

Article

Analysis of Agronomic and Genetic Components of Conilon Clones in an Irrigated Production System in the Central Cerrado

Thiago Paulo da Silva ^{1,*}, Adriano Delly Veiga ¹, Renato Fernando Amabile ¹ , Juaci Malaquias ¹ , Michelle Souza Vilela ², Sônia Maria Costa Celestino ¹, Arlini Rodrigues Fialho ², João Victor Pinheiro Melo ² , and Gustavo Barbosa Cobalchini Santos ²

¹ Embrapa Cerrados, Rodovia BR-020, Km 18, Caixa Postal 08233, Planaltina CEP 73301-970, DF, Brazil; adriano.veiga@embrapa.br (A.D.V.); renato.amabile@embrapa.br (R.F.A.); juaci.malaquias@embrapa.br (J.M.); sonia.celestino@embrapa.br (S.M.C.C.)

² Faculdade de Agronomia e Medicina Veterinária (FAV), Campus Darcy Ribeiro, University of Brasília (UnB), ICC-Sul, Asa Norte, Brasília CEP 70910-900, DF, Brazil; michellevilelaunb@gmail.com (M.S.V.); arlinirf@gmail.com (A.R.F.); joaovictormelo29@gmail.com (J.V.P.M.); gustavocobalchini@gmail.com (G.B.C.S.)

* Correspondence: thiagopaulodasilva@hotmail.com

Abstract

Canephora coffee genotypes developed in other growing regions, with traits of interest such as drought tolerance and high coffee bean yield, need to be introduced and characterized in other locations to check adaptability. The aim of this study was to check the agronomic performance and determine the genetic parameters of the clonal canephora coffee cultivar Marilândia ES 8143, composed by twelve genotypes, developed by the Capixaba Institute of Research, Technical Assistance and Rural Extension (Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural—Incaper), in an irrigated system of the Central Cerrado region of Brazil. The study was conducted in the experimental areas of Embrapa Cerrados at 1050 m altitude in a center pivot irrigation system using a management system with water stress controlled for around 65 days. A randomized block experimental design was used with three replications, and each plot consisted of eight plants. The clones were planted in February 2019 and in 2021 and 2022. Phenotyping was carried out to evaluate the following traits: coffee bean yields, sieve retention percentages, plant height, canopy projection, number of pairs of plagiotropic branches, and frost damage using a scoring scale. Clone 5 stood out in mean value in the two years evaluated for bean yield. Clones 5, 6, 7, 8, and 9 had higher mean values for flat-type coffee beans in both years. Clones 1 and 5 exhibited mean values indicating good vegetative development. Clones 5 and 12 showed no visible symptoms for low air temperatures and frost effects. Highly significant differences were observed among the genotypes for all the morphoagronomic traits evaluated, and high values of heritability, genetic coefficients of variation, and selective accuracy showed conditions favorable to the selection of clones for the agronomic traits analyzed. Clones 1, 2 and 6 have values in lower groups for chlorogenic acids and caffeine, and in higher groups for protein and soluble solids, thus showing greater potential for obtaining quality beverages.

Keywords: *Coffea canephora* Pierre ex Froehner; agronomic performance; frost; heritability; accuracy



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1. Introduction

Coffea canephora is native to the African continent, with lowland tropical forests extending from the west coast to the central region of the continent. It is a species widely adapted to tropical soil and climate conditions with high air temperatures and altitudes below 500 m [1]. In Brazil, *Coffea canephora* Pierre ex Froehner is grown in low-altitude and high-temperature regions in the Brazilian states of Espírito Santo, Rondônia, and Bahia.

Due to its broad genetic variability and good adaptability to high air temperatures, *C. canephora* coffee has potential for cultivation in Cerrado areas. However, this species is considered more susceptible to water stress, which can compromise growth, production, and bean quality. Therefore, the use of irrigation, combined with the adoption of management practices and technologies, is essential to ensure the maintenance of the plants' water balance, enabling greater production stability under these environmental conditions [2].

In the irrigated growing system under Cerrado conditions, yield and quality can be increased due to the climate conditions appropriate for good vegetative and reproductive development of the plants, conditions of high air temperatures, higher levels of sunlight, low relative humidity at harvest time, and the possibility of using a high level of technology with inputs, irrigation, and mechanization [3].

Therefore, a breeding program is required that is directed toward obtaining cultivars adapted to the irrigated growing system, and that has characteristics such as high yield potential, high vigor, low production of defective beans, high water use efficiency, resistance to the attack of the main diseases and pests, such as rust and coffee leaf miner, and plant architecture suitable for mechanized harvest. With the introduction of accessions from partner institutions, it is possible to check adaptability to the edaphic and climatic conditions of the region and select genotypes with traits of interest.

Knowledge of the genetic structures of the species under study is necessary to create a plant breeding strategy aiming at selection of individuals in the most efficient way and at their use in the breeding program [4].

