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Biology-Botany

Phenotypic characterization of fruits and pseudofruits of shrubby cashew from Cerrado (*Anacardium othonianum* Rizz. Anacardiaceae)

Caracterização fenotípica de frutos e pseudofrutos de caju arbóreo do Cerrado (*Anacardium othonianum* Rizz. Anacardiaceae)

Jeniffer Raniely Batista Sousa[I], Igor Richards Lamounier de Faria[III], Elitânia Gomes Xavier[III], Luciana Borges e Silva[IV], Eli Regina Barboza de Souza[I], Elias Emanuel Silva Mota[II]

[I] Universidade Federal de Goiás, Goiânia, GO, Brasil
[II] Universidade de Rio Verde, Rio Verde, GO, Brasil
[III] Centro Universitário Evangélico de Goianésia, Goianésia, GO, Brasil
[IV] Instituto Federal Goiano, Goías, GO, Brasil

ABSTRACT

Studies on physical and chemical characteristics of fruits are essential tools that assist pre-improvement programs and the identification of variability among individuals or accessions of a population. Thus, aiming to characterize fruits and pseudofruits of 15 natural subpopulations of *Anacardium othonianum* Rizz. in order to contribute to the elaboration of efficient strategies for its use and genetic conservation, at least 12 fruits without mechanical and/or phytosanitary damage of ten matrices in each subpopulation were collected. Biometric characteristics of fruits and pseudofruits were evaluated. The data were submitted to descriptive analysis, variance analysis and phenotypic correlation. Through variance components, we estimated the proportions of the total phenotypic variation attributed to the difference among subpopulations, matrices within subpopulations, and fruits/pseudofruits within matrices, in addition to the quantitative phenotypic divergence among subpopulations (P_{ST} parameter). The largest phenotypic variations occurred among the characters related to the fruits/pseudofruits mass and coloration. Shrubby cashew fruits from Cerrado presented predominance of red-orange color. There were highly significant variations for all evaluated characters, in all hierarchical levels: among subpopulations, among matrices within subpopulations, and among fruits within matrices. As for the genetic structure of the species, the most genetic variability was found among matrices within subpopulations. The subpopulations presented phenotypic differentiation based on the characteristics: pseudofruit larger width, pseudofruit smaller width and pseudofruit thickness, according to the P_{ST} parameter. The pseudofruit constitutes the majority of the fruit; therefore, the mass and length measurements are directly correlated to the mass measurements and total length of the samples. There is low correlation between the fruits and pseudofruits mass and size.

Keywords: Genetic structure; Biometry; Brazilian neotropical savana; Conservation

RESUMO

Os estudos sobre as características físicas e químicas dos frutos são ferramentas essenciais que auxiliam os programas de pré-melhoramento e a identificação da variabilidade entre indivíduos ou acessos de uma população. Assim, com objetivo de avaliar a estrutura genética de 15 subpopulações naturais da espécie *Anacardium othonianum* Rizz. a fim de contribuir para a elaboração de estratégias eficientes para o seu uso e conservação genética, coletaram-se no mínimo 12 frutos sem danos mecânicos e/ou fitossanitários de dez matrizes em cada subpopulação. Foram avaliadas características biométricas dos frutos e pseudofrutos. Os dados foram submetidos à análise descritiva, à análise de variância e correlação fenotípica. Por meio dos componentes de variância, estimaram-se as proporções da variação fenotípica total atribuída a diferença entre subpopulações, matrizes dentro de subpopulações e entre frutos/pseudofrutos dentro de matrizes e o parâmetro P_{ST}. As maiores variações fenotípicas ocorreram entre os caracteres relacionados à massa dos frutos/pseudofrutos e coloração. Os frutos de caju arbóreo do Cerrado apresentaram predominância da cor vermelho alaranjado. Houve variação altamente significativa para todos os caracteres avaliados, em todos os níveis hierárquicos: entre subpopulações, entre matrizes dentro de subpopulações e entre frutos dentro de matrizes. Quanto a estrutura genética da espécie, a maior parte da variabilidade genética encontra-se entre matrizes dentro de subpopulações. As subpopulações apresentaram diferenciação fenotípica com base nas características: largura maior do pseudofruto, largura menor do pseudofruto e espessura do pseudofruto, de acordo com o parâmetro P_{ST}. O pseudofruto constitui a maior parte do fruto, portanto, as medidas de massa e comprimento estão diretamente correlacionadas as médias de massa e comprimento total das amostras. Há baixa correlação entre as medidas de massa e tamanho de frutos e pseudofrutos.

Palavras-chave: Estrutura genética; Biometria; Cerrado; Conservação

1 INTRODUCTION

The quantification of genetic variability and the description of how the distribution of genotypes among and within natural populations are fundamental for the development of strategies of conservation and use of natural resources in pre-improvement programs (Cruz, Ferreira & Pessoni, 2011; Delialioğlu et al., 2022; Akan, 2022). However, the drastic reduction of natural populations of shrubby plants in Brazil neotropical savanna has led them to the loss of genetic variability by drift (Sebbenn & Ettori, 2001). This loss of variability results in the reduction of the species' adaptation capacity to environmental factors, as well as in the loss of genotypic and phenotypic characteristics (Ritland, 1996; Campus & Maia, 2019). Additionally, the loss of genetic diversity is also associated with the reduction of the species evolutionary potential and the reduction of the reproduction rate (Allendorf, Hohenlohe & Luikart, 2010).

