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Original Article

Multivariate analysis of agronomic, physicochemical, and physiological characters of passion fruit hybrids cultivated at different environments

Análise multivariada de caracteres agronômicos, físico-químicos e fisiológicos de híbridos de maracujá cultivados em diferentes ambientes

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Abstract

Simultaneous analysis studies of several agronomic traits in cultivated plants make it possible to identify phenotypic and genotypic differences due to environmental variations, such as altitude. Therefore, the objective was to evaluate, through multivariate analysis of agronomic, physicochemical and physiological characters, passion fruit hybrids cultivated in different environments. The hybrids used were Gigante Amarelo, Rubi do Cerrado and Sol do Cerrado, cultivated in the southern region of Espírito Santo in four municipalities/environments: Marataízes (41 m), Jerônimo Monteiro (104 m), Alegre (711 m), and Ibitirama (1016 m). The agronomic characters of the plants, the physical-chemical characteristics of the fruits and the physical, biochemical and physiological qualities of the seeds were analyzed. The Singh method was used to determine the most important differentiating characters between hybrids growing in different environments. Based on these characters, a dissimilarity matrix was generated and a principal coordinate analysis was performed. It was observed that the pulp yield was influenced by altitude. The three hybrids showed greater performance in terms of agronomic characters at altitude (41 m) than at altitude (104 m). The Sol do Cerrado hybrid showed high performance in the physical-chemical characteristics of the fruits at altitude (104 m).

Keywords: *passiflora edulis*, physiological quality of seeds, biochemistry, singh method.

Resumo

Estudos de análise simultânea de diversos caracteres agronômicos em plantas cultivadas permitem identificar diferenças fenotípicas e genotípicas devido a variações ambientais, como a altitude. Diante disso, objetivou-se avaliar através da análise multivariada de caracteres agronômicos, fisico-químicos e fisiológicos, híbridos de maracujazeiros cultivados em diferentes ambientes. Os híbridos utilizados foram Gigante Amarelo, Rubi do Cerrado e Sol do Cerrado, cultivados na região sul do Espírito Santo em quatro municípios/ambientes: Marataízes (41 m), Jerônimo Monteiro (104 m), Alegre (711 m), e Ibitirama (1016 m). Foram analisados os caracteres agronômicos das plantas, as características físico-químicas dos frutos e as qualidades físicas, bioquímicas e fisiológicas das sementes. O método Singh foi usado para determinar os caracteres diferenciadores mais importantes entre híbridos crescendo em diferentes ambientes. Com base nesses caracteres, uma matriz de dissimilaridade foi gerada e uma análise de coordenadas principais foi realizada. Observou-se que o rendimento de polpa foi influenciado pela altitude. Os três híbridos apresentaram maior desempenho em termos de caracteres agronômicos na altitude (41 m) do que na altitude (104 m). O híbrido Sol do Cerrado apresentou alto desempenho nas características físico-químicas dos frutos na altitude (104 m).

Palavras-chave: *passiflora edulis*, qualidade fisiológica de sementes, bioquímica, método singh.

1. Introduction

The fruits of the species *Passiflora edulis* Sims f. *flavicarpa* Degener (sour passion fruit) are rich in antioxidant compounds (Xin et al., 2021), and this species originated from tropical and subtropical countries (Almeida et al., 2021). The sour passion fruit is widely cultivated because of the high commercial yield of its fruits, which are used for fresh consumption and production of derivatives. Brazil is one of the main producers and consumers of passion

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fruit; 554.598 tons was produced in 2017 in 41.216 ha, with an average productivity of 13.497 ton.ha^{-1} (IBGE, 2018), mainly concentrated in the northeast region and part of the southeast regions close to the equator (Rosado et al., 2017).

Three hybrids of *P. edulis* Sims f. *flavicarpa* Degener were developed by Embrapa Mandioca and Fruticultura through crosses with the selected parents, namely BRS Gigante Amarelo, BRS Rubi do Cerrado, and BRS Sol do Cerrado, which were included in this study. The hybrids exhibited desirable agronomic characteristics, such as tolerance to major diseases, high productivity, uniformity in production, high pulp yield, acceptable acidity, and sweetness (Neves et al., 2013).

Brazil is the center of passion fruit diversity and has excellent cultivation conditions. The plant grows well in tropical and subtropical regions, where the climate is hot and humid. Variations in altitude, temperature, relative humidity, luminosity, and precipitation have an important influence on the plant longevity and yield (Borges and Lima, 2009). Altitude plays a crucial role in the ecophysiological performance of a plant as it directly influences the abiotic factors (Joët et al., 2010). Microclimate variations, such as air temperature, air humidity, and soil water potential, can induce distinct regeneration strategies along altitudinal gradients (Oda et al., 2016).

Regions with the following conditions are the most suitable for growing passion fruit plants 100-1000 m altitude, an average temperature of 25–26 °C, ideal rainfall of 1.20–1.40 mm that is well distributed throughout the year, low relative humidity, and high brightness. The plant needs 11 h of light/day to induce flowering and produce fruits with great appearance, flavor, and aroma (Fraife Filho et al., 2010). Although the passion fruit shows good adaptation to different types of soils, it is necessary that it is deep and has good drainage (Lopes et al., 2013).

Studies based on multivariate analysis of agronomic, physicochemical, and physiological traits of plants grown at different altitudes allow possible identification of phenotypic and genotypic differences due to environmental variations. Certain environmental conditions can favor the expression of certain characteristics that would not manifest in other environmental conditions. Therefore, the objective was to evaluate, through multivariate analysis of agronomic, physicochemical and physiological characters, passion fruit hybrids cultivated in different environments.

2. Material and Methods

The experiment was performed at the Seed Analysis Laboratory, Center for Agricultural Sciences and Engineering, Federal University of Espírito Santo, located in the city of Alegre, Espírito Santo, Brazil. Seeds of passion fruit hybrids from Embrapa Cerrado were used and classified as BRS Gigante Amarelo (BRS GA), BRS Rubi do Cerrado (BRS RC), and BRS Sol do Cerrado (BRS SC).

