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Harvest-Dependent Variability in the Ripening and Fruit Characteristics of the Cenicafé 1 Variety of Coffee

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Abstract

The phenological responses of different progenies to the effect of ambient temperature on the duration of the fruit ripening cycle in *Coffea arabica* L. remain poorly understood. In this study, the ripening cycle in the coffee progenies of the Cenicafé 1 variety was recorded using the number of growing degree days during the main and secondary harvests. Concurrently, variables such as the number of fruits per node, firmness, diameter, volume, fresh mass, dry mass of the pericarp and bean, and the fruit respiration rate were measured. A semiparametric repeated-measures analysis of variance was used to assess inferential components, and Spearman's multiple correlations were used to examine the associations between variables. No significant differences were observed between the progenies for any variable. However, we detected differences between harvests in terms of the number of growing degree days, number of fruits per node, fruit firmness, fruit diameter, fruit fresh mass, and pericarp and grain dry mass. Furthermore, the correlation analysis revealed that the physical characteristics of the fruit exhibited the strongest associations among themselves. The absence of significant differences in the ripening cycle and fruit characteristics among the progenies may be attributed to their shared genetic origin. Finally, the observed change in the number of fruits per node between harvests directly influenced the physical characteristics of the fruits (diameter, volume, fresh mass, and pericarp dry mass), as the reduced physical space available for individual fruit growth when the node fruit load was higher limited their development.

Keywords: *Coffea arabica* L.; growing degree-days; fresh mass; dry mass; fruit load

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1. Introduction

Among the 124 species belonging to the genus *Coffea* [1], *Coffea arabica* L., a tetraploid, autogamous species adapted to altitudes above 1000 m, is responsible for 58% of global production, with Brazil (36%), Vietnam (18%), Colombia (8%), and Indonesia (6%) as the world's main producers [2]. In Colombia, *C. arabica* is cultivated between 0°55′22″ and 11°16′37″ north latitude and accounts for 842,420 hectares as of 2022; of these, 86% are

planted with improved varieties that are resistant to coffee leaf rust (*Hemileia vastatrix* Berk. & Broome) [3]. In Colombia, the "Colombia", Tabi, Castillo® General, Castillo® Regionales, Cenicafé 1, Castillo® Zonales, and Castillo® 2.0 varieties are composite, which means that they were developed by blending different progenies with comparable phenotypic and agronomic characteristics and possess different resistance mechanisms against coffee leaf rust [4,5].

One aspect to consider in these composite varieties is the duration of the ripening cycle, which is defined as the time in days elapsed from anthesis until the fruit reaches ripening, as this affects activities such as harvest scheduling, quality, and commercialization [6,7]. In *C. arabica*, the ripening cycle averages between 220 and 243 days after flowering (DAF) [8–13]. However, environmental conditions can cause the cycle duration to fluctuate between 204 and 266 DAF for a given cultivar [14]. Another factor affecting ripening cycle duration is the genotype, with differences exceeding 30 days between early- and late-ripening cultivars [12,15,16].

Moreover, the relationship between the plant development rate and air temperature can be used to describe the ripening cycle from a physiological perspective using growing degree-days (GDD) and the concept of base temperature (the temperature at which the growth rate tends to zero) [17]. This measurement is more objective because it depends more on the genotype's own development and less on the environmental and physiological conditions that influence chronological time [7]. Early-ripening *C. arabica* cultivars require between 2587 and 2707 GDD during the ripening cycle, unlike late-ripening cultivars, which require between 2845 and 2935 GDD [12]. The Colombia variety (composite) completed the ripening cycle in 2836 GDD during the main harvest [13]. In both studies, the base temperature used for coffee was 10 °C [12,13].

In Colombia, flowering events are distributed into two flowering periods (FP): the first from November to April (FP-I) and the second from May to October (FP-II). Notably, heavier flowering occurs during FP-I above 4° north latitude, whereas below this latitude, it occurs in FP-II [18]. This distinction between FPs determines the fruit load per harvest, which is distributed into a main harvest (high fruit load) and secondary harvest (low fruit load). For example, in the department of Caldas, which is located in Colombia's central coffee-growing zone, the main harvest (between July and December) represents 60% to 70% of the total fruits harvested per year, whereas the secondary harvest (between January and June) accounts for 30% to 40% [14,19,20]. These changes in fructification across harvests modify the physical characteristics of the fruit, such as fresh mass, size, and dry mass, primarily through changes in the leaf-to-fruit ratio [21–24]. Furthermore, under full-sun exposure, variations in the leaf-to-fruit ratio occur mainly because of changes in fruit number rather than significant fluctuations in the leaf area [23,25].

