

Pods Filling in Natural Pollination of 10 Spontaneous Cocoa Trees from French Guiana

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Abstract

The study focuses on the filling of pods from ten cacao clones originating from French Guiana in Côte d'Ivoire. Two reference clones (IFC5 and NA32) were used as controls. The parameters studied include the number of ovules per ovary, the average number of beans per pod, the fresh bean weight, and the pod index. The aim was to evaluate the genetic variability and agronomic performance of these clones under natural pollination conditions. The results show significant genetic variability between the clones for all traits studied. The IFC5 clone, known for its excellent pod filling, exhibited the highest apparent fertility (0.91), while the GU183/A clone had the lowest filling (0.47). Three types of distributions of the number of beans per pod were identified: a right-skewed unimodal distribution, characteristic of well-filled clones; a left-skewed unimodal distribution, associated with poorly filled clones; and an intermediate bimodal distribution. These differences could be related to pollination compatibility and the availability of compatible pollen. Regarding the fresh bean weight and pod index, the GU183/A clone stood out with the heaviest beans (3.27 g) but had a high pod index (49.58), indicating relatively low productivity. None of the Guyanese clones achieved the filling level of the IFC5 clone, although some surpassed the NA32 control. This study highlights the importance of apparent fertility and the number of beans per pod as essential criteria for cacao genetic improvement programs. The authors recommend extending research to a larger number of Guyanese clones and exploring complementary traits, such as the influence of pollination type and intergroup compatibility.

Keywords

Theobroma cacao, *Phytophthora*, Pod Index, Apparent Fertility

1. Introduction

Black pod rot is one of the main threats to global cocoa production, causing losses of up to 60% of the annual crop in endemic areas. This issue is especially problematic for cocoa-producing countries in West Africa, which supply over 70% of the world's cocoa. The search for sustainable solutions against this disease has led breeders to conduct surveys in the regions where cocoa originated. Four surveys conducted in southeastern French Guiana [1] identified “wild” genetic material belonging to the “Guiana” group [2]. A large number of samples were collected and distributed to cocoa-producing countries, with about a hundred samples sent to Côte d'Ivoire.

Numerous studies have been conducted on these clones, mainly to provide breeders with essential data. These studies on a large population of Guyanese clones revealed significant genetic variability in agronomic traits such as vigor, early maturity, yield, pod size [3] [4], as well as morphological and organoleptic characteristics of the beans [5]. Additionally, evaluations of disease and pest resistance have shown high resistance potential to *Phytophthora* spp. [6] and mirids. However, certain agronomic criteria, such as seed filling and pod index, have not been sufficiently studied.

Considering the proven performance of Guiana clones, their use as parents in breeding program would be beneficial for improving progenies. However, the study of certain characteristics of the pods and seeds from these crosses is essential to deepen the understanding of Guyanese clones. This study aims to evaluate, in Côte d'Ivoire, the pods filling under natural pollination of ten Guiana clones whose resistance to *P. palmivora* has been confirmed in the laboratory.

2. Material and Methods

2.1. Geographical Location of the Study Area

The study was conducted in the Loh-Djiboua region, specifically in the Divo department, at the research station of the National Center for Agronomic Research (CNRA) (5.769814 N, 5.236746 W), Côte d'Ivoire. This station records average annual maximum and minimum temperatures of 31.6°C (± 0.9)°C and 21.7°C (± 0.8)°C, respectively, as well as an average annual precipitation of 1229 (± 194) mm, based on local meteorological data collected from 1972 to 2019. Rainfall follows a bimodal distribution, with peaks in June and October, a short dry spell in August, and a main dry season from December to early March [7].

2.2. Plant Material

The plant material studied comprises 12 clones:

- 10 Guiana clones derived from wild mother plants collected in French Guiana were selected for their excellent performance in the resistance test against *Phytophthora palmivora* through leaf disc inoculation at the CIRAD laboratory in Montpellier: GU 133/1, GU 144/B, GU 257/A, GU 322/B, GU 125/G, GU 114/F, GU 154/B, GU 255/K, GU 307/F, GU 183/A. These clones were introduced to

Côte d'Ivoire in 1987 [8] and planted based on the availability of graft wood in two collections, B8 and A21. The trees in these collections had between 1 and 5 trees each.