Studies with this species of the Conilon botanical variety have been carried out for many years in traditional coffee growing regions of Espírito Santo, with evaluations and selections of genotypes, generating studies on the genetic parameters [5]. There is potential for use of the species in the central Cerrado region, making it possible for growers to earn income, which has been evaluated and shown in studies with phenotypes for different traits [6]. It is important to note that the Cerrado is a region predominantly occupied by the cultivation of *C. arabica*, and so evaluating the performance of Conilon materials in this area is essential to expand the diversity of production systems, identify adapted genotypes, and offer more resilient alternatives to local conditions.

The aim of the study was to evaluate the agronomic performance and determine the genetic parameters of canephora coffee clones that are components of the cultivar Marilândia ES 8143 under the conditions of the central Cerrado at high altitude in an irrigated growing system.

2. Materials and Methods

2.1. Study Site

The experiment was set up in the Cerrado region of the Central Plateau in February 2019 in the experimental area of Embrapa Cerrados, Planaltina—FD, Brazil, with the geographic coordinates 15°35'30" S and 47°42'30" W. The area is at an altitude of 1050 m, with flat topography, a Dark Red Latosol (Oxisol) soil of clayey texture, and the following particle size composition: clay 500 g kg⁻¹, sand 400 g kg⁻¹, and silt 100 g kg⁻¹. According to the Köppen classification, the climate is Aw type, tropical rainy with dry winter, with a

mean annual rainfall of 1200 mm and a mean temperature of 22 °C. The experiment was established in February 2019.

2.2. Plant Material, Experimental Design, and Irrigation

The clonal cultivar of *Coffea canephora* used was Marilândia ES 8143, composed of 12 compatible clones with higher drought tolerance. Plants were spaced at 3.50×0.5 m, resulting in 5556 plants per hectare (approximately 11,112 stems considering two orthotropic stems per plant). Between rows, *Urochloa decumbens* was cultivated and managed. The experiment followed a randomized block design with three replications, and each plot consisted of eight plants. Data were collected during the 2020/21 and 2021/22 crop years. Irrigation was provided using a center-pivot system, managed through soil water balance with the Cerrado Irrigation Monitoring System [7], with water supplied at five-day intervals whenever necessary.

2.3. Fertilization Management

In the planting year (2019), 300 kg ha^{-1} P_2O_5 and 24.5 g of fritted trace elements (FTE BR 12[®], Nutriplant Indústria e Comércio S/A, Barueri, SP, Brazil) were applied per plant hole, according to the levels of soil analysis. Consequently, P_2O_5 was not supplied in topdressed fertilizer application in the first year after planting and in plant formation (2020) because base fertilization was made at planting. Nitrogen and potassium were topdressed using 200 kg ha^{-1} of the nutrient in four split applications every 40 days.

In the second year after planting (2021), 300 kg ha^{-1} of P_2O_5 was supplied in split application, two-thirds in September and one-third in December, and 400 kg ha^{-1} of nitrogen and potassium, in split application in September, November, January, and March. The micronutrients were supplied with 100 kg ha^{-1} of FTE BR 12[®], applied as topdressing in December. In 2022, the same fertilization protocol was followed.

2.4. Plant Management

Two months after planting, shoots were thinned to maintain two orthotropic stems per plant. Subsequent thinning was carried out regularly to preserve the selected stems. Weed control was performed manually along the planting rows.

2.5. Agronomic Evaluations

The variables evaluated in 2021 and 2022 were:

Plant height—Measured after harvest, from the root collar of the plant to the apical bud of the stem (orthotropic branch), in cm;

Canopy projection—Measured in meters at approximately 1 m above the ground, across the row of plants, taken after harvest, in cm;

Number of plagiotropic branches—Count of all branches in production on all sides of the plant, analysis performed after harvest.

2.6. Statistical Analyses

Simple correlation analysis was performed among the variables of coffee bean yield (BY) in kg ha^{-1} , plant height (Height) in cm, number of pairs of plagiotropic branches (NPP), and canopy projection (CP) in cm, based on the Pearson correlation coefficient, with the aid of the R 3.6.3 (2020) statistical program at the level of 5% probability.

2.7. Frost Damage Evaluation

In 2022, frost occurred in the experimental area on 19 May 2022, injuring the leaves of the plants in the experiment.

Visual observations were made on 20 May 2022, allowing a scale of leaf damage to be created, with scores ranging from 0 to 3, as shown in Table 1.

Table 1. Visual scale of damage caused by frost on the leaves and on the fruit.

Damage Scale	Damage to the Leaves
0	No damage to leaves
1	Less than 20% damage to leaves
2	From 21% to 50% damage on the leaves and little leaf drop
3	Greater than 51% damage on most leaves and accentuated leaf drop

To evaluate and analyze the damage caused by frost, the non-parametric Kruskal–Wallis test was used, transforming numerical values into ranks and clustering them in a single dataset with the aid of the R 3.6.3 (2020) statistical program, over the scores of the scale of damage brought about for each of the 12 genotypes in the three blocks.

2.8. Genetic and Selection Analyses

For analysis of the agronomic data, the genotypes (clones) and the years were considered as sources of variation, using the GENES statistical software [8], and the means were grouped by the Scott–Knott test at 5% probability.