Therefore, this study aimed to evaluate the effects of progeny and/or harvest on the duration of the ripening cycle and the physical and respiratory characteristics of the fruit during ripening. We formulated the following hypothesis: the duration of the ripening cycle between progenies differed according to the time of harvest, modifying the physical characteristics of the fruit through changes in fruit load. This information is useful for understanding coffee fruit growth and development and its relationship with changes in harvests.

2. Materials and Methods

2.1. Location and Plant Material

The study was conducted at the Naranjal Experimental Station (Chinchiná, Caldas, Colombia; 4°58′19.1″ N, 75°39′8.2″ W, 1407 m) (Figure 1), which is located in the central coffee-growing zone of Colombia [26]. In a field lot, two experimental plots were established

for each evaluated progeny (CU1819, CU1825, CU1953, CU2021, and CU2034), which represent parts of the progenies that constitute the *C. arabica* variety Cenicafé 1. Each plot contained nine five-year-old plants (seven effective plants and two plants as borders). Two effective plants per plot were selected for evaluation during the secondary harvest (SH) (January–June 2024) (n = 4) and in the main harvest (MH) (July–December 2024) (n = 4). The initial experimental design comprised three plots; however, due to phytosanitary issues, a substantial loss of sampling units occurred, resulting in a reduced sample size. Fertilization was performed according to crop requirements [27], and integrated weed, pest, and disease management was performed in accordance with Cenicafé's recommendations [28].

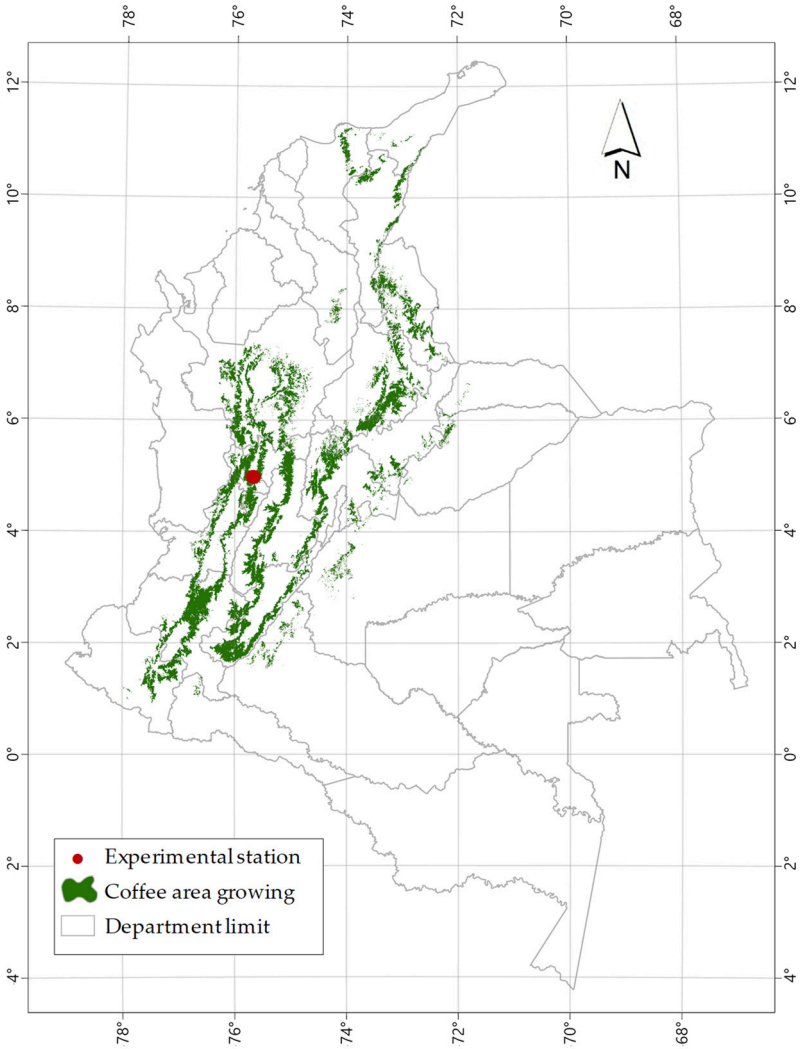

Figure 1. Colombian coffee zone and location of the Naranjal (Caldas department) experimental stations where the experimental lots were established.

