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Morphological characterization, genetic divergence and indication of crossings in dragon fruit

Caracterização morfológica, divergência genética e indicação de cruzamentos em pitaya

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Commercial cultivation of dragon fruit in Brazil is recent and, due to the lack of selected matrices, there is wide phenotypic variability, observed in production, size and shape of the fruits and in the physico-chemical traits. The development of varieties adapted to the different agroecosystems, with agronomic potential, will ensure uniformity of production. This research aimed to characterize morphologically 25 dragon fruit genotypes, the estimation of genetic divergence and the indication of biparental crosses. The research was carried out on matrices installed in an active germplasm bank located in Maragogi, Alagoas State, Brazil. The evaluation of cladode variables showed wide phenotypic variability, both in quantitative descriptors, highlighting length, with the formation of nine groups by the Tocher test, with Boreal Red having the highest average (127.0 cm), and in qualitative descriptors, in which the rough texture of the cladode predominated in 68% of the genotypes. In the fruits, the color of the skin and pulp showed six and eight groups of similarity, in which 44 and 68% of the genotypes presented dark pink and reddish/purple colors, respectively. The PCA method revealed that the variables linked to the fruit were the most important for the analysis of genetic divergence, which was of high magnitude, with the formation of seven divergent groups by the UPGMA method, making it possible to indicate the crosses between the genotypes 'Vermelha Colombiana x Boreal Red', 'Golden de Israel x Vietnamese White', 'Makisupa x Boreal Red', allow gains with greater heterosis and superior progenies.
Palavras-chave: *Hylocereus* spp., *Selenicereus* spp., multivariate analysis.

O cultivo comercial da pitaia no Brasil é recente e, devido à carência de matrizes selecionadas, há ampla variabilidade fenotípica, observada na produção, tamanho e formato dos frutos e nas características físico-químicas. O desenvolvimento de variedades adaptadas aos diferentes agroecossistemas, com potencial agronômico, garantirá uniformidade de produção. Portanto, esta pesquisa objetivou a caracterização morfológica de 25 genótipos de pitaya, estimar a divergência genética e indicar cruzamentos biparentais. A pesquisa foi realizada em matrizes instaladas em um banco ativo de germoplasma localizado em Maragogi, Alagoas - Brasil. A avaliação das variáveis do cladódio demonstrou ampla variabilidade fenotípica, tanto nos descritores quantitativos, destacando-se o comprimento, com a formação de nove grupos pelo teste de Tocher, tendo o genótipo Boreal Red a maior média (127,0 cm), quanto nos descritores qualitativos, em que a textura rugosa do cladódio predominou em 68% dos genótipos. Nos frutos, a coloração da casca e da polpa apresentaram seis e oito grupos de similaridade, nos quais 44 e 68% dos genótipos apresentaram coloração rosa escuro e vermelho/roxo, respectivamente. O método PCA revelou que as variáveis ligadas ao fruto foram as mais importantes para a análise da divergência genética, que foi de alta magnitude, com a formação de sete grupos divergentes pelo método UPGMA, permitindo a indicação de cruzamentos entre os genótipos 'Vermelha Colombiana x Boreal Red', 'Golden de Israel x Vietnamese White', 'Makisupa x Boreal Red', possibilitando ganhos com maior heterose e progênies superiores.
Keywords: *Hylocereus* spp., *Selenicereus* spp., análise multivariada.

1. INTRODUCTION

Dragon fruit or pitaya orbelongs to the Cactaceae family and originates from the Americas, where the genus *Hylocereus* spp. and *Selenicereus* spp., composed of 36 species, stand out for having potential for human and animal consumption, and for ornamental purposes [1]. Although commercial cultivation in Brazil is recent, between 2017 and 2021, 330 thousand tons of dragon fruit were exported, with revenue of R$ 1.4 million [2]. The Southeast region of Brazil has the largest number of establishments (45%), with the state of São Paulo standing out, with a production of 586 tons in 186 ha [3].

What makes dragon fruit an attractive species to consumers, in addition to its exotic appearance, is its pulp of different colors: translucent, white, light gray, light pink, medium pink, dark pink, medium red, dark red, and purple; according to Faleiro et al. (2021) [4], which are reflected in its nutritional composition [5]. In addition to the presence of vitamins, proteins, and minerals, it presents bioactive compounds (anthocyanins, betacyanins, betanins, betaxanthins) that act on human health, with antioxidant properties, playing an important role in the areas of anti-inflammatory, cancer resistance, and prevention of vascular and neurodegenerative diseases [6]. According to Widyaningsih et al. (2017) [7], the consumption of dragon fruit juice (500 g/day, for seven days) may increase hemoglobin and erythrocyte levels, and can be used to combat anemia in pregnant women.

Dragon fruit germplasm presents wide genetic variability due to intra and interspecific crosses [8], allowing cultivation in temperate, tropical, subtropical and semiarid climates [9]. Although commercial cultivation are increasing, the use of unselected plants promotes variation in fruit production, fruit size and shape, as well as their physical-chemical characteristics [4], resulting in losses in marketing, both on the part of wholesalers, who tend to reduce the price, and on the part of the consumer, who rejects part of the product displayed for sale [10].