The Brazilian neotropical savanna presents among 39 (priorities) and 76 fruit species with economic exploration potential. Knowing the physico-chemical characteristics, the nutritional and functional value of the Cerrado fruits are means of encouraging consumption and the creation of new products (Vieira et al., 2016). The physical characterization, of macros and micronutrients and the existing compounds in these fruits enables a better indication regarding their use and better use in the food industry (Soares et al., 2019).

Among the species with high sustainable exploration potential found in the Cerrado biome, the *Anacardium othonianum* Rizz, can be highlighted (Agostini-Costa et al., 2016), popularly known as shrubby cashew from Cerrado or small cashew from Cerrado, considered the main cashew plant in the mid-west region, and presents reddish yellow fruits, with acid flavor and high succulence (Silva, Silva & Oliveira, 2007; Bessa et al., 2013). This fruit stands out for presenting economic potential for use in cooking and in natura consumption (Allendorf, Hohenlohe & Luikart, 2010), besides presenting potential for use in pharmaceutical industry (Padilha et al., 2020). Cashew is a non-climacteric fruit that presents high vitamin C content; it is a source of antioxidants and bioactive components (Silva et al., 2021). The true fruit also constitutes an important source of food and can be used as an oil source or consumed when toasted (Sousa et al., 2017; Silva et al., 2017).

The shrubby cashew from Cerrado can reach three to four meters high, for three to four meters in canopy diameter; it is native to the Cerrado area “stricto sensu”, big Cerrado and dirty fields (Silva et al., 2001; Agostini-Costa et al., 2010; Agostini-Costa et al., 2016). They occur mainly in acidic latosol areas with low nutrient availability. Its flowering and fruiting begin during the dry season, between May and June, and end in October. The fruit production per plant concentrates between 200 and 600 fruits, with total weight between 5 and 12 grams (Agostini-Costa et al., 2010). The species under study presents potential for genotypes selection with desired behaviors for use in genetic improvement programs (Belo et al., 2019).

The present study aimed to characterize fruits and pseudofruits 15 natural subpopulations of *A. othonianum* species, in order to contribute to the elaboration of efficient strategies for its use and genetic conservation.

2 MATERIAL AND METHODS

2.1 Study area and collection

The material collection for this study was performed in 15 subpopulations distributed in the state of Goiás (Fig. 1). The term "subpopulation" was assigned to the group of sampled plants, considering a minimum distance of approximately 20 km, as indicated by Silva, Chaves e Naves (2001). In each area, matrix trees were identified through field surveys in their respective occurrence sites (Cerradão, Campo Sujo, and pasture), followed by the pre-selection of individuals with good phytosanitary conditions and fruits suitable for collection.

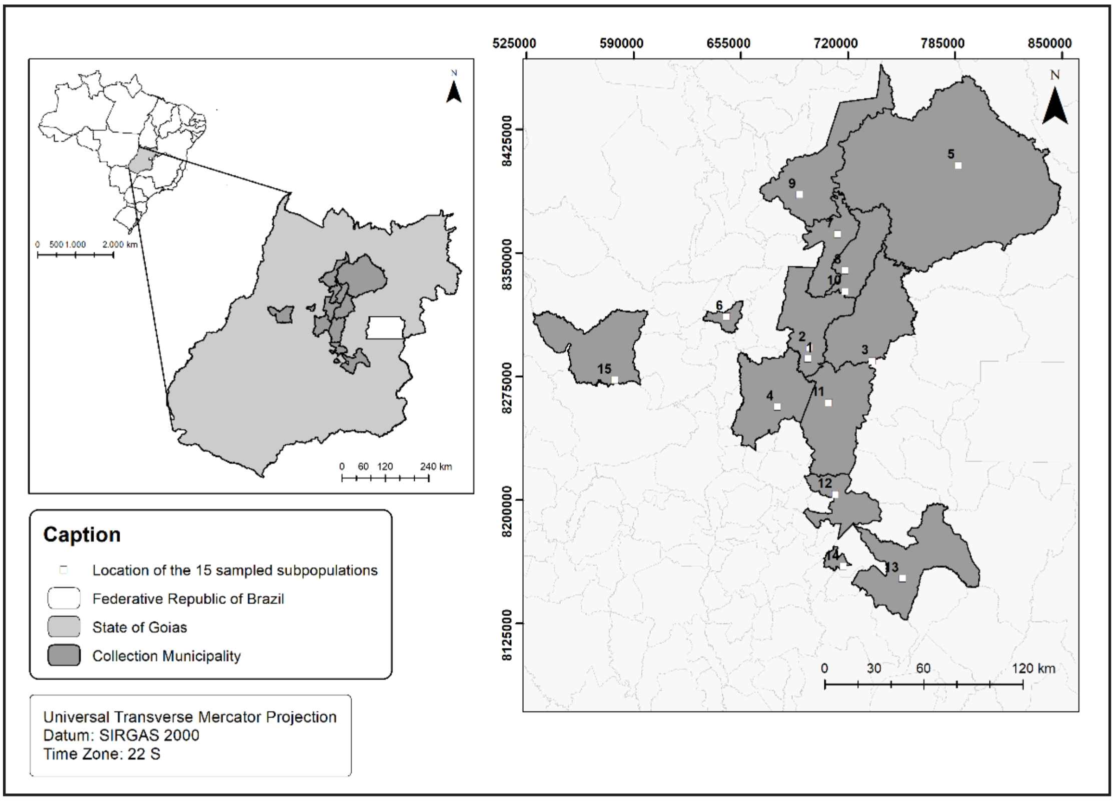
Ripe fruits were collected directly from the matrix tree or from the ground, provided they showed no signs of deterioration. Subpopulations were considered suitable for data collection if they had at least 15 adult cashew trees with sufficient production (12 fruits). The matrices were randomly sampled within each subpopulation. If more than one phytophysiognomy was present at the collection site, efforts were made to sample the different phytophysiognomies where the species occurs. The fruiting of shrubby cashew occurs, normally, in the months of June to October (Agostini-Costa et al., 2016).

