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Selection of Elite *dura*-Type Parents to Produce Dwarf Progenies of *Elaeis guineensis* Using Genetic Parameters

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Abstract: The low annual growth rate of the stipe in oil palm progenies is desirable to increase these crops' productive and economic life. Recurrent reciprocal selection (R.R.S.) has allowed the development of oil palm populations through several breeding cycles with an increased frequency of favorable alleles associated with traits of interest. The present study evaluated families derived from Deli *dura* × African *dura* crosses. For 12 years, the yield, vegetative characteristics, and the amount of oil in seven *dura* progenies were assessed to estimate, from the information collected, the genetic parameters, heritability, and phenotypic correlations among quantitative genetic traits of high-yielding dwarf progenies. The analysis was carried out using analysis of variance, followed by a comparison of means for all estimated traits. The effect of the progenies was highly significant ($p \leq 0.01$) for most traits. The yield values, expressed in fresh fruit bunches (FFB) for the progenies, ranged from 165 to 208 kg per palm per year. The oil-to-bunch ratio (O/B) ranged from 17% to 19%, with an overall average of 18%. One of the essential characteristics in this study was the vertical growth of the stipe. Progenies P6 and P7 were identified as those with the lowest annual increase in height, with values of 0.29 and 0.33 m year^{-1}. The values indicate that these are slow-growing cultivars with a high FFB yield and O/B. The highest heritabilities were found for the vegetative trait height (71.62%) and the number of leaflets (46.64%). The development of *dura* parents with slow growth characteristics in combination with a high bunch and oil production allows extending the productive life of the crop to more than 35 years, providing added value to obtaining differentiated cultivars of oil palm.

Keywords: introgression; heritability; genetic traits; reduced growth; oil palm

1. Introduction

The oil palm (*Elaeis guineensis* Jacq.) is a perennial oilseed crop grown in humid tropical regions. The agronomic importance of oil palm is the result of its high capacity to produce oil, producing between 3 and 10 t ha^{-1} in optimal conditions [1]. It is the second-largest source of vegetable oil globally after soy, and more than 23 million hectares are cultivated globally. Latin America is one of the continents called upon to satisfy the global demand for oils. It has enough additional hectares of land suitable for oilseed crops like oil palm.

In 2050, it is estimated that production will reach 240 million tons [2]. One of the reasons for increasing palm oil production is the high demand for vegetable oils and biofuels. Colombia ranks fourth worldwide, behind Indonesia, Malaysia, and Thailand, and the first in Latin America in oil production [1].

In oil palm, there are three fruit forms: *dura*, *pisifera*, and *tenera*, the latter being an intraspecific hybrid between palms with *dura* × *pisifera*-fruits forms [3]. The fruit types that define the thickness or absence of the endocarp or shell are encoded by the Sh gene [4,5].

Commercial cultivars are of the *tenera* type because they have higher mesocarp contents in the fruit than the *dura* type and, therefore, higher oil contents per hectare [6,7].

To produce commercial seeds, the female parent is always *dura* [8]. Genetic breeding programs in oil palm, including the MPOB (Malaysian Palm Oil Board) in Malaysia, CIRAD (La Recherche Agronomique pour de Developement) in France, A.S.D. (oil palm seeds and clones) in Costa Rica, and others located in Ecuador and Colombia, have carried out collections or exchanges of oil palm germplasm as an essential resource for developing new cultivars [8]. In this sense, the development of progenies plays a vital role in identifying high-yield genotypes with high genetic variability and an opportunity to introgress desirable traits in a breeding program [9].

The Colombian oil palm research center, Cenipalma, has a *dura*-type progeny test from Asian and African genotypes. Originally, Deli *dura* palm genotypes were introduced to the agricultural station of Lancetillas in Honduras in Central America from Southeast Asia around the 1940s [10]. Subsequently, selected progenies were taken to Colombia by the Instituto de Fomento Algodonero (IFA) to the plantations of Patuca and Pepilla in the Colombian Caribbean, where the best families were crossed with African genotypes. They gave rise to the first commercial plantations of oil palm in Colombia in the 1960s with *dura*-IFA cultivars. Unlike the current plantations around the world that are *tenera* type, they were cultivars with *dura* fruits. Thus, new processes of genetic breeding with evaluations and selections of the best individuals for their yield components and vegetative characteristics such as the slow growth of the stipe were performed. Elite *dura* progenies were generated from the best selections, introducing slow growth characteristics with high bunch yields and oil potential. The selected palms were established in the field in 2005 and are known as the slow-growing dura population or dwarf dura progenies of Cenipalma.

