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Original Article

Morpho-agronomic traits and bean quality of elite cacao clones from southern Bahia, Brazil[1]

Características morfo-agronômicas e qualidade de amêndoas de cultivares clonais de cacau elite do sul da Bahia, Brasil

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HIGHLIGHTS:

Brazilian clonal cacao cultivars (FA 13, PS 1319, SJ 02, and CP 49) produced more pods per tree than CCN 51.
FA 13 achieved the highest yield, while PS 1319 and SJ 02 exhibited superior sensory quality compared to CP 49 and CCN 51.
The number of pods per tree was strongly correlated with yield, whereas pod and seed indices showed no correlation.

ABSTRACT: Morpho-agronomic characterization is essential for assessing morphological variability among cultivars and identifying materials with high agronomic potential and commercial value. It also expands the knowledge base on clonal cacao cultivars, supporting selection and breeding strategies. This study evaluated the morpho-agronomic traits of flowers, pods (fruits), seeds, and sensory qualities in five cacao clones (CCN 51, PS 1319, SJ 02, FA 13, and CP 49) grown in an irrigated experimental area in southern Bahia, Brazil. The experiment followed a randomized block design with two blocks and five plots, each containing 20 trees per cultivar. FA 13 showed the highest productive potential, with more seeds per pod and pods per tree, despite lower pod and seed indices. CCN 51 stood out for its larger pod and seed size and weight. PS 1319 and SJ 02 had similar profiles and good sensory quality, indicating potential for premium markets. CP 49 had the lowest overall performance. Multivariate analysis revealed that pod and seed indices were weakly correlated with yield, whereas the number of pods per tree and seeds per pod were positively associated with yield, particularly in FA 13. These findings suggest that the latter traits should be prioritized when selecting superior clones. Brazilian clones PS 1319, SJ 02, FA 13, and CP 49 were more strongly associated with yield than the Ecuadorian clone CCN 51, with FA 13 emerging as a promising candidate for breeding programs and irrigated production systems in southern Bahia.

Key words: cocoa clones, *Theobroma cacao* L., production components

RESUMO: A caracterização morfo-agronômica é importante para avaliar a variabilidade morfológica entre cultivares e identificar materiais com maior potencial agronômico e valor comercial. Também amplia a base de informações sobre cultivares clonais de cacau, subsidiando estratégias de seleção e melhoramento genético. Este estudo teve como objetivo avaliar características morfo-agronômicas de flores, frutos, sementes e qualidade sensorial em cinco clones de cacau (CCN 51, PS 1319, SJ 02, FA 13 e CP 49) em área experimental irrigada no sul da Bahia. O experimento foi implantado em blocos casualizados, com dois blocos e cinco parcelas, cada uma com 20 plantas por cultivar. Os resultados indicam que o FA 13 apresentou maior produtividade, exibindo maior número de sementes por fruto e frutos por planta, mesmo com baixos índices de fruto e semente. CCN 51 destacou-se pelo maior tamanho e peso de frutos e sementes. PS 1319 e SJ 02 mostraram semelhanças e melhor qualidade sensorial, indicando aptidão para mercados de qualidade. O CP 49 teve o desempenho mais baixo. A análise multivariada evidenciou que índices de fruto e semente apresentam baixa correlação com produtividade, enquanto número de frutos por planta e sementes por fruto mostraram associação positiva com produtividade, sobretudo em FA 13. Conclui-se que essas características devem ser priorizadas na seleção de clones superiores. Clones brasileiros PS 1319, SJ 02, FA 13 e CP 49 apresentaram maior associação com produtividade do que o clone equatoriano CCN 51, e FA 13 mais promissor para programas de melhoramento e sistemas irrigados no sul da Bahia.

Palavras-chave: clones de cacau, *Theobroma cacao* L., componentes de produção

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Introduction

The global cocoa and chocolate market is on an upward trajectory, with prices recently exceeding US$ 10 000 per ton due to restricted supply (ICCO, 2024). Demand is projected to reach US$ 182.52 billion by 2026 (Guirlanda et al., 2021). Once the world's leading cocoa producer, Brazil now ranks sixth, hindered by aging plantations, inadequate management, climate change, and phytosanitary and socioeconomic challenges (Lopes et al., 2011; Ahnert et al., 2018). In Bahia, the main producing state, average productivity remains low at around 326 kg ha^{-1} (IBGE, 2023). Addressing this decline requires coordinated actions, including the renewal of old plantations with more productive and disease-resistant clonal cultivars (Ahnert & Eskes, 2018; Somarriba et al., 2021; Lopes et al., 2022). Increasing productivity on existing farmland is also essential to meet growing demand, prevent deforestation, and reduce pressure on forested areas (Asante et al., 2022).

Breeding strategies have intensified in response to persistent challenges such as disease pressure, climate change, labor shortages, aging orchards, the need for mechanization, and demands for improved bean quality (Freitas et al., 2025). Breeding and selection programs prioritize clones that are high-yielding, pest- and disease-resistant, and well accepted by farmers (Ahnert et al., 2009; Lopes et al., 2011; Santos et al., 2015). Key morpho-agronomic traits include larger pods, low pod index (PI), and mean bean weight above 1 g (Dias & Resende, 2001; Ahnert, 2009; Bekele et al., 2019). Production components such as pod and bean yield (BY), number of pods per tree (NPT), number of seeds per pod (NSP), and seed index (SI) are useful for identifying superior genotypes (Dias & Resende, 2001; Alexandre et al., 2015; Lopes et al., 2022). Mean bean weight is highly heritable but influenced by the number of pods and SI (Doaré et al., 2020).

Rising market demand for beans with specific physicochemical attributes underscores the need for continued research on production and quality traits. Morpho-agronomic characterization reveals phenotypic variation and supports the selection of well-adapted, high-performing cultivars (Dias & Resende, 2001; Duval et al., 2017). These traits are critical for yield and quality, guiding genetic material choice and the establishment of productive clonal orchards (Ahnert et al., 2018; Adenuga et al., 2022). Identifying superior genotypes enhances cultivation success and market value (Ahnert et al., 2009; Georges et al., 2023). Breeding programs have developed productive, pest- and disease-resistant clones - such as CCN 51, PS 1319, SJ 02, FA 13, and CP 49 - widely used in southern Bahia (Lopes et al., 2011; Macêdo et al., 2021). Because clonal performance is influenced by genotype, environment, and management, testing under varying conditions remains essential (Bartley, 2005; Ahnert & Eskes, 2018).

Recent studies have evaluated PS 1319, CCN 51, SJ 02, and CP 49 under irrigated, full-sun conditions. CCN 51 was the most productive, reaching up to 2 890 kg ha^{-1}, while PS 1319 also exceeded 2 000 kg ha^{-1}; CP 49 and SJ 02 achieved lower but still satisfactory yields (Benjamin et al., 2025). Under rainfed conditions, PS 1319, SJ 02, and FA 13 outperformed CCN 51 (Freitas et al., 2025). Across farms in southern Bahia, mean yields were 2,252.4 kg ha^{-1} for FA 13, 1,746.5 kg ha^{-1} for SJ 02, 1,490.1 kg ha^{-1} for CCN 51, 1,395.3 kg ha^{-1} for PS 1319, and 1,202.3 kg ha^{-1} for CP 49. These results show that CCN 51, SJ 02, and FA 13 outperformed PS 1319 and other local clones, highlighting the potential of ongoing selection programs in Bahia (Macêdo et al., 2022). However, no studies have compared CCN 51, PS 1319, SJ 02, FA 13, and CP 49 simultaneously under irrigated, full-sun conditions, even though clonal cultivars are the main option for establishing technologically advanced, high-yielding cocoa plantations.

Cacao cultivation under irrigation, full sun, and improved practices is expanding in Brazil, but clonal cultivars remain understudied under these conditions. Cocoa trees are highly responsive to water availability and vulnerable to drought, particularly during critical stages, which can reduce yield and cause plant mortality (Almeida & Valle, 2007; Lahive et al., 2019; Santos et al., 2023; Araújo et al., 2024). In Ghana, only 20% of seedlings survive prolonged dry spells, while in southern Bahia, even short droughts in February and December highlight the need for supplemental irrigation (Medauar et al., 2020; Kaba et al., 2022). Climate projections indicate greater rainfall variability and more frequent droughts, making Bahia's coastal zone suitable for drip irrigation (Olegário et al., 2022; Talero-Sarmiento et al., 2025). Dry-season irrigation, combined with potassium fertilization, improves nutrient uptake and pod development (Adet et al., 2024). These findings emphasize the importance of integrated management strategies that combine efficient irrigation, balanced nutrition, and adapted genotypes to maintain productivity under climate change (Lahive et al., 2019; Adet et al., 2024; Araújo et al., 2024). Principal component analysis (PCA) and cluster analysis remain valuable tools for assessing diversity and guiding breeding programs (Santos et al., 2023).