The collection was carried out in areas of Latossolo, a predominant soil class in the Cerrado biome, according to the classification of the Brazilian Soil Classification System (EMBRAPA, 1999). Within this class, variations such as Red-Yellow Latosol and Red Latosol stand out, which are widely representative of the Cerrado.

The specific environmental conditions of the study area in the Cerrado are predominantly characterized by an Aw climate type, according to the Köppen-Geiger classification, which describes a climate with a rainy summer and dry winter (Köppen & Geiger, 1961; Silva, Assad & Evangelista, 2008). In the collection area, located in the Central-West region of the Cerrado, the annual precipitation is approximately 600 mm.

At least 12 undamaged fruits of ten matrices were collected from each of the 15 sampled subpopulations. This is a sampling considered suitable for studies of this nature, according to simulations made by Goudet and Buchi (Goudet & Buchi, 2006). The fruit collection was performed between August and October, respecting its physiological maturation point. Once collected, the fruits were packaged in plastic bags, stored in a thermal box with ice and transported to the Microbiology Laboratory of the Goianésia Evangelical Faculty (FACEG), in Goianésia, GO, Brazil. The fruits were kept in freezer (-18 °C) until the quantitative data were collected, without deterioration.

Figure 1 – Location of the collection areas of the 15 *Anacardium othonianum* Rizz. subpopulations sampled in the Cerrado of the state of Goiás, Brazil



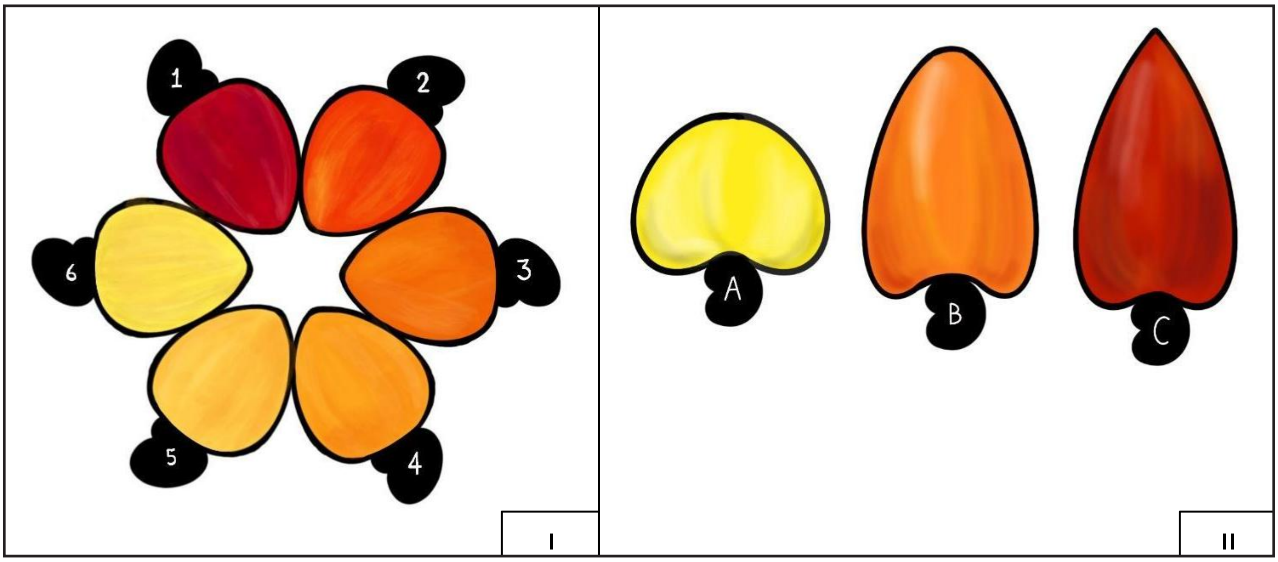
Source: Gustavo Henrique Mendes Brito, 2021 (QGIS)