In oil palm, recurrent reciprocal selection (R.R.S.) allows the breeding of two different populations, independent of the traits of interest. The populations are later combined to evaluate and select the best for a new breeding cycle, maintaining a high degree of genetic variation. The cultivation cycle of oil palm is between 25 and 30 years of productive life, which can be exceeded if reduced growth cultivars with high yields and other characteristics of interest are generated [11].

The estimates of genetic parameters of the populations under breeding are of great importance for the breeder since they allow us to know the genetic structure of the populations and the genetic control of the characteristics of interest. Furthermore, they are essential to assess the genetic variability of the populations and guide the selection of the appropriate breeding method to maximize genetic gains [12–15]. Thus, the objective of this research was to estimate the behavior of genetic parameters of the main traits of interest in dwarf oil palm dura populations to optimize the selection and breeding processes of highly productive cultivars with a longer economic life of the crop.

2. Materials and Methods

2.1. Plant Material

The dwarf *dura*- or slow-growing population of Cenipalma is made up of seven progenies of full sibs (FS) from recurrent selection processes of *dura*-IFA populations and African *dura* from Eala in Congo (Former Zaire) [10]. The *dura*-IFA populations characterized by high oil production and bunches were crossed with slow-vertical growing parents, identified in the present study as P1 to P7. The produced progenies were in the nursery for 12 months and were subsequently transplanted to the final site in 2005. A randomized block design (RBD) was used with three blocks and 12 plants for each experimental unit. The measurements were made between 2008 and 2020. In the study area, the climatic conditions recorded annual rainfalls between 2194 and 4005 mm year^{-1}, with an average of 3115 mm. The management and agronomic practices were performed under the plantation standards of the El Palmar de la Vizcaína Experimental Field. They included balanced fertilization in kilograms per plant of N (1.23), P (0.50), K (2.51), Mg. (0.34), S (0.21), and B (0.05) according to foliar and soil analysis [16].

2.2. Data Collection

The data were collected from years three to twelve after planting in the field. The yield components fresh fruit bunches (FFB), bunch number (BN), and average bunch weight (BW) were recorded for each palm in all experimental units of the trial two and three harvest cycles per month.

The values of these performance components were obtained as follows:

$$\text{FFB (kg palm}^{-1}\text{ yr}^{-1}) = \sum_{i-1}^{n} \text{BWTi} \quad (1)$$

$$\text{BN (bunches palm}^{-1}\text{ year}^{-1}) = \sum_{i-1}^{n} \text{BNi}$$

$$\text{BW (kg)} = \frac{\text{FFB}}{\text{BN}}$$

Note. n represents the number of harvesting rounds and BWT the total bunch weight (kg).

Five rounds of vegetative measurements were performed between 2009 and 2020. The frond production (FP), petiole cross-section (PCS), rachis length (RL), leaflet length (LL), leaflet width (LW), leaflet number (LN), leaf area (LA), leaf area index (LAI), and the palm trunk diameter (DI) were calculated using the methodology proposed by Corley and Breure [16]. To calculate the annual height increase (HT), the palm height was measured from ground level to the base of leaf 41 according to the palm phyllotaxis [17]. Then HT was calculated using the formula:

$$\text{HT per year (height increase/year)} = \text{(height in year t)/(t} - 2)$$

where t is the age of the palm in years from planting date to the time of a given measurement.

The leaf area (LA) was calculated using the equation proposed by [18]:

$$\text{LA} = \text{b} \times (\text{n} \times \text{lw})$$

where:

LA: The leaf area (m^2)

n: leaflet number

lw: leaflet width × leaflet length (cm)

b: correction factor (0.55)

The leaf area index (LAI) is defined as the proportion of leaf area per unit of land area. It is considered an essential factor in the ability of the crop to capture solar energy [19]. The LAI was calculated using the following formula:

$$\text{LAI} = \text{LA} \times \text{FP} \times \text{planting density}/10{,}000$$

where:

LA: Leaf area

FP: Frond production (total leaves per palm)

The methodologies proposed before [19,20], modified by Prada and Romero [21], were used to calculate the oil content and bunch components. Two to three bunches of each palm were sampled between 2008 and 2020. To avoid seasonal variation over time, mature bunches (at least five loose fruits on the ground) were sampled at least three months after the previous sampling of the same palm. The oil traits calculated were mean fruit weight (M/FW.), spike bunch ratio (S.B.), oil-to-dry mesocarp ratio (ODM), oil-to-fresh mesocarp ratio (O/FM), oil-to-bunch ratio (O/B), normal fruit-to-bunch ratio (NF/B), fruit set (FS), mesocarp-to-fruit ratio (M/F), kernel-to-fruit ratio (K/F), and shell-to-fruit ratio (S/F).