Seed germination of passion fruit hybrids was performed in 14 × 28 cm plastic bags containing soil, barnyard manure, and sand (1:1:1). Two seeds were sown per bag and watered daily according to the needs of the crop. After 120 d of sowing, the seedlings were transplanted at a definitive location. The hybrids were grown in four municipalities/environments in the southern regions of the State of Espírito Santo; climatic conditions and soil analysis results of the regions are shown in Table 1.

The experiment was performed in a randomized block design with a split-plot scheme (4 × 3), in which the plots represented the four environment and the subplots represented the three hybrids. Four blocks and five plants per block were present, totaling 60 plants at each environment. The system of conduction and support of the plants was in a vertical espalier, with a height of 1.8 m and na area of 3.0 m× 4.0 m. The plants were pollinated naturally, and the areas were not irrigated. Also, invasive plants were controlled by mowing between the lines and manual weeding in the lines.

The analyses were performed during two crop production cycles (2015 and 2016). For the agronomic analysis of the plants, the number of fruits per plant and the content of chlorophyll *a*, *b*, and *total* chlorophyll content using Clorofilog CFL1030 (Falker) were evaluated.

The average weight of the fruit (g) was evaluated on a precision scale of 0.001 g. The fruit length (cm), fruit diameter (cm), and shell thickness (cm) were measured using a digital caliper with a precision of 0.1 mm. Pulp yield (%) was calculated by subtracting the mass of the skin from the pulp mass and dividing by the total mass of the fruit, followed by multiplication by 100 to obtain a percentage. Fruit firmness (g f^{-1}) was determined at three points using a texturometer (Stevens LFRA Texture Analyzer; T9/1000 tip, 2 mm s^{-1}, and 20 mm depth). Also, number of seeds per fruit were determined.

The soluble solid content (ºBrix) was evaluated using a digital refractometer with automatic temperature compensation. The titratable acidity was analyzed by neutralization titration, with the dilution of 10 mL of pure juice in 90 mL of distilled water, and titration was performed with 0.1 N NaOH solution until the juice reached a pH of 8.1; pH was determinedusing the Digimed DMPH-2 pH meter with automatic temperature correction expressed as percentage (%) of citric acid (AOAC, 1990).

The ratio between soluble solid content and titratable acidity was determined, and the pH of the pulp was measured using a digital Digimed DMPH-2pH meter. The vitamin C content (mg) was determined by taking 10 g of the juice in an Erlenmeyer flask containing 50 mL of oxalic acid solution and performing titration with the DCFI indicator (2,6-Dichlorophenol-indophenol sodium salt dihydrate) until a persistent pink color was obtained for 15 s. Electrical conductivity of the pulp was determined using an MS Tecnopon conductivity meter, and the results were expressed in µS cm^{-1} g^{-1}.

The weight of 1000 seeds was determined using an analytical balance (0.0001 g), with eight replications of 100 seeds per treatment. Based on the evaluation of four replications of 25 seeds per treatment, the length and diameter of the seeds were determined using a digital caliper (0.01 mm). Seed water content (%) was determined by the oven method at 105 ± 3 °C for 24 h (Brasil, 2009). To measure the electrical conductivity, three replicates each of 50 seeds were taken and immersed in 75 mL of deionized water in plastic cups (200 mL capacity) (Barbosa et al.,

Table 1. Geographical description, climatic conditions, and soil chemical analysis of the areas where passion fruit hybrids were cultivated.

Altitude (m)	Descriptions of cultivation areas				
	Latitude	**Longitude**	**Climate (Köppen-Geiger climate classification)**	**Average temperature (ºC)**	**Average annual rainfall (mm)**
41	21° 05' 13.73'' S	40° 54' 15.71'' O	Tropical - Aw	23.8	1014
104	20º 48' 9.93'' S	41º 24' 24.85'' O	Tropical - Aw	23.8	1094
711	20° 37' 51.91'' S	41° 36' 15.97'' O	Subtropical dry winter and hot summer - Cwa	23	1341
1016	20° 28' 09.40'' S	41° 43' 31.63'' O	Hot and tempered - Cwa	19.8	1286

Soil analysis of the experimental areas																	
Altitude (m)	pH	P	K	Na	Ca	Mg	Al	H+Al	BS	t	T	V (%)	M (%)	OM g Kg^{-1}	Sand (%)	Silt (%)	Clay (%)	Soil Class
	H_2O		mg dm^{-3}					cmol$_c$ dm^{-3}										
41	5.51	13.07	57	12	1.65	0.84	0.10	5.12	2.69	2.79	7.81	34.50	3.58	15.51	59	1	39	clayey
104	6.50	37.43	205	4	3.55	1.00	0.00	2.97	5.10	5.10	8.07	63.19	0.00	11.46	73	7	19	Average
711	5.86	2.55	42	2	3.00	1.11	0.00	3.80	4.23	4.23	8.02	52.71	0.00	20.91	49	7	42	clayey
1016	5.06	3.91	11	0	0.07	0.03	0.55	14.36	0.12	0.67	14.48	0.85	81.73	40.13	64	10	26	Average

41: Marataízes; 104: Jerônimo Monteiro; 711: Alegre; 1016: Ibitirama; potential of hydrogen (pH), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), aluminum (Al), hydrogen + aluminum (H + Al), base sum (BS), effective cation exchange capacity (t), cation exchange capacity at pH 7 (T), base saturation index (V), aluminum saturation index (M), organic matter (OM).

2012). They were maintained at 25 °C for 24 h, and the conductivity of the solution was determined using an MS Tecnopon conductivity meter; the results were expressed in μS cm^{-1} g^{-1}. Potassium leaching (mg L^{-1}) was determine dusing a flame photometer (Digimed).