2.2 Characterization of fruits and pseudofruits

Ten fruits per matrix were evaluated and 10 matrices for each of the 15 subpopulations, except for 6 (Ceres) and 12 (Anápolis) (Fig. 1), where 9 and 8 matrices were evaluated, respectively. The total number of fruits and pseudofruits of A. othonianum characterized was 1470. In the fruit evaluation, performed between the months of August and October 2020, the following morphological descriptors were used: Total Mass (MT), Pseudofruit Mass (PFM) and Fruit Mass (FM) - with the aid of an analytical scale, expressed in grams; Total Length (TL), Pseudofruit length (PFL), Pseudofruit Larger Width (PFLW), Pseudofruit Smaller Width (PFSW), Pseudofruit Thickness (PFTh), Fruit Length (FL), Fruit Larger Width (FLW), Fruit Smaller Width (FSW) and Fruit Thickness (FTh) - data taken with the aid of a digital caliper, expressed in millimeters. The coloration was determined through a color scale and the pseudofruit format was classified in apple, pyriform and pyramidal (Fig. 2). These biometric characteristics were selected because they are fundamental in the selection of plants for the genetic improvement of cultivated cashews. They directly influence the productivity and quality of the fruits, which are crucial aspects for both the market and the conservation of the species (Aliyn & Awopetu, 2011; Rossetti, Vidal-Neto & Barros, 2019).

The biometric characteristics were measured using standardized methods to ensure accuracy and consistency in the results. The mass of the pseudofruits and fruits was determined using a high-precision analytical balance, equipped with a glass enclosure to protect against air currents and other interferences. The balance was calibrated before each weighing session to ensure measurement accuracy. Before weighing, the pseudofruits and fruits were carefully dried with absorbent paper to remove any surface moisture, minimizing potential weight variations. Additionally, size measurements of the fruits and pseudofruits were taken with a high-precision digital caliper. The caliper's display was zeroed (calibrated) before each new measurement to guarantee accuracy and repeatability. All measurements were conducted under controlled environmental conditions, such as temperature (20 °C) and humidity (60%), to avoid fluctuations that could affect the results.

Figure 2 – Patterns for the classification of cashew peduncles. I. Color scale (1- red, 2- orange red, 3- orange, 4- yellow, 5- orange yellow, 6- light yellow) and II. Formats: A- apple, B- piriform and C- pyramidal. Adapted from Silva (2001)



Source: Design made by the plastic artist Leonardo Santana Mendes Moreira (2021)

2.3 Statistical analyses

The data were submitted to descriptive statistics and, subsequently, to the variance analysis based on a hierarchical model that considers the effect of subpopulations, matrices within subpopulations and fruits within matrices. The adapted model (Mota et al., 2020) was:

$$Y_{ijk} = \mu + s_i + p_{j(i)} + f_{k(ij)} \quad (1)$$

in which: Y_{ijk} ,: phenotypic fruit value (or pseudofruit) *k* of the matrix *j* of the subpopulation *i*; μ : general average of observations; s_i : random effect of the subpopulation *i,* i = 1, 2, ..., S; $p_{j(i)}$: random effect of the matrix *j* within the subpopulation *i,* j = 1, 2, ..., m_i; $f_{k(ij)}$: random effect of the fruit/pseudofruit *k* within the matrix *j* of the subpopulation *i*, k =1, 2, ..., f_j.

In the present study, the number of matrices per subpopulation (m_i = 10 - exception for Ceres and Anápolis) and fruits per matrix (f_j = 10) were constant. According to the adopted statistical model, the variance components were estimated among subpopulation, among matrices within subpopulations and residual (fruits/pseudofruits within matrices) according to the expected average squares. Subsequently, the proportions of the total phenotypic variation were estimated, which is due to the difference among subpopulations (P_S), difference among matrices within subpopulations ($P_{M/S}$) and difference among fruits/pseudofruits within matrices within subpopulations ($P_{F/M}$) (Mota et al., 2020). Through the variance components we estimated the P_{ST} parameter, which measures the quantitative phenotypic divergence among subpopulations, using the following formulas:

$$P_S = \frac{\hat{\sigma}^2_{Sub}}{\hat{\sigma}^2_{Sub} + \hat{\sigma}^2_{Mat(Sub)} + \hat{\sigma}^2_{Frut(Mat)}} \quad (2);$$

$$P_{M/S} = \frac{\hat{\sigma}^2_{Mat(Sub)}}{\hat{\sigma}^2_{Sub} + \hat{\sigma}^2_{Mat(Sub)} + \hat{\sigma}^2_{Frut(Mat)}} \quad (3);$$

$$P_{F/M} = \frac{\hat{\sigma}^2_{Frut(Mat)}}{\hat{\sigma}^2_{Sub} + \hat{\sigma}^2_{Mat(Sub)} + \hat{\sigma}^2_{Frut(Mat)}} \quad (4);$$

$$P_{ST} = \frac{\hat{\sigma}^2_{Sub}}{\hat{\sigma}^2_{Sub} + 2\hat{\sigma}^2_{Mat(Sub)}} \quad (5).$$

The phenotypic correlation coefficients were also estimated among the evaluated characters. The analyses were performed based on genetic and statistical procedure of the R software version 3.4.3 (R DEVELOPMENT CORE TEAM, 2017).

3 RESULTS

The largest phenotypic variations occurred among the characters related to the sample mass and pseudofruit coloration. The total mass (TM), pseudofruit mass (PFM) and fruit mass (FM) presented the following general averages: 11.977 g, 9.260 g and 2.718 g, respectively, as well as the highest coefficient of variation (CVs%) among the evaluated characteristics, higher than 31% (Table 1).