2.3. Statistical Analysis

The data collected were subjected to an analysis of variance (ANOVA) under a generalized linear model, detailed in Table 1, using GENES software and R package version 4.1.1. Due to the perennial characteristic of cultivation, the years were considered environments for the linear model. The linear model is presented below:

$$Y_{ijk} = \mu + G_i + B_k + A_j + GE_{ij} + \varepsilon_{ijk}$$

where:

Y_{ijk}: is the phenotype of the kth palm of the ith progeny and the jth replicate.
μ: is the general average.
G_i: is the effect of the ith progeny.
B_k: is the effect of the kth block.
A_j: is the effect of the jth year.
GE_{ij}: is the interaction between progeny and year.
ε_{ijk}: is the residual error resulting from environmental contributions.

Table 1. Outline of ANOVA and expected mean squares (EMS) for full-sib progeny analysis.

Scheme	df	MS	EMS
Replicates (R)	(r−1)	MS1	σ^2 e + σ^2 ga + σ^2 r
Progenies (G)	(g−1)	MS2	σ^2 e + σ^2 ga + σ^2 g
Year (E)	(a−1)	MS3	σ^2 e + σ^2 ga + σ^2 a
G × E	(g−1) (a−1)	MS4	σ^2 e + σ^2 ga
Error			σ^2 e

σ^2 g = genotype variance, σ^2 ga = interaction between genotype and year variance and σ^2 e = error.

The averages were compared using the HSD test (honestly significant difference) or Tukey's test. The correlation coefficient of class or heritability in the broad sense (H^2) was used to estimate heritability in all the evaluated traits [22].

$$H^2 = \frac{\sigma^2 g}{(\sigma^2 g + \sigma^2 ga + \sigma^2 e)}$$

where:

σ^2 g: genotype variance.
σ^2 ga: interaction between genotype and year variance.
σ^2 e: environment variance.

For the multiple correlations, the Pearson correlation coefficient was used to measure the degree of association of the quantitative genetic traits of the studied progenies.

3. Results and Discussion

3.1. Yield Component Traits

The mean squares of the analysis of variance for the characteristics FFB, BN, and BW are presented in Table 2. The progeny and the year effects were significant for all the yield components. In the same way, significance was found for the G × E interaction in the BN and BW components but not in FFB, reflecting a consistent behavior of FFB in the years of evaluation. Nevertheless, although significant differences in the G × E were found, the variance component for G × E was low compared with the progenies and the reps. The high significance found ($p \leq 0.01$) in FFB, BN, and BW in the evaluated progenies and the years of evaluation show a high genetic variation that offers a wide selection margin to explore and advance in the acquisition of highly productive progenies. Arolu et al. [23] reported similar results in cultivars from Deli *dura* × Nigeria *pisifera*. They found high significance for the effect of the progenies on the yield components (FFB, BN, BW) of the oil palm crop. Likewise, studies carried out in Indonesia for 23 *dura* × *pisifera* progenies showed significant differences between the years of evaluation [24].

Table 2. Mean square and variance components for yield traits of *dura* × *dura* progenies.

Source of Variation	df	FFB	BNO	ABW
Replicates (R)	2	5329.40	15.29	4.72
Progenies (G)	6	7739.85 **	47.99 **	50.45 **
Year (E)	9	29,154.64 **	782.39 **	533.39 **
G × E	54	808.50 ns	10.54 **	3.00 **
Error	138	854.14	3.66	2.02
Variance components				
σ^2 G		231.05 (21.5) §	1.25 (18.2)	1.58 (40.7)
σ^2 G.E.		−13.04 (−1.2)	1.96 (28.6)	0.28 (7.2)
σ^2 e		854.14 (79.7)	3.66 (53.3)	2.02 (52.0)

FFB: Fresh fruit bunch (kg/palm^{-1}), BNO: Bunch number (bunches/palm^{-1}), ABW: Average bunch weight (kg/bunch), σ^2G: progeny variance, σ^2 GE: progeny by year variance, σ^2 e error variance, § variance component as percentage of total variance. ** $p < 0.01$; non-significant (ns) $p > 0.05$.

The comparison of means using the Tukey test showed that the FFB trait ranged between 165 and 208.4 kg palm^{-1}, with progenies P3 (208.4) and P1 (192.6) standing out, which were significantly different from the others. The BN component was between 11.04 and 14.25 bunches palm^{-1}. The progenies P5 and P3 were significantly different from the others and had the highest values with 14.25 and 13.99 bunches palm^{-1}. The values for the BW were between 15.30 and 18.75 kg bunch^{-1}, with outstanding progenies such as P1 (18.75 kg) and P6 (18.15 kg) (Table 3). Noh et al. [25] reported BN values between 5.9 and 11 and BW values between 18 kg and 28.1 kg in Nigerian *dura* × Deli *dura* progenies, which are lower comparing the BN values, and in BW they are above those recorded in this study.