This study hypothesizes that southern Bahia clonal cultivars (PS 1319, SJ 02, FA 13, and CP 49) exhibit superior morpho-agronomic traits and productivity compared with the Ecuadorian clone CCN 51. Therefore, the aim was to evaluate floral, pod, and seed morpho-agronomic traits of these cultivars under optimal management and supplemental drip irrigation to identify the clones and traits with the greatest agronomic and commercial potential.

Material and Methods

Pods were collected in 2021 from 6-year-old trees in a farm field trial in Una, southern Bahia, Brazil (S 15° 20.616′, W 039° 04.861′). Genetic divergence among cultivars can be assessed based on a single favorable year, resulting in substantial savings of labor, financial resources, and time compared with multi-year evaluations (Dias & Kageyama, 1997).

In 2020, the site received 1,573 mm of rainfall, with a monthly mean of 131 mm. Although the rainfall regime influences variability in production components (Muller & Valle, 2012), water availability in the preceding year did not affect this study's sampling cycles. In southern Bahia's cocoa-growing region, historical mean precipitation exceeds 1,500 mm annually and 60 mm monthly, with mean temperatures ranging from 18 °C in the coldest month to 24 °C in the warmest (Santos Filho et al., 2019). The trial was established on flat, sandy-clay soil with drip irrigation and full-sun exposure to ensure uniform water supply and solar radiation.

The experiment followed a randomized block design with two blocks and five plots per block, totaling 10 plots. Each plot contained 20 cacao trees per cultivar, totaling 200 sampling units (2 blocks × 5 plots × 20 trees). In each block, 20 pods were sampled per cultivar to analyze production components. Plant spacing was 3 × 3 m in a triangular arrangement, with 2.6 m between single rows and 4 m between double rows.

Block 1 consisted of P1 (PS 1319), P2 (CP 49), P3 (SJ 02), P4 (CCN 51), and P5 (FA 13), while block 2 consisted of P6 (CCN 51), P7 (FA 13), P8 (PS 1319), P9 (SJ 02), and P10 (CP 49). From each plot, monthly data were collected on the NPT for all 20 trees. Additionally, 20 healthy, mature pods at harvest stage were sampled from each plot during the main crop season. In Bahia, the cacao cropping year runs from April to March, with the early crop season from April to August and the main crop season from September to March (Almeida & Valle, 2007).

Supplemental irrigation targeted the canopy projection zone of young trees, providing water during dry spells to minimize water stress and promote root development. Irrigation scheduling was based on regional rainfall patterns and crop water requirements to ensure efficient use of water resources.

Soil preparation began with composite sampling (25 cores per plot) of the 0-20 cm and 20-40 cm layers. Dolomitic lime was applied to the surface to raise base saturation to 75% in the top 5 cm, and gypsum was applied to reduce Al^{3+} saturation to 20% in the 20-40 cm layer; both were lightly incorporated using a leaf blower without tillage. Planting pits (60 × 20 cm) received single superphosphate, KCl, dolomitic lime, FTE BR12, and poultry manure. Establishment fertilization consisted of 1 292 g per plant of NPK 19-04-19, followed by NPK 16-16-16 at 500 g in the 1st year and 800 g in the 2nd year. From the 3rd to the 6th year, fertilization was applied in 6 annual splits of urea, MAP, triple superphosphate, and KCl, adjusted according to soil tests and crop removal, with micronutrients applied via irrigation.

Integrated pest and disease management included bimonthly de-suckering and sanitary pruning, shade regulation, and stumping of senescent trees. Weed control involved mechanical mowing combined with directed glufosinate-ammonium (0.58 L ha^{-1}). Foliar pathogens and key pests were treated once per season with a tank mix of azoxystrobin (0.10 L ha^{-1}) and copper hydroxide-mancozeb (0.04 kg ha^{-1}) by using a backpack sprayer, with varietal resistance and balanced nutrition serving as the primary defense to minimize chemical inputs.

A total of 56 morpho-agronomic traits related to flowers, pods, seeds, and sensory attributes were evaluated in elite clonal cultivars from southern Bahia (PS 1319, SJ 02, CP 49, and FA 13) and compared with the international cultivar CCN 51. All selected cultivars are self-compatible, productive, and disease-resistant (Lopes et al., 2011; Ahnert et al., 2018; Macêdo et al., 2021). Evaluations included 10 quantitative floral dimension traits and six qualitative floral coloration traits. Additionally, 26 quantitative traits - covering measurements, weight, and yield of pods, seeds, and beans, as well as productivity - were assessed. A total of 14 qualitative traits related to the sensory evaluation of cocoa liquor were also analyzed.

CCN 51, originally from the Colección Castro Naranjal in Ecuador, is the result of the cross (IMC 67 × ICS 95) × Canelo and belongs to the Amelonado, Criollo, and Iquitos groups. It is self-compatible, medium-sized, with an upright, uniform canopy, high productivity, medium precocity, and purple pods with moderate rugosity. Recommended for large-scale planting, it has a maximum yield of 1.2 kg per tree, adapts well to diverse topographies, and is resistant to witches' broom and brown rot but susceptible to Ceratocystis wilt (Arévalo et al., 2012; Pereira & Valle, 2012; Boza et al., 2014; Sodré et al., 2017; Ahnert et al., 2018; Jaimez et al., 2022).

CP 49, developed by the Cocoa Research Center Herbarium (CEPEC), part of the Executive Commission of the Cacao Farming Plan (CEPLAC) in Ilhéus, Bahia, Brazil, is from the cross (TSH 565 × CEPEC 11) × CCN 51 and belongs to the Amelonado, Contamana, Criollo, and Iquitos groups (Lopes et al., 2011). It is self-compatible, medium-sized, with a uniform canopy, medium precocity, and large pods with moderate rugosity. Suitable for large-scale planting, it has a maximum yield of 1.2 kg per tree, adapts well to all topographies, and shows tolerance to waterlogging (Lopes et al., 2011; Arévalo et al., 2012; Pereira & Valle, 2012; Sodré, 2017).

FA 13, selected through mass selection at Fazenda Angola, Itajuípe, Bahia, Brazil, has an unknown lineage. It is self-compatible, medium-sized, with an upright canopy, high precocity, and is recommended for small-scale planting. It achieves a maximum yield of 1.6 kg per tree, with a harvest proportion of 0.33 in the main season and 0.67 in the early season. FA 13 is resistant to witches' broom and brown rot but moderately susceptible to Ceratocystis wilt (Lopes et al., 2011; Arévalo et al., 2012; Silva et al., 2012; Pereira & Valle, 2012; Sodré et al., 2017; Ahnert et al., 2018; Macêdo et al., 2021).

PS 1319, selected as an F_2 generation from a hybrid population at Fazenda Porto Seguro, Ilhéus, Bahia, Brazil, also has an unknown lineage. It is self-compatible, medium-sized, with an upright canopy, high precocity, and medium-sized reddish-purple pods. With high productivity, it is recommended for large-scale planting, achieving a maximum yield of 0.9 kg per tree, with a harvest proportion of 0.43 in the main season and 0.57 in the early season. PS 1319 is suitable as a rootstock, well adapted to hillsides and elevated areas with light shading, and resistant to witches' broom, brown rot, and Ceratocystis wilt (Silva et al., 2012; Arévalo et al., 2012; Pereira & Valle, 2012; Monteiro & Ahnert, 2012; Sodré, 2017; Ahnert et al., 2018).

Finally, the SJ 02 clone, also derived from mass selection at Fazenda São José, Itajuípe, Bahia, Brazil, has an unknown lineage. It is self-compatible, large-sized, and recommended for large-scale planting, with a maximum yield of 1.2 kg per tree and a harvest proportion of 0.47 in the main season and 0.53 in the early season. It adapts well to all topographies, is resistant to witches' broom and brown rot, but susceptible to Ceratocystis wilt (Lopes et al., 2011; Silva et al., 2012; Arévalo et al., 2012; Pereira & Valle, 2012; Sodré et al., 2017; Ahnert et al., 2018).