2.2. Fruit Characteristics During Maturity

Two plagiotropic branches from the middle stratum were selected for each effective plant per progeny. On these branches, five reproductive nodes exhibiting more than 70% anthesis (BBCH stage 67) [29] during the peak flowering events in the SH and MH were tagged, and the dates were recorded. Subsequently, the variable chronological time to fruit ripening (CTFR) corresponds to the duration of the ripening cycle from the anthesis date (BBCH stage 67) [29] until the date when more than 80% of the fruits per node originating from the peak flowering event reached ripening (BBCH stage 88). Ripening was identified by the red pericarp color, which is a widely used indicator of the ripening cycle in coffee

research [7,12,30]. In the present study, measurements associated with fruit maturity, such as pulp soluble solids content (°Brix), were not included. The fruit ripening cycle was evaluated in physiological terms using GDD (Equation (1)) recorded during the CTFR for each progeny and harvest. Finally, temperature monitoring was performed using a RAWS-F remote automatic weather station (FireWeather, Campbell Scientific, Logan, UT, USA) in the field.

$$GDD = \sum_{i=1}^{n} \frac{Tmax + Tmin}{2} - Tb \quad (1)$$

where GDD = accumulated growing degree-days; $Tmax$ = daily maximum air temperature (°C); $Tmin$ = daily minimum air temperature (°C); Tb = base temperature (°C), with a value of 10.0 °C for coffee [31]; and n = number of days from anthesis to fruit ripening.

After the fruit ripening date (BBCH stage 88) for each tagged node was recorded, the number of fruits per node was quantified (F_Node). For each effective plant, ten fruits were sampled from each plagiotropic branch. Equatorial fruit firmness (FE), equatorial fruit diameter (Diam-F), and fruit volume (Vol-F) were measured for each fruit. A PCE-PTR200 digital penetrometer (PCE-Iberica, Tobarra, Spain) was used to assess the firmness. The fresh mass of the ten fruits (M-F) was recorded using an AR3130 electronic balance (Ohaus, México D.F., México). Subsequently, the pericarp and the bean (endosperm + embryo) were separated from each fruit and stored separately in paper bags, which were then kept in an oven at 60 °C for 72 h. The AR3130 electronic balance was used to record the variables pericarp dry mass (MS_P), bean dry mass (MS_G), and total fruit dry mass (MS_F = MS_P + MS_G).

Two or three days after the fruits ripened, a third sample of 36.0 ± 4.4 g of ripe fruits (BBCH stage 88) was randomly collected per effective plot. The fruit peduncle was then removed. The fruit mass was placed in a 250 mL chamber for 20 min at 21 °C. A Go Direct CO_2 infrared sensor with Vernier Graphical Analysis software v6.0.0-3443 (Vernier Software & Technology, Beaverton, OR, USA) was used to record CO_2 emission readings every 5 s to reflect respiratory activity [32]. The fruit respiration rate (RR) was calculated on the basis of the fruit mass in the chamber according to Equation (2) [33].

$$\mathrm{RR} = \frac{V_f}{W} \frac{\left(yCO_2 - y^iCO_2\right)}{(t - t_i) \times 100} \quad (2)$$

where RR is the fruit respiration rate (mL kg^{-1} h^{-1}), V_f is the free volume in the chamber minus the volume occupied by fruit (mL), W is the mass of the fruit (kg), and yCO_2 and y^iCO_2 are the concentrations of carbon dioxide (%) at time t (h) and the initial time, t_i (h), respectively.