The biochemical composition of the seeds was determined using four replicates each of 100 seeds. Total lipid content was quantified using the gravimetric method (Bligh and Dyer, 1959). Total soluble phenol content was determined according to the Folin–Ciocalteu method, and the absorbance of the samples was measured using a spectrophotometer at 725 nm (Bonoli et al., 2004). Total carbohydrate content was determined using the anthrone reagent (Hodge and Hofreiter, 1962), and the absorbance was measured at 620 nm. Total protein content was quantified according to the method of Bradford (1976), in which bovine serum albumin was used as the standard and absorbance was determined at 595 nm. To determine starch content, acid hydrolysis was performed to obtain monosaccharides, disaccharides, and oligosaccharides, which were subsequently allowed to react with anthrone (Hodge and Hofreiter, 1962), followed by absorbance determination at 620 nm. Fiber content was determined by taking the pellet obtained from the extraction of starch and placing it in a forced circulation oven at a temperature of 60 °C until a constant weight was achieved. The results were expressed as percentage of the function of the initial mass used for biochemical determination. Ash content was determinedas described by Silva (1981).

Germination was performed in four replications each of 25 seeds sown in rolls of Germitest® paper and moistened with distilled water at a proportion of 2.5x the dry paper mass, which was placed in a germination chamber, regulated at an alternating temperature of 20–30 ºC in the dark. Analyses were performed up to 28 d after sowing. The percentage of normal seedlings was computed (Brasil, 2009); the results were expressed as the percentage of germination. The germination speed index (GSI) was determined concomitantly with the germination test, and the number of seeds was computed daily based on the criteria that they showed a primary root protrusion equal to or greater than 2 mm (Maguire, 1962).

The length of the shoot was determined 28 d after sowing by measuring the length between the stem and the apex of the last leafusing a millimeter ruler, and the results were expressed in cm. Total fresh and dry mass of the seedlings were determined 28 d after sowing using an analytical balance (0.0001 g). After measuring the fresh mass, the seedlings were kept in a convection oven at 72 °C for 72 h, contained within Kraft paper bags. Subsequently, the samples were weighed to obtain the total dry mass, and the results were expressed in mg. Used were 10 seedling replications.

The data were submitted for analysis of variance based on mixed models to obtain the plot, subplot, and genetic coefficients of variation, as well as the heritability for each analyzed character. For this purpose, a randomized block design, split-plot arrangement with factor A (P) as fixed (environment) and factor B (S) as random (hybrids) was considered with the genetic component as the subplot and environmental component Error A (environment) as: Yijk = u + Pi + Bj + Ea + Sk + PSik + Eb, where Y = data vector, u = overall mean, Pi = vector of the effects of factor A (allocated in the plots, assumed to be fixed), Bj = vector of the effects of factor B (allocated in the subplots, assumed to be random), Ea = error associated with the interaction of factor A (environment) with the factor repetitions, Sk = vector of block or repetition effects, PSik = vector of the effects of factor B x factor A interaction, or hybrid interactions × environment, and Eb = error associated with factor B residues (hybrids).

The Genes program (Cruz, 2016) was used to perform the multivariate analyses to evaluate the performance of the hybrids at different altitudes using the main characteristics analyzed in 12 treatments (combination of four environment and the three hybrids). The characters were separated into four groups: agronomic characteristics (number of fruits per plant and chlorophyll *a* and *b* index); physicochemical characteristics of the fruit (fruit length, skin thickness, yield, firmness, soluble solid content, titratable acidity, pH, electrical conductivity of the pulp, and vitamin C content); physicochemical characteristics of the seeds (seed diameter, seed moisture, electrical conductivity of the seed, lipids, phenol, sugar, protein, starch, fiber, and ash), and physiological quality of the seeds (germination, GSI, shoot length, root length, total fresh mass, and total dry mass).

Initially, the data were standardized (mean value/mean standard deviation), and a phenotypic correlation matrix was obtained to separate characters with a correlation coefficient greater than 0.90. Then, the diagnosis of multicollinearity was performed by excluding the characters with high values, considering the variance inflation factor, to obtain a set of multicharacters with weak collinearity. With the obtained set of characters, the ones with greater weight in the first eigenvectors were determined, together with Singh's (1981) relative contribution analysis based on the Mahalanobis distance.

For each group of characteristics, a dissimilarity matrix was obtained based on the standardized mean Euclidean distance (Cruz, 2016). Subsequently, principal coordinate analysis (PCoA) was performed using the DarWin program to obtain the dispersion of the two axes representing most of the observed variation. Finally, considering the significant effect ofthe characters with the greatest contributions to the multivariate analyses in each group, the means for each of the interactions (hybrid × environment) were calculated.

3. Results

The coefficient of genetic variation (CVg), which was calculated as the ratio of the genetic standard deviation to the average of the hybrids, was the highest for starch (14.90) among all the characteristics. The coefficient of variation of the plot (CVP, 110.54), which was calculated as the ratio of the standard deviation of the plot to the average of the hybrids, and the coefficient of variation of the subplot (CVS, 112.33), which was calculated as the ratio of the standard deviation of the subplot to the hybrids, were higher for root length of the seedlings than the other analyzed characters (Table 2).

Table 2. Coefficient of genetic variation (CVg), coefficient of variation of the plot (CVP), coefficient of variation of the subplot (CVS), and heritability (h^2) of 28 variables related to agronomic characters, physicochemical characteristics of fruits, physicochemical characteristics of seeds, and physiological quality of seeds of passion fruit hybrids at different environments.