In genetic breeding programs, the characterization of germplasm is of great importance because, with the result, in addition to knowing the potential of each genotype, with the data, it is possible to estimate genetic divergence [11-14] and, from distance matrices (Gower, Euclidean, Mahalanobis), to indicate crosses between more divergent genotypes, aiming at maximum heterosis [15]. With this, it is possible to develop new cultivars that can be adapted to different agroecosystems.

The exchange of genotypes from different regions and countries was an important strategy, which allowed the cultivation of species and the expansion of genetic bases in breeding programs. However, this initiative does not guarantee the adaptation of the genotype to the production sites, which can promote the introduction of exogenous quarantine pests and diseases. Therefore, the development of varieties becomes the best strategy, since it considers, in the selection phase, adapted and productive hybrid progenies, resistant to biotic and abiotic factors, and to the production systems of the regions. Therefore, this research aimed to promote the morphological characterization of 25 dragon fruit genotypes, estimate genetic divergence and indicate biparental crosses.

2. MATERIAL AND METHODS

2.1 Research area

The research was carried out in the 2023/2024 biennium, on private property located in the Bom Jesus agrarian reform settlement, in the municipality of Maragogi, Alagoas State - Brazil, under the geographic coordinates 8° 54’ 0.421” S and 35° 18’ 53.114” W (Figure 1), at an altitude of 107 m (sea level). The climate in the region is type As, hot with rainy winter, according to the Köppen classification, with annual averages of temperature, rainfall and relative humidity of 27ºC, 1,144 mm and 80%, respectively [16].

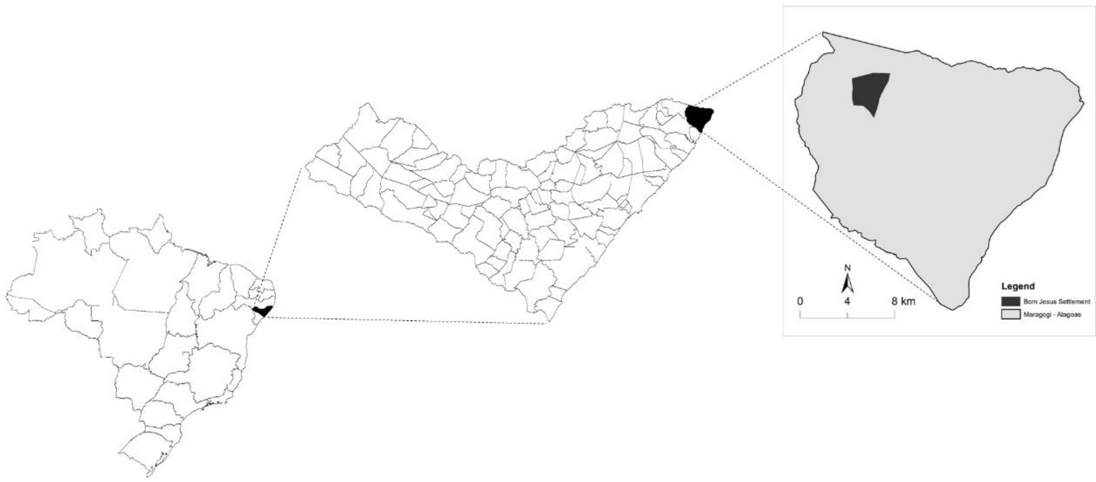

Figure 1. Geographical location of the research area (Bom Jesus settlement, Maragogi, Alagoas State – Brazil).

2.2 Genotypes evaluated

A total of 25 dragon fruit genotypes from seven states of Brazil (Bahia, Pará, Rio de Janeiro, Rio Grande do Norte, Rio Grande do Sul, Rondônia and São Paulo) were being maintained in an active germplasm bank, using the *ex situ* conservation strategy, with plants ranging in age from two to three years. The genotypes were: Almeida White (*Hylocereus* spp.), Boreal Red (*S. monacanthus*), Branca Comum (Common White), Brune (*H. stenopterus* x *H. undantus*), Conar (*Hylocereus* spp.), Condor (*H. guatemalensis*), De Light (*H. undatus* x *H. polyrhizus*), Golden de Israel (*H. undatus*), Makisupa (*H. undatus* x *H. polyrhizus*), Nicaragua (*H. Costaricensis*), Orange do Havaí (*S. megalanthus*), Orejona (*H. polyrhizus*), Pepino Dulce (*Hylocereus* spp.), Pink Panther (*H. purposii*), Physical Graffiti (*H. undatus* x *H. polyrhizus*), R Roxa (*H. costaricensis*), R Roxa 1 (*H. costaricensis*), R Roxa 2 (*H. costaricensis*), Rabilonga (*Hylocereus* spp.), Roxa do Pará (*H. costaricense*), Tiú, Valdívia Roja (*H. ocamponis*), Vermelha Autofértil (*H. polyrhizus*), Vermelha Colombiana (*H. megalanthus* x *H. polyrhizus*) and Vietnamese White (*H. undatus*).