To estimate genetic parameters, combined analysis of variance was performed based on the mean of the variables of the plots in two years of production. To analyze the genetic parameters, the GENES program was used [8], carried out according to the split-plot in time design, involving the individual sources of variation (genotypes and years) and their interaction. Some indices and parameters were estimated using the following formulas:

The index of selective accuracy was calculated using the formula:

$$\hat{r}_{gg} = \sqrt{1 - 1/F}$$

From the predicted genotypic values, gains from selection were estimated by means of the expression:

$GS = h^2 \times ds$, where GS = gain from selection; h^2 = heritability coefficient; and ds = selection differential.

Selection was based on the overall mean (Mo) and on the mean of each clone of the years of 2021 and 2022 for each variable. Thus, the clones were selected with the mean for positive gain from selection and, when necessary, negative gain from selection. The mean of the selected clones was calculated (Ms).

The selection differential (ds) was calculated by:

$$ds = Ms - Mo$$

where:

Ms = mean of the selected clones;

Mo = overall mean.

3. Results

3.1. Analysis of Variance and Genetic Variability

The analysis of variance for data collected in 2021 and 2022 showed significant differences for the genotype $\times$ year interaction for coffee bean yield (BY), number of pairs of plagiotropic branches (NPP), and canopy projection (CP). All evaluated traits presented highly significant differences among genotypes, with coefficients of variation ranging from 4.4% to 21.8% for genotypes and from 3.0% to 18.5% for years (Table 2).

Table 2. Summary of analysis of variance, with mean squares, of the variables of coffee bean yield (BY) in kg ha^{−1}, plant height (Height) in cm, number of pairs of plagiotropic branches (NPP), and canopy projection (CP) in cm, in 2021 and 2022. Embrapa Cerrados, Planaltina—FD, Brazil.

SV	D.F.	BY	Height	NPP	CP
Genotypes	11	7,222,744.3 ***	1532.4 ***	110.78 ***	299.5 ***
Block	2	394,994.5 n.s.	317.4 **	59.01 ***	18.1 n.s.
Error a	22	302,464.1 n.s.	53.1 n.s.	3.83 n.s.	25.1 n.s.
Years	1	24,766,722.0 ***	30,752.0 n.s.	1901.39 ***	3669.4 ***
Genotypes × Years	11	2,424,448.6 ***	152 n.s.	31.69 ***	70.8 *
Error b	24	215,321.1 n.s.	22.2 n.s.	6.21 n.s.	30.9 n.s.
CV Genotypes %		21.8	4.7	4.4	7.2
CV Years %		18.5	3.0	5.6	8.0

***, **, and *, significant at 0.1%, 1%, and 5% probability, respectively, by the F test. DF, degrees of freedom. n.s., not significant. CV, coefficient of variation.

Performance of Clones for Productive and Vegetative Traits

Mean values for yield, plant height, NPP, and CP were presented for both years. In 2021, clone 4 stood out with the highest yield (3966.5 kg ha^{−1}), whereas in 2022, clone 5 showed the highest yield (7102.6 kg ha^{−1}). An average increase in yield was observed from 2021 to 2022 among all clones. Plant height increased for all genotypes between years, with changes in ranking. For NPP and CP, distinct groups were identified across years and clones, indicating variability (Table 3).

Table 3. The variables of coffee bean yield (BY, in kg ha^{−1}), plant height (Height, cm), number of pairs of plagiotropic branches (NPP, numbers), and canopy projection (CP, in cm) in Conilon coffee plants, Marilândia ES 8143 cultivar, as of 2 years of age in 2021 and 2022. Embrapa Cerrados, Planaltina—FD, Brazil.

Clone	BY kg ha ^{−1} 2021	BY kg ha ^{−1} 2022	Height (cm) 2021	Height (cm) 2022	NPP 2021	NPP 2022	CP (cm) 2021	CP (cm) 2022
1	1545.1 cB	2874.0 bA	145.0 aB	197.6 aA	42 aB	53 bA	67.0 aB	91.6 aA
2	1561.3 cB	3463.4 bA	135.8 bB	187.6 bA	42 aB	48 cA	61.0 aA	65.0 cA
3	538.9 dB	1700.9 cA	128.1 bB	153.6 eA	41 aB	56 aA	57.3 bB	75.3 bA
4	3966.5 aA	3777.6 bA	119.0 cB	167.5 dA	36 bB	51 bA	64.0 aB	80.0 aA
5	2927.0 bB	7102.6 aA	153.5 aB	200.6 aA	41 aB	53 bA	72.6 aB	85.6 aA
6	1484.4 cB	3691.4 bA	134.2 bB	187.6 bA	41 aB	57 aA	63.3 aB	81.6 aA
7	2695.4 bA	3295.1 bA	134.3 bB	178.0 cA	35 bB	47 cA	64.6 aA	70.6 bA
8	2108.6 bA	2714.8 bA	132.3 bB	168.0 dA	32 bB	44 cA	62.6 aB	87.6 aA
9	841.2 dA	1397.9 cA	124.3 cB	148.6 eA	43 aA	44 cA	54.3 bB	65.0 cA
10	2448.8 bA	1876.7 cA	134.0 bB	173.0 cA	41 aB	46 cA	63.6 aB	80.6 aA
11	1436.9 cA	1811.1 cA	103.3 dB	136.6 fA	32 bB	38 dA	51.0 bB	63.3 cA
12	1559.6 cB	3486.1 bA	144.0 aB	184.8 bA	41 aB	53 bA	66.3 aA	72.6 bA
Mean	1926.1	3099.3	132.3	173.6	38.9	49.1	62.3	76.5