The highest estimated averages for the characters related to the mass were observed in subpopulations 6 (Ceres), 9 (Uruaçu) and 10 (Souzalândia). While the lowest average for TM and PFM were observed in subpopulations 4 (Jaraguá) and 11 (Pirenópolis). It is noted that, in the case of subpopulation 4, the average value found for TM was approximately 49% lower than the value found for the same characteristic in the subpopulation 6. As for the FM, the lowest averages were observed by subpopulations 1 (Santa Familia River) and 3 (Vila Propício) (Table 1).

Table 1 – Averages per subpopulation, general average (per plant), maximum and minimum values and coefficient of variation of quantitative fruit and pseudofruits of *Anacardium othonianum* Rizz. from 15 native subpopulations from the Cerrado in the state of Goiás, Brazil

(To be continued...)

Subpopulation	**Characters**							
	TM	**PFM**	**FM**	**TL**	**PFL**	**PFLW**	**PFSW**	**PFTh**
1 - Santa Família	10.501	8.3755	2.125	40.727	23.972	21.680	17.863	20.268
2 – Goianésia	10.658	8.1410	2.517	39.321	21.515	23.342	19.219	23.365
3 - Vila Propício	12.519	10.290	2.228	42.857	25.401	24.970	19.280	23.883
4 – Jaraguá	8.6181	6.0992	2.519	42.665	23.630	19.561	13.757	17.722
5 – Niquelândia	9.6055	7.0117	2.594	42.013	21.962	20.208	15.672	19.744
6 – Ceres	17.504	14.434	3.092	48.829	30.037	27.229	18.991	25.672
7 – Placa	9.6606	7.2675	2.393	41.750	23.029	20.375	15.216	20.013
8 - Barro Alto	14.545	11.614	2.932	47.049	26.896	24.932	19.062	24.230
9 – Uruaçu	16.447	13.245	3.203	48.822	28.650	25.909	20.083	25.052
10 - Souzalândia	15.571	12.376	3.195	45.104	26.791	25.993	21.114	25.230
11 - Pirenópolis	9.3125	6.9126	2.400	41.220	23.658	20.240	14.757	18.529
12 – Anápolis	10.319	7.3263	2.992	43.369	23.539	19.758	14.250	18.285
13 – Silvânia	14.287	11.351	2.935	45.355	26.063	24.218	17.285	23.299
14 - Bonfinópolis	9.7707	7.1170	2.654	42.399	22.832	20.640	14.449	19.198
15 – Faina	10.526	7.4439	3.082	45.559	24.484	19.476	12.932	16.720
Average	11.977	9.2604	2.7181	43.775	24.814	22.577	16.953	21.430
Minimum	3.1600	1.5000	0.7800	25.670	10.700	10.920	5.8300	8.5900
Maximum	34.010	30.040	6.4500	71.160	49.700	39.170	32.140	37.460
CV %	44.401	52.684	31.514	16.825	26.020	21.643	26.881	23.323

Table 1 – Averages per subpopulation, general average (per plant), maximum and minimum values and coefficient of variation of quantitative fruit and pseudofruits of *Anacardium othonianum* Rizz. from 15 native subpopulations from the Cerrado in the state of Goiás, Brazil

(Conclusion)

Subpopulation	Characters				
	FL	FLW	FSW	FTh	COLOR
1 - Santa Família	16.715	16.395	13.254	10.590	1.9600
2 – Goianésia	17.817	18.247	14.466	10.993	1.8900
3 - Vila Propício	17.456	17.050	14.009	10.054	1.9600
4 – Jaraguá	19.035	17.243	12.926	10.515	2.1810
5 – Niquelândia	20.051	17.467	13.711	10.508	1.8400
6 – Ceres	18.792	17.142	13.220	11.054	2.4555
7 – Placa	18.721	14.596	11.615	10.080	1.4500
8 - Barro Alto	20.154	17.089	12.937	10.572	1.8800
9 – Uruaçu	20.172	17.717	14.693	11.102	1.7500
10 - Souzalândia	18.312	16.624	13.393	10.772	1.8800
11 - Pirenópolis	17.562	16.672	12.785	10.416	2.3000
12 – Anápolis	19.831	16.702	12.115	11.231	2.2375
13 – Silvânia	19.291	17.376	13.892	11.377	3.0500
14 - Bonfinópolis	19.567	16.490	12.501	10.443	1.9100
15 – Faina	21.091	17.532	13.581	11.424	3.9300
Average	18.961	16.958	13.290	10.734	2.1750
Minimum	10.370	8.1700	6.3000	4.6600	1.0000
Maximum	31.990	24.860	20.520	18.320	6.0000
CV %	16.471	14.152	15.129	13.779	50.878

TM: total mass (g); PFM: pseudofruit mass; FM: fruit mass (g); TL: total length (mm); PFL: pseudofruit length (mm); FL: fruit length; PFLW: pseudofruit larger width (mm); PFSW: pseudofruit smaller width (mm); PFTh: pseudofruit thickness (mm); FLW: fruit larger width (mm); FSW: fruit smaller width (mm); FTh: fruit thickness (mm). Source: the authors (2021)

Regarding the characters based on the sample length, the pseudofruit length (PFL) presented the highest coefficient of variation (CV%= 26), corroborated by its variation amplitude of 10.7 mm to 49.7 mm. The total length (TL) and fruit length (FL) manifested similar CVs, close to 16%. The subpopulations 6 (Ceres) and 9 (Uruaçu) presented the highest values for TL and PFL. Most of the matrices of the two subpopulations mentioned above were sampled in pasture environment, probably with soils that are more fertile and less shade, factors that may have influenced the size of the TL and

PFL. For the FL, the highest averages were observed by the subpopulations 15 (Faina), 9 and 8 (Barro Alto) (Table 1).