2.3 Management practices

The dragon fruit plants were maintained on trellis-type trellises, with 1.5 m high wooden posts, with wooden support at the top to support the cladodes. The spacing was 3.0 x 3.0 m, with two per post made of sabiá (*Mimosa caesalpiniaefolia* Benth.). Fertilization was organic, with the use of cattle manure and irrigations carried out by micro-sprinkler, when necessary. There was no incidence of pests or diseases and weed control between the rows was carried out with the aid of a manual mower. The canopy area was kept covered with Soiltain® DW geosynthetic blanket, with dimensions of 1.20 x 1.20 m, to control weeds and maintain soil moisture [17]. Between April and September, the plants were kept under artificial lighting for flowering induction, using warm-white led reflector (100w), installed at 3.0 m height, reaching 10 to 15 plants/reflector, with lights on at 22:00 pm and off at 02:00 am.

2.4 Variables analyzed

Nineteen morphological descriptors of dragon fruit were evaluated, both qualitative (grade scale) and quantitative, of which nine were related to the cladodes [length and width, distance between areoles, arch height (cm), number of areole spines, surface texture (1 – smooth; 2 – medium; 3 – rough), rib margin (1 – concave, 2 – flat, 3 – convex), gray color of the areoles (1 – light, 2 – medium, 3 – dark), reddish color of the cladode (1 – absent or weak, 2 – medium, 3 – strong) and number of spines per areole] and 10 of the fruits [peel color, apical cavity (1 – absent or shallow, 2 – medium, 3 – deep), fruit length and width (cm), soluble solids (ºBrix), peel thickness (mm), pulp color, peel and pulp weight (g), pulp yield (%), number of bracts and presence of thorns (1 – absent, 2 – present)], following the recommendations of Faleiro et al. (2021) [4].

The colors of the peel and pulp were evaluated according to the Munsell Color System [18]. The variables related to the cladodes were obtained from two plants, and the quantitative variables were obtained with the aid of a digital caliper. Those related to the fruits were obtained from five units/plant, using a digital caliper, digital scale and refractometer.

2.5 Data analysis

In the data analysis, considering the qualitative variables, descriptive statistics were used. In the quantitative variables, the Tocher univariate clustering test was applied, using the euclidean distance, in which the intergroup distance limit (IDL) considered the maximum value of the dissimilarity measure found in the set of smallest distances involving each genotype [19], using the Genes software, version 1990.2022.23 [20].

To estimate genetic divergence, the principal components analysis (PCA) was applied, using orthogonal rotation (Varimax), adopting the Kaiser criterion [21] to indicate the number of components (eigenvalues greater than unity). Quantitative variables that had a correlation with the components lower than ‘r = < |0.70|’, as well as relative importance lower than 10% [22] were removed from the database and a new analysis was conducted [19].

From the dissimilarity matrix, through the standardized euclidean distance, the genotypes were grouped using the UPGMA method, adopting the Frey criterion to estimate the number of groups. The cophenetic correlation coefficient (CCC) was calculated to assess the robustness of the grouping, applying the Mantel test at 5% probability. For these analyses was used the *MultivariateAnalysis* package, version 0.4.4 [23], of the R software, version 3.5.2 [24].

3. RESULTS AND DISCUSSION

3.1 Cladode traits

Variation was observed in the morphological traits of the cladodes among the dragon fruit genotypes (Table 1). The quantitative descriptors presented a high coefficient of variation, reaching 57.0% for arch height, which, according to Cavalcante and Costa (2021) [25], may be an indicator of the existence of genetic variability in genotypes, indicating the possibility of selection.

The length of the cladode showed the formation of nine similarity groups, with the Boreal Red genotype standing out with the highest average, followed by the Branca Comum, Vermelha Colombiana, Brune and Golden de Israel, respectively, classified as having a very long cladode, according to Faleiro et al. (2021) [4]. The cladode width showed the formation of four groups, in which the Rabilonga and Roxa do Pará genotypes presented the lowest and highest average, being classified as narrow and very wide, respectively [4]. These are important descriptors, used in the selection of cuttings for the formation of seedlings, as they are directly linked to the percentage of rooting and the development of the seedlings [26].

The Physical Graffiti, Vermelha Colombiana and Vietnamese White genotypes presented the largest distance between areoles and Orejona and Tiú, the smallest (Table 1), being classified as short and medium-long, respectively [4]. The smaller the distance, the greater the number of axillary buds, promoting a greater number of shoots, important for the formation of the canopy. According to Marques et al. (2011) [27], cladodes between 15 and 25 cm are the most recommended for seedling production. Therefore, the genotypes with the largest and smallest distances would have, on average, 9.6 and 4.5 buds (cuttings with 25 cm).

Table 1. Morphological traits of cladodes of 25 dragon fruit genotypes.