2.3. Statistical Analysis

The medians of the values obtained for each experimental plot were used for inferential analysis. The effects of progeny, harvest, and their interaction on the variables were evaluated using an ANOVA-type analysis for repeated measures [34,35], with progeny as the between-subjects factor (fixed factor) and harvest (SH and MH) as the within-subjects factor (random factor), using MANOVA.RM package v0.5.4 [35]. The Wild Bootstrap (WBS) approximation (n = 1000) was used to estimate p values and assess whether the variability in the evaluated variables depended on progeny, harvest, or both factors. The repeated-measures model with an ANOVA-type statistic enables hypothesis testing, even without normality or equal covariance matrices and with small sample sizes [34]. A descriptive analysis using violin plots differentiated on the basis of harvest was performed for variables evaluated. Spearman's multiple correlations were adjusted using the Bonferroni method to

analyze relationships between variables using the "correlation" package [36]. All packages were run using R software version 4.4.1 [37].

3. Results

The statistical analysis performed for each variable (Table 1) revealed that for the variables F_Node, FE, Diam-F, Vol-F, M-F, and MS_P, there was no evidence of an effect from progeny or the interaction, in contrast to the harvest effect, for which the null hypothesis was rejected. This finding indicates that the differences among the variables were primarily due to the harvest effect rather than the progeny effect. The values of the variables F_Node and FE showed significantly higher values (43.2% and 24.7%, respectively) in the MH than in the SH (Table 1, Figure 2c,d). Conversely, the variables Vol-F, M-F, MS_P, GDD, and Diam-F were significantly higher in the SH, with differences of 17.0%, 9.5%, 9.3%, 5.3%, and 3.4%, respectively (Table 1, Figure 2a,e–h). Furthermore, the statistical analysis did not provide sufficient evidence to reject the null hypothesis for the Progeny × Harvest interaction effect or for the main effects of the variables CTFR, RR, MS_G, and MS_F (Table 1). For the CTFR variable, which is associated with the ripening cycle, there were no significant differences between harvests (3.4%), or for the variables RR, MS_G, and MS_F, which did not show differences greater than 9.4% (Table 1, Figure 2b,i–k).