Characters	Variables							
	Average	**CVg**	**CVP**	**CVS**	**CVg/CVP**	**CVg/CVS**	**CVP/CVS**	**h^2**
Agronomic characters								
Number of fruits per plant	28.75	7.82	3.17	2.24	2.46	3.49	1.41	98.98
Chlorophyll *a* index	38.93	2.31	9.29	6.77	0.24	0.34	1.37	49.88
Chlorophyll *b* index	9.66	0.00	25.50	16.34	0.00	0.00	1.56	0.00
Physicochemical characteristics of fruits								
Length (cm)	8.92	3.90	1.01	2.34	3.86	1.66	0.43	99.58
Thickness (cm)	6.88	5.38	2.66	2.28	2.02	2.35	1.16	98.48
Pulp yield (%)	44.24	8.46	0.98	1.53	8.63	5.52	0.64	99.91
Firmness (g f^{-1})	213.43	9.20	12.48	13.94	0.73	0.65	0.89	89.69
Soluble solid content (°Brix)	14.78	2.39	4.12	3.68	0.58	0.64	1.11	84.35
Titratable acidity	3.69	5.21	11.85	10.53	0.43	0.49	1.12	75.53
pH	2.90	1.56	2.48	2.20	0.62	0.70	1.12	86.34
Pulp electrical conductivity (µS $cm^{-1}g^{-1}$)	1.23	12.29	16.84	17.73	0.72	0.69	0.94	89.50
Vitamin C (mg)	42.23	8.39	5.38	5.00	1.55	1.67	1.07	97.48
Physicochemical characteristics of seeds								
Diameter (mm)	4.46	4.18	1.21	1.12	3.45	3.73	1.08	99.47
Water content (%)	8.99	0.80	1.64	1.59	0.48	0.50	1.03	79.52
Electrical conductivity (µS $cm^{-1}g^{-1}$)	6.81	11.70	8.84	9.47	1.32	1.23	0.93	96.54
Lipid (%)	6.95	5.28	13.54	12.61	0.38	0.41	1.07	70.89
Phenol (%)	1.19	5.07	9.44	8.37	0.53	0.60	1.12	82.20
Sugar (%)	1.61	6.30	25.13	19.05	0.25	0.33	1.31	50.15
Protein (%)	13.32	5.09	9.49	14.52	0.53	0.35	0.65	82.14
Starch (%)	11.09	14.90	16.65	13.83	0.89	1.07	1.20	92.76
Fiber (%)	52.85	2.54	3.09	4.03	0.82	0.63	0.76	91.53
Gray (%)	1.92	3.23	11.77	20.20	0.27	0.15	0.58	54.72
Physiological quality of seeds								
Germination (%)	86.00	0.00	7.29	4.91	0.00	0.00	1.48	0.00
Germination speed index	2.20	0.00	9.85	7.91	0.00	0.00	1.24	0.00
Length of shoot (cm)	3.91	0.00	4.44	5.03	0.00	0.00	0.88	0.00
Root length (cm)	3.86	0.00	110.54	112.33	0.00	0.00	0.98	0.00
Total fresh mass (mg)	61.02	7.97	9.50	11.88	0.83	0.67	0.79	91.85
Total dry mass (mg)	6.83	2.09	8.19	6.17	0.25	0.33	1.32	51.02

The CVg/CVP ratio, which represents the ratio between the variations resulting from genetic causes and the plots (environment), was the highest for the fruit pulp yield (8.23); the CVg/CVS ratio, which is the ratio between the variations resulting from genetic causes and the subplots (hybrids) showed higher values for fruit pulp yield (5.52) than the other characteristics. Thus, environment does not affect the pulp yield significantly, and the genetic factor contributes more to such characteristics. The CVP/CVS ratio, which represents the ratio between the variations in plots and subplots, was the highest for the chlorophyll *b* index of the leaves (1.56).

The agronomic characteristics (chlorophyll *b* index) and physiological quality of seeds (germination, GSI, shoot and root length) would be the most influenced by the changes in environment in the analyzed passion fruit hybrids because they have low heritability (Table 2).

The largest relative contribution (RC%) observed in this study was of the number of fruits per plant (NFP, 99.53%) among the agronomic characteristics (Figure 1A), pulp yield (60.44%) and fruit length (19.73%) among the physicochemical characteristics of the fruits (Figure 1B), ash content (26%), seed diameter (16.75%), sugar content (13.44%), fiber content (13.31%), and phenol content (11.23%) among the physicochemical characteristics of the seeds (Figure 1C), and GSI (23.53%), root length (21.60%), germination (20.31%), and shoot length (19.03%) among the physiological quality of the seeds (Figure 1D).

The PCoA of the group of agronomic characteristics considering the 12 treatments explained 91.33% of the total variance, based on the first two axes (Figure 2A). It was observed that the hybrid GA at 41 m altitude (2), BRS RC at 104 m (4), and BRS SC at 104 m (6) showed higher agronomic performance as they were positioned in the upper right quadrant and associated with the highest averages for the NFP and chlorophyll *a* and *b* indices. The hybrid SC at 104 m (6), BRS GA at 711 m (8), and SC at 711 m (9), positioned in the upper right quadrant, exhibited better physicochemical properties of fruits than the hybrids at other environment (Figure 2B).

PCoA explained 50.43% of the total variance in the physicochemical characteristics of the seeds. The hybrid RC at 41 m altitude (1) and BRS GA at 104 m (5) and 711 m altitudes (8) showed better physicochemical performance of passion fruit seeds than the others (Figure 3A). PCoA explained 82.76% of the total variance in the physiological quality of the seeds. The hybrid GA at 41 m altitude (2) and BRS SC at 41 m (3) and 1016 m altitude (12) showed better performance in terms of the physiological quality of passion fruit seeds than the others (Figure 3B).

The hybrids studied showed higher NFP at environment of 104 m and 711 m than at other altitudes; the hybrid BRS RC at these same altitudes had a higher NFP than the other hybrids. The highest content of chlorophyll *a* (42.99%) and *b* (14.85%) was observed in the hybrid SC at 104 m (Table 3).

The largest seed diameter (4.96 mm) was observed for the hybrid RC at 711 m among all the hybrids at different environment (Table 4).