Mean values followed by the same lowercase letter in the column and uppercase letter in the row do not differ statistically from each other by the Scott–Knott test at 5% probability for each response variable.

In terms of yield, clone 4 was superior to the others in 2021, producing 3966.5 kg ha^{−1}. This clone had also shown superior performance in 2017 at INCAPER experimental fields, with a mean yield of 5825 kg ha^{−1}. Two other groups were formed: the second group included clones 5, 7, 8, and 10, and the third group consisted of clones 2, 6, 11, and 12. The lowest yields were found in clone 3 (538.9 kg ha^{−1}) and clone 9 (841.2 kg ha^{−1}). In 2022, clone 4 was surpassed by clone 5, which yielded 7102.6 kg ha^{−1}, a value higher than that recorded for clone 5 at INCAPER in 2017 (4266 kg ha^{−1}). The Brazilian national mean yield

increased by 7.9% in 2022 compared to 2021, reaching 2808.0 kg ha⁻¹, which is 10.45% lower than the mean yield of the Marilândia ES 8143 cultivar found in this study (3099.3 kg ha⁻¹). Clones 4 and 10 showed a decline in yield in 2022 compared to 2021 without statistical difference, while clone 5 differed statistically between years and was the highest yielding in 2022. Clones 7, 8, 9, 10, and 11 showed no statistical difference in yield between years.

Regarding plant height, clones 1, 5, and 12 were in the superior group in 2021, but in 2022 only clones 1 and 5 stood out with mean heights of 197.6 cm and 200.6 cm, respectively. Clone 12 moved to a secondary group in 2022, and clone 11 consistently had the lowest mean height in both years. All clones grew significantly in height from 2021 to 2022, with clone 5 being the tallest and also the highest yielding in the 2021/2022 crop year. The tallest clones in 2021 were not necessarily the highest yielding.

For the number of pairs of plagiotropic branches (NPP), in 2021 clones 1, 2, 3, 5, 6, 9, 10, and 12 formed a superior group, while clones 4, 7, 8, and 11 had the lowest NPP. In 2022, only clones 3 and 6 stood out with higher NPP values. The highest NPP did not guarantee the highest yields, as clones 9 and 3 had high NPP but low yields, and clone 5 had the highest yield without the highest NPP.

Regarding canopy projection (CP), in 2021, clones 1, 2, 4, 5, 6, 7, 8, 10, and 12 were in the superior group. In 2022, clones 1, 4, 5, 6, 8, and 10 remained in this group. Clones 2, 7, and 12 showed no statistical difference between years for CP.

3.2. Correlations Among Coffee Plant Agronomic Traits

Dispersion among the variables coffee bean yield (BY), plant height (Height), canopy projection (CP), and number of pairs of plagiotropic branches (NPP) was examined, and all correlations were significant. The correlations for BY ranged from 0.3 to 0.6, indicating a moderate linear relationship, with the highest correlation observed between BY and CP. The strongest linear correlations were found between Height and CP ($r = 0.78$) and between Height and NPP ($r = 0.80$), which aligns with expectations among vegetative traits (Figure 1).

Analysis of variance of data obtained in 2021 and 2022 for complementary reproductive traits revealed significant differences among clones for the percentage of flat coffee beans retained in circular mesh sieves numbered 14 to 19, as well as for peaberries retained in oblong mesh sieves numbered 8 to 13, according to the F test. The sources of variation showed significant differences at 0.1%, 1%, and 5% probability levels for both sieve types. These results indicate the presence of genetic variability among clones regarding these sieve classifications, with notable interaction effects between genotypes and years.

3.3. Percentage of Flat Beans and Peaberries in Conilon Coffee Clones over Two Harvests

Table 4 presents the percentage of flat beans retained in sieves numbered 14 to 19 and peaberries retained in sieves numbered 8 to 13 for each genotype during the 2021 and 2022 harvests. The mean percentage of peaberries was 49.6% in 2021 and 50.8% in 2022, values higher than those of flat beans, which were 43.5% in 2021 and 46.35% in 2022. Among the clones, clone 2 showed the highest percentage of flat beans in both years, with approximately 70%, while clone 5 exhibited the highest percentage of peaberries, exceeding 68% in 2021 and 73% in 2022. Statistical analysis using the Scott–Knott test at 5% probability indicated significant differences among clones for these traits. The breeding work that led to the development of the Marilândia ES 8143 cultivar.