Table 3. Progeny means yield component traits.

Progenies	FFB	BN	ABW
P1	192.62 b	11.52 bc	18.75 a
P2	173.07 cd	11.75 bc	16.71 b
P3	208.44 a	13.99 a	17.40 b
P4	165.02 d	12.17 b	15.30 c
P5	182.50 bc	14.25 a	15.86 c
P6	169.34 cd	11.04 c	18.15 a
P7	166.27 cd	11.64 bc	15.81 c
Trial mean	179.61	12.34	16.85
CV (%)	8.94	10.25	7.69
Years after Planting (Y.A.P.)			
Y.A.P. 3	185.07 c	20.80 b	9.15 g
Y.A.P. 4	221.70 a	23.28 a	9.55 g
Y.A.P. 5	206.65 ab	15.87 c	13.02 f
Y.A.P. 6	193.49 bc	13.13 d	14.72 e
Y.A.P. 7	175.87 c	9.05 f	19.51 c
Y.A.P. 10	207.77 ab	11.76 e	17.71 d
Y.A.P. 11	176.01 c	8.95 f	19.76 c
Y.A.P. 12	186.44 c	9.67 f	19.37 c
Y.A.P. 13	154.39 d	7.07 g	21.96 b
Y.A.P. 14	88.69 e	3.78 h	23.78 a
Young stage mean (A.Y.P. 3–5)	204.47	19.98	10.57
CV (%)	9.00	18.88	20.13
Adult stage mean (Y.A.P. 6–14)	168.95	9.05	19.54
CV (%)	23.13	33.68	14.84
Trial mean	179.61	12.34	16.85
CV (%)	20.75	49.48	29.90

FFB: fresh fruit bunch (kg/palm^{-1}), BN bunch number (bunches/palm^{-1}), ABW average bunch weight (kg/bunch), CV: coefficient of variation. Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey ($n = 252$).

For the years of evaluation, the Tukey test showed significant differences (Table 3). In the first productive years or young stage, the evaluated progenies show a high BN (between 15 and 20 bunches palm^{-1}) and a low BW (9 to 13 kg bunch^{-1}), in contrast to the following years when the plant is more adult. The BN values were lower (between 7 and 13 bunches palm^{-1}), and the values increased in the BW (14 to 23 kg bunch^{-1}). This behavior was typical for the crop, and the values agreed with those reported in commercial *tenera* cultivars [16]. The year 14 after planting presented the lowest values for the FFB and BN traits, mainly due to climatic effects that impacted the crop yield in the CEPV where the trial was located. The behavior of the precipitation had a decrease of more than 300 mm of rainfall compared with previous years, with the aggravate, this particular year presented five months of water deficit with monthly records less than 150 mm (optimal value for the crop).

3.2. Vegetative Traits

The mean squares for the vegetative characteristics can be observed in Table 4. The influence of the progenies was highly significant ($p \leq 0.01$) in almost all the traits, except in the DI. In the same way, the effect of the year showed high significance in the vegetative characteristics, except for the HT This information is essential in determining the growing stability of the progenies. Since this characteristic presents more than 71% of the genetic variance, it should have low environmental influence. Studies carried out in *dura* × *pisifera* oil palm progenies showed that the genetic variance component for these vegetative traits varied between 35.2 and 82.5%. The height characteristic was the most significant genetic influence [26]; information that contrasts with the results in this study where the most important genetic effect is for the HT trait, with values from 12% to 71%. Significant differences were also found for the LAI across progenies and years of evaluation. Recent works in *Elaeis guineensis* germplasm record significant directions for this characteristic. [27].

Table 4. Mean square and variance component for vegetative traits of *dura* × *dura* progenies.

Source of Variation	df	FP	PCS	RL	LL	LW	LN	HT	LA	LAI	DI
Replicates (R)	2	50.280	0.100	0.020	119.870	0.410	35.200	0.019	0.656	0.495	0.000
Progenie (G)	6	91.480 **	0.200 *	0.640 **	520.360 **	3.080 *	410.760 **	0.061 **	2.200 **	1.213 **	0.005 ns
Year (E)	4	3269.880 **	102.300 **	7.610 **	27,410.430 **	154.850 **	3276.130 **	0.003 ns	58.512 **	13.218 **	0.347 **
G × E	24	22.720 ns	0.060 ns	0.060 ns	75.260 *	0.840 **	29.610 ns	0.002 ns	0.454 ns	0.300 ns	0.003 **
Error	68	23.880	0.070	0.050	44.380	0.180	28.860	0.002	0.284	0.252	0.000
Variance components											
σ^2 G		4.584 (16.3) §	0.009 (12.2)	0.039 (42.2)	29.673 (35.8)	0.149 (28.8)	25.410 (46.6)	0.004 (71.6)	0.116 (25.9)	0.061 (18.7)	0.000 (12.6)
σ^2 G.E.		−0.331 (−1.2)	−0.003 (−3.7)	0.003 (3.1)	8.823 (10.6)	0.189 (36.4)	0.214 (0.4)	0.000 (0.7)	0.049 (10.8)	0.014 (4.3)	0.001 (55.0)
σ^2 e		23.880 (84.9)	0.070 (91.5)	0.050 (54.6)	44.380 (53.5)	0.180 (34.8)	28.860 (53.0)	0.002 (27.7)	0.284 (63.3)	0.252 (77.1)	0.000 (32.4)