As for the biochemical composition of the seeds of the hybrids, the seeds of the hybrid SC had the highest total lipid (12.89%) and total protein (17.71%) content at 41 m, and the highest total soluble phenol content (2.05%) at 711 m. RC hybrid seeds showed higher sugar content (2.28%) at 711 m, starch content (21.06%) at 1016 m, and fiber content (62.60%) and ash (2.89%) at 104 m, compared to other environments (Table 4).

Passion fruit plants had higher germination percentages at environments 104, 711, and 1016 m than at 41 m, and these values showed no statistically significant difference

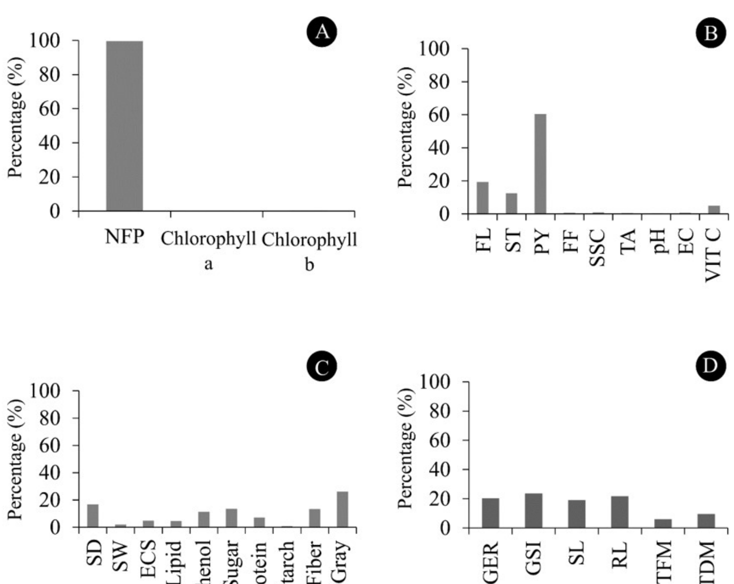

Figure 1. Importance of characters based on relative contribution (RC%) as described by Singh (1981), which is based on D^2 of Mahalanobis related to agronomic characters (A); physicochemical properties of fruits (B), physicochemical properties of seeds (C), and physiological quality of seeds (D) of passion fruit hybrids at different environments. NFP: number of fruits per plant; FL: fruit length; ST: shell thickness; PY: pulp yield; FF: fruit firmness; SSC: soluble solid content; TA: titratable acidity; pH: potential of hydrogen; EC: electrical conductivity; VIT C: vitamin C; SD: seed diameter; SW: seed water content; ECS: electrical conductivity of seeds; GER: germination; GSI: germination speed index; SL: shoot length; RL: root length; TFM: total fresh mass; TDM: total dry mass.

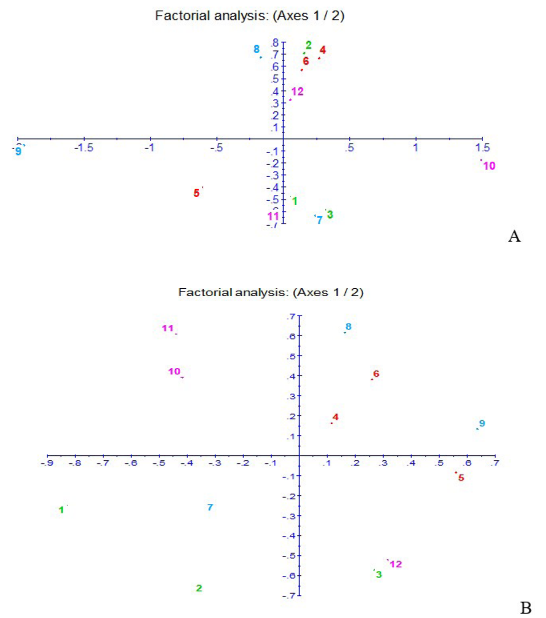

Figure 2. Graphical analysis of principal coordinates for the agronomic characteristics (A) and physicochemical characteristics of the fruits (B) for 12 treatments (combinations between environments × passion fruit hybrids). Green = 41 m; red = 104 m; blue = 711 m; pink = 1016 m; 1 = BRS Rubi do Cerrado; 2 = BRS Gigante Amarelo; 3 = BRS Sol do Cerrado; 4 = BRS Rubi do Cerrado; 5 = BRS Gigante Amarelo; 6 = BRS Sol do Cerrado; 7 = BRS Rubi do Cerrado; 8 = BRS Gigante Amarelo; 9 = BRS Sol do Cerrado; 10 = BRS Rubi do Cerrado; 11 = BRS Gigante Amarelo; 12 = BRS Sol do Cerrado (A represents 91.33% of the total variance, eigenvalue of axis 1 = 60.79% and that of axis 2 = 30.54%; B represents 41.07% of the total variance, with CP1 = 20.74% and CP2 = 20.33%).