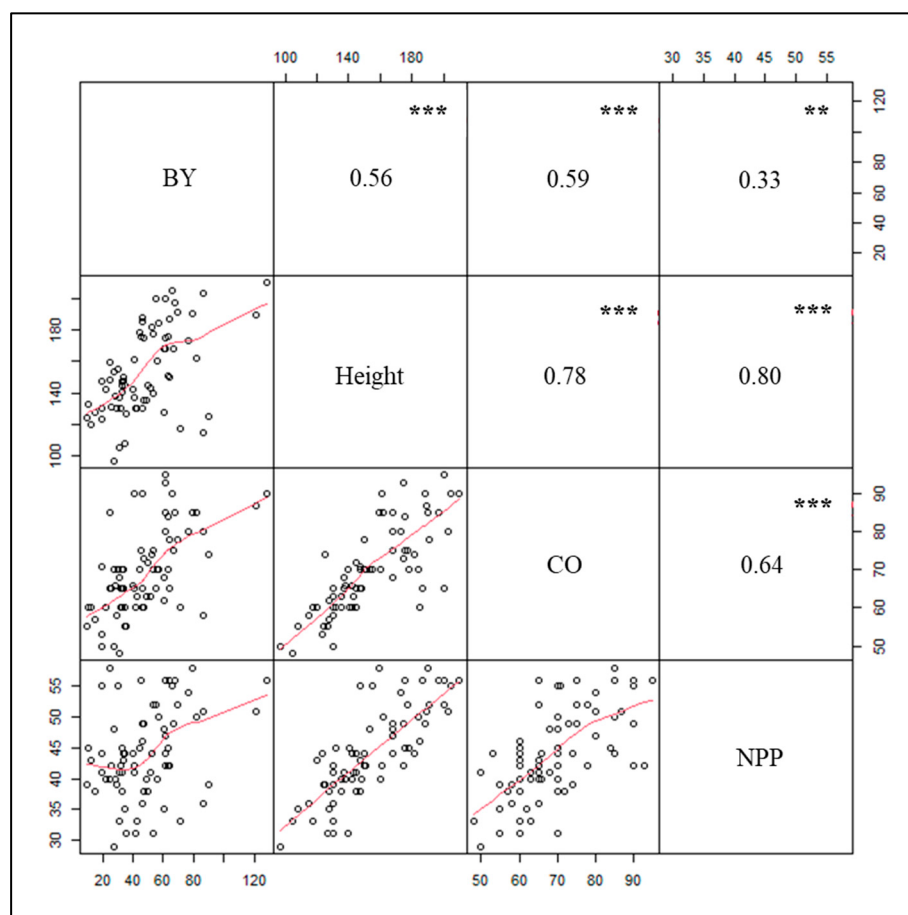


Figure 1. Estimates of Pearson coefficients among the variables of coffee bean yield (BY, in kg ha^{-1}), plant height (Height, cm), canopy projection (CP, in cm), and number of pairs of plagiotropic branches (NPP, number) in Conilon coffee plants, Marilândia ES 8143 cultivar, as of 2 years of age in the years 2021 and 2022 under irrigation. Embrapa Cerrados, Planaltina—FD, Brazil. ***, **, and *—significant at 0.1%, 1%, and 5% probability for the correlation test, respectively.

Table 4. Mean values of flat coffee beans and peaberries in (%), evaluated after harvest of the fruit in Conilon coffee plants, Marilândia ES 8143 cultivar, as of 2 years of age in 2021 and 2022 under irrigation. Embrapa Cerrados, Planaltina—FD, Brazil.

Clone	Flat Beans (%) (2021)	Flat Beans (%) (2022)	Peaberries (%) (2021)	Peaberries (%) (2022)
1	45.2 cA	51.4 bA	41.3 cA	44.2 dA
2	70.6 aA	70.0 aA	27.9 dA	29.4 eA
3	41.4 dA	34.0 dA	44.2 bB	54.7 cA
4	49.5 cB	59.5 aA	48.9 bA	40.0 dB
5	27.8 eA	23.5 eA	68.6 aA	73.9 aA
6	30.2 eA	31.3 dA	66.5 aA	66.9 bA
7	33.3 eA	34.1 dA	64.1 aA	63.9 bA
8	31.6 eB	45.5 cA	63.6 aA	53.2 cB
9	28.2 eA	33.4 dA	64.5 aA	62.5 bA
10	57.9 bA	45.2 cB	39.7 cB	52.5 cA
11	54.7 bB	64.5 aA	37.9 cA	34.3 eA
12	52.6 bB	63.8 aA	28.4 dB	34.9 aA
Mean	43.5	46.35	49.6	50.8

Mean values followed by the same lowercase letter in the column and uppercase letter in the row do not differ statistically from each other by the Scott–Knott test at 5% probability.

The mean percentage of peaberries was 49.6% in 2021 and 50.8% in 2022, both higher than the percentages of flat beans, which were 43.5% in 2021 and 46.35% in 2022. The percentage of peaberries found in this study was considerably higher than previously reported values for the same cultivar. Water deficiency and nutritional deficiency were controlled during the experiment.