- 2 Forastero clones used as controls: the Upper Amazonian NA32 clone, known for its incomplete pod filling, and the local Amelonado IFC5 clone, characterized by excellent pod filling.

2.3. Methods

The study was conducted from September to January the main harvest period in Côte d'Ivoire during the 2012-2013. Seven variables were studied on samples of 20 to 60 pods per clone.

2.3.1. Bean-to-Pod Ratio

Mature pods were harvested from each clone and opened with a club to count the number of normal beans (Nfn) in each pod.

2.3.2. Number of Ovules Per Ovary

Twenty flowers per clone were used to determine the average number of ovules per ovary. Flowers were collected directly from the trees and preserved in 70°C alcohol. Afterward, the flowers were stripped of their sepals and petals, boiled for one minute at 100°C, and one carpel chamber was dissected. The number of ovules in the chamber was determined under a binocular microscope. Since the cocoa flower is pentamerous, the number of ovules in the chamber was multiplied by 5 to obtain the total number of ovules per flower [9].

2.3.3. Apparent Fertility

For a given clone, apparent fertility (Fa) is defined as the ratio of the average number of normal beans (Nfn) per pod to the average number of ovules per ovary (Nov). This parameter indicates the pod filling level of a clone. According to the scale used in Côte d'Ivoire, a Fa above 0.80 indicates well-filled pods, while a Fa below 0.60 indicates poorly filled pods [10].

2.3.4. Determination of Average Fresh Bean and Commercial Bean Weight

The average fresh bean weight (Nfn) was determined using at least 20 healthy, mature pods per clone. The day after harvesting, the pods were opened, and the beans were weighed using a Sartorius scale (0.01 g accuracy) in batches of 30 normal beans per pod. The fresh beans from the pods of each clone were placed in labeled mesh bags and stored in fermentation boxes for 7 days. After fermentation, the beans were sun-dried for eight days to produce marketable cocoa beans. The marketable cocoa beans were then weighed in batches of 100, and the average weight of 100 beans (P100F) was calculated from at least 10 batches per clone.

2.3.5. Seed Grading and Pod Index

Seed grading studies the size of marketable cocoa beans. For each clone, seed grading was determined by the number of beans per 100 g of commercial cocoa beans (Nmf100g).

The pod index is a quantitative measure used to assess the productivity of cocoa clones. It represents the number of pods necessary to harvest 1 kg of commercial cocoa beans. A lower pod index is considered advantageous, as it indicates that a clone produces more beans per pod, thereby enhancing overall production efficiency.

The pod index (PI) calculated using the formula:

$$PI = \frac{1000 \times 100}{P100F \times Nfn}$$

With

P100F = Average weight of 100 bean.

Nfn = Number of normal bean.

2.3.6. Statistical Analysis

The statistical analyses included the use of SAS 9.4 software [11] to evaluate the significance of mean differences among clones for the traits studied. Pairwise comparisons of means were performed at a 5% significance level using the Newman-Keuls test, which also grouped clones into homogeneous categories for each trait.

Multivariate analyses were conducted to explore relationships between variables and similarities among clones. Principal Component Analysis (PCA) was used to reduce correlated variables into independent components, enabling the identification of traits contributing most to differentiation. Discriminant Factor Analysis (DFA) assessed significant differences among predefined groups and identified the variables that best characterized these differences, while also classifying ungrouped individuals.

The distribution of bean numbers in the pods of each clone was observed from histograms created using the ggplot package in the R software [12].

3. Results

3.1. Pod Filling Study

Pod filling was studied through three parameters: the average number of normal beans per pod, the average number of ovules per ovary, and apparent fertility. A significant clone effect ($p < 0.0001$) was observed for the three traits studied (**Table 1**).

Table 1. Ranking of clones based on the number of normal beans, the number of ovules per ovary, and apparent fertility.