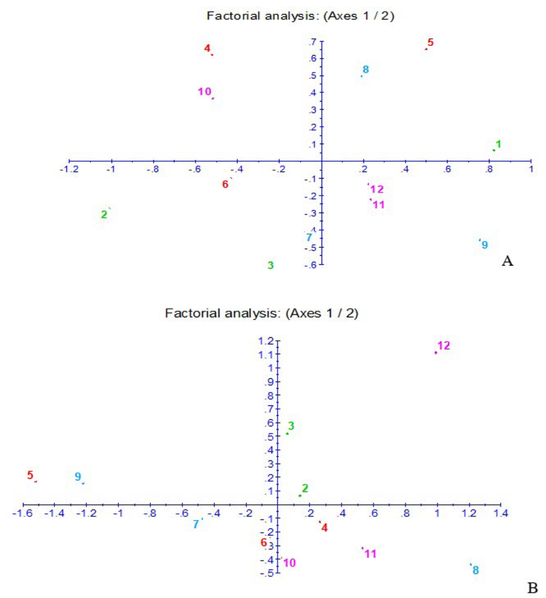

Figure 3. Graphical analysis of principal coordinates with the physicochemical characteristics (A) and physiological quality of the seeds (B) for 12 treatments (environments × passion fruit hybrids). Green = 41 m; red = 104 m; blue = 711 m; pink = 1016 m; 1 = BRS Rubi do Cerrado; 2 = BRS Gigante Amarelo; 3 = BRS Sol do Cerrado; 4 = BRS Rubi do Cerrado; 5 = BRS Gigante Amarelo; 6 = BRS Sol do Cerrado; 7 = BRS Rubi do Cerrado; 8 = BRS Gigante Amarelo; 9 = BRS Sol do Cerrado; 10 = BRS Rubi do Cerrado; 11 = BRS Gigante Amarelo; 12 = BRS Sol do Cerrado (A represents 50.43% of the total variance, with CP1 = 31.49% and CP2 = 18.94%, and B represents 82.76% of the total variance, with CP1 = 62.38% and CP2 = 20.38%).

between the hybrids (Table 5). Seeds of the three hybrids at an altitude of 41 m showed the lowest germination percentages—GA (48%), RC (72%), and SC (50%). The seeds of the hybrid GA at 711 m altitude showed the highest GSI (3.15), shoot length (4.53 cm), and total fresh mass (72.50 mg) among all the other hybrids at different environments. The seedlings of the hybrid RC at 104 e 1016 m showed the highest root length (3.99 and 4.18 cm, respectively) among all the other hybrids at different environment. Seedlings of the GA and SC hybrid had the highest total dry mass (8.30 and 8.40 mg, respectively) at 711 m among all the other hybrids at different environments.

4. Discussion

The estimation of genetic parameters allows the identification of genetic variability and helps in understanding the contribution of genetic and environmental (or experimental) factors to the phenotype (Cruz et al., 2011). Heritability, together with the genotypic determination coefficient, determines the amount of phenotypic variation that can be attributed to genetic factors (Cordeiro et al., 2019) characters with higher heritability are less influenced by the environment. The Singh (1981) method, based on the Mahalanobis distance, considers the characters capable of expressing the highest percentage of variability to be of greater importance.

The evaluation of the relative importance of the characters allows the rejection ofthe characters that contribute less to the discrimination of the evaluated material, and exclusion of such characters would reduce the man power, time, and cost required for the experiment (Correa and Gonçalves, 2012), thus allowing to focus on the analyses of the characters that show greater variability and are, therefore, more relevant in the discrimination of genetic materials and their ecophysiological responses. In this study, the most representative characteristics in the discrimination of hybrids at different environments were number of NFP, pulp yield, fruit length, ash content, seed diameter, sugar content, fiber percentage, phenol content, GSI, root length, germination, and shoot length.

Better results were observed at altitudes (104 m), especially for the hybrid SC. This hybrid did not flower under short photoperiod and low temperature conditions when studied by Cordeiro et al. (2019) because low temperatures are observed at high altitudes. In this study, seed quality of the hybrids was different at each altitude, which may be related to the segregation of these hybrids in the

Table 3. Agronomic and physicochemical characteristics of the fruits of passion fruit hybrids cultivated at different environment. GA = Gigante Amarelo; RC = Rubi do Cerrado; SC = Sol do Cerrado.

Altitude (m)	**Number of fruits plant^{-1}**			**Chlorophyll *a* Index (%)**			**Chlorophyll *b* Index (%)**			**Fruit length (cm)**		
	GA	**RC**	**SC**	**GA**	**RC**	**SC**	**GA**	**RC**	**SC**	**GA**	**RC**	**SC**
41	19 bAB(*)	20 bA	18 bB	35.23 aB	41.56 aA	28.60 bC	9.29 aA	9.30 aA	5.92 cB	7.53 cB	7.58 cB	8.01 bA
104	38 aB	41 aA	34 aC	39.83 aA	39.06 aA	42.99 aA	9.02 aB	9.30 aB	14.85 aA	9.43 aB	10.04 aA	8.70 bC
711	38 aB	41 aA	34 aC	38.55 aA	39.30 aA	38.71 aA	8.06 aA	9.76 aA	9.55 bA	9.63 aB	10.22 aA	9.92 aB
1016	19 bAB	20 bA	18 bB	41.22 aA	41.31 aA	40.84 aA	10.57 aA	10.83 aA	9.49 bA	8.11 bB	9.43 bA	8.43 bB
CV (%)		2.92			8.43			23.44			1.59	
Altitude (m)	Bark thickness (cm)			Performance (%)			Firmness (g f^{-1})			Soluble solids (ºBrix)		
	GA	RC	SC	GA	RC	SC	GA	RC	SC	GA	RC	SC
41	7.04 bA	6.30 bB	5.29 dC	47 bA	37 cC	43 cB	252.00 aA	251.00 aA	182.00 cB	14.55 bA	14.85 abA	14.25 bA
104	6.59 cB	7.06 aA	5.80 cC	51 aA	50 aB	47 aC	190.00 bA	177.75 bA	201.75 bcA	12.52 cC	13.65 cB	15.60 aA
711	6.80 bcB	6.23 bC	8.01 bA	47 bB	51 aA	45 bC	240.25 abA	160.00 bB	271.25 aA	15.40 abA	15.84 aA	15.55 aA
1016	8.14 aB	6.24 bC	9.13 aA	38 cB	48 bA	23 dC	215.75 abAB	169.25 bB	250.25 abA	15.87 aA	13.77 bcB	15.50 aA
CV (%)		2.55			1.20			12.99			3.99	
Altitude (m)	Titratable acidity			pH			Electric conductivity (µS cm^{-1}g^{-1})			Vitamin C (mg)		
	GA	RC	SC	GA	RC	SC	GA	RC	SC	GA	RC	SC
41	2.89 bA	3.04 aA	3.41 bA	3.01 aAB	3.10 aA	2.97 aB	1.42 aC	1.55 bB	1.70 aA	43.51 aA	39.68 bA	32.22 cB
104	4.35 aAB	3.90 aB	5.02 aA	2.71 bB	2.89 bA	2.74 bB	0.82 cB	1.10 cA	1.03 dA	42.83 aB	40.14 bB	54.23 aA
711	3.19 bA	3.50 aA	3.34 bA	2.93 aA	2.97 abA	2.96 aA	1.25 bC	1.98 aA	1.47 bB	31.20 cC	45.52 aB	56.21 aA
1016	4.37 aA	3.44 aB	3.88 bAB	2.76 bA	2.84 bA	2.88 aA	0.71 dC	1.02 cB	1.34 cA	37.82 bB	42.14 abA	41.30 bAB
CV (%)		11.43			2.40			3.70			5.23	