3.4. Influence of Climatic Conditions and Genotypic Variability on Peaberry Percentage and Flowering

Factors such as water deficiency and nutritional deficiency were controlled throughout the experiment. The factors that may have led to a higher percentage of peaberries were genetic abnormality and maximum air temperature.

The flowering of the plants evaluated in this study was concentrated around 11–12 September for both years, following controlled water stress. Maximum air temperatures reached 34 °C on the days corresponding to flowering in 2021 and 2022 (Figure 2). In September, maximum temperatures peaked at 37 °C on 21 September 2021, and 35 °C on 14 September 2022. During this period, minimum relative humidity was very low, reaching 12.8% in 2021 and 13.4% in 2022, coinciding with the flowering time (Figure 2).

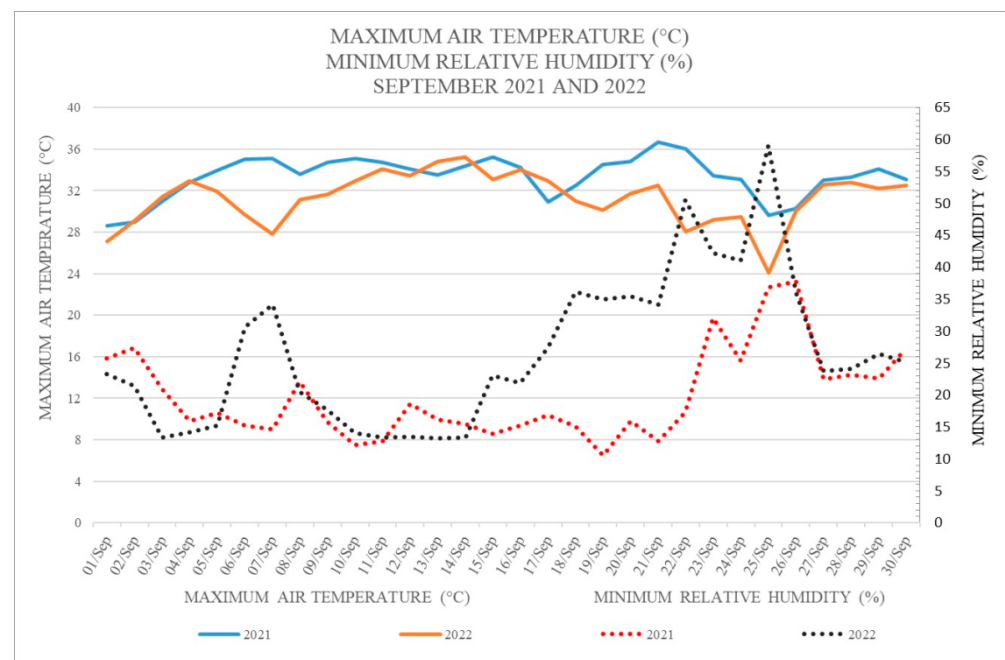


Figure 2. Maximum air temperatures (°C) in September during the evaluations. Minimum relative humidity (%) in September 2021 and 2022 during the evaluations, Embrapa Cerrados, Planaltina—FD, Brazil. Embrapa Cerrados, Planaltina, DF, Brazil, 2021 and 2022.

In 2021, clone 2 stood out from the others in the flat bean variable, showing the lowest mean percentage of peaberries. The same pattern was observed in 2022, where clone 2 had 70% flat beans and 29.4% peaberries. Comparison between 2022 and 2021 showed changes in the ranking of flat bean percentages; the superior group in 2022 included clones 4, 11, and 12, while the lowest group consisted only of clone 5, with 23.5%.

Clone 5 did not differ statistically between years for these variables. For the peaberry variable, clone 5 had the highest mean value in both years, achieving the highest yield in 2022 at 7120 kg ha⁻¹ and the second highest yield in 2021 at 2927 kg ha⁻¹.

In 2022, abnormal climate conditions occurred in May, with very low minimum air temperatures preceded by rainfall, leading to frost damage responses in the genotypes (Figure 3).