Genotypes	CL (cm)	CW (cm)	DBA (cm)	AH (cm)	NSA	ST	RM	GCA	RCC
Almeida White	55.0 g	6.6 b	3.9 c	0.9 b	1 e	3	3	3	2
Boreal Red	127.0 a	5.1 c	5.0 b	0.4 c	2 d	2	3	1	1
Branca Comum	120.0 b	6.8 b	5.2 b	0.1 c	2 d	2	3	1	1
Brune	106.5 c	6.0 b	4.8 b	0.8 b	1 e	2	3	2	1
Conar	60.3 g	5.1 c	3.3 d	0.5 c	5 a	2	3	2	2
Condor	91.1 d	6.7 b	5.2 b	0.9 b	2 d	3	3	2	2
De Light	48.0 g	5.6 b	4.3 c	0.4 c	2 d	3	3	2	1
Golden de Israel	106.0 c	6.6 b	4.7 b	0.4 c	2 d	3	3	3	1
Makisupa	83.9 d	3.8 c	4.1 c	0.5 c	2 d	2	3	1	1
Nicarágua	58.2 g	4.4 c	3.7 d	0.5 c	4 a	3	2	2	1
Orange Havaí	95.0 d	4.3 c	4.6 b	0.5 c	2 d	3	3	3	1
Orejona	53.0 g	5.9 b	2.6 e	0.1 c	3 c	1	3	3	2
Pepino Dulce	41.6 g	6.6 b	4.7 b	0.7 b	2 d	3	3	2	1
Pink Panther	49.2 g	5.5 c	3.2 d	0.3 c	4 b	3	3	1	2
Physical Graffiti	96.0 d	5.8 b	5.4 a	0.7 b	1 e	3	3	2	2
R Roxa	66.0 f	4.2 c	3.5 d	0.3 c	1 e	3	3	2	1
R Roxa 1	37.0 h	3.7 c	3.5 d	0.3 c	3 c	3	3	2	1
R Roxa 2	60.0 g	6.2 b	4.2 c	0.6 b	5 a	3	3	2	2
Rabilonga	68.0 f	2.9 d	3.6 d	0.3 c	3 c	3	3	2	3
Roxa do Pará	99.0 c	9.5 a	4.9 b	1.5 a	2 d	3	3	3	1
Tiú	75.5 e	4.3 c	3.0 e	0.6 b	2 d	2	1	1	1
Valdívia Roja	89.0 d	6.7 b	4.9 b	0.7 b	3 c	3	3	3	2
Vermelha Autofértil	93.0 d	4.8 c	4.7 b	0.5 c	4 b	3	2	2	1
Vermelha Colombiana	115.0 b	7.5 b	5.4 a	0.2 c	4 b	3	2	2	3
Vietnamese White	83.0 d	6.6 b	5.5 a	1.0 b	4 b	2	3	1	1
IDL	7.5	2.0	0.4	0.5	1.0	--	--	--	--
Mean	78.9	5.6	4.3	0.6	3.2	--	--	--	--
CV (%)	32.7	25.4	19.3	57.0	32.5	--	--	--	--
Mode	--	--	--	--	--	3	3	2	1

CL: cladode length; CW: cladode width; DBA: distance between areoles; AH: arch height; NSA: number of spines on the areole (1: < 3 units = low; 2: 3 to 4 units = medium; 3: >4 units = high); ST: surface texture (1: smooth; 2: medium; 3: rough); RM: rib margin (1: concave; 2: flat; 3: convex); GCA, gray color of the areoles (1: light; 2: medium; 3: high); RCC: reddish color of the cladode (1: absent; 2: medium; 3: strong). IDL: intergroup distance limit. Means followed by the same letter in the column belong to the same group by Tocher's clustering test. CV: coefficient of variation.

Three similarity groups were formed for arch height, with the highest average for the Roxa do Pará genotype (Table 1), classified as tall [4]. The high magnitude coefficient of variation indicates that this is a variable that presents wide phenotypic variability. The number of spines in the areole varied from 1 to 5 units, with the highest average for the Conar and R Roxa 1 genotypes, being a characteristic of interest in breeding programs, as it is associated with cases of accidents during handling, mainly during pruning and harvesting.

The genotypes evaluated presented all classes for the cladode surface texture, with a predominance of the rough (68.0%) and medium (28.0%) classes. The convex shape of the rib margin predominated in 84.0% of the genotypes. The gray color of the areoles varied from light gray (24.0%), medium (52.0%) and dark gray (24.0%), in which 60.0% of the genotypes presented an absence of reddish color in the cladodes. The formation of different similarity groups by the Tocher method for the cladode descriptors highlights the presence of phenotypic variability among the 25 dragon fruit genotypes, making it possible to indicate crosses and select superior genotypes.

3.2 Fruit traits

Six different types of fruit peel color were observed, with a predominance of dark pink in 44.0% of the genotypes (Table 2), which is a characteristic considered by consumers when purchasing [28]. However, as dragon fruit germplasm is formed by little-known species, consumers are still unfamiliar with fruits with yellow and orange colors, which could become a differentiator in marketing.

Table 2. Morphological descriptors external to fruits of 25 dragon fruits genotypes.