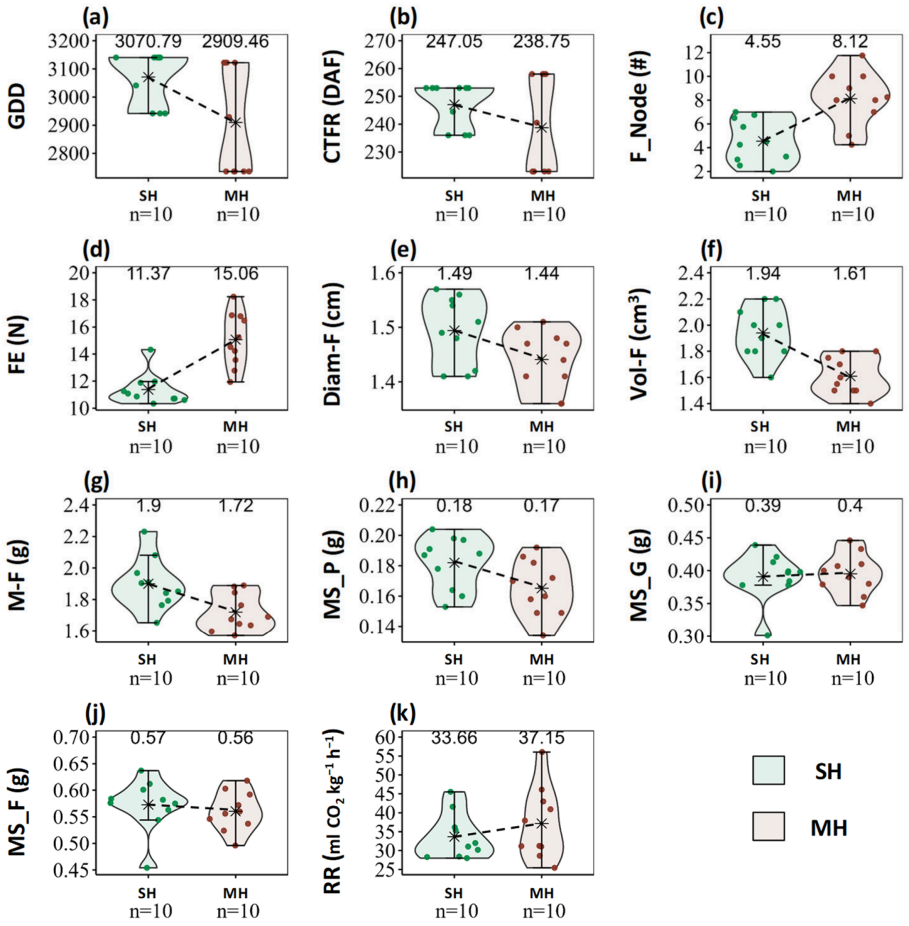

Figure 2. Distribution of the variables: (**a**) growing degree-days (GDD), (**b**) chronological time to fruit ripening (CTFR), (**c**) fruits per node (F_Node), (**d**) equatorial fruit firmness (FE), (**e**) equatorial fruit diameter (Diam-F), (**f**) fruit volume (Vol-F), (**g**) fruit fresh mass (M-F), (**h**) pericarp dry mass (MS_P), (**i**) bean dry mass (MS_G), (**j**) fruit dry mass (MS_F), and (**k**) fruit respiration rate (RR) for the secondary harvest (SH) and main harvest (MH) in the coffee progenies. The asterisk symbol and values above the violin plot correspond to the average. Dashed lines represent comparisons between harvests.

Table 1. ANOVA-type analysis of variance for repeated measures with p value estimation using the Wild Bootstrap (WBS) approximation for the following variables: growing degree-days (GDD), chronological time to fruit ripening (CTFR), fruits per node (F_Node), equatorial fruit firmness (FE), equatorial fruit diameter (Diam-F), fruit volume (Vol-F), fruit fresh mass (M-F), pericarp dry mass (MS_P), bean dry mass (MS_G), fruit dry mass (MS_F), and fruit respiration rate (RR) in the two harvests of the coffee progenies. The evaluated factors corresponded to progeny (P) as the between-subjects factor, harvest (H) as the within-subjects factor, and their interaction (P × H).

Variable	Factor	Test Statistic	WBS p Value
GDD	P	1.2441	0.488
	H	6.7369	0.039
	P × H	1.0939	0.643
CTFR	P	1.2457	0.237
	H	2.2158	0.17
	P × H	1.1013	0.528
F_Node	P	0.4226	0.884
	H	33.3589	<0.001
	P × H	1.9315	0.78
FE	P	5.0323	0.532
	H	21.8689	<0.001
	P × H	0.7067	0.954
Diam-F	P	0.7284	0.512
	H	11.3725	0.006
	P × H	0.9777	0.837
Vol-F	P	0.692	0.532
	H	45.375	<0.001
	P × H	0.6875	0.989
M-F	P	0.7058	0.173
	H	76.7425	<0.001
	P × H	3.2712	0.861
MS_P	P	2.3223	0.125
	H	38.3478	0.039
	P × H	12.6617	0.291
MS_G	P	1.5731	0.088
	H	0.1074	0.737
	P × H	0.2554	0.869
MS_F	P	1.0843	0.307
	H	1.218	0.367
	P × H	2.0834	0.179
RR	P	1.5565	0.112
	H	1.2641	0.276
	P × H	0.8993	0.701

The multiple correlations between the variable pairs M-F vs. Vol-F were strongly positively correlated ($\gamma \geq 0.90$), whereas between the variables M-F vs. Diam-F, M-F vs. MS_F, Vol-F vs. Diam-F, Diam-F vs. MS_F, CTFR vs. GDD, MS_G vs. MS_F, M-F vs. MS_P, and Vol-F vs. MS_P, a strong positive statistical association was present (γ = 0.75–0.89) (Table 2). In these correlations, the p value showed a confidence level greater than 99% (Table 2). For the variables Vol-F vs. MS_F, GDD vs. Vol-F, and MS_P vs. M-F, the statistical association at 95% confidence was positive and high (γ = 0.70–0.75) (Table 2). In the remaining multiple correlations between variable pairs, the coefficient did not exceed the 95% confidence threshold (γ = −0.54–0.69).

Table 2. Spearman's multiple correlation coefficients (γ), adjusted by the Bonferroni method, were calculated between variable pairs (n = 20). The coefficient was deemed statistically significant at a 95% confidence level. Lower (LCI) and upper (UCI) 95% confidence intervals for γ are reported. The abbreviations correspond to CTFR (chronological time to fruit ripening), GDD (growth degree-days), Diam-F (equatorial fruit diameter), Vol-F (fruit volume), M-F (fruit fresh mass), MS-P (pericarp dry mass), MS-G (bean dry mass), and MS-F (fruit dry mass).