Flowers were collected in the early morning from 20 open flowers per cultivar, each from a different tree, during the off-season harvest in 2021. All floral parts were measured using a caliper, forceps, and scalpel. The following variables were recorded: sepal length (SL), sepal width (SW), petal length (PL), petal width (PW), staminode length (SLe), stigma length (SLa), ovary length (OL), and ovary width (OW). Using a 10× magnifying lens, a lateral incision was made in the ovaries to count the number of ovules (NO) per ovary. The ovules-to-seeds ratio (O:S) was calculated. Additionally, the color of the pendulum, petal, sepal, guide lines, staminode, and stigma was recorded for 5 flowers using the Munsell color system (Munsell, 1905).

Pods were processed in the Agro-Industry Laboratory at the Universidade Estadual de Santa Cruz (UESC). Measurements were taken using a semi-analytical scale (LS1 1010 g Marte Electronic Precision Balance, sensitivity 0.2 g), calipers (ABS plastic and electronic models with LR44 battery, measuring range 0-150 mm / 0-6 in, resolution ± 0.1 mm / 0.01 in), and a stainless steel ruler (Vonder 24-inch Basic Metal Square, length 60 inches). The following morpho-agronomic characteristics were recorded (Figure 1): NPT; pod weight (PWe); pod length (PL); pod width (PWi); pod husk thickness (PHT); pod husk weight per pod (PHW); pod placenta weight (PPW); weight of 10 seeds with pulp (WSP10); wet weight of 10 seeds (WWS10, with pulp removed using cotton cloth and a 2 mm mesh sieve); NSP; empty seeds per pod (ESP); and usable seeds per pod (USP).

Seeds underwent a 5-day fermentation process in 5 L styrofoam boxes, progressing through anaerobic and aerobic phases. The temperature of the cocoa mass was monitored daily at different depths using a digital thermometer (Model TP101; 50-300 °C; accuracy: ± 1%). Fermentation began anaerobically without stirring until the mass reached 32 °C or up to 48 hours. Once aerobic fermentation started, the mass was turned daily at approximately 10 a.m. to maintain optimal microbial activity, reaching peak temperatures of 48-52 °C by the fourth day.

A squeeze test was performed to check for “cocoa blood” release, indicating the final stage. Fermentation was concluded when the cut test confirmed that more than 60% of beans were properly fermented, totaling about five to six days, depending on climate and management. Drying followed in a solar oven for 10 days.

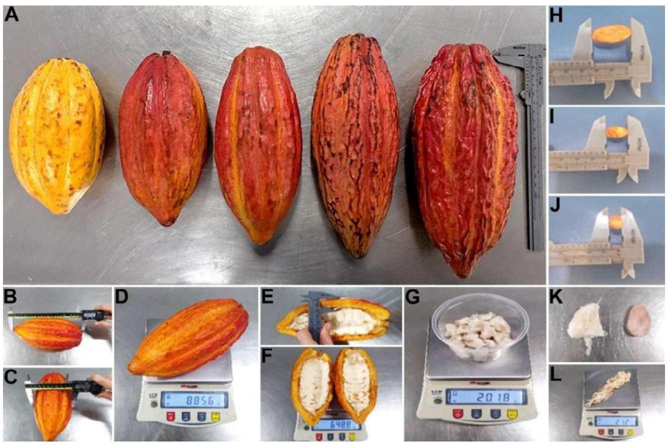


Figure 1. Morpho-agronomic characterization of pods and seeds of the clonal cultivars analyzed. Pods of FA 13, PS 1319, SJ 02, CP 49, and CCN 51, respectively (A), pod length (B), pod width (C), pod weight (D), pod husk thickness (E), pod husk weight (F), wet seed weight (G), bean width (H), bean length (I), bean thickness (J), pulp yield (K), placenta weight (L)

After drying, morpho-agronomic traits were recorded, including dry weight of 10 beans (DWB10), bean thickness (BT), bean length (BL), and bean width (BW) (Figure 1). The following variables were then calculated: pulp yield (PY) - difference in weight between WSP10 and WWS10, expressed as a percentage; BY - quantity of seeds per pod, in percentage; husk yield (HY) - quantity of husk per pod, in percentage; SI - weight of 1 dry bean, obtained from DWB10; conversion factor (CF) from wet to dry beans - proportion of WWS10 weight resulting in DWB10; dry bean weight per pod (BWP) - estimated dry bean weight per pod, calculated as wet seed weight per pod (SWP) × CF; efficiency index (EI) - ratio of PWe to BWP; and PI - obtained according to Eq. 1 (Dias & Resende, 2001). Productivity (kg ha^{-1} per year) was calculated by dividing NPT by PI to obtain dry bean weight per tree, then multiplying by a standard planting density of 1 000 trees ha^{-1} (Eq. 2).

$$\mathrm{PI} = \frac{1000\mathrm{g}}{(\mathrm{USP} \cdot \mathrm{SI})} \tag{1}$$

where:

PI - pod index (nº);

USP - usable seeds per pod (nº); and,

SI - seed index (g).

$$\mathrm{YIELD} = \left(\frac{\mathrm{NSP}}{\mathrm{PI}}\right) \cdot 1000 \tag{2}$$

where:

NSP - number of seeds per pod (no kg^{-1});

PI - pod index (nº kg^{-1}); and,

1000 - tree ha^{-1}.

For the analysis of sensory characteristics, 5 kg of dry, fermented cocoa bean samples from each clonal cultivar were evaluated at the Cocoa Innovation Center (CIC), located at UESC. The sensory evaluation of cocoa liquor followed the guidelines by the Association of Chocolate, Biscuit and Confectionery Industries of Europe (CAOBISCO), the European Cocoa Association (ECA), and the Federation of Cocoa Commerce (FCC) (2015). Overall quality and the following attributes were assessed: acidity, astringency, woody, bitterness, nutty, sweet, spicy, floral, fresh pod, brown pod, cocoa flavor, roasted, and other attributes as well as off-flavors such as animal/leather, smoke, mold, overfermented/putrid, and dirty.

Morpho-agronomic traits of pods and seeds/beans were first tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene’s test in SISVAR version 5.8 (Ferreira, 2019). Data were subjected to ANOVA at $p \leq 0.05$. Means for morpho-agronomic traits of pods, seeds/beans, and flowers were compared using Tukey’s test at $p \leq 0.05$ in SISVAR version 5.8 (Ferreira, 2019).

Multivariate analysis was performed for all 5 clones and all traits using the vegan package (Oksanen, 2017). Correlation analysis between clones and variables was conducted with the “heatmaply” package (Galili, 2018). The central section of the figure displays the heatmap, transformed using log(x) and a logarithmic scale. Cluster analysis was based on Euclidean distance as a measure of similarity. Heatmap dendrograms were used to identify patterns of similarity and correlations among the morpho-agronomic traits of pods, seeds/beans, and sensory characteristics of the cocoa clones.

Data on morpho-agronomic traits of pods, seeds/beans, and productivity were subjected to PCA using the “factoextra” package (Kassambara, 2023).

Results and Discussion

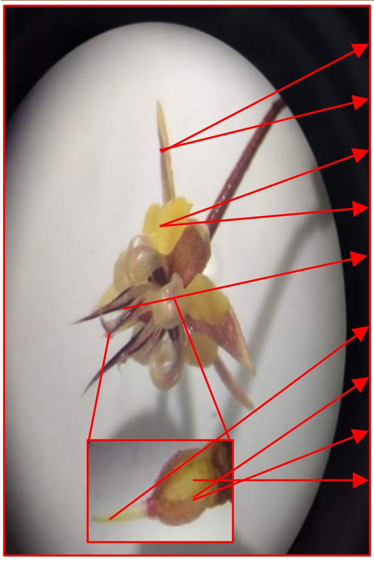
The morpho-agronomic traits of flowers, analyzed using Tukey’s test, revealed significant differences ($p \leq 0.05$) among the clones (Table 1). These results indicate that floral characteristics can be useful for the identification and differentiation of clonal cultivars in the field.

FA 13 exhibited the highest means for most floral traits, particularly for O:S (Table 1). SJ 02 also performed well, except for SL. CCN 51 recorded the highest averages for SLe, SLa, OL, OW, and NO, while PS 1319 and CP 49 had the lowest NO means. No significant differences were observed in SLe and OL among the clonal cultivars.