The characters pseudofruit larger (PFLW), small (PFSW) width and thickness (PFT) presented CVs considered average for Cerrado fruits and general averages of 22.57 mm, 16.95 mm and 21.43 mm, respectively. The subpopulations 6 (Ceres), 10 (Souzalândia) and 9 (Uruaçu) presented the highest averages for PFLW and PFTh. For the characteristic PFSW, the subpopulations that presented the highest average values were 10, 9 and 3 (Vila Propício) (Table 1).

The characteristics related to the width (FLW and FSW) and fruit thickness (FTh) presented the lowest variations among the quantitative variables evaluated, based on their CVs and variation, minimum and maximum amplitudes. It was noted that the subpopulations 9 (Uruaçu), 2 (Goianésia) and 15 (Faina) obtained higher averages for FLW, and the subpopulations 9, 2 and 3 (Vila Propício) manifested higher averages for FSW. For the variable FTh, the highest averages were presented by the subpopulations 15, 13 (Silvânia) and 12 (Anápolis) (Table 1).

The fruits presented a predominance of 47% for the pyriform format, followed by 34% for the apple format and 19% for the pyramidal form. Using the patterns for the classification of cashew peduncles by the color variable, it was verified that all six colors are present in the sampled subpopulations and twelve of the fifteen subpopulations presented predominance of color 2 (orange red) (Table 1). The subpopulations that presented pseudofruit coloration different from the general average were 7 (Placa) - red color, 13 (Silvânia) - orange color and 15 (Faina) - yellow color.

There were highly significant variations for all the evaluated characters, in all hierarchical levels, Eq. (01): among subpopulations (P_S) – Eq. (2), among matrices within subpopulations ($P_{M/S}$) – Eq. (3) and among fruits within matrices ($P_{F/M}$) – Eq. (4). However, higher levels of variation were found among matrices within subpopulations, with the highest values presented by the TL and PFL. Subsequently, the variability was verified among fruits within matrices, except for the pseudofruit thickness variable, which presented the highest variation at the subpopulation level (Table 2). The variables that presented the highest values for the P_{ST} parameter (divergence among subpopulations – Eq. (5),) were pseudofruit thickness (PFTh) and pseudofruit smaller width (PFSW) (Table 2).

Table 2 – Analysis of variance and quantitative parameters estimates of 15 native subpopulations of *Anacardium othonianum* Rizz

Variable	Parameters estimates						
	$\hat{\sigma}^2_S$	$\hat{\sigma}^2_{M/S}$	$\hat{\sigma}^2_{F/M}$	P_S%	$P_{M/S}$%	$P_{F/M}$%	P_{ST}
TM	821.19***	157.89***	6.94	23.50	52.41	24.09	18.313
PFM	699.97***	131.75***	5.86	23.91	51.92	24.17	18.718
FM	12.6519***	4.7903***	0.2024	10.82	61.88	27.30	8.040
TL	811.22***	422.98***	9.410	7.238	75.57	17.19	4.571
PFL	574.21***	313.25***	8.93	6.336	72.41	21.25	4.192
FL	148.435***	63.605***	2.907	8.794	61.67	29.54	6.656
PFLW	730.41***	110.79***	7.72	25.97	42.33	31.70	23.472
PFSW	676.15***	89.45***	6.97	28.23	39.90	32.87	26.628
PFTh	915.38***	105.51***	7.51	32.31	38.32	29.37	29.658
FLW	67.842***	38.632***	1.820	5.140	63.48	31.38	3.891
FSW	68.218***	21.879***	1.582	11.58	49.69	38.73	10.433
FTh	18.6062***	12.7871***	0.9552	2.701	53.84	43.46	2.448
COLOR	36.941***	6.659***	0.305	24.76	50.85	24.41	19.559

***, Significant F test at 0.01% of probability $\hat{\sigma}^2_S$: variance among subpopulations $\hat{\sigma}^2_{M/S}$: variance among matrices; $\hat{\sigma}^2_{F/M}$: variance among fruits ; P_S% : proportion of the total variance that is due to the variation among fruits; PST: quantitative genetic divergence among subpopulation; TM: total mass; TL: total length; PFL: pseudofruit length; PFlW: pseudofruit larger width; PFSW: pseudofruit smaller width; PFTh: pseudofruit thickness; PFM: pseudofruit mass; FM: fruit mass; FL: fruit length; FLW: fruit larger width; FSW: fruit smaller width; FTh: fruit thickness. Source: the authors (2021)

High and significant correlation levels were observed among the mass and length measurements of the pseudofruit with the total mass and length measurements (Table 3), indicating that the higher the pulp mass (pseudofruit), the higher the total size, or vice versa. In addition to this, the PFLW presented a high and significant correlation with the PFT (0.906), and partially high correlation between the PFLW vs. PFSW (0.826) and PFLW vs. PFM (0.855). As observed in Table 1, the average length and weight of the pseudofruit represent 56.7% and 77.3% of the total length averages and total mass of the samples, explaining the high correlation levels found among the pseudofruit measurements and the total samples measurements for length and mass (Table 3).