Clones	Number of normal bean	number of ovules per ovary	Apparent Fertility
NA32	30.42 ± 9.07 bc	58.25 ± 0.49 a	0.52 ± 0.16 ed
GU257/A	35.89 ± 10.44 ab	53.75 ± 0.72 b	0.66 ± 0.19 bcd
GU144/B	28.30 ± 12.05 cd	44.5 ± 1.02 ef	0.63 ± 0.27 bcd

Continued

GU154/B	26.05 ± 8.98 cd	47.75 ± 0.76 cd	0.54 ± 0.19 ed
GU183/A	21.50 ± 10.18 d	46 ± 0.41 ed	0.47 ± 0.22 ± e
GU307/F	26.45 ± 12.59 cd	47.75 ± 0.51 cd	0.55 ± 0.26 cde
GU114/F	36.77 ± 9.39 ab	48.33 ± 0.49 cd	0.76 ± 0.19 b
GU322/B	29.97 ± 9.87 bc	49 ± 0.41 cd	0.61 ± 0.20 bcd
GU255/K	33.21 ± 8.10 abc	47.10 ± 0.61 d	0.70 ± 0.17 bc
GU125/G	28.28 ± 8.93 dc	44.25 ± 0.81 ef	0.64 ± 0.20 bcd
IFC5	38.8 ± 4.77 a	44.25 ± 0.69 f	0.91 ± 0.11 a
GU133/1	30.26 ± 11.54 bc	50.75 ± 0.81 c	0.61 ± 0.21 bcd
Mean	31.19	47.9	0.64
CV (%)	31.89	7.2	31.2

Means followed by the same letters within the same column are not significantly different at the 5% threshold according to the SNK test.

Regarding the average number of normal beans per pod, the IFC5 clone ranks first with approximately 39 beans, followed by clones GU 114/F (36.8 beans), GU 257/A (35.9 beans), and GU 255/K (33.2 beans). Clone GU183/A ranks lowest with 21.50 beans. Most Guyanese clones have fewer normal beans per pod than the NA32 control clone, with only three Guyanese clones having a higher bean count than NA32.

Concerning the average number of ovules per ovary, NA32 ranks first with 58.25 ovules, followed by clones GU 257/A (57.7 ovules), GU 133/1 (50.7 ovules), and GU 322/B (49 ovules). IFC5 has the lowest ovule count at 44.25.

IFC5 stands out with an apparent fertility of 0.91, far exceeding other clones. It is followed by clones GU 114/F (0.76) and GU 255/K (0.70), with apparent fertility equal to or above 0.70. Clone GU 183/A has the lowest fertility at 0.47. Six Guyanese clones (GU 257/A, GU 144/B, GU 322/B, GU 255/K, GU 125/G, and GU 114/F) have higher apparent fertility than the NA32 control clone. Based on apparent fertility values, the 12 clones studied are classified into 3 groups:

- **Group 1:** GU 114/F, and GU 255/K, characterized by excellent or good filling with apparent fertility values between 0.96 and 0.76.
- **Group 2:** GU 183/A with very poor filling and apparent fertility of 0.47.
- **Group 3:** GU257/A, GU 144/B, GU 154/B, GU 307/F, GU 322/B, GU 125/G, and GU 133/1, with apparent fertility ranging from 0.52 to 0.66, indicating incomplete filling.

3.2. Fresh Bean Weight, Seed Grading, and Pod Index

Variance analysis on fresh bean weight, seed grading, and pod index showed a significant clone effect ($p < 0.0001$) for each of these variables. The coefficient of variation (CV) was high for fresh bean weight (20.35%) and pod index (28.22%) but low for seed grading (5.21%) (**Table 2**).

Table 2. Ranking of clones based on weight of a fresh bean. Number of beans per 100 g. and Pod Index.

Clones	Weight of a fresh bean (g)	Number of beans per 100 g	Pod Index
GU114/F	2.70 ± 0.60 bcde	111.85 ± 6.02 a	32.81 ± 11.79 abc
GU125/G	2.38 ± 0.43 ed	104.21 ± 2.42 ab	42.11 ± 19.79 abc
GU133/1	2.34 ± 0.65 e	104.31 ± 7.28 ab	55.16 ± 103.54 a
GU144/B	2.68 ± 0.50 bcde	95.12 ± 3.04 b	42.53 ± 23.49 abc
GU154/B	3.06 ± 0.37 ab	84.33 ± 0.58 c	36.91 ± 14.74 abc
GU183/A	3.27 ± 0.54 a	84 c	49.58 ± 25.58 a
GU255/K	2.77 ± 0.39 bcd	102.61 ± 3.71 ab	33.57 ± 12.48 abc
GU257/A	2.66 ± 0.61 cde	96.79 ± 8.85 b	29.71 ± 14.78 bc
GU307/F	2.81 ± 0.54 bc	95.20 ± 1.30 b	47.91 ± 28.17 ab
GU322/B	2.61 ± 0.63 cde	96.87 ± 1.46 b	37.92 ± 18.18 abc
IFC5	2.50 ± 0.33 cde	100.33 ± 2.52 b	26.14 ± 3.24 bc
NA32	2.76 ± 0.50 bcd	112 ± 4.24 a	39.85 ± 15.83 abc
Mean	2.64	101.83	39.53
CV (%)	20.35	5.21	28.22