Cacao flowers are hermaphroditic and pentamerous, with petals, sepals, stamens, staminodes, and an ovary containing 30-70 ovules (Alvim, 1977). In this study, mean ovule numbers ranged from 46.70 in CP 49 to 54.74 in CCN 51 (Table 1). The number of ovules per ovary is genetically determined, without environmental influence, and varies by racial group and cultivar (Dias & Resende, 2001). FA 13 had the highest O:S ratio among cultivars (Table 1). Factors beyond fertilization and pollination intensity, such as physiological aspects, influence seed filling (Webber et al., 2020). Climate change also affects the reproductive potential of cacao (García-Cruzatty et al., 2020). Consequently, the number of seeds is not directly proportional to the ovule count, depending on fertilization rate and pod development.

Cacao clonal cultivar flowers showed similar colors, but with variations in tone for most traits, except for the stigma, which showed no differences (Table 2). The pendulum

Table 1. Mean values of 10 morpho-agronomic flower traits in 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13



Traits	CCN 51	PS 1319	SJ 02	CP 49	FA 13
SL (mm)	9.10 b	8.80 bc	8.44 c	7.58 d	10.00 a
SW (mm)	2.61 b	1.99 c	2.66 a	2.14 bc	2.42 ab
PL (mm)	6.86 b	7.34 ab	7.56 a	7.30 ab	6.98 ab
PW (mm)	2.34 bc	2.00 d	2.75 a	2.11 cd	2.54 ab
SLe (mm)	7.62 a	7.58 a	8.18 a	7.58 a	7.76 a
SLa (mm)	1.98 a	1.62 b	1.72 ab	1.98 a	1.70 b
OL (mm)	1.88 a	1.80 a	1.70 a	1.80 a	1.90 a
OW (mm)	1.00 a	0.98 a	0.90 b	1.00 a	1.00 a
NO (nº)	54.75 a	48.30 c	51.15 b	46.70 c	50.35 b
O:S (%)	83.47 b	84.40 b	80.40 b	80.60 b	89.57 a

Means followed by the same letter in the row do not differ significantly according to Tukey’s test ($p \geq 0.05$). SL - Sepal length; SW - Sepal width; PL - Petal length; PW - Petal width; SLe - Staminode length; SLa - Stigma length; OL - Ovary length; OW - Ovary width; NO - Number of ovules; O:S - Ovules-to-seeds ratio

Table 2. Description of 6 morpho-agronomic traits of flower colors of 5 cacao clonal cultivars – CCN 51, PS 1319, SJ 02, CP 49, and FA 13

Traits	CCN 51	PS 1319	SJ 02	CP 49	FA 13
Pendulum	5 R 4/10; 2.5 GY 7/8; purple; green	5 R 4/8; 2.5 GY 8/6; purple; green	5R 4/10; 2.5 GY 8/6; purple; green	5 Y 7/8; greeny	5 Y 7/8; greeny
Petal	2.5Y 8/10; yellow	5Y 8/8; yellow	5Y 8/6; yellow	5Y 8/12; 5R 6/19; yellow; purple	5Y 8/12; 5R 6/19; yellow; purple
Sepal	2.5 Y 8/4; 5R 4/10; yellow; purple	2.5Y 8/4; yellow	5 Y 8/4; 5R 6/10; yellow; purple	5 Y 8/6; yellow	5 Y 8/6; yellow
Guide lines	5 R; 3/8; wine	5 R 3/12; wine	5R3/6; wine	5R 3/6; wine	5R 3/6; wine
Staminode	5 R 3/6; 2.5 Y (8/4); wine; yellow	5 R 3/4; 2.5 Y (8/4); wine; yellow	5R 3/2; 2.5 Y (8/4); wine; yellow	5R 3/4; 2.5 Y (8/4); wine; yellow	5R 3/4; 2.5 Y (8/4); wine; yellow
Stigma	2.5 Y 8/6; yellow	2.5 Y 8/6; yellow	2.5 Y 8/6; yellow	2.5 Y (8/6); yellow	2.5 Y (8/6); yellow

exhibited the greatest variation in color: CCN 51, PS 1319, and SJ 02 displayed purple and green tones, whereas CP 49 and FA 13 showed a greenish tone. Petal colors also varied, being yellow in CCN 51, PS 1319, and SJ 02, and yellow with purple in CP 49 and FA 13. Sepal colors were yellow with purple in CCN 51 and SJ 02, and yellow in CP 49, FA 13, and PS 1319.

The results of this study on floral characteristics have practical implications for identifying clones, both for cocoa producers and researchers (Table 1). Recognizing floral traits is particularly useful when cacao trees are without pods (Table 2).

Analysis of variance revealed a significant difference ($p \leq 0.01$) according to the F-test for all morpho-agronomic characteristics analyzed (Table 3). Variables PL, PWi, PHT, BL, PWe, PHW, WSP10, WWS10, DWB10, CF, SI, and HY exhibited low coefficients of variation (CV), all below 10%, indicating low dispersion and high data homogeneity. In contrast, ESP and NPT showed very high CVs, exceeding 30%. This high variability stems from low mean values and zero-inflated count data, where small absolute differences substantially increase relative dispersion.

In perennial species, sporadic fruiting and genotype–environment interactions often produce asymmetric distributions for count traits (Silva et al., 2011). The occurrence of ESP is influenced by pollination efficiency, partial self-incompatibility, and carbohydrate availability during seed filling, all of which vary among clones and between seasons (Sant'Ana et al., 2020).

Tukey's test revealed significant differences ($p \leq 0.05$) for all variables analyzed (Table 4). Among the 25 pod and seed traits evaluated, CCN 51 had the highest means in 13 parameters: pod and seed dimensions (PL, PWi, BL, BW), pod and seed weights (PWe, SWP, BWP, WWS10, WSP10, DWB10), and pod and seed yield indices (SI, PI, PY). These values differed statistically from those of the other clones.

CCN 51, developed in Ecuador through breeding programs, is one of the most extensively studied cacao clones, known for its economically desirable traits, high productivity, and adaptability to diverse environments, making it among the most widely cultivated clones worldwide (Boza et al., 2014;

Table 3. Summary of analysis of variance of 25 morpho-agronomic traits of pods and seeds/beans in 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13

Traits	FC	CV (%)	Trait	FC	CV (%)
PL	203.70*	4.06	BWP	19.78*	16.43
PWi	24.06*	3.16	WSP10	129.08*	9.88
PHT	43.18*	9.39	WWS10	102.02*	7.99
BL	14.81*	5.09	DWB10	366.20*	3.95
BW	26.71*	5.91	NPT	19.88*	34.71
BT	25.62*	11.78	CF	21.94*	10.00
NSP	3.78*	12.50	SI	366.20*	3.95
ESP	3.28*	110.13	EI	8.75*	18.36
USP	4.27*	12.78	PI	18.12*	17.05
PWe	106.90*	7.67	PY	45.26*	13.34
PHW	82.50*	9.06	HY	53.40*	4.25
PPW	158.00*	14.73	BY	52.70*	12.62
SWP	60.75*	13.99			

*FC - F calculated; * - Significant at $p \leq 0.01$ by F-test; CV - Coefficient of variation. PL - Pod length; PWi - Pod width; PHT - Pod husk thickness; BL - Bean length; BW - Bean width; BT - Bean thickness; NSP - Number of seeds per pod; ESP - Empty seeds per pod; USP - Usable seeds per pod; PWe - Pod weight; PHW - Pod husk weight; PPW - Pod placenta weight; SWP - Wet seed weight per pod

Table 4. Mean values of 25 morpho-agronomic traits of pods, seeds, and beans in 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13