(*)Averages followed by the same letter, lowercase in the column (altitude) and uppercase in the row (hybrids), do not differ from each other based on Tukey's test at a 5% probability level. Coefficient of variation (CV).

Table 4. Physicochemical characteristics of seeds of passion fruit hybrids cultivated at different environments. GA = Gigante Amarelo; RC = Ruby do Cerrado; SC = Sol do Cerrado.

Altitude (m)	**Seed diameter (mm)**			**Seed humidity (%)**			**Electric conductivity (μS $cm^{-1}g^{-1}$)**			**Total lipids (%)**		
	GA	**RC**	**SC**	**GA**	**RC**	**SC**	**GA**	**RC**	**SC**	**GA**	**RC**	**SC**
41	4.51 bA(*)	4.54 cA	4.37 aB	9.75 aA	9.46 aB	9.31 aB	8.75 bA	9.03 aA	7.00 aB	4.18 bC	7.08 aB	12.89 aA
104	4.49 bB	4.70 bA	4.45 aB	9.34 bA	8.68 cB	8.73 bB	5.13 dB	5.42 bcB	7.53 aA	7.29 aA	7.48 aA	3.38 dB
711	4.61 aB	4.96 aA	4.09 bC	8.81 cB	9.03 bB	9.07 aA	9.96 aA	4.30 cB	5.01 bB	8.01 aA	6.25 aB	7.72 bAB
1016	4.20 cB	4.40 dA	4.19 bB	8.24 dB	8.41 cB	9.03 aA	6.94 cA	5.63 bB	7.08 aA	6.74 aA	6.78 aA	5.70 cA
CV (%)		1.19			1.63			9.06			13.25	
Altitude (m)	Total soluble phenols (%)			Sugars (%)			Total proteins (%)			Starch (%)		
	GA	RC	SC	GA	RC	SC	GA	RC	SC	GA	RC	SC
41	1.14 bB	1.92 aA	1.01 bB	2.23 aA	1.18 bB	1.47 aB	15.75 aA	15.50 aA	17.71 aA	2.62 cB	1.20 dB	4.65 cA
104	0.90 cA	0.85 cA	0.93 bA	1.21 bAB	1.10 bB	1.79 aA	11.51 bA	12.05 bA	11.31 bA	16.79 aA	17.50 bA	17.29 aA
711	1.58 aB	0.72 cC	2.05 aA	2.21 aA	2.28 aA	1.51 aB	10.84 bA	10.16 bA	11.38 bA	11.74 bA	12.08 cA	5.81 cB
1016	1.04 bcA	1.06 bA	1.07 bA	1.39 bA	1.35 bA	1.57 aA	11.82 bB	16.49 aA	15.29 aA	11.81 bB	21.06 aA	10.56 bB
CV (%)		9.10			23.29			11.42			15.77	

Altitude (m)	Fibers (%)			Ashes (%)		
	GA	RC	SC	GA	RC	SC
41	53.80 aA	51.00 bAB	50.00 aB	1.79 bA	1.60 bcA	1.33 bA
104	52.90 aB	62.60 aA	51.40 aB	2.48 aA	2.89 aA	2.84 aA
711	51.40 aA	51.30 bA	51.70 aA	1.85 bAB	1.99 bB	2.45 aA
1016	52.00 aA	52.70 bA	53.50 aA	1.19 cA	1.40 cA	1.30 bA
CV (%)		3.44			15.12	

(*)Means followed by the same letter, lowercase in the column (altitude) and uppercase in the row (hybrids), do not differ from each other based on the Tukey test at a 5% probability level. Coefficient of variation (CV).

Table 5. Physiological quality characteristics of seeds of passion fruit hybrids cultivated at different environment. GA = Gigante Amarelo; RC = Rubi do Cerrado; SC = Sol do Cerrado.

Altitude (m)	**Germination (%)**			**Germination speed index**		
	GA	**RC**	**SC**	**GA**	**RC**	**SC**
41	48 bB(*)	72 bA	50 bB	1.48 dB	2.46 aA	1.67 cB
104	98 aA	94 aA	99 aA	2.47 bB	2.19 aB	2.61 aA
711	98 aA	92 aA	97 aA	3.15 aA	2.24 aB	2.08 bB
1016	96 aA	93 aA	99 aA	1.92 cB	1.71 bB	2.42 abA
CV (%)		6.60			9.25	
Altitude (m)	Plant length (cm)			Root length (cm)		
	GA	RC	SC	GA	RC	SC
41	3.36 cB	4.31 aA	3.31 cB	3.06 bB	3.36 bA	2.58 bC
104	3.79 bA	3.77 bcA	3.78 bA	3.36 aB	3.99 aA	3.22 aB
711	4.53 aA	4.11 abB	4.13 abB	3.47 aA	3.51 bA	3.20 aB
1016	3.80 bB	3.57 cB	4.43 aA	2.77 cC	4.18 aA	3.25 aB
CV (%)		4.65			3.93	
Altitude (m)	Total fresh mass(mg)			Total dry mass (mg)		
	GA	RC	SC	GA	RC	SC
41	45.62 bB	63.28 aA	51.83 bB	5.23 cB	6.16 bA	5.84 cAB
104	54.44 bB	66.37 aA	61.34 abAB	6.70 bA	6.93 abA	6.17 bcA
711	72.50 aA	65.38 aA	70.50 aA	8.30 aA	7.10 abB	8.40 aA
1016	48.85 bB	65.63 aA	66.49 aA	6.29 bB	7.92 aA	6.95 bB
CV (%)		10.36			7.58	