Means followed by the same letters within the same column are not significantly different at the 5% threshold according to the SNK test.

Fresh bean weight ranged from 2.34 g to 3.27 g, with an overall average of 2.64 g. Clone GU183/A had the heaviest beans, followed by clones GU154/B (3.1 g), GU 307/F (2.81 g), and GU 125/G (2.77 g). Clone GU133/1 ranked lowest at 2.34 g.

In terms of seed grading (measured by the number of beans per 100 g of commercial cocoa beans), the best clone was GU 183/A, requiring only 84 beans to reach 100 g of cocoa, followed by clones GU 154/B (84.33 beans), GU 144/B (95.12 beans), and GU 257/A (96.8 beans).

For the pod index, the IFC5 and GU257/A clones are the best, with pod index values of 26.14 and 29.71 pods, respectively. They are followed by the GU 114/F (32.8 pods), GU 255/K (33.6 pods), and GU 154/B (36.9 pods) clones.

3.3. Bean Distribution per Pod

Various distributions of bean count per pod were observed. Clones IFC 5, GU114/F, GU255/K, GU257/A, GU133/1, and GU125/G show a right-skewed monomodal distribution (**Figure 1**). Clone GU183/A has a left-skewed monomodal distribution (**Figure 2**), while NA32, GU144/B, GU154/B, GU307/F, and GU322/B display a bimodal distribution (**Figure 3**).

3.4. Correlation between the Different Variables

The number of principal components (axes) was set to 2 based on eigenvalues

greater than or equal to 1. The cumulative information captured by these two axes explained 80.66% of the total variability (**Figure 4**).

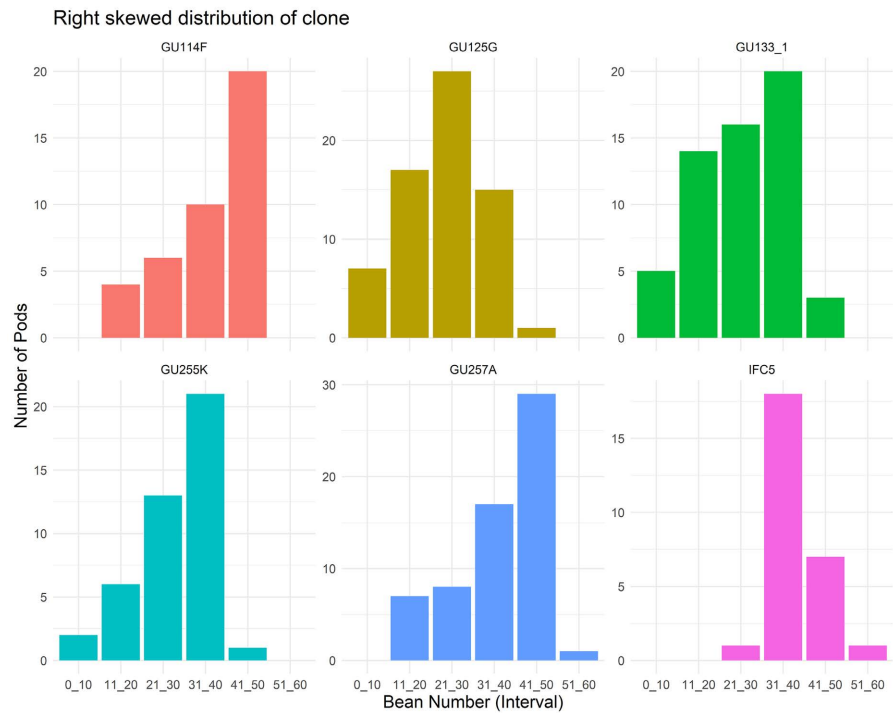


Figure 1. Distribution of the number of beans per pod for 6 clones showing right-skewed distributions.