Trait	CCN 51	PS 1319	SJ 02	CP 49	FA 13
PL (mm)	230.60 a	179.70 c	200.65 b	228.35 a	174.60 c
PWi (mm)	96.05 a	89.85 b	89.10 b	89.15 b	93.90 a
PHT (mm)	20.10 a	13.65 c	17.55 b	17.85 b	18.90 ab
BL (mm)	26.35 a	25.15 b	24.65 b	23.40 c	24.35 bc
BW (mm)	13.40 a	12.70 b	11.60 c	11.55 c	11.65 c
BT (mm)	8.20 ab	6.60 c	7.65 b	8.60 a	6.30 c
NSP (nº)	45.55 ab	45.55 ab	45.25 ab	41.70 b	48.65 a
ESP (nº)	0.95 ab	1.35 a	0.40 b	1.00 ab	0.55 ab
USP (nº)	44.60 ab	44.20 ab	44.85 ab	40.70 b	48.10 a
PWe (g)	881.27 a	571.31 c	723.65 b	682.75 b	598.68 c
PHW (g)	656.59 a	396.06 d	558.18 b	567.28 b	482.36 c
PPW (g)	23.63 a	18.81 b	14.80 c	11.53 d	7.37 e
SWP (g)	194.90 a	157.98 b	152.50 b	109.54 c	112.40 c
BWP (g)	76.01 a	59.69 bc	61.80 b	51.71 c	52.24 c
WWS10 (g)	43.05 a	35.15 b	33.29 b	25.26 c	23.15 c
WSP10 (g)	27.29 a	24.15 b	21.47 c	19.65 d	17.08 e
DWB10 (g)	16.62 a	13.12 b	13.44 b	11.89 c	10.69 d
NPT (nº)	55.20 d	84.60 bc	63.40 cd	91.75 b	130.45 a
CF	0.39 b	0.38 b	0.41 b	0.47 a	0.46 a
SI (g)	1.66 a	1.31 b	1.34 b	1.19 c	1.07 d
EI (g)	11.83 b	9.81 c	11.90 b	13.86 a	11.67 bc
PI (nº)	13.76 a	17.68 bc	16.77 b	21.31 d	19.78 cd
PY (%)	36.40 a	30.95 b	35.27 a	22.12 d	26.11 c
HY (%)	74.48 b	69.33 c	77.11 b	83.08 a	80.55 a
BY (%)	22.17 b	27.64 a	21.15 bc	16.00 d	18.81 c

Values followed by the same letter in the row do not differ significantly according to Tukey's test ($p \leq 0.05$).
PL - Pod length; PWi - Pod width; PHT - Pod husk thickness; BL - Bean length; BW - Bean width; BT - Bean thickness; NSP - Number of seeds per pod; ESP - Empty seeds per pod; USP - Usable seeds per pod; PWe - Pod weight; PHW - Pod husk weight; PPW - Pod placenta weight; SWP - Wet seed weight per pod; BWP - Dry bean weight per pod; WSP10 - Weight of 10 seeds with pulp; WWS10 - Wet weight of 10 seeds; DWB10 - Dry weight of 10 beans; NPT - Number of pods per tree; CF - Conversion factor; SI - Seed index; EI - Efficiency index; PI - Pod index; PY - Pulp yield; HY - Husk yield; BY - Bean yield

Jaimez et al., 2022). Alexandre et al. (2015) identified genetic divergence among seven clones in Espírito Santo, Brazil, with CCN 10 and CCN 51 considered the most suitable for high cocoa BYs. Reges et al. (2021) reported that CCN 51 produced the largest pods among four clones in Ceará, Brazil. In French Guiana, Doaré et al. (2020) found that CCN 51 had the highest average seed weight, which correlated with the NSP in seven clones. Almeida et al. (2013) demonstrated that varying irrigation schemes and nitrogen rates significantly increased the production of pods in CCN 51. Although tolerant to certain climatic conditions, CCN 51 is often associated with a weaker flavor profile and is typically marketed as bulk cocoa (Herrmann, 2015). In western Colombia, it was also identified as one of the most productive clones (Reges et al., 2021). In contrast, in the present study, CCN 51 was the least productive compared with other Brazilian clones, showing large pods and seeds but a low pod set index, resulting in fewer pods per tree (Table 4).

CP 49, developed at CEPEC in Ilhéus, Bahia, from the cross (TSH 565 × CEPEC 11) × CCN 51 (Lopes et al., 2011), exhibited PL comparable to CCN 51 but had the lowest means for most traits - 14 in total (PWi, BW, BL, NSP, USP, PHW, SWP, BWP, WWS10, EI, PI, PY, HY, and BY) - contrary to expectations based on its breeding background.

FA 13 recorded the lowest means for 13 traits (PL, BW, BT, PWe, SWP, BWP, WSP10, WWS10, DWB10, SI, PY, HY, and BY) but stood out for its highest values in PWi, NSP, USP, PPW, NPT, and CF, indicating a resource allocation strategy favoring increased unit number over individual size and weight.

PS 1319 and SJ 02 showed intermediate means, with no significant differences between them for most traits (Table 4). Both, along with FA 13, were originally selected on farms in southern Bahia and later registered by CEPLAC. In the Republic of Côte d'Ivoire, the world's leading cocoa producer and exporter, greater allelic richness has been found in farm accessions compared to parental clones from seed orchards, suggesting potential to expand breeding programs by incorporating farm accessions into the working collection (Pokou et al., 2014).

Despite their productive potential and classification as elite clones, PS 1319, SJ 02, and FA 13 remain little known or cultivated in southern Bahia and other cocoa-producing regions. In the region, CCN 51 and PS 1319 are the most widely planted clones, although several studies have identified superior alternatives. These clones represent technological advances in cacao cultivation, offering uniformity, high yield, self-compatibility, and resistance to pests and diseases (Ahnert et al., 2018). CEPLAC recommends clones such as SJ 02, BN 34, CEPEC 2004, PH 16, PH 09, CCN 10, FA 13, CEPEC 2002, PS 1030, and PH 15 for commercial planting in Bahia (Ahnert et al., 2018). Among these, FA 13, SJ 02, CCN 51, PS 1319, CEPEC 2002, CCN 10, and Vencedora 20 are the most productive (Macêdo et al., 2021). Other promising clones with yields significantly higher than PS 1319 include PS 5785, VT 05, RLF 1938, VT 10, CSG 70, FL 89, SL 06, BN 34, and FL 76 (Macêdo et al., 2021).

In Espírito Santo, clonal cultivars PS 1319 and CCN 51 account for 23.9 and 23.3% of the total cacao area, respectively, due to their high productivity and adaptability (INCAPER, 2022). In Rondônia, between 2012 and 2018, producers progressively replaced hybrids with clones such as CCN 51, PH 16, SJ 02, PS 1319, CCN 10, and BN 34 (Almeida et al., 2020). In Ceará, research on cacao adaptation and pod quality remains ongoing (Moreira et al., 2020).

Morpho-agronomic responses of these clones vary regionally. Results from Alexandre et al. (2015) in Espírito Santo were consistent with those obtained in the present study, whereas Reges et al. (2021) reported different findings in the semiarid region of Ceará, which suggests that factors beyond water availability influence trait variation. Both studies, conducted under irrigation, highlight the role of environmental factors in determining pod morphology in clonal cacao. For example, the PHW of CCN 51 differed significantly ($p \leq 0.05$), averaging 656.59 g in this study, compared to 558.76 g reported by Alexandre et al. (2015) and 475.50 g by Reges et al. (2021). Greater similarity was observed between this study and Alexandre et al. (2015), both conducted in tropical forest regions, than with results from the semiarid environment.

In southern Bahia, rainfed trials reported higher average yields for CCN 51, SJ 02, FA 13, and PS 1319 compared with this study (Macêdo et al., 2021). Here, FA 13, CP 49, PS 1319, SJ 02, and CCN 51 ranked in descending order for pod production per tree (Table 4). These results confirm the substantial genetic variability among cacao genotypes in morpho-agronomic traits, as well as the divergent outcomes arising from environmental conditions and management practices (Ahnert & Eskes, 2018; Doaré et al., 2020; Jaimes-Suárez et al., 2022; Georges et al., 2023). They also reinforce that the same clone can express both similar and contrasting characteristics across regions due to these factors (Ahnert & Eskes, 2018; Doaré et al., 2020; Jaimes-Suárez et al., 2022). In northeastern Peru, a comparable study identified the Indes and Bagüinos groups as having superior sensory attributes and yields at altitudes above 500 m (Oliva-Cruz et al., 2023).

Although WSP10, WWS10, and DWB10 are essential for calculating yield traits such as BWP, PY, and BY, these variables showed different behaviors among the cultivars (Table 4). For instance, PS 1319 and SJ 02, which had intermediate means for WSP10, WWS10, and DWB10, differed in their yield performance: PS 1319 achieved the highest BY (27.64%) due to a greater proportion of beans per pod, while SJ 02 reached a higher PY (35.27%), similar to CCN 51 (36.40%), with no significant difference between them (Table 4).