The TM also presented moderate correlation levels with the TL variables (0.717) and PFT (0.784). It was also observed partially high correlation among TM vs. PFLW (0.847). The PFM presented average and significant correlation with the other peduncle dimension measurements: PFL (0.723) PFSW (0.702) and PFT (0.797) (Table 3).

Table 3 – Phenotypic correlation among physical variables of 15 native subpopulations of *Anacardium othonianum* Rizz

(To be continued...)

VARIABLE	TM	TL	PFL	PFLW	PFSW	PFTh
TM	-	0.717**	0.716**	0.847**	0.683**	0.784**
TL	-	-	0.905**	0.484**	0.247**	0.350**
PFL	-	-	-	0.542**	0.308**	0.409**
PFLW	-	-	-	-	0.826**	0.906**
PFSW	-	-	-	-	-	0.858**
PFTh	-	-	-	-	-	-
PFM	-	-	-	-	-	-
FM	-	-	-	-	-	-
FL	-	-	-	-	-	-
FLW	-	-	-	-	-	-
FSW	-	-	-	-	-	-
FTh	-	-	-	-	-	-

Table 3 – Phenotypic correlation among physical variables of 15 native subpopulations of *Anacardium othonianum* Rizz

(Conclusion)

VARIABLE	PFM	FM	FL	FLW	FSW	FTh
TM	0.989**	0.570**	0.210**	0.384**	0.382***	0.324**
TL	0.686**	0.548**	0.482**	0.405**	0.385**	0.273**
PFL	0.723**	0.330**	0.066*	0.270**	0.245**	0.213**
PFLW	0.855**	0.378**	-0.004 NS	0.351**	0.346**	0.269**
PFSW	0.702**	0.297**	-0.057*	0.343**	0.362**	0.214**
PFTh	0.797**	0.323**	-0.019 NS	0.318**	0.324**	0.216**
PFM	-	0.445**	0.122**	0.308**	0.318**	0.242**
FM	-	-	0.611**	0.638**	0.559**	0.623**
FL	-	-	-	0.396**	0.403**	0.201**
FLW	-	-	-	-	0.716**	0.477**
FSW	-	-	-	-	-	0.391**
FTh	-	-	-	-	-	-

*,**, Significant at 0.5%, 0.01% of probability. NS Not significant. TM: total mass; TL: total length; PFL: pseudofruit length; PFLW: pseudofruit larger width; PFSW: pseudofruit smaller width; PFTh: pseudofruit thickness; PFM: pseudofruit mass; FM: fruit mass; FL: fruit length; FLW: fruit larger width; FSW: fruit smaller width; FTh: fruit thickness. Source: the authors (2021)

4 DISCUSSION

In two studies conducted with subpopulations of *A. othonianum* in the state of Goiás (Corrêa et al., 2008; Borges, 2012) and one in the city of Teresina – Piauí (Rocha et al., 2013), observed mean total mass values of 11.14 g, 8.99 g and 7.9 g, respectively, lower than the general average found in the present study. The researcher in the previously mentioned study (Borges, 2012) also observed lower averages than the present study for the FM variables (2.21 g) and PFM (8.93 g). The studies with Cerrado's native fruit have demonstrated that the characteristics related to the fruit mass present phenotypic variation amplitudes higher than the other quantitative fruit variables (Moura, Chaves & Naves, 2013; Boaventura-Novaes, 2018; Mota et al., 2020).

As for the characters related to the cashew size, in a study (Borges, 2012) that evaluated 22 shrubby cashew subpopulations from the Cerrado in the state of Goiás, verified general averages for fruit length of 20.84 mm and pseudofruit of 25.40 mm, similar to the present study. A research conducted in the Brazilian Central Plateau (Rizzini, 1969) described fruits with TL lower than the ones reported in this research, between 15 mm and 25 mm.

The phenotypic variations observed for the characteristics related to fruit/pseudofruit mass and size are desirable for the potential commercial exploitation of the species and/or possible genetic improvement programs. The higher the fruit mass, the higher the capacity to generate products that will be used as raw material, besides, knowing the biometric characteristics of the fruits is of extreme importance for the equipment dimensioning used by the industry (Silva & Abud, 2017).

A study conducted with tree cashew from the Piauí Cerrado (Rocha et al., 2013) verified average value for the pseudofruit width of 21.8 mm, similar to the average (per fruit) found in this study for the PFLW. In another study conducted with fruit-bearing plants from the Cerrado (Corrêa et al., 2008), the authors observed fruits with average width of 15.39 mm, slightly higher than the FSW and lower than the FLW reported in the present study.

In a study with a population of early dwarf cashew trees clones (Moura et al., 2001), the authors reported that 44% of the evaluated cashews presented the pyriform format, also predominant in this study. The authors also classified this format as ideal for use in commercial packaging.

A study characterizing pseudofruits of different subpopulations of *A. occidentale* (local) species (Paiva et al., 1998), verified variations among the color patterns red, orange and orange red, and did not report results for the other cashew coloration patterns. The consumer market of the pseudofruit mainly in *natural* form prefers peduncles that present handling resistance, piriform format and orange and red colors (Silva et al., 2014).