FP: Frond production (number of leaf palms^{-1}), PCS: Petiole cross-section (cm^2), RL: Rachis length (cm), LL: Leaflet length (cm), LW: Leaflet width (cm), LN: Leaflet number, HT: Annual palm height (m year^{-1}), LA: Leaf area (cm^2), LAI: Leaf area index, DI: Diameter of palm trunk (m), σ^2 G = progeny variance, σ^2 G.E. = progeny by replicate variance, σ^2 e = error variance, Negative estimate of variance is considered zero, § variance component as a percentage of the total variance.* Significant at $p < 0.05$; ** Significant at $p < 0.01$; ns non-significant at $p > 0.05$.

The genotype and year effect showed highly significant differences ($p \leq 0.01$) for the RL characteristic. Arolu. [22] showed significance in the genotype, replicate and genotype × replicate interaction in this characteristic (RL) traits for *dura* × *pisifera* progenies. On the other hand, Myint et al. [27] reported highly significant differences for the effect of families, populations, and families × populations interaction for the RL trait in the germplasm of *Elaeis guineensis* from Senegal. In general, the environmental effect significantly contributes to the less stable vegetative characteristics, which change with the years of plant development, as in the specific case of the diameter of the plant stipe

Alvarado and Henry [28] reported that 4 to 5 cycles of cultivation (60 years of field tests) are necessary to fix the genetic trait of a compact phenotype with acceptable yield values. The present study recorded values for the different genetic traits of two breeding cycles with very promising progenies in the compact plant trait and high yields. The differences found in this study show a wide variability present among the study progenies, which will allow progress in obtaining slow-growing cultivars. The slow growth is a vital characteristic to increase the economic life of oil palm plantations, changing the stage of replanting close to 25 years. Thus, an increase of 35% more productive life for palm cultivation could be predicted.

Table 5 shows the vegetative traits of the evaluated progenies and the comparison between each year of evaluation. The FP averages ranged from 40.74 to 46.67. Only the progenies P1 and P7 were significantly different ($p \leq 0.01$) for this trait. For the PCS trait, the progenies P3 and P4 were significantly different from the others, with values of 26.32 and 22.68, respectively. The other progenies were similar.

Table 5. Progeny means for vegetative traits.

Progenies	FP	PCS	RL	LL	LW	LN	HT	LA	LAI	DI
P1	46.67 a	24.16 ab	4.68 a	93.78 a	8.71 a	157.71 a	0.47 a	7.35 a	5.49 a	0.33 a
P2	45.90 ab	23.87 ab	4.34 b	75.09 c	7.62 c	150.49 b	0.43 ab	6.59 cd	5.09 ab	0.33 a
P3	41.33 ab	26.32 a	4.76 a	85.46 b	8.57 a	156.98 a	0.42 b	7.19 ab	5.17 ab	0.30 bc
P4	46.21 a	22.68 b	4.28 b	78.68 bc	7.56 c	144.08 c	0.43 ab	6.40 d	5.12 b	0.32 ab
P5	43.06 ab	24.01 ab	4.68 a	82.54 b	7.86 bc	157.38 a	0.39 b	6.54 d	4.72 b	0.29 c
P6	42.33 ab	24.81 ab	4.69 a	84.57 b	8.28 ab	158.42 a	0.29 d	7.17 abc	5.43 ab	0.29 c
P7	40.74 b	23.50 ab	4.34 b	81.55 bc	7.92 bc	154.01 ab	0.33 c	6.63 bcd	5.09 b	0.30 c
Trial mean	43.75	24.19	4.54	83.09	8.07	154.15	0.39	6.84	5.16	0.31
CV (%)	5.64	4.72	4.56	7.09	5.61	3.39	16.14	5.60	4.93	5.65
Years after planting (Y.A.P.)										
YAP 4	63.05 a	9.96 d	4.28 c	103.60 b	5.62 d	135.00 d	0.38 a	4.76 e	4.30 b	0.25 a
YAP 6	48.04 b	11.84 c	4.77 b	114.74 a	6.12 c	150.28 c	0.40 a	5.91 d	4.02 b	0.26 a
YAP 8	30.43 d	40.54 b	3.60 d	47.65 c	11.10 a	157.23 b	0.41 a	6.76 c	2.94 c	0.25 a
YAP 10	37.68 c	12.39 c	4.96 ab	109.41 a	6.58 b	160.03 b	0.40 a	7.61 b	4.06 b	0.25 a
Y.A.P. 14	39.53 c	65.66 a	5.06 a	40.07 d	10.96 a	168.23 a	0.39 a	9.16 a	5.16 a	N.A.
Trial mean	43.75	28.08	4.54	83.09	8.08	154.15	0.40	6.84	4.10	0.25
CV (%)	28.53	87.34	13.27	43.48	33.66	8.10	2.88	24.43	19.37	1.98