The HY of FA 13 did not differ significantly from that of CP 49, which recorded the highest HY (Table 4). In contrast, PS 1319 presented the lowest HY, significantly different from the other cultivars. Considering that cultivars have an average husk-to-pod ratio of 76.91% (Table 3), there is a need for improved management practices to address husk residues. Although cocoa husks have potential as a potassium source for crops, they are often left concentrated in the field, contributing to disease inoculum (Chepote, 2003). Guirlanda et al. (2021) highlight the importance of developing innovative techniques in cocoa-producing countries to add value to cocoa residues, which account for approximately 80% of the pod. One example is the production of methyl esters using a novel catalyst synthesized from cocoa pod husk mixtures (Olatundun et al., 2020).

The pulp is another important pod byproduct, containing compounds relevant to fermentation, including sugars, acids, and minerals (Nunes et al., 2020). CCN 51 and SJ 02 recorded the highest PY values, significantly differing from other clones (Table 4). Moreira et al. (2020) reported that PS 1319 had higher pulp percentages and elevated ascorbic acid, moisture, and protein contents, making it a superior genotype for quality. Reges et al. (2021) also observed higher PY for PS 1319, underscoring its relevance for pulp production, fermentation, and quality improvement. Although PY is not a current priority for most farmers, pulp extraction generates additional income, particularly through cocoa juice and cocoa honey, a fermentation byproduct rich in pectin, minerals, and fructose, with potential for new product development (Guirlanda et al., 2021). The pulp can be incorporated into diets, food supplements, and industrial processing (Freitas et al., 2022), including bioethanol production (Delgado-Noboa et al., 2021). Studies also show that partial pulp removal for other applications does not compromise fermentation and can enhance chocolate quality, adding value to the pulp and benefiting the cocoa production chain (Silveira et al., 2024).

Determining BWP from SWP and CF is essential for accurately estimating dry cocoa bean production. While pod production is important, the wet weight of seeds is the primary determinant of the final product since these seeds are processed into dry beans for sale (Carvalho et al., 2001). Typically, fresh cocoa is converted to dry cocoa using a CF of 40% (Almeida et al., 2009). However, in this study, significant CF differences were observed among cultivars (Table 4), directly affecting production estimates. Therefore, using clone-specific CF values is necessary for precise yield predictions.

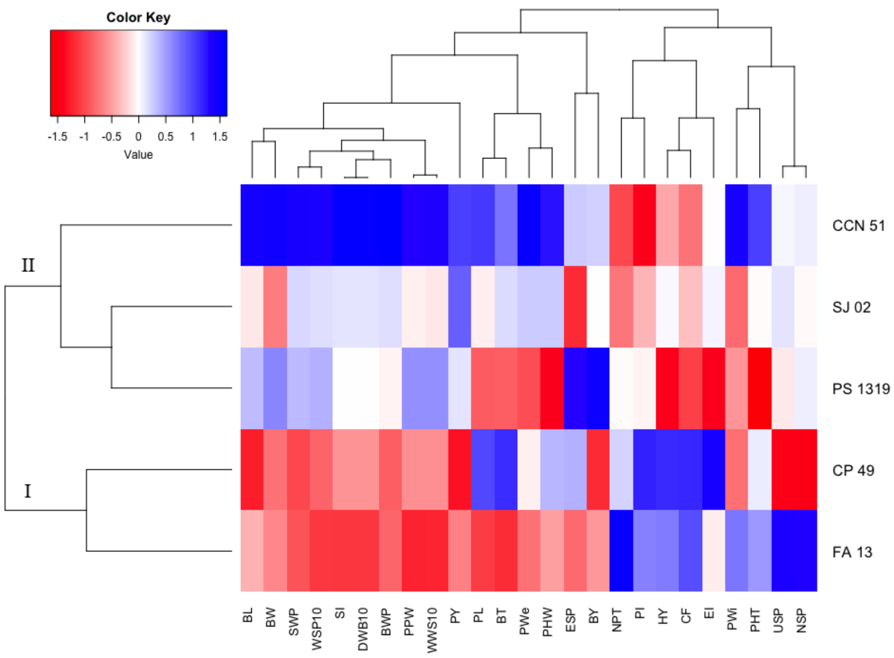
The BWP is obtained by multiplying SWP by CF. For example, CCN 51 recorded an SWP of 194.9 g and a CF of 0.39 (Table 4), resulting in a BWP of 76.01 g. CCN 51 showed the highest SW and DW values, statistically different from those of the other clonal cultivars (Table 4).

Significant differences were also observed among cultivars for NSP, ESP, and USP (Table 4). However, within each cultivar, no significant variation occurred between NSP and USP, despite differences in ESP. SJ 02 stood out with the lowest ESP value.

CCN 51 had the lowest PI, requiring fewer pods to produce 1 kg of cocoa beans compared to SJ 02, PS 1319, FA 13, and CP 49 (Table 4). All cultivars presented SI values above 1 g, ranging from 1.1 g in FA 13 to 1.6 g in CCN 51, meeting the industry standard of bean weights over 1 g (Ahnert et al., 2018). DuVal et al. (2017) also reported a wide PI range among regions.

Complex interactions were observed among SI, NSP, and NPT. FA 13 had the highest NSP (48.1), significantly different from the other cultivars. However, larger seeds did not necessarily result in higher pod production; in fact, an inverse relationship emerged, where higher SI corresponded to lower NPT. The highest NPT values, in decreasing order, were found in FA 13, CP 49, PS 1319, SJ 02, and CCN 51. NPT is strongly influenced by indirect factors such as pod and seed weight, with temporal variations in these interactions (Dessauw et al., 2024). Phytosanitary management also plays a direct role in determining the number of healthy pods (Dessauw et al., 2024). Despite significant differences among clones, some quantitative morpho-agronomic descriptors may not consistently differentiate genotypes due to polygenic control (Bartley, 2005; Maharaj et al., 2019; Ngidi et al., 2024). Dias & Resende (2001) identified PI, SI, NSP, and NPT as key traits for cocoa producers.

The hierarchical clustering analysis presented in the heatmap (Figure 2) highlights consistent variation patterns



BL - Bean length; BW - Bean width; SWP - Wet seed weight per pod; WSP10 - Weight of 10 seeds with pulp; SI - Seed index; DWB10 - Dry weight of 10 beans; BWP - Dry bean weight per pod; PW - Placenta weight; WWS10 - Wet weight of 10 seeds; PY - Pulp yield; PL - Pod length; BT - Bean thickness; PWe - Pod weight; PHW - Pod husk weight; ESP - Empty seeds per pod; BY - Bean yield; NPT - Number of pods per tree; PI - Pod index; HY - Husk yield; CF - Conversion factor; EI - Efficiency index; PWi - Pod width; PHT - Pod husk thickness; USP - Usable seeds per pod; NSP - Number of seeds per pod

Figure 2. Dendrogram with heatmap of 25 pod and seed/bean morpho-agronomic traits of 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA

among cacao clones and the morpho-agronomic traits evaluated. The central panel shows a color gradient from –1.5 (red, strong negative association) to +1.5 (blue, strong positive association), providing a quantitative interpretation scale. The top and side dendrograms represent cluster analyses based on Euclidean distance as the similarity measure.

Regarding clones, FA 13 and CP 49 showed the greatest overall similarity according to the cluster analysis, being grouped in Group I (Figure 2). These clones recorded the lowest means for most traits, including BL, BW, SWP, SI, BWP, BY, and PY, corroborating Table 4. In contrast, SJ 02 and PS 1319 formed Group II, characterized by greater similarity in traits associated with PY. Although CCN 51 clustered closer to SJ 02 and PS 1319, it remained more distant from CP 49. The heatmap clearly showed the strong positive association of CCN 51 with seed and pod size and weight traits. For FA 13, the strong positive association with NSP and NPT was evident, highlighting the inverse relationship between FA 13 and CCN 51.

The trait most similar to NPT was PI. In contrast, NSP showed low similarity with SI and BWP, but clustered with PHT, PWi, EI, CF, HY, PI, and NPT, reflecting a pattern of association among these traits, strongly positively associated with FA 13. Clones such as CCN 51 and SJ 02, with higher SI values and lower PI - commercially desirable attributes - showed lower NPT, reinforcing the inverse relationship between seed size and pod number (Figure 2).