(*)Means followed by the same letter, lowercase in the column (altitude) and uppercase in the row (hybrids), do not differ from each other based on the Tukey's test at a 5% probability level. Coefficient of variation (CV).

F2 generation. Furthermore, the direct relationship between seed mass and altitude can be influenced by factors that can covary with altitudinal variations (Guo et al., 2010).

Factors intrinsic to the parent plant that directly affect seed mass, such as the size and number of seeds per fruit, can be influenced by altitudinal variations, thus confounding the direct effect of altitude on seed mass (Bolmgren and Cowan, 2008). The environmental conditions to which the parent plants are exposed during fruit formation affect seed germination characteristics, which would increase the chances of persistence ofthe species in its habitat under environmental changes (Oda et al., 2016). Besides the effects of the genotype and environment, the interaction between these two factors also affects the plants (Resende, 2004). The evaluation of cultivars in different environments revealed different behaviors under different environmental conditions (Rosado et al., 2012).

The hybrid SC, launched in 2008 (Embrapa, 2008), was obtained through population improvement by recurrent selection and evaluation of intraspecific hybrids. The fruits of the said hybrid were bright yellow in color and oblong in shape with strong yellow pulp (higher amount of vitamin C), good productivity (40 t ha^{-1} in the first year under Brazilian Cerrado conditions), and high pulp quality and yield. Based on the assessment areas, there are also indicators of the cultivar's adaptation at altitudes between 376 and 1,100 m, latitude from 9 to 23°, and planting at any time of the year (when irrigated) in different types of soil. In this study, the hybrid SC showed greater adaptation between environments of 41 and 1016 m than the other hybrids for the physicochemical characteristics of the fruits and physiological quality of the seeds.

The hybrid RC at 711 m of altitude showed greater fruit length (10.22 cm), and SC showed greater values for bark thickness (9.13 cm) at 1016 m and firmness (271.25 g f^{-1}) at 711 m compared to the other hybrids at different altitudes. Other studies reported that shell thickness and firmness are quite variable, mainly due to the genetic nature of the materials evaluated (Freitas et al., 2011).

The highest pulp yield was observed for the hybrids GA (51%) at 104 m and RC at 104 (50%) and 711 m (51%). Neves et al. (2013) studied passion fruit pulp yield in Cruz das Almas, Bahia at an altitude of 200 m, where environmental conditions strongly influenced the pulp yield. This characteristic is of great importance because fruits that can provide high juice yield and have high soluble solid content are preferred in the juice industry (Krause et al., 2012). The highest amount of soluble solids was observed for the hybrid GA at an altitude of 1016 m (15.87 °Brix). The hybrid SC at 104, 711, and 1016 m showed a higher soluble solid content than at low altitude. Aguiar et al. (2015) studied passion fruit hybrids from IAPAR and similarly observed high values of soluble solids, with average ranging from 13.7 °Brix to 15.4 °Brix.

The hybrid SC showed higher titratable acidity (5.02) at 104 m and higher vitamin C content (56.21 mg) at 711 m altitude compared to the other hybrids. GA hybrid showed higher pH (3.01) at 41 m altitude compared to the other hybrids at different altitudes. The RC hybrid showed higher electrical conductivity (1.98 µS cm^{-1g-1}) at 711 m compared to the other hybrids and environments. The sugar content and acidity of the fruits may vary due to the environmental factors and cultivation practices, such as the quality of sunlight, temperature, and factors closely linked to altitudinal variations. Acidity highly affects the quality of the beverage produced from the pulp (Oliveira et al., 2017).

The direct relationship between seed mass and environments may be influenced by factors that may covary with the variation in environments (Guo et al., 2010). The hybrid GA had higher seed water content (9.75%) at 41 m altitude and higher seed electrical conductivity (9.96 µS $cm^{-1}g^{-1}$) at 711 m altitude compared to the other hybrids.

Germination and vigor are influenced by the content of the compounds present in the seed, and generally, the higher the content of the reserves in the seeds, the better the development of the seedlings (Carvalho and Nakagawa, 2012). Thus, the compounds present in the reserve of the seeds, especially those that can be used as sources of energy and carbon in the processes of germination, development, and establishment of the seedling, are important tools for understanding the response of the species, in terms of mobilization of these compounds during germination, to the changes in factors related to environments.

5. Conclusions

For the genetic coefficient of variation (CVg), the highest value was found for starch (14.90), for the coefficient of variation of the plot (CVP), as well as for the coefficient of variation of the subplot (CVS), they presented higher values for seedling root length (110.54 and 112.33, respectively).

The most representative characteristics in the discrimination of hybrids at different environments are the NFP, pulp yield, fruit length, ash content, seed diameter, sugar content, fiber percentage, phenol content, GSI, root length, germination, and shoot length.

Pulp yield is less influenced by altitude and is directly related to the genotype of each passion fruit hybrid.

The three hybrids showed better performance at low altitudes (41 and 104 m) in terms of agronomic characters.

The hybrids SC at low (104 m) and medium (711 m) altitudes and GA at a medium altitude (711 m) showed the highest values for the physicochemical characteristics of fruits.

The hybrids showed different responses at each altitude for seed quality.

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