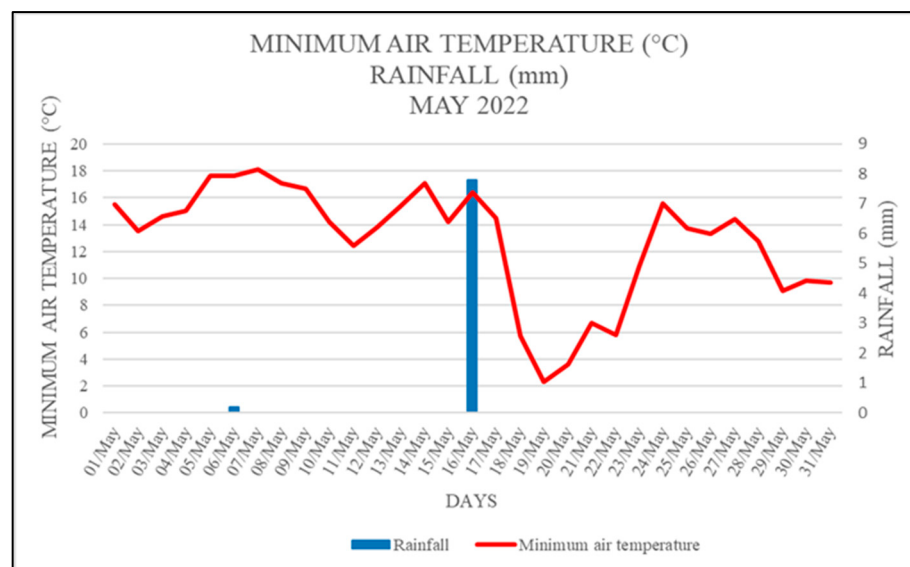


Figure 3. Minimum air temperature (°C) and rainfall (mm) in May 2022, Embrapa Cerrados, Planaltina—FD, Brazil, 2022.

3.5. Genotypic Variation in Frost Damage and Leaf Retention

Through comparison and ranking of the non-parametric Kruskal–Wallis test, it was possible to differentiate the genotypes according to frost damage (Table 5). Clones 1 and 7, with the highest mean values of significant scores, most experienced frost damage, and afterwards exhibited intense leaf drop. Clones 5 and 12 had the least damage, maintaining green leaves without visible symptoms, even after the minimum temperature of the air recorded in the weather station of the unit was 2.7 °C.

Table 5. Non-parametric Kruskal–Wallis test, with mean values of the scores of frost damage (FD) and clustered, in 2022 under irrigation. Embrapa Cerrados, Planaltina—FD, Brazil.

Genotype	FD
1	3.00 a
2	1.66 bc
3	1.66 bc
4	0.66 de
5	0.33 e
6	1.33 bcd
7	3.00 a
8	1.00 cde
9	1.00 cde
10	0.66 de
11	2.00 ab
12	0.33 e

Mean values followed by the same lowercase letter in the column do not differ statistically from each other by the Kruskal–Wallis test.

3.6. Genetic Parameters of the Marilândia ES 8143 Cultivar

Genetic parameters were estimated based on the mean values of the variables of the plots in two years of production of the Marilândia ES 8143 cultivar. The parameters are presented in Table 6.

Table 6. Genetic parameters of the variables: coffee bean yield (BY) in kg ha^{−1}, plant height (Height) in cm, number of pairs of plagiotropic branches (NPP), canopy projection (CP) in cm, flat beans in %, and peaberries in %, evaluated after harvest of coffee fruit in Conilon coffee plants, Marilândia ES 8143 cultivar. Embrapa Cerrados, Planaltina—FD, Brazil.

	BY (kg ha ^{−1})	Height (cm)	CP (cm)	NPP	Flat Beans (%)	Peaberries (%)
$\hat{\phi}_g$	785,192.11	225.65	39.08	13.57	182.80	194.41
σ_a^2	681,983.35	853.59	101.06	52.64	3.12	0.37
σ_{ga}^2	675,011.17	39.24	12.18	7.78	22.25	18.19
h^2 (%)	65.22	88.16	78.30	73.53	92.55	94.36
Mean	2512.75	153.02	69.47	44.02	44.99	50.28
CV _g = (%)	35.26	9.81	8.99	8.36	30.05	27.72
CV _{genotype} = (%)	21.88	4.77	7.21	4.44	8.71	6.32
CV _e = (%)	18.46	3.09	8.00	5.65	11.35	7.50
CV _r	1.91	1.23	1.12	1.47	2.64	3.69
$\hat{r}_{gg}$	0.79	0.93	0.84	0.83	0.95	0.96

Quadratic component ($\hat{\phi}_g$), component of variance associated with the year (σ_a^2), component of variance associated with the interaction (σ_{ga}^2), heritability at the mean level (h^2), genetic coefficient of variation (CV_g), genotypic coefficient of variation (CV_{genotype}), experimental coefficient of variation (CV_e), relative coefficient of correlation (CV_r), and accuracy ($\hat{r}_{gg}$).

3.7. Genotypic Selection Results Based on Agronomic Performance

According to Table 7, considering the characteristics of the genotypes selected and their respective mean values in 2021 and 2022, positive gains from selection were obtained of 22.99% for bean yield (BY), 6.98% for canopy projection (CP), and 5.68% for number of pairs of plagiotropic branches, which is desirable.

Table 7. Specific gains from selection (GS), specific gains from selection in percentage (GS) (%), heritability estimates (h^2), mean of the original population (X_o), mean of the breeding population (X_s), coffee bean yield (BY), plant height (Height), canopy projection (CP), and number of pairs of plagiotropic branches (NPP). Embrapa Cerrados, Planaltina—FD, Brazil, 2021 and 2022.