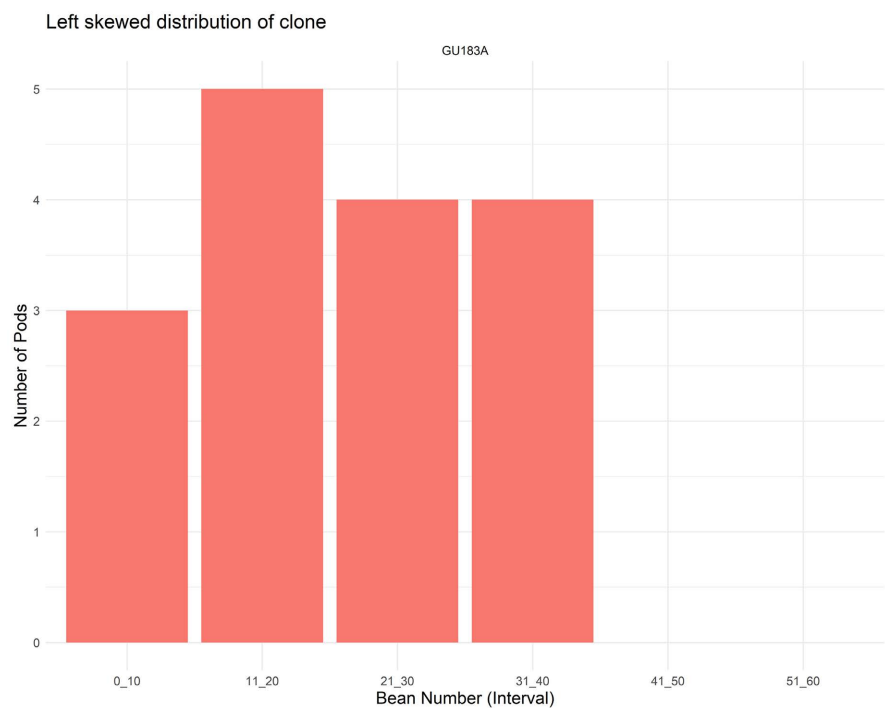


Figure 2. Histograms of the number of beans per pod for 6 clones showing a left-skewed distribution (GU 183/A).