Genotypes	PC	AC	FL (cm)	FW (cm)	NB	PE
Almeida White	10 RP 5.9/14.0	3	11.3 b	8.4 b	24 b	1
Boreal Red	3.0 R 3.9/13.0	1	11.0 b	8.9 b	24 b	1
Branca Comum	10 RP 5.9/14.0	3	12.6 b	9.2 b	22 b	1
Brune	1.0 GY 9.7/11.4	3	9.1 c	6.0 d	15 b	1
Conar	7.0 R 5.0/16.4	2	12.1 b	8.9 b	12 b	1
Condor	3.0 R 3.9/13.0	3	10.2 c	9.2 b	13 b	1
De Light	3.0 R 3.9/13.0	3	12.1 b	9.0 b	15 b	1
Golden de Israel	1.0 GY 9.7/11.4	3	14.0 a	7.4 c	17 b	1
Makisupa	3.0 R 3.9/13.0	1	11.1 b	7.0 c	28 b	1
Nicaragua	7.0 R 5.0/16.4	2	12.4 b	8.1 b	12 b	1
Orange Havaí	3.0 YR 6.6/14.8	3	10.1 c	6.4 c	22 b	1
Orejona	3.0 R 3.9/13.0	1	11.5 b	9.4 b	38 a	1
Pepino Dulce	10 RP 5.9/14.0	3	13.0 b	10.0 b	14 b	1
Pink Panther	1.0 R 3.4/9.0	3	11.7 b	7.4 c	11 b	1
Physical Graffiti	10 RP 5.9/14.0	1	13.2 b	9.7 b	18 b	1
R Roxa	10 RP 5.9/14.0	2	8.6 c	7.4 c	31 a	1
R Roxa 1	3.0 R 3.9/13.0	3	10.1 c	7.9 b	16 b	1
R Roxa 2	3.0 R 3.9/13.0	2	11.9 b	8.1 b	13 b	1
Rabilonga	3.0 R 3.9/13.0	3	11.7 b	8.2 b	14 b	1
Roxa do Pará	10 RP 5.9/14.0	1	9.7 c	9.5 b	14 b	1
Tiú	1.0 R 3.4/9.0	2	7.0 d	5.9 d	0 c	2
Valdívia Roja	10 RP 5.9/14.0	1	13.3 b	7.6 c	10 b	1
Vermelha Autofértil	3.0 R 3.9/13.0	3	12.2 b	8.7 b	14 b	1
Vermelha Colombiana	3.0 R 3.9/13.0	3	9.4 c	7.3 c	16 b	1
Vietnamese White	3.0 R 3.9/13.0	3	14.9 a	11.2 a	14 b	1
IDL	--	--	1.6	1.2	10.0	--
Mean	--	--	11.4	8.3	17.1	--
CV (%)	--	--	15.8	15.5	44.4	--
Mode	3.0 R 3.9/13.0	3	--	--	--	1

PC: peel color; AC: apical cavity (1: absent; 2: medium; 3: deep); FL: fruit length; FW: fruit width; PF: fruit weight; NB: number of bracts; PE: presence of thorns (1: absence; 2: presence). IDL: intergroup distance limit. Means followed by the same letter in the column belong to the same group by Tocher's clustering test. CV: coefficient of variation.

The apical cavity is a characteristic that can cause cracks in the fruits, which are discarded for commercialization, causing the producer to anticipate the harvest or increase costs with the application of gibberellic acid, which promotes fruit growth and firmness [29], reducing cracking. Among the genotypes evaluated, there was a predominance of deep cavity in 56% of the genotypes (Table 2). However, genotypes with the absence of this descriptor were observed (Boreal Red, Makisupa, Orejona, Physical Graffiti, Roxa do Pará and Valdívia Roja), allowing the incorporation of this characteristic in the development of new cultivars.

Fruit length and width are characteristics considered by consumers, with those measuring less than 8.0 and 5.0 cm, respectively, being rejected and discarded for commercialization [30]. These variables are important characteristics that are positively correlated with fruit weight [31], being decisive for commercial yield. Four similarity groups were formed for length, with the Golden de Israel/Vietnamese White and Tiú genotypes standing out with the highest and lowest averages (Table 2), classified as very long and short, respectively [4]. All genotypes presented the minimum diameter for commercialization [30], with the Vietnamese White genotype standing out with the highest average, classified as wide. The Tiú genotype presented fruits with a smaller diameter, classified as narrow [4].

Bracts are leaf structures present in the peel that give the fruit an exotic appearance [32], highlighting the genotypes Orejona and R Roxa with the highest number, classified as high [4]. On the other hand, the genotype Tiú, in addition to not presenting this characteristic, among the genotypes evaluated, was the only one that presented thorns on the fruits, being an undesirable characteristic, as it requires care at the time of harvest.

Soluble solids are reflected in the sweetness level of the fruit, because they are related to total sugar content [33]. In the dragon fruit genotypes, two similarity groups were formed for this characteristic (Table 3), in which the Makisupa genotype presented low concentration (between 10 and 12º Brix) and the others, medium (14 to 16º Brix), according to Faleiro et al. (2021) [4], being indicated for the production of fermented beverages [34], considering that Naoto et al. (2014) [35] produced beer containing red and white dragon fruit as an adjunct, with soluble solids concentration of 13.5 and 14.9º Brix, respectively.

Table 3. Morphological descriptors internal to fruits of 25 dragon fruits genotypes.