FP: Frond production (number of leaves palm^{-1}), PCS: Petiole cross-section (cm^2), RL: Rachis length (m), LL: Leaflet length (cm), LW: Leaflet width (cm), LN: Leaflet number, HT: Annual palm height (m $^{-1}$), LA: Leaf area (cm^2), LAI: Leaf area index, DI: Diameter of palm trunk (m), CV: coefficient of variation. Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey ($n = 252$).

For the RL trait, two significantly different groups were formed; the progenies P1, P3, P5, and P6 with values ranging between 4.68 and 4.76, and the progenies P2, P4, and P7 with lower values ranging between 4.28 and 4.34.

For the LL and LW traits, the P1 progeny with values of 93.78 and 8.71 were significantly different from the other progenies and stood out for presenting the highest values for these characteristics of vegetative development. In different Deli *dura* × AVROS *pisifera* progenies, the overall averages for LL and LW were 94.89 and 5.57, respectively [24], values comparable with this study. The LN was a vegetative trait that did not present a wide statistical variation between the progenies. Progenies P1, P3, P5, and P6, were grouped in the same group within the comparisons, and P2 and P7 were in another group. The P4 progeny was significantly different, with the lowest value. LA varied between 6.40 m^2 in the P4 progeny and 7.35 m^2 for the P1 progeny, with a general average for the entire population of 6.84 m^2.

There were significant differences in the evaluated progenies for the LAI. The P1 progeny had the highest value (5.49), and the P5 progeny had the lowest (4.72). A range between 5 and 5.5 has been considered an optimal value for oil palm after ten years of planting [18,29], which can be achieved through an optimal planting density.

A maximum yield per hectare for commercial oil palm cultivars could be achieved with an LAI ranging between 5.5 and 6 [30]. The LAI values presented in this study refer to year 14 after sowing (last measurement of this characteristic) with a general average for the entire population of 5.16. The progenies P1 and P6 had LAI values close to 5.5, the optimal for achieving maximum yields.

The comparisons in the evaluation years show a normal development described for the crop, where, as the plant grows, some of the vegetative traits also do so, such as LL, LW, LN, LA, and LAI. These vegetative traits define the architecture of the plant, which is very important for implementing agronomic practices to reduce labor costs and improve harvest mechanization [31].

The annual increase in height varied between 0.29 m year^{-1} in the P6 progeny and 0.47 m year^{-1} in the P1 progeny, with a general average of 0.39 m year^{-1} for the entire population evaluated. We also compared this growth rate with commercial cultivars planted in the same experimental station, under similar soil and management, where the dwarf *dura* progenies of Cenipalma showed lower values than the most common cultivars grown around the world, such as Deli × AVROS, Deli × La Mé and Deli × Yanganbi (Figure 1). Arolu et al. [22] reported the characteristics of compact Deli *dura* × Nigeria *pisifera* cultivars, with height increases between 0.22 m year^{-1} and 0.34 m year^{-1} in different *tenera* progenies. Studies performed on commercial oil palm cultivars from Deli × AVROS, and Deli × Ghana recorded annual growth in stem height from 0.90 to 1.20 m [32], values much higher than those recorded in these Cenipalma *dura* progenies. In contrast, studies with interspecific OxG hybrids (Elaeis oleifera × Elaeis guineensis) showed annual increases in plant height of an average of 0.41 m year^{-1}. It ranged between 0.23 m year^{-1} and 0.65 m year^{-1} [33], similar to the results obtained for this study. However, despite the stem growth rate in our study being highly repeatable (H^2) across years, with low GxE, it may be different when we compare with other locations/environments due to different soil fertility, water availability, and agronomic management.