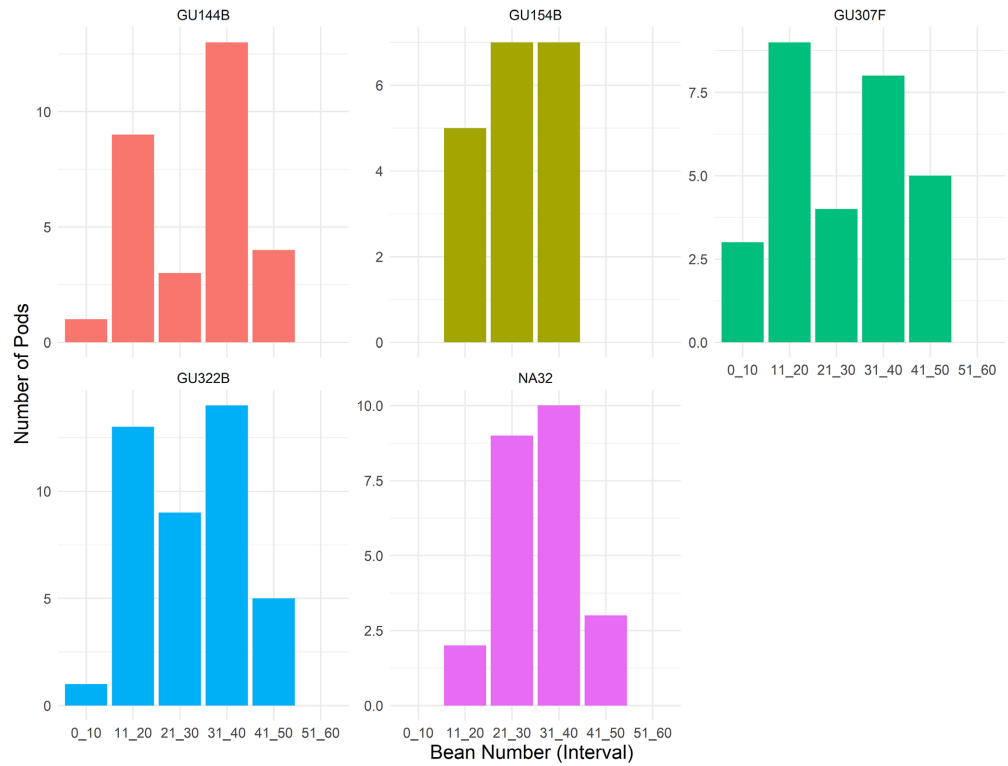


Figure 3. Histograms of the number of beans per pod for 6 clones showing a bimodal distributions.

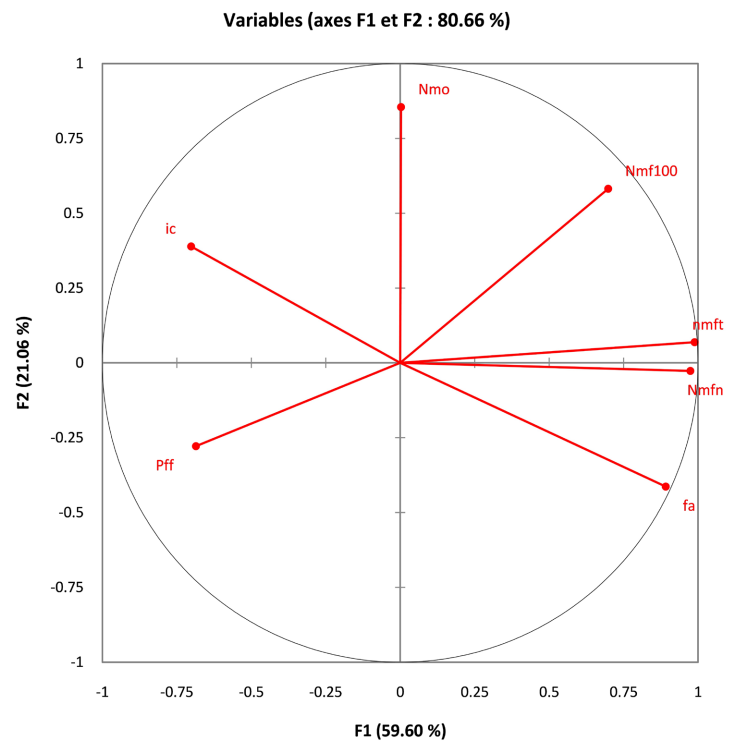


Figure 4. Correlation circle (variables/factors) from PCA showing the representativeness of variables on axes F1 and F2.

The first component (F1), which accounts for 59.59% of the total variability, is the most significant for characterizing the clones. The variables contributing most to this axis, in order, are the total average number of beans (Nmft), the average number of normal beans (Nmfn), apparent fertility (Fa), pod index (IC), the number of beans per 100 g of processed cocoa (Nmf100g), and the weight of a fresh bean (Pff).

The second component (F2), which represents 21.06% of the variability, is primarily defined by the average number of ovules per ovary (Nmo) and the number of beans per 100 g (Nmf100g).

PCA revealed the degree of similarity among variables. Based on this, the variables were grouped into two main clusters around the synthetic factors represented by the axes.

3.5. Distribution of Groups of Individuals Based on Different Variables

A Discriminant Factor Analysis (DFA) was performed on the 12 clones using the variables applied in the PCA. This analysis allowed us to model group membership of individuals based on the values of these variables and to determine the most probable group for each clone, given only the values of the variables characterizing them. Thus, the following three groups were defined (**Figure 5**):