HY demonstrated greater similarity with CF and EI (Figure 2), indicating that these traits jointly contribute to the potential yield of dry beans. DWB10 was the trait most similar to SI, which is consistent with the fact that SI is calculated using bean weight. The clustering and greater similarity among most of the seed and bean traits suggest that these variables exhibit similar behavior among clones, a pattern that also extends to other traits related to bean measurements. Only BT was less similar to the other seed traits, clustering instead with PL, PHW, and PWe. This grouping showed a positive association with CCN 51, SJ 02, and CP 49, and a negative association with FA 13 and PS 1319. These patterns illustrate how clones with larger seeds and pods tend to allocate resources differently from those with smaller pods, thinner seeds, and a higher pod number, resulting in distinct yield strategies.

PCA allowed the identification of differentiation and associations among clonal cultivars in relation to pod and seed/bean traits (Table 5). PCA is a dimensionality reduction technique that improves interpretability and minimizes information loss in large datasets (Jolliffe & Cadima, 2016). The first 3 PCs accounted for 72.69% of total variance: PC1 explained 37.94%, PC2 added 21.26% (cumulative 59.21%), and PC3 contributed 13.48%. This distribution indicates that most covariance among morpho-agronomic and yield traits is captured by the first 2 axes, enabling substantial dimensionality reduction with minimal information loss.

The loadings of the most representative variables in the first 3 PCs summarized most of the covariance between morpho-agronomic and yield traits (Table 5). Each coefficient reflects the correlation between the original variable and the component; higher absolute values indicate greater contribution to that axis. The sign of the loadings reveals the direction of variation relative to the component score. In PC1, for example, positive loadings for PWe (+0.69) and PPW (+0.92) indicate that clones with high scores on this axis tend to have heavier pods, while negative loadings for PI (–0.74) and NPT (–0.54) indicate that these same clones produce fewer pods per tree and larger pods, requiring fewer fruits to produce 1 kg of dry beans. In PC2, positive loadings for PL (+0.66), PHT (+0.67), and PHW (+0.70) contrast with a negative loading for YIELD (–0.54), indicating that larger pods with thicker husks are not necessarily associated with higher productivity (Table 5). The interpretation of these loadings allows identification of the variation gradients that distinguish the 5 clones evaluated.

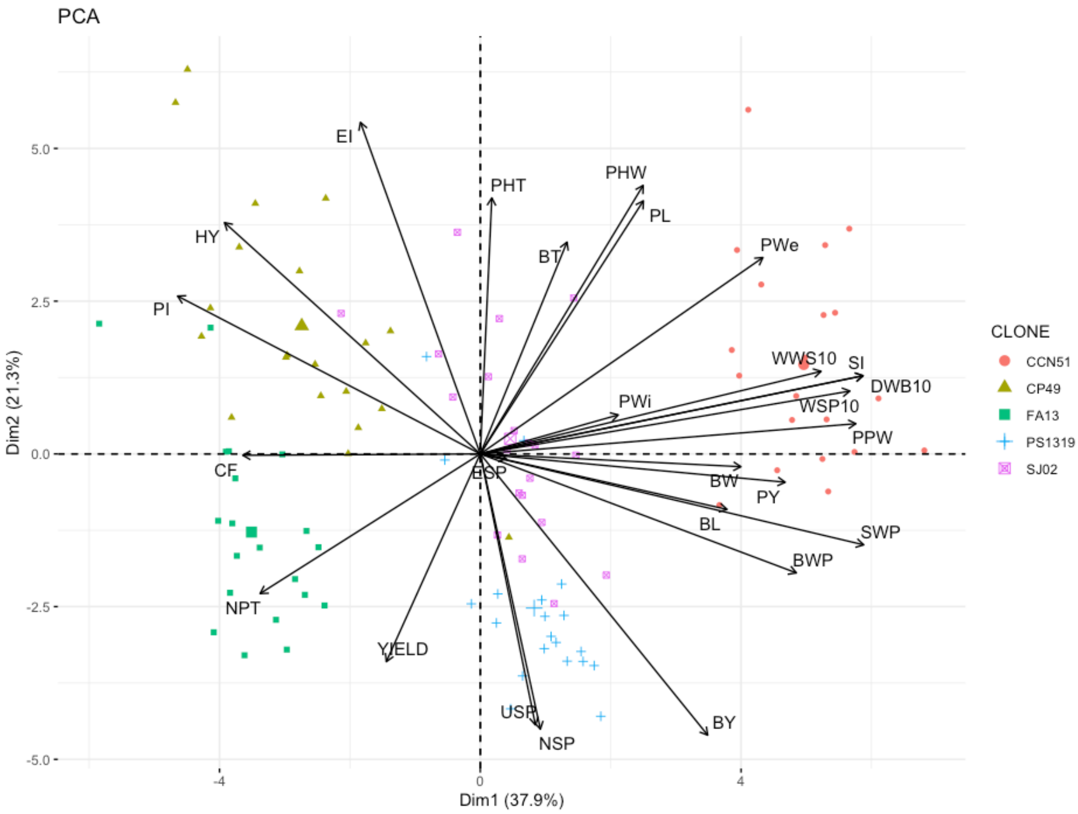
PC1 accounted for 38% of the variance and was driven by FA 13, CCN 51, and CP 49, influenced by traits such as NPT, PI, PWe, HY, and PPW. PC2 explained 21% of the variance, primarily associated with YIELD, PL, PHT, PHW, and HY. The PCA revealed a positive correlation between YIELD and NPT (Figure 3). YIELD exhibited a strong correlation with FA 13, which was further associated with NPT and CF. Conversely, YIELD showed negative correlations with BT, PL, PHW, PHT, and PWe.

CCN 51 demonstrated a strong association with seed weight traits, which correlated negatively with PI, CF, and HY — traits that were more closely associated with CP 49. PS 1319 and SJ 02 exhibited intermediate values, with lower variability and contributions to the total variation compared with the other clones. However, PS 1319 showed a strong positive association with NSP, which in turn displayed a strong negative correlation with EI. Specifically, PS 1319 required 9.81 g of pod weight to produce 1 g of dry beans, indicating exceptional dry matter conversion efficiency and highlighting the discriminative capacity of the pod EI. Dias & Resende (2001) reported EI values of 13.0 and 15.1 g for cultivars from the Amelonado and Forastero Amazon racial groups, respectively.

Table 5. Principal components obtained from the correlation of morpho-agronomic characteristics and yield of 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13 — in a farm field trial in southern Bahia, Brazil

	PC1	PC2	PC3
Eigenvalues	9.87	5.53	3.51
Variance (%)	37.94	21.26	13.48
Cumulative (%)	37.95	59.21	72.69
NPT	-0.54	-0.36	0.20
PI	-0.74	0.41	-0.45
YIELD	-0.23	-0.54	0.37
PL	0.40	0.66	0.37
PWi	0.34	0.10	0.47
PWe	0.69	0.51	0.46
PHT	0.03	0.67	0.46
PHW	0.40	0.70	0.55
HY	-0.62	0.60	0.36
PPW	0.92	0.08	-0.18
CCN 51	4.96	1.46	0.93
CP 49	-2.74	2.09	0.48
FA 13	-3.51	-1.28	1.08
PS 1319	0.83	-2.52	-2.35
SJ 02	0.46	0.25	-0.13

NPT - Number of pods per tree; PI - Pod index; YIELD - Yield; PL - Pod length; PWi - Pod width; PWe - Pod weight; PHT - Pod husk thickness; PHW - Pod husk weight; HY - Husk yield; PPW - Pod placenta weight; PC1 - Principal component 1; PC2 - Principal component 2; PC3 - Principal component 3



BL - Bean length; BW - Bean width; BT - Bean thickness; BWP - Dry bean weight per pod; BY - Bean yield; CF - Conversion factor; DWB10 - Dry weight of 10 beans; EI - Efficiency index; ESP - Empty seeds per pod; HY - Husk yield; NPT - Number of pods per tree; NSP - Number of seeds per pod; PI - Pod index; PHW - Pod husk weight; PHT - Pod husk thickness; PL - Pod length; PPW - Pod placenta weight; PWe - Pod weight; PWi - Pod width; PY - Pulp yield; SI - Seed index; SWP - Wet seed weight per pod; USP - Usable seeds per pod; WSP10 - Weight of 10 seeds with pulp; WWS10 - Wet weight of 10 seeds; YIELD - Yield

Figure 3. Principal component analysis (PCA) of 26 morpho-agronomic traits of pods, seeds/beans, and yield of 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13

Although cocoa bean weight is often underemphasized in breeding programs, it remains a critical trait due to its high heritability (Doaré et al., 2020). In the study by Doaré et al. (2020) involving 7 clonal cultivars, the average weight of a seed with pulp was 5.64 g for CCN 51. In the present study, this trait, labeled WWS10, ranged from 2.3 g in FA 13 to 4.3 g in CCN 51 (Table 4). However, WWS10 did not correlate with YIELD, but showed significant associations with SI and BWP, and a negative correlation with CF, NPT, and PI (Figure 3). Similarly, Trinitario cacao cultivars have shown a significant negative correlation between seed mass and seed number (Bekele et al., 2019). Such variability may be influenced by genetic factors, pod position, and fruiting cycle duration, all of which affect seed filling and weight (Doaré et al., 2020).