Variable 1	Variable 2	γ	LCI	UCI	*p* Value
M-F	Vol-F	0.91	0.77	0.96	<0.001
M-F	Diam-F	0.89	0.74	0.96	<0.001
M-F	MS_F	0.88	0.71	0.95	<0.001
Vol-F	Diam-F	0.83	0.61	0.93	<0.001
Diam-F	MS_F	0.81	0.57	0.92	<0.001
CTFR	GDD	0.80	0.54	0.92	0.001
MS_G	MS_F	0.79	0.52	0.91	0.003
M-F	MS_P	0.75	0.46	0.90	0.008
Vol-F	MS_P	0.75	0.45	0.90	0.009
Vol-F	MS_F	0.75	0.44	0.90	0.010
GDD	Vol-F	0.71	0.37	0.88	0.033
MS_P	M-F	0.70	0.36	0.88	0.037

4. Discussion

In this study, the GDD requirements to complete the ripening cycle were significantly higher in the SH than in the MH at the 95% confidence level ($p = 0.039$) (Table 1, Figure 2a), as previously reported. *C. arabica* var. Caturra requires 2560 GDD to complete the ripening cycle in the SH and 2445 GDD in the MH (base temperature of 10 °C) [38]. The mean GDD values observed in this study (Figure 2a) were higher than those reported for *C. arabica* progenies (2587–2935 GDD) and the Colombia variety (2836 GDD) at a base temperature of 10 °C [12,13]. The differences in GDD between harvests may reflect physiological variations linked to fruit load, as reflected in the response of F_Node (Table 1). Intra-and interspecific hybrids of coffee have shown less accumulation of GDD at MH than SH, probably in response to intra-canopy temperature variations that source–sink relationship (leaf area fruit ratio, yield per plant, and F_Node) produces [39], a response similar to that found in the present study (Figure 2a,c). However, future studies should examine this hypothesis to clarify these relationships, because under different conditions, such as comparisons between shaded and full-sun coffee systems, longer ripening cycles have previously been reported under lower fruit loads [24].

Nonetheless, these differences were not detected for the CTFR variable (Table 1, Figure 2b), possibly because, within the same number of days, thermal accumulation can vary because of changes in daily temperature, causing minor differences in CTFR (3.4%) compared with that in GDD (5.3%) (Figure 2a,b). In this sense, GDD is a better measure of genotype development because it provides a standardized method for monitoring plant development based on temperature accumulation, which induces changes in the conformation of enzymes and consequently their functionality [40]. From a biological standpoint, it has been postulated that air temperature affects plant growth, particularly its velocity, which affects the growth rates of organs and tissues [41]. This is because GDD shows lower variability in terms of describing phenological changes between different stages, as it is less influenced by environmental conditions [42]. In addition, the lack of differences in CTFRs should be interpreted with caution because only four replications were available per progeny, which limits the statistical power of the test to detect subtle differences in the reduced sample sizes. This could change the results in large sample sizes.

The results of the present investigation corroborate the strong correlation between CTFR and GDD (Table 2), as reported in previous studies [7].

Compared with that in the SH, the F_Node variable in the MH increased 1.76-fold (Table 1, Figure 2c), which is consistent with the expected increase in fruit load during the MH reported for Colombia's central coffee-growing zone [14,19]. These findings suggest that the change in the source–sink relationship assumed is primarily due to changes in fruit quantity rather than drastic changes in leaf area, which occur over longer time horizons in coffee plants that are less than three years old and between harvest in Colombia [23,39,43]. In the MH, the significant increase in the F_Node quantity has a collateral effect such that each fruit has less physical space for its growth, and this promotes competition that can be related to the significant decrease in the Vol-F and M-F (Table 1, Figure 2e,g). Conversely, during the SH, when the F_Node number was lower, the Vol-F and M-F of each fruit increased (Table 1, Figure 2e,g). The competition between vegetative and reproductive organs in coffee increases under high fruit loads; as a result, M-F decreases because the sink strength of the competing organs is greater [22,44]. A lower Vol-F implies a higher FE, as observed in MH (Table 1, Figure 2f). The FE values in the present study were similar to those reported for *C. arabica* var. Colombia [45], whereas the Diam-F and Vol-F values were similar to those recorded for ripe fruits of *C. arabica* var. Castillo [46]. Similar M-F values have been reported in previous studies on *C. arabica* (1.6–2.1 g) [13,47].