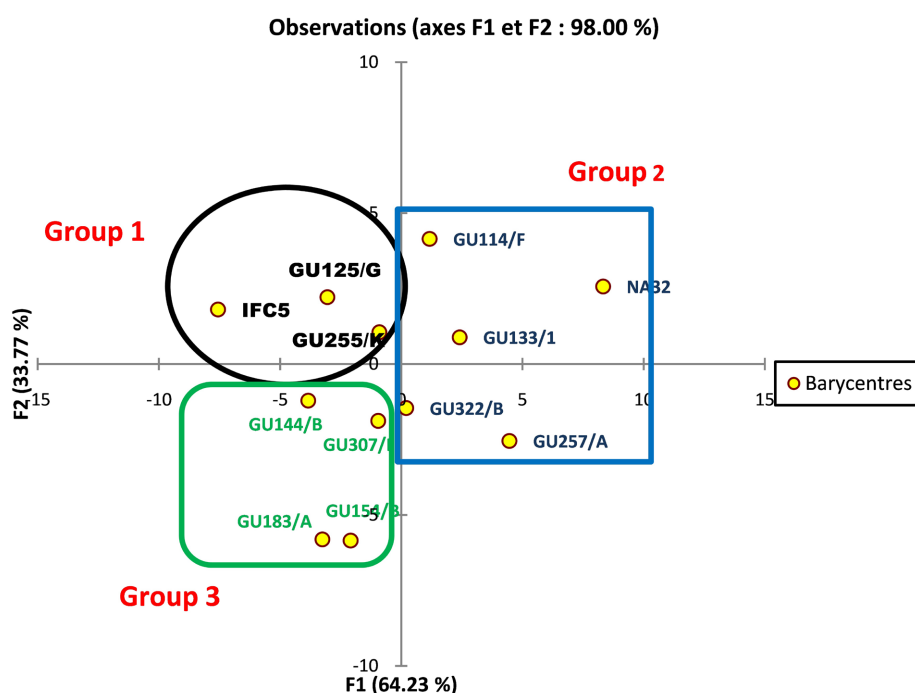


Figure 5. Distribution of clones in the F1 × F2 Cartesian plane (98% of total variability).

- Group 1, composed of clones IFC5 (control), GU 125/G, GU 144/B, and GU 255/K, is distinguished by a low pod index.

- Group 2, composed of clones GU 114/F, GU 133/1, GU 257/A, GU 322/B, and NA32 (control), is characterized by a high number of normal beans per pod, good bean size, and moderate apparent fertility.
- Group 3, composed of clones GU 144/B, GU 307/F, GU 154/B, and GU 183/A, is characterized by a high fresh bean weight and good bean size.

4. Discussion

Ten cocoa tree clones from the Divo Station, of Guyanese origin and resistant to *Phytophthora*, were characterized for pod filling, bean size, and pod index. Two reference clones were used as controls: the Amelonado IFC5, known for its excellent pod filling with an apparent fertility of about 0.90, and the Upper Amazon Forastero NA32, a clone considered underfilled in Côte d'Ivoire, with an apparent fertility of 0.65 [13].

The results of the apparent fertility study indicated an average apparent fertility of 0.62 for the ten Guyanese clones (with extremes of 0.47 and 0.76). Referring to the scale used in Côte d'Ivoire ($*Fa^* < 0.60$ = poorly filled clone, $*Fa^* > 0.80$ = well-filled clone), only three Guyanese clones (GU 154/B, GU 183/A, and GU 307/F) exhibited poor pod filling, with apparent fertility values between 0.47 and 0.54. This was also true of the NA 32 control, whose apparent fertility (0.52) was below the average of the ten Guyanese clones (0.62).

In contrast, the clones GU 125/G, GU 255/K, GU 322/B, GU 114/F, GU 144/B, GU 257/A, and GU 133/1 were found to be better filled with seeds. Significant differences were also noted between the Guyanese clones regarding pod filling, a result previously highlighted by earlier studies on different populations of Guyanese clones (Lachenaud *et al.*, 2006).

Histograms of the number of seeds per pod were created to visualize the shape of distributions. On these histograms, three types of distributions associated with certain clones can be observed:

- A right-skewed unimodal distribution, with clones IFC 5, GU 114/F, GU 255/K, GU 257/A, GU 133/1, and GU 125/G;
- A left-skewed unimodal distribution, with the GU 183/A clone alone;
- An intermediate, more or less pronounced bimodal distribution, with clones NA 32, GU 144/B, GU 154/B, GU 307/F, and GU 322/B.

The clones with right-skewed distributions are those whose pods are well-filled with seeds [14]. This is the case for clones IFC5 or GU 114/F, which may have low self-incompatibility. The good pod filling of these clones could be due to a sufficient amount of compatible pollen, allowing effective flower pollination.