From the results obtained in the *dura* × *dura* progenies, it is possible to select the best families and the best palms per family using the family and individual palm selection-FIPS methodology [34]. The best individuals could be used to develop new dwarf progenies in a new R.R.S. cycle. For this purpose, individuals growing below 0.20 m year^{-1} were identified to create commercial slow growth cultivars and prolong the crops' economic and productive life, increasing profitability.

3.3. Bunch Quality Traits

The mean squares of the bunch conformation traits are presented in Table 6. The effect of the evaluated progenies was highly significant ($p \leq 0.01$) for most oil characteristics, except for ODM, NF/B, and FS These differences indicate great genetic diversity in these oil traits, broadening the opportunity to select progenitors with good oil characteristics and advancing in the oil palm breeding program. Studies by Marhalil et al. [35] reported highly significant differences in these oil characteristics in the evaluated progenies in germplasms from Nigeria, Zaire, and Cameroon. The influence of the years evaluated showed highly significant differences ($p \leq 0.01$) for all traits considered. The effect of the interaction between GxE did not present significant differences in ANOVA, except for the S.B. characteristic ($p \leq 0.05$).

Table 6. Mean square and variance component for bunch quality traits of *dura* × *dura* progenies.

Source of Variation	df	MFW	SB	ODM	OFM	OB	NFB	FS	MF	K/F	S/F
Replicates (R)	2	5.51	3.6	15.52	60.32	18.69	88.1	45.63	18.56	2.53	9.05
Progenies (G)	6	11.62 **	21.21 **	5.86 ns	68.96 **	20.14 *	158.12 ns	83.51 ns	114.52 **	47.48 **	32.74 **
Year (E)	5	42.24 **	9.00 **	76.46 **	94.4 **	61.26 **	1037.93 **	1782.49 **	98.99 **	51.7 **	50.32 **
G × E	30	1.47 ns	1.90 *	7.54 ns	11.78 ns	6.01 ns	85.18 ns	44.93 ns	11.83 ns	3.1 ns	5.67 ns
Error	82	1.99	1.04	4.84	11.44	5.79	58.35	52.44	11.88	3.07	5.22
σ^2 G		0.56 (23.44) §	1.07 (45.49)	0.09 (−1.69)	3.18 (21.59)	0.79 (11.83)	4.05 (5.78)	2.14 (4.09)	5.71 (32.47)	2.47 (44.47)	1.50 (21.95)
σ^2 GE		−0.15 (−6.18)	0.25 (10.42)	0.77 (13.98)	0.10 (0.66)	0.06 (0.95)	7.67 (10.94)	−2.15 (−4.09)	−0.01 (−0.08)	0.01 (0.15)	0.13 (1.88)
σ^2 e		1.99 (82.73)	1.04 (44.10)	4.84 (87.71)	11.44 (77.75)	5.79 (87.23)	58.35 (83.28)	52.44 (100)	11.88 (67.61)	3.07 (55.37)	5.22 (76.18)

MFW: Mean fruit weight (gr), SB: Spikes bunch ratio (%), ODM: Oil to dry mesocarp ratio (%), OFM: Oil to fresh mesocarp ratio (%), OB: Oil to bunch ratio (%), NFB: Normal fruit to bunch ratio (%), FS: Fruit set (%), MF: Mesocarp to fruit ratio (%), KF: Kernel to fruit ratio (%), SF: Shell to fruit ratio (%), σ^2 G = progeny variance, σ^2 GE = progeny by year variance, σ^2 e = error variance, σ^2 ga = progeny × year variance, Negative estimate of variance is considered zero, § variance component as a percentage of the total variance. * Significant at $p < 0.05$; ** Significant at $p < 0.01$; ns non-significant at $p > 0.05$