Genotypes	**SS (°Brix)**	**PT (mm)**	**PC**	**FPW (g)**	**PW (g)**	**PY (%)**
Almeida White	15 a	2.07 d	N 8.5	77.0 b	347.7 b	80.8 b
Boreal Red	14 a	2.75 c	8.0 R 4.5/17.5	86.0 b	357.0 b	80.1 b
Branca Comum	14 a	2.87 c	N 0.0	104.0 b	431.3 b	79.8 b
Brune	15 a	3.10 c	N 8.5	62.0 b	150.0 b	62.7 h
Conar	14 a	2.21 d	6.0 RP 4.9/17.6	83.0 b	297.0 b	72.1 e
Condor	17 a	3.18 c	4.0 RP 3.4/11.6	112.0 b	574.0 b	80.5 b
De Light	16 a	1.90 d	N 8.5	98.0 b	477.7 b	78.3 c
Golden de Israel	15 a	3.70 b	N 8.5	88.0 b	305.3 b	73.7 d
Makisupa	11 b	4.20 b	5.0 R 1.3/4.8	72.0 b	259.7 b	71.7 e
Nicaragua	17 a	2.54 c	8.0 R 4.5/17.5	98.0 b	271.0 b	63.8 h
Orange Havaí	15 a	1.48 d	4.0 RP 3.4/11.6	67.0 b	229.0 b	70.7 e
Orejona	15 a	1.61 d	8.0 R 4.5/17.5	94.0 b	398.0 b	81.7 a
Pepino Dulce	15 a	2.75 c	N 8.5	105.3 b	317.4 b	66.8 f
Pink Panther	15 a	1.90 d	4.0 RP 3.4/11.6	87.0 b	248.0 b	64.9 g
Physical Graffiti	16 a	4.40 a	6.0 RP 4.9/17.6	108.0 b	554.0 b	80.0 b
R Roxa	15 a	3.58 b	3.0 R 3.0/10.1	82.0 b	242.0 b	65.8 g
R Roxa 1	16 a	3.25 c	3.0 R 3.0/10.1	99.0 b	342.0 b	71.1 e
R Roxa 2	14 a	2.51 c	3.0 R 3.0/10.1	77.0 b	344.9 b	77.7 c
Rabilonga	16 a	3.11 c	5.0 R 1.3/4.8	109.2 b	491.4 b	77.8 c
Roxa do Pará	15 a	1.77 d	4.0 RP 3.4/11.6	74.0 b	310.3 b	82.2 a
Tiú	14 a	0.92 e	N 8.5	26.0 b	121.0 b	78.3 c
Valdívia Roja	18 a	3.01 c	8.0 R 4.5/17.5	112.0 b	392.0 b	71.4 e
Vermelha Autofértil	14 a	2.29 d	7.0 R 3.5/12.1	98.0 b	453.0 b	78.4 c
Vermelha Colombiana	16 a	2.13 d	5.0 R 1.3/4.8	66.0 b	264.7 b	73.4 d
Vietnamese White	15 a	3.27 c	N 8.5	200.0 a	628.7 a	78.1 c
IDL	3.0	0.56	--	88.0	253.0	1.1
Mean	15.1	2.7	--	91.4	288.9	74.5
CV (%)	8.9	31.9	--	32.7	48.1	7.1
Mode	--	--	N 8.5	--	--	--

SS: soluble solids; PT: peel thickness; PC: pulp color; FPW: peel weight; PW: pulp weight; PY: pulp yield. IDL: intergroup distance limit. Means followed by the same letter in the column belong to the same group by Tocher's clustering test. CV: coefficient of variation.

The thickness of the fruit peel, despite reducing pulp yield, is decisive in reducing injuries and maintaining quality during the harvest and post-harvest stages [36]. Although the Physical Graffiti genotype presented the highest average (Table 2), together with Makisupa genotype, it presented peel thickness classified as thick (> 4.0 mm), with a predominance of thin thickness (< 3.0 mm) in 60% of the genotypes [4], being more susceptible to physical damage. On the other hand, the chemical composition and the presence of bioactive compounds make it possible to incorporate the peel in the formulation of functional foods [37]. According to Khoo et al. (2022) [38], the levels of total betacyanins and total anthocyanins in the red dragon fruit peel were higher than in the pulp extract, reducing oxidative stress, considered an alternate source of nutraceutical.

The color of dragon fruit pulp is one of the characteristics considered by consumers, especially types with reddish/purple pigmentation, rich in antioxidant compounds [39]. Among the genotypes evaluated, there were eight types of colors, with a higher frequency of light gray (28.0%). However, 68.0% of the genotypes presented pulp with reddish/purple tones, which indicates high concentrations of anthocyanins and betalains, bioactive compounds that may help human health, also as a nutraceutical alternative [7]. Therefore, they may be used by the pharmaceutical and food industries as a functional ingredient [40].

Two similarity groups were formed for the weight of the fruit peel and the weight of the pulp. The Vietnamese White genotype stood out with the largest masses, forming an isolated group. The genotypes in group 2 did not present a statistical difference between them (Table 2). The pulp yield above 70% is considered of high magnitude [41], being observed in 80.0% of the genotypes, with Roxa do Pará and Orejona standing out, with the highest averages, indicating that they are types of interest to the consumer and the processing industry.