Based on the cluster analysis (Figure 2) and PCA (Figure 3), although PI exhibited greater similarity with NPT - a trait considered critical for selecting cacao cultivars (Dias & Resende, 2001) - no significant correlation was observed between them. This suggests a deviation from typical selection methods, indicating an inverse relationship between SI and NPT (Figure 2). Furthermore, YIELD was more strongly correlated with NPT and NSP (Figure 3), which contrasts with the usual trend in which higher pod production reduces seed numbers due to internal competition for photoassimilates (Dias & Resende, 2001). The clustering of NPT with traits such as PI, HY, CF, EI, PWi, PHT, and NSP highlights alternative characteristics that may influence BY (Figure 2), alongside other traits also showing significant correlations with productivity (Figure 3). These findings indicate that productivity is more strongly associated with NPT and NSP, suggesting that PI is not the primary determinant of production.

Guimarães et al. (2022) reported the highest significant correlations between the number of healthy pods and both the average SWP and the average seed weight. Similarly, Sodré & Nery (2023) proposed that the relationship between pod mass and cocoa bean mass, expressed as the EI, is a more appropriate indicator of cacao production. Advances in Quantitative Trait Loci (QTL) mapping have further highlighted the genetic influence on production components, with candidate genes identified that are involved in various stages of pod development and seed filling (Fernandes et al., 2020).

The heatmap generated from sensory evaluation data revealed distinct patterns in quality ratings (Figure 4). The top section illustrates the similarity between the clonal cultivars, while the side indicates the similarity between sensory characteristics. The upper scale shows global quality scores ranging from 5.0 to 7.5. Red tones represent strong positive correlations, whereas blue tones indicate strong negative correlations. Warmer colors correspond to higher scores, and cooler blue tones correspond to lower ratings. PS 1319 and SJ 02 exhibited superior quality and greater similarity, clustering together with fruity, floral, and spicy flavor profiles. PS 1319 had the sweetest flavor, while SJ 02 was characterized by a cocoa flavor. Despite being in the same cluster, CP 49 showed greater bitterness and a less pronounced cocoa flavor. CCN 51 and FA 13 were the most similar in sensory attributes, both

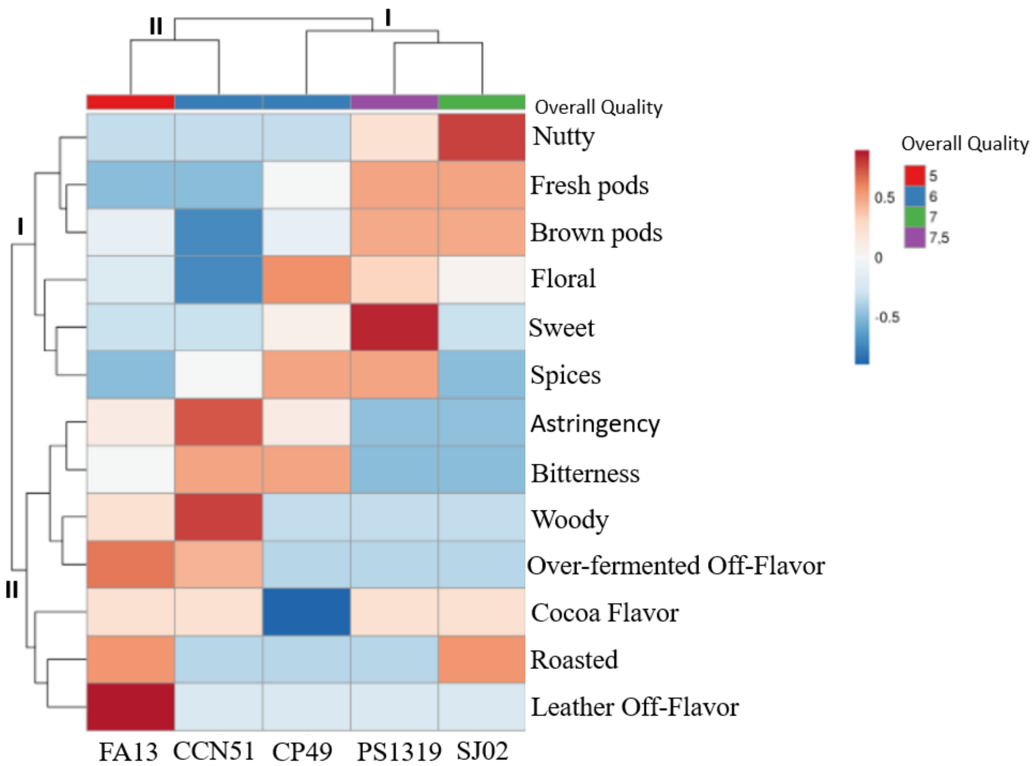


Figure 4. Dendrogram and heatmap of 14 sensory evaluation traits in 5 cacao clonal cultivars — CCN 51, PS 1319, SJ 02, CP 49, and FA 13

receiving lower scores. CCN 51 was noted for its bitterness and astringency, while FA 13 obtained the lowest score due to over-fermentation and off-flavor characteristics. Other quality parameters — such as moisture content, mold incidence, bean color, pH, titratable acidity, fat content, and acetic acid concentration — are also widely evaluated (Dzelagha et al., 2020).

FA 13 showed higher productivity and excelled in several morpho-agronomic traits; however, it ranked lowest in quality (Figures 3 and 4), receiving the poorest overall score due to undesirable off-flavors, likely resulting from inadequate fermentation. Reges et al. (2021) suggest that selection criteria such as SI should be considered for fermentation suitability, which aligns with this study's finding of FA 13's low SI performance. The interaction between productivity and traits such as BT, SI, and sensory characteristics indicates a trade-off between pod and seed quality and quantity. This raises an important question for cocoa breeding: should productivity be prioritized over bean quality traits? More productive cultivars, such as FA 13, may present inferior sensory qualities — an issue critical to the sustainability of the cocoa value chain, where bean quality directly impacts market value.

Cuellar et al. (2023) argue however that fermentation techniques have a greater influence on quality than SI. Further research is needed to evaluate processing methods tailored to specific cultivars. In CCN 51, fermentation was shown to influence the production of desirable volatile compounds more than drying, with four days of box fermentation followed by five days of natural sun drying recommended to enhance aroma precursors (Pallares-Pallares et al., 2016). Similarly, Santander et al. (2021) demonstrated that controlled fermentation using acetic and lactic acid reagents enhanced fine aromatic notes - such as fruity, nutty, and floral - in chocolates made from FEAR 5 and CCN 51 compared to spontaneous fermentation. Adopting modified or non-conventional processing techniques is essential to optimize the preservation and utilization of beneficial bioactive compounds in cocoa beans (Febrianto et al., 2021).

The growing market demand for both quantity and quality underscores the need for research aimed at improving productivity alongside bean attributes. Post-harvest and processing technologies remain significant challenges in the cocoa production chain in Bahia (Ahnert & Eskes, 2018). Furthermore, there is limited understanding of the complex relationships between bean and pod husk biomass and soil-plant mineral nutrition, particularly regarding their multifaceted interactions (Quintino et al., 2020).

Conclusions

1. Morpho-agronomic characterization revealed significant differences among the evaluated clones. FA 13 stood out for its higher number of seeds per pod (NSP) and number of pods per tree (NPT), traits that showed a stronger correlation with yield, whereas pod and seed indices exhibited low correlation with productivity.

2. CCN 51 was notable for its larger pod and seed size and weight but showed lower productivity, being surpassed in pod production by the Brazilian clones FA 13, PS 1319, SJ 02, and CP 49.

3. PS 1319 and SJ 02 showed strong performance in sensory quality and pulp content, indicating potential for premium cocoa markets.

4. The results support recommending FA 13, PS 1319, and SJ 02 as promising clones for breeding programs and irrigated production systems in southern Bahia.

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