Furthermore, as MS_G did not vary between harvests, the observed changes in Diam-F, Vol-F, and M-F were linked to alterations in MS_P but not in the bean (Table 1, Figure 2e–h). Although the pericarp represented a considerable portion of the total fruit dry mass (29.5% to 31.7%), it was not sufficient to produce significant differences between harvests in the MS_F variable (Table 1, Figure 2j), as it may have for M-F (Table 1, Figure 2g). In the MH, the MS_F values were close to those recorded for *C. arabica* var. Colombia [45] and different *C. arabica* cultivars [48]. These findings suggest that MS_G can remain relatively stable between harvests, even when the quantity of F_Node changes the pericarp and affects Diam-F, Vol-F, and M-F. This is important because dry matter accumulation in coffee fruits, especially in the endosperm, affects the green coffee yield [49]. This indicates that green coffee yields per unit volume would be similar between harvests, according to the results of the present study. Similar results were obtained for *C. arabica* var. Cenicafé 1, where no differences in bean size distribution were found between plants with 50% and 100% fruit load [23]. Other reports have shown differences in bean size under these fruit loads, but these differences may be linked to the use of a shaded coffee system [21]. In this regard, further research is required to determine the effects of the fruit load on MS_G.

The RR variable showed no differences between harvests, but the values reported in the present study were 1.8 times higher than those previously reported [45]. This response may be linked to the removal of the fruit peduncle. Finally, the lack of differences in all the evaluated variables among the progenies may be related to their shared genetic origin, given that all the genotypes originated from a cross between the Caturra variety and Timor Hybrid 1343, which presents a relatively narrow genetic variability [50]. However, the sample size may have influenced the detection of differences between genotypes as well as the number of genotypes evaluated, even though the statistical method was shown to be robust in small sample sizes [34]; therefore, these results should be interpreted with caution and verified in future studies.

High correlations between the variables M-F vs. Vol-F, M-F vs. Diam-F, M-F vs. MS_F, Vol-F vs. Diam-F, Diam-F vs. MS_F, MS_G vs. MS_F, M-F vs. MS_P, Vol-F vs. MS_P, Vol-F vs. MS_F and MS_P vs. M-F were expected (Table 2) given the mass–volume relationship. In *C. arabica* var. Colombia, M-F and MS-F were significantly positively associated with Diam-F, indicating that morphometric variations in diameter directly influence fruit growth [51].

These associations suggest the potential of fruit diameter as an indirect, non-destructive predictor of fruit mass, which requires further validation in future studies. Similarly, the positive correlation between M-F and MS-F (Table 2) is consistent with reports from nine *C. arabica* cultivars in Mozambique, given that dry matter accumulation in grains is influenced by mature fruit growth [48]. No dependence was found between MS_G and M-F, possibly because the selection process weighted a large bean size independently of the pericarp [50]. This consideration is reinforced by the observation that M-F and MS-F maintain significant correlations only with variables that include the pericarp (Diam-F, Vol-F) (Table 2). However, it should be noted that this result could change under greater genetic diversity.

5. Conclusions

In the present study, the effect of the progeny did not produce differences in the evaluated variables, possibly because of the shared genetic origin. The significant differences in GDD between harvests suggest that changes in the fruit ripening cycle may be linked to the fruit-load intensities of each harvest. However, the low confidence level at which the differences were detected and the absence of such differences in the CTFR variable indicate caution regarding this association and the need to conduct future studies with progenies that exhibit longer ripening cycles. Furthermore, the fruit load, represented by the F_Node variable, increased in the MH compared with the SH, as expected. Changes in fruit quantity positively influenced FE and negatively influenced Diam-F, Vol-F, M-F, and MS_P. MS_G was not affected by changes in F_Node across harvests, possibly because of the selection processes used to obtain the progenies. These findings increase the understanding of the ripening process in the progenies of the Cenicafé 1 variety and of the physical characteristics of the fruit between the main harvest and the secondary harvest, known as "mitaca".

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