Studies on intra and interspecific genetic variability in natural populations of tropical regions prove that the native species present wide intrapopulational variability (Boaventura-Novaes et al., 2018; Mota et al., 2020). In addition, the reproductive system of the species, effective population size, gene flow and geographical distribution (Paiva et al., 1998) also influence the distribution of this variability.

Regarding the genetic structure presented by the shrubby cashew from Cerrado, higher variation levels among matrices within subpopulations were also observed in studies with different fruit species from Cerrado: mangaba (*Hancornia speciosa* Gomes) (Almeida et al., 2019), jatobá-do-Cerrado (*Hymenaea stigonocarpa* Mart. ex Hayne) (Tiago et al., 2018), cagaita (*Eugenia dysenterica* DC.) (Boaventura-Novaes et al., 2018) and with baru (*Dipteryx alata* Vog.) (Mota et al., 2020). For pequi tree (*Caryocar brasiliense* Camb.), the studies (Vera et al., 2007; Moura et al., 2013) found a genetic structure in which the majority of the variability is among subpopulations or regions and subsequently among matrices within subpopulations.

The P_{ST}, Eq. (5), is a parameter that portrays the phenotypic differentiation among the subpopulations, and then, a measure that resembles the Q_{ST}, which measures the quantitative genetic differentiation among the subpopulations (Brommer & Whither, 2011). The estimated P_{ST}, Eq. (5), values did not detect high phenotypic differentiation among the subpopulations, indicating that probably the sampled subpopulations still share genes among the individuals. When studying the genetic diversity in wild populations of the salt marshes ecotype of *A. occidentale* in the coast of Piaui, the authors (Santos et al., 2019) detected strong genetic heterogeneity among the wild populations studied, despite the probable gene flow among them. Therefore, studies with genetic markers that enable a better estimate of genetic divergence among the *A. othonianum* subpopulations, occurring in the mid-west region of Brazil are necessary.

In a study with *A. othonianum*, the author (Borges, 2012) also found positive and highly significant correlation ($p<0.01$) between TM vs. PFM (0.983) and TM vs. PFLW

(0.815). When analyzing fruits and pseudofruits of early dwarf cashew clones, the authors (Pereira et al., 2005) observed high correlation (0.84) between fruit mass and pseudofruit. However, as expected in the present study, there was no correlation between the dimensional and mass measurements of fruits and pseudofruits, that is, pseudofruit length and mass do not influence the same parameters as the fruit, and there may be small and heavy fruits, and large and light pseudofruits. Similar results were obtained by a study with cashew tree (Borges, 2012), which also verified low correlation between the fruit and pseudofruit measurements. The disparity among the results obtained is explained by the fact that, as there was no selection of genotypes and phenotypic markers for the species, once the studies were performed in Cerrado native plants, it was not possible to standardize the results found among fruits and pseudofruit.

5 CONCLUSION

The biometric characteristics of fruits and pseudofruits of shrubby cashew species from Cerrado presented high phenotypic variation among all the evaluated hierarchical levels. As for the species genetic structure, most of the genetic variability is among matrices within subpopulations and among fruits within matrices. The subpopulations presented phenotypic differentiation based on the characteristics: pseudofruit larger width, pseudofruit smaller width and pseudofruit thickness, according to the P_{ST} parameter. The pseudofruit represents 78% of the total mass measure of the fruit, while the pseudofruit length constitutes 57% of the total fruit length. There is a predominance of the red-orange color of the pseudofruit of *A. othonianum* species in the sampled municipalities. The largest correlations were observed among the mass and length measurements of the pseudofruit and mass and total length. There is low correlation between the fruit and pseudofruits mass and size. Future studies should integrate genetic analyses and experiments under controlled cultivation conditions in order to disentangle genetic and environmental effects and to minimize phenotypic variation associated with contrasting environments, such as pasture areas.

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Authorship contributions

1 – Jeniffer Raniely Batista Sousa

Graduated in Agronomy from the Evangelical College of Goianésia
https://orcid.org/0009-0002-0747-3444 • jrbsoussa@gmail.com
Contribution: Conceptualization – Methodology – Investigation – Data Curation – Writing – Review

2 – Igor Richards Lamounier de Faria

Graduated in Agronomy from the Evangelical Faculty of Goianésia
https://orcid.org/0009-0000-5034-7297 • lamounierigor12@gmail.com
Contribution: Investigation – Data Curation – Writing – Review

3 – Elitânia Gomes Xavier

Master's degree in Ecology and Sustainable Production from the Pontifical Catholic University of Goiás
https://orcid.org/0000-0002-7795-6954 • elixavier15@yahoo.com.br
Contribution: Investigation – Data Curation – Review

4 – Luciana Borges e Silva

PhD in Agronomy from the Federal University of Goiás
https://orcid.org/0000-0002-7206-7488 • luciana.silva@ifgoiano.edu.br
Contribution: Investigation – Data Curation – Review

5 – Eli Regina Barboza de Souza

PhD in Agronomy from the Federal University of Goiás
https://orcid.org/0000-0001-6225-6122 • eliregina@ufg.br
Contribution: Investigation – Review

6 – Elias Emanuel Silva Mota

PhD in Genetics and Plant Breeding from the Federal University of Goiás
https://orcid.org/0000-0003-2572-3400 • elias-emanuel@hotmail.com
Contribution: Conceptualization – Methodology – Investigation – Resources – Data Curation – Supervision – Project Administration – Writing

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