The clones with left-skewed distributions are those with poorly filled pods [14]. These clones, like GU 183/A, may be self-incompatible. Poor pod filling in these clones could be related to a deficiency of compatible pollen during the receptive period of the flowers. This assertion contrasts with Lachenaud [9] finding that in manual pollination, the genetic origin of pollen can influence the average number of seeds per pod, meaning that the sensitivity to poor filling of some clones, such

as Upper Amazonians, is not directly linked to their self-incompatibility. Other authors suggest that poor pod filling may increase with tree aging in sensitive clones [15]. Such observations are confirmed by Trebissou [16], who, suggest a relationship of this phenomenon with competition between trees and soil nutrient depletion.

The clones with relatively symmetrical distributions and a more or less pronounced bimodality have intermediate behavior. These clones, such as NA 32, GU 144/B, or GU 307/F, are also self-incompatible, but, unlike the previous group, their self-incompatibility may be overcome by the presence of compatible foreign pollen, as has been observed for some clones [17] [18].

Regarding the variables fresh bean weight, bean size, and pod index, clone GU183/A has the highest fresh bean weight (3.27 g) with excellent bean size (84 beans per 100 g of marketable cocoa) and a high pod index of around 50 pods. In contrast, clone IFC5, with an average fresh bean weight of 2.50 g and a bean size of 100.33 beans, has the most favorable pod index at 26 pods. This apparent “ambiguity” may be due to the number of beans in the pod: while clone GU 183/A has large beans that give it excellent bean size, unlike clone IFC5, its pods are under-filled (it has the lowest apparent fertility). Thus, our study highlights the importance of the number of beans per pod, an essential trait in cocoa production that is generally not considered a selection criterion in cocoa breeding programs.

Simultaneous consideration of all the studied variables through Discriminant Factor Analysis (DFA) allows the classification of the twelve (12) clones into three groups with similar characteristics. These include Group 1, composed of clones IFC5 (control), GU125/G, GU144/B, and GU255/K, which are distinguished by a low pod index; Group 3, composed of clones GU144/B, GU307/F, GU154/B, and GU183/A, notable for high fresh bean weight and good bean size. Group 2, which has characteristics more or less intermediate between those of the other two groups, includes clones GU 114/F, GU 133/1, GU322/B, and GU257/A.

5. Conclusions

The results obtained in this study have strengthened our understanding of parameters related to the pods of Guyanese clones present in Côte d’Ivoire, an essential condition for better orienting the selection of parent plants.

The study highlighted a clone effect for all the traits studied. In particular, poor pod filling is more pronounced in three Guyanese clones (GU 183/A, GU 154/B, and GU 307/F) compared to the NA 32 control. None of the ten Guyanese clones exhibited an apparent fertility close to that of the IFC5 clone, which confirmed in this study the excellent pod-filling characteristic attributed to it. Despite the limited number of Guyanese clones used in this study, significant genetic variability was revealed among the clones in this group, particularly in pod filling and the average number of beans per pod, two criteria whose importance for genetic improvement was underscored by this study.

The observed results also confirmed that the distribution of the number of

beans per pod does not follow a normal distribution for the different clones studied. Three types of distribution were identified:

- A right-skewed unimodal distribution (type 1);
- A left-skewed unimodal distribution (type 2);
- A more or less pronounced bimodal distribution (type 3).

The examination of these distributions indicates that type 2 corresponds to apparent fertility values below 0.6, and for higher values, the histograms evolve either toward type 1 or type 3 distributions.

6. Perspectives

This study was essential for gaining additional knowledge about ten Guyanese clones present at the Divo Station. However, it will need to be expanded in the future by examining new traits necessary to better explain certain phenomena for which divergent results have been reported by different authors. This will involve considering a larger range of Guyanese clones and focusing on the following aspects:

- The influence of pollination type (natural or manual) on pod filling;
- The compatibility of clones from different genetic groups, including Guyanese, in relation to the level of pod filling;
- The relationship between the incomplete filling of some clones and the percentage of flat beans.

As the Guyanese clones represent a particular genetic group that has already demonstrated resistance to many pests, it is now time to consider testing these clones against the Swollen Shoot disease, which currently poses a serious threat to the sustainability of cocoa cultivation in Côte d'Ivoire.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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