Traits	X _o	X _s	h^2 (%)	GS (%)	GS
BY (kg ha ^{−1})	2512.70	3398.57	65.22	22.99	577.76
Height (cm)	152.95	135.12	88.16	−10.27	−15.71
CP (cm)	69.4	75.59	78.30	6.98	4.84
NPP	44	47.4	73.53	5.68	2.50

The Height trait, in turn, had negative gain from selection, which is desired for the crop, since plants that have shorter height favor crop management and harvest. For plants of smaller size, the negative gain was 15.71 cm. These 22.99% of gain from selection for BY would represent a 577.76 kg ha^{−1} increase in yield; in relation to NPP, the increase would be 2.50 lateral branches; and for CP, the gain would be 4.84 cm.

4. Discussion

The significant genotype × year interaction observed for traits such as bean yield (BY), canopy projection (CP), and number of pairs of plagiotropic branches (NPP) underscores the importance of multi-year evaluations to capture the temporal variation in the performance of *Coffea canephora* clones under irrigated systems. Such interactions are common in perennial crops and reflect differential clone responses to environmental conditions, as reported by [9,10].

The broad genetic variability observed among genotypes is a favorable condition for selection programs, particularly for yield and plant architecture traits. According to

the findings of [11,12], variability is a prerequisite for genetic gain, and the significant differences among clones confirm the presence of such diversity.

Regarding productivity, clone 4 had superior performance in 2021 but was surpassed by clone 5 in 2022. This alternation suggests environmental influence on productivity stability, which is consistent with the findings of [13], who highlighted the need for stability analysis in multi-year evaluations. Notably, clone 5 maintained high performance across years, which is desirable in breeding programs aimed at improving both mean yield and stability [14].

Vegetative traits such as plant height and canopy projection showed moderate to high correlations with one another, which is expected given their physiological interdependence. However, the lack of consistent association between plant height and productivity, as observed in clones 1, 5, and 12, supports previous findings that excessive vegetative vigor does not necessarily lead to greater yield [15,16]. Indeed, compact plant architecture is often preferred in modern coffee plantations for facilitating mechanization and reducing production costs [17].

The high incidence of peaberries in both years can be partly attributed to abiotic stress during flowering. Air temperatures above 34 °C and relative humidity below 15% were recorded during peak flowering, creating unfavorable conditions for fertilization and increasing the risk of flower abortion. Similar impacts of heat and water stress on reproductive success and peaberry formation have been reported by [18,19], who highlight the sensitivity of floral development to thermal extremes, particularly under irrigated yet hot climates.

Despite this, clone 2 demonstrated a consistently lower percentage of peaberries and a higher proportion of flat beans across both years, indicating greater genetic stability in reproductive development. This trait is highly valued in coffee quality markets [20].

The frost event in 2022 served as a natural screening tool for cold tolerance. Clones 1 and 7 exhibited significant damage, while clones 5 and 12 maintained green leaves and exhibited minimal symptoms. Cold tolerance is an increasingly important selection criterion in light of climatic unpredictability, and differential responses among clones to low temperatures have been reported in other studies [16,21].

Estimates of genetic parameters revealed high heritability and accuracy for the majority of traits, indicating strong genetic control and reliability of phenotypic selection. Heritability values above 70% for traits such as bean yield, plant height, and bean classification have been reported in similar studies [22,23], reinforcing the feasibility of effective selection.

Genetic gains obtained through selection were positive for key traits, particularly bean yield (22.99%), canopy projection (6.98%), and number of plagiotropic branch pairs (5.68%). These gains confirm the potential for rapid progress through recurrent selection, particularly when guided by multi-trait indices [24]. The negative gain in plant height aligns with breeding goals targeting reduced plant size, which facilitates mechanization and enhances resilience to lodging [15].

Altogether, the clones evaluated demonstrate favorable agronomic traits for breeding under irrigated conditions. Clone 5, in particular, combines high yield, moderate plant height, resilience to frost, and adaptability across years, suggesting its suitability for commercial cultivation and inclusion in future hybridization schemes. Continued evaluation and multi-location trials are essential to validate these findings and expand genetic gain across diverse environments.

Furthermore, it is important to consider that the full expression of the productive potential and stability of *C. canephora* clones requires evaluations over longer cycles. Therefore, conducting trials with the most prominent materials for a minimum period of five years would allow for more consistent observation of their performance across different

harvests and environmental conditions. This approach would provide greater security for commercial recommendations and contribute to consolidating breeding strategies aimed at the sustainability of coffee farming in the central Cerrado.

5. Conclusions

Considering mean value of the two years, clone 5 achieved the highest bean yield. Clones 1 and 5 exhibited mean values for good vegetative development.

High mean values were observed for peaberry type beans. Genotype 2 obtained the best results for flat-type beans in both years. Clones 5 and 12 did not exhibit visible symptoms for low air temperatures and frost effects that occurred in 2022.

The low environmental coefficients of variation for all the traits indicate good experimental accuracy and high heritability values. The greatest gain from selection was observed for coffee bean yield.

Clones 1, 2 and 6 have values in lower groups for chlorogenic acids and caffeine, and in higher groups for protein and soluble solids, thus showing greater potential for obtaining quality beverages.

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