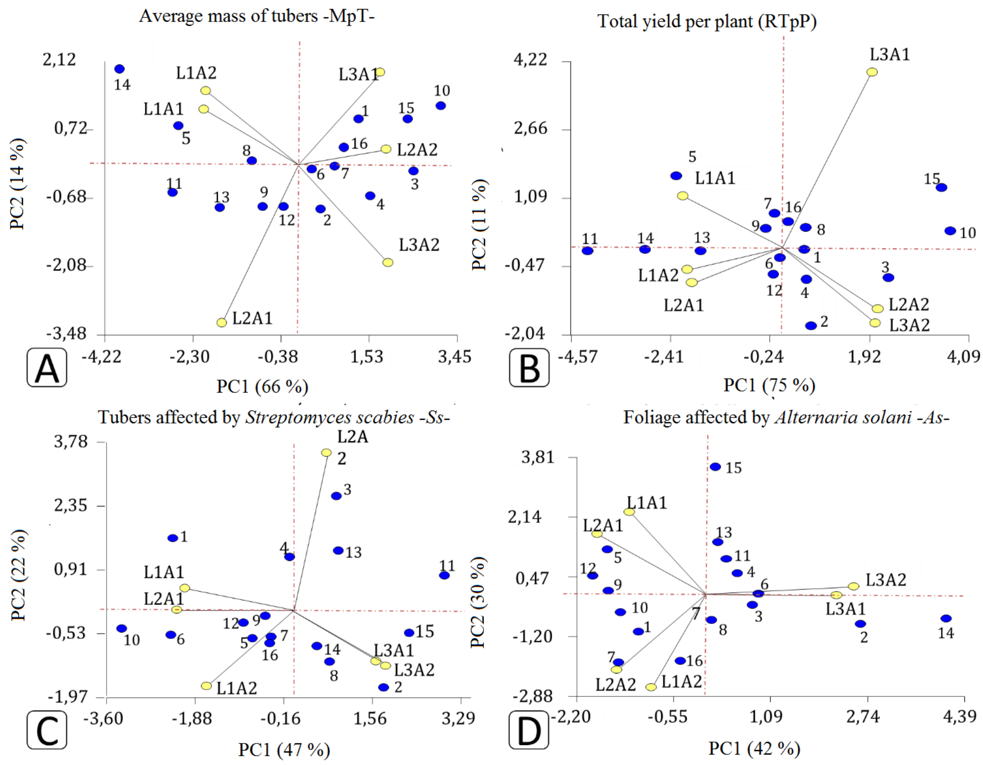

Figura 4. Graphical representation of the AMMI of the genotype-environment interaction for the quantitative characters average tuber mass -MpT-(A), total yield per plant -RTpP-(B), tuber affectation by *Streptomyces scabies* -Ss- (C) and *Alternaria solani* -dAs- (D) in the cultivars analyzed. [1- Melanto; 2- Burren; 3- Faluka; 4- Panamera; 5- Santana; 6- Rudolph; 7- Ultra; 8- Dirosso; 9- Zinared; 10- Spunta; 11- Taisiya; 12- Romano; 13- Electra; 14- Passion; 15- Barna; 16- La Perla] [(LnAn: Effects of the Locality x Year Interaction; L1: Experimental area of "Las Papas" Farm, National Institute of Agricultural Sciences (INCA), San José de Las Lajas municipality Mayabeque province; L2: "Máximo Gómez" Agricultural Farming Enterprise, Perico municipality, Matanzas province; L3: "La Cuba" Various Crops Enterprise, Ciego Ávila municipality, Ciego de Ávila province; A1: 2015-2016; A2: 2016-2017].)

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