3.3 Genetic divergence and indication of crosses

The principal component analysis, based on biometric traits, revealed that the accumulated variation in the first two components accounted for 49.44% of the total variation, resulting from the linear combination of all variables (Table 4). However, when analyzing the correlations of the variables with the components, as well as the relative importance of the traits, only four variables were used, in which the accumulated variation increased to 87.57% (Figure 2). According to Cruz et al. (2020) [15], genetic divergence studies based on multivariate analysis are possible and acceptable when the sum of the variation in the components exceeds 80%, that is, it can be concluded that there is genetic variability among the 25 dragon fruit genotypes.

Table 4. Eigenvalues, variance and correlation coefficient (r) between 14 original variables (cladodes and fruits) and the relative importance of the characters of 25 dragon fruit genotypes.

Parameters	Principal component (PC)		Relative importance (%)
	PC1	PC2	
Eigenvalues (λ)	5.23	2.19	--
Variance (%)	34.87	14.56	--
Cumulative variance (%)	34.87	49.44	--
Cladodes (r)			
Length	0.28	-0.33	6.18
Width	0.54	-0.57	3.24
Distance between areoles	0.68	-0.24	3.45
Arch height	0.35	-0.56	5.31
Number of spines per areole	-0.07	-0.29	3.34
Fruit (r)			
Length	**0.71**	0.31	**10.24**
Width	**0.82**	-0.02	**12.02**
Peel thickness	0.20	-0.01	5.41
Soluble solids	0.43	0.56	3.16
Peel weight	**0.80**	0.27	**12.89**
Pulp weight	**0.74**	-0.12	**14.38**
Pulp yield	0.41	-0.49	8.79
Number of bracts	0.16	0.50	7.18
Number of thorns	0.55	0.54	4.41

In **bold**, variables selected for a new analysis by PCA method.

The variables that met the criterion described by Regazzi and Cruz (2020) [19], $|r > 0.70|$, were fruit length and width, peel and pulp weight (Table 4), all positively correlated between themselves (see vectors in Figure 2) and with the first principal component, indicating that these were the most important in the study of genetic divergence being, the rest, discardable. These results were corroborated by the relative importance method proposed by Singh (1981) [22]. Similar results were obtained by Morillo-Coronado et al. (2021) [8] and Santos-Pelaez et al. (2024) [13], with the same variables in importance.

Genotype 25 (Vietnamese White) presented the highest peel weight, pulp weight and fruit width (Figure 2). Genotype 20 (Roxa do Pará) presented the largest cladodes. Regarding the variables analyzed, the genotypes close to the origin (1 - Almeida White, 2 - Boreal Red, 3 - Branca Comum, 6 - Condor, 7 - De Light, 12 - Orejona, 13 - Pepino Dulce and 15 - Physical Graffiti) presented values around the general average. On the other hand, all genotypes in quadrants 1 and 4 (Q1 and Q4), highlighting 21 (Tiú), presented the lowest averages, considering the evaluated descriptors.

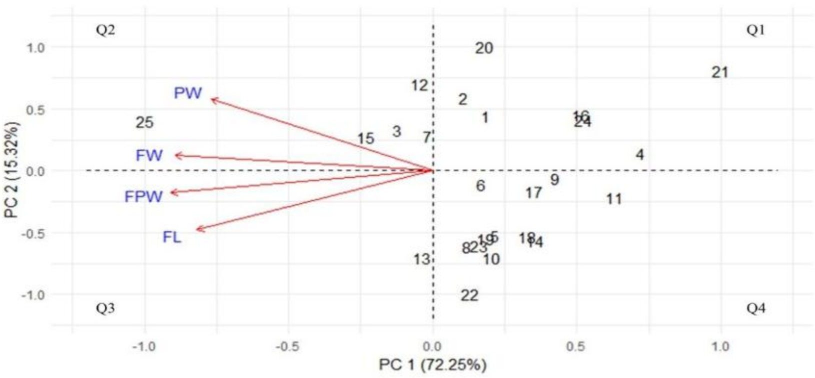

Figure 2. Biplot of the first two principal components and contribution of biometric traits of 25 dragon fruit genotypes. FL: fruit length; FW: fruit width; FPW: fruit peel weight; PW: pulp weight. Q1, Q2, Q3 and Q4: quadrants.

Using the UPGMA method, seven divergent groups were formed (Figure 3), with group G7 standing out, with 11 genotypes that gathered similar characteristics. The cophenetic correlation coefficient was CCC = 0.82**, indicating robustness of the method in forming the groups. The largest euclidean distance (genetic) was observed between Tiú x Vietnamese White (10.28); the smallest distance, between Orange do Havaí x Orejona (1.63), with maximum similarity, which may indicate the existence of duplicates or genotypes with a high degree of kinship. The greater the distance between the genotypes, the greater the hybrid vigor (heterosis) carried out by breeding programs [42].

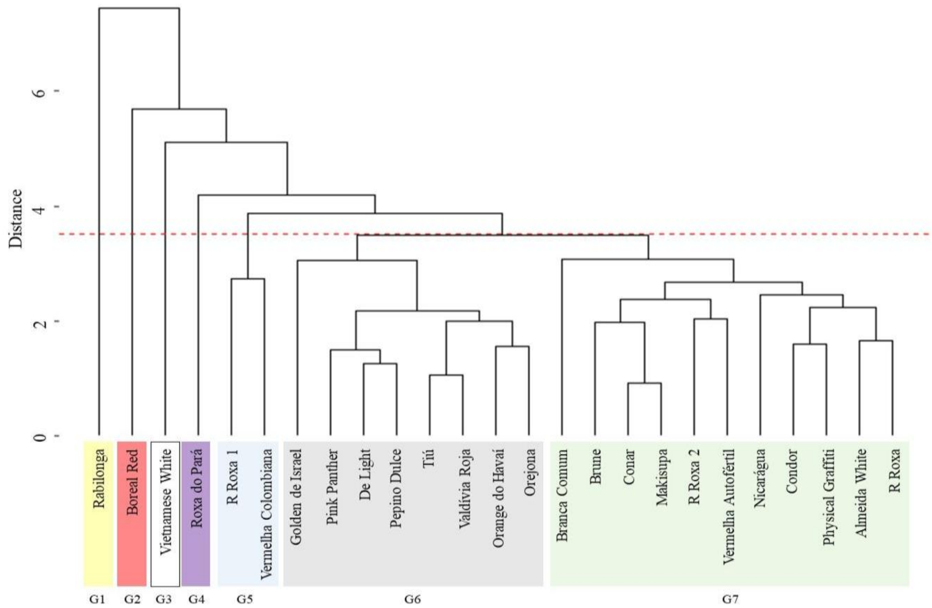

Figure 3. Grouping of 25 dragon fruit genotypes by the UPGMA method. G1 to G7: similarity groups.

Considering not only the euclidean distance, but also the agromorphological characteristics of the genotypes, some biparental crosses are proposed, as described in Table 4, in which each genotype will be a male (pollen donor) and female (pollen receptor) parent at the same time. This allows for gains with greater heterosis and superior progenies.

Table 4. Characteristics of the parents, criteria for crossing and ideotype of dragon fruit hybrids.

Male/female parent	Female/male parent	Criterion/ideotype
Vermelha Colombiana (*H. megalanthus* x *H. polyrhizus*): **Traits**: red color of the pulp, pink color of the fruit peel, susceptible to induction of flowering (artificial light at night), precocity in production, high production, high sprouting of cladodes after thinning pruning, cladode length (115 cm), soluble solids (16º Brix), pulp weight (264.7 g).	**Boreal Red** (*S. monacanthus*): **Traits**: pink color of the pulp, pink color of the fruit peel, susceptible to sun cracking, cladode length (127 cm), soluble solids (14º Brix), pulp weight (357 g).	Criteria: **1. Euclidean distance**: 7.80 **2. Ideotype**: plants with long cladodes, susceptible to early floral induction, high sweetness and pulp yield, with tolerance to cracking of the cladode by the sun and high budding intensity in thinning pruning.
Golden de Israel (*Hylocereus* sp.): **Traits**: white pulp color, pink fruit peel color, disease tolerant, large fruits, susceptible to cracking of cladodes (106 cm) by the sun and floral induction, high sweetness (15º Brix), pulp yield (305.3 g), many cladodes after thinning pruning.	**Vietnamense White** (*H. undatus*): **Traits**: white color of the pulp, yellow color of the fruit peel, high pulp yield (628.7 g), good production, short cladodes (83 cm), low response to floral induction, few cladodes after thinning pruning.	Criteria: **1. Euclidean distance**: 6.21 **2. Ideotype**: pink peel and white pulp, with high sweetness and pulp yield, with long cladodes, susceptible to floral induction and many cladodes after thinning pruning.
Makisupa (*H. undatus* x *H. polyrhizus*): **Traits**: purple color of the pulp (high concentration of anthocyanins), pink peel of the fruit, small cladodes (83 cm), low pulp yield (259.7 g), low sweetness (11º Brix), susceptible to floral induction and not very sensitive to the sun.	**Boreal Red** (*H. costaricensis*): **Traits**: pink color of the pulp, pink color of the fruit peel, susceptible to sun cracking, cladode length (127 cm), soluble solids (14º Brix), pulp weight (357 g), susceptible to floral induction, with problems of cracking in the cladodes due to the sun.	Criteria: **1. Euclidean distance**: 7.75 **2. Ideotype**: purple color of the pulp, with high sweetness and pulp yield, with long cladodes, susceptible to floral induction and insensitive to the sun.

Morphological characterization is an important tool in breeding programs. In this research, it allowed the description of 25 dragon fruit genotypes, highlighting their potential and allowed to estimate the genetic divergence, which was of high magnitude. With the results, it was possible to indicate crosses, aiming at the exploration of maximum heterosis in the hybrids.

4. CONCLUSIONS

The morphological descriptors of the cladodes and fruits of 25 dragon fruit genotypes showed the existence of phenotypic variability, as well as the presence of genetic divergence, with the formation of seven diversity groups, allowing the indication of the biparental crosses ‘Vermelha Colombiana x Boreal Red’, ‘Golden de Israel x Vietnamese White’, ‘Makisupa x Boreal Red’.

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