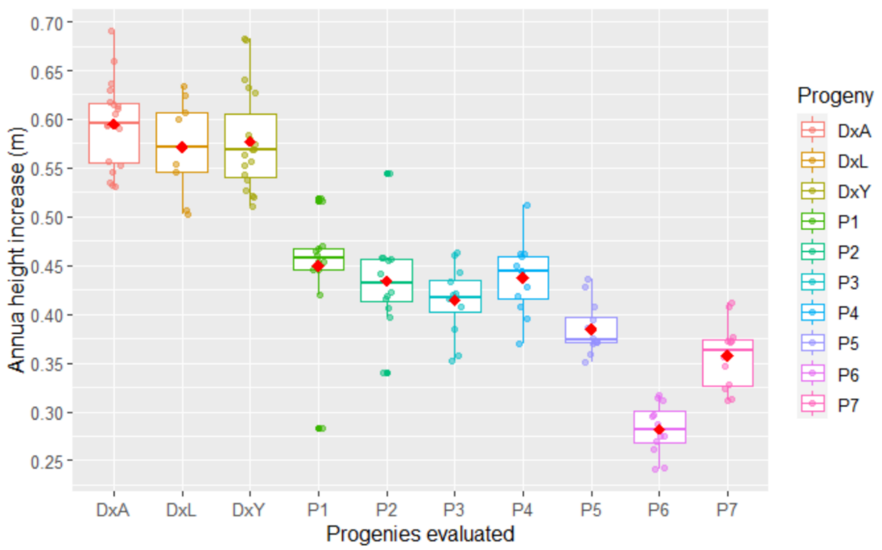

Figure 1. Annual height increment of seven *dura* × *dura* progenies and three commercial *tenera* cultivars. The red point corresponds to the general average of the progenies or cultivars and the horizontal line to the median. DxA: Deli × AVROS, DxL: Deli × La Mé, DxY: Deli × Yangambi, and P1 to P7: *dura* × *dura* dwarf progenies.

The genetic variation found in the progenies of this study for bunch components and oil quantity will allow the introgression of new traits, which would broaden the scope of the selection of female dura-type parents. O/B is one of the most critical characteristics in crop breeding programs. With the results obtained in this research, it is possible to advance in creating new progenies that maintain high oil extraction values and fruit components traits such as the relationship between M/F, S/F, and K/F The results found for these traits are promising for the generation of progenies that introgress more than one trait of high agronomic value for the cultivation of oil palm and complement both the O/B and the FFB The results of the studies by Marhalil et al. [35] highlight the importance of finding a wide variability and genetic diversity of these characteristics for the appropriate selection of parents in oil palm cultivation. Knowledge about the genetic parameters in oil palm materials is strategic to improve selection. For the O/B trait, there is wide variation, and research carried out in African oil palm germplasm presents values that oscillate between 19.51% and 5.61%, which favors the selection for this characteristic [36].

Table 7 shows the Tukey test's comparison for the traits of bunch components in the progenies and the years under evaluation. The progenies presented an average of 9.88 g for this trait, and the S.B. trait ranged between 88.97% and 91.81%, with an overall average of the progenies understudy of 90.48%. For the M/FW. trait, the P5 and P2 progenies were classified with the lowest and highest values of 8.53 g and 10.94 g, respectively. The values were between 78% and 79.62% for the ODM trait, and the O/FM trait ranged from 50.68% to 55.12%. P5 obtained the highest values of the entire population for these two genetic traits.

The O/B trait showed the P4 progeny with the highest value at 19.02%, followed by the P5 and P2 progenies with 18.98% and 18.96%, respectively, and the general population presented an average value of 18.25%. The population of Deli *dura* palms of the A.S.D. genetic breeding program in Costa Rica shows O/B contents average 20% [28], values comparable with this study. On the other hand, research made in different *tenera* progenies showed O/B values between 21% and 23% [35]. However, the appropriate combination of *dura* palms with *pisifera* palms can considerably increase the O/B content, as reported by the records of different *dura* × *pisifera* progenies evaluated in Malaysia with O/B contents ranging between 25% and 29% [22].

Table 7. Progeny means of bunch quality traits.

Progenies	MFW	SB	ODM	OFM	OB	NFB	FS	MF	KF	SF
P1	10.42 ab	90.54 bc	78.77 a	51.19 b	18.51 a	67.46 a	74.09 a	57.30 ab	13.81 bc	28.89 b
P2	10.94 a	91.81 a	78.42 a	53.32 ab	18.96 a	65.86 a	76.35 a	56.04 abc	14.82 b	29.13 b
P3	10.08 ab	89.78 cd	78.38 a	52.03 ab	16.84 a	61.03 a	69.98 a	52.89 cd	14.68 b	32.42 a
P4	9.67 abc	91.49 ab	78.00 a	55.07 a	19.02 a	66.39 a	74.71 a	53.97 bcd	15.27 b	30.75 ab
P5	8.53 c	88.97 d	79.62 a	55.12 a	18.98 a	68.67 a	72.44 a	54.55 bcd	15.18 b	30.27 ab
P6	10.29 ab	89.50 d	78.29 a	50.68 b	16.61 a	65.34 a	71.92 a	51.87 d	17.82 a	30.31 ab
P7	9.25 bc	91.23 ab	79.21 a	55.21 a	18.84 a	61.17 a	71.60 a	59.04 a	12.48 c	28.48 b
Trial mean	9.88	90.48	78.67	53.23	18.25	65.13	73.01	55.10	14.87	30.04
CV (%)	8.13	1.20	0.73	3.68	5.80	4.55	2.95	4.58	10.92	4.49
Years after planting (Y.A.P.)										
YAP 3	8.70 d	91.49 a	79.55 a	51.34 c	17.93 b	74.88 a	87.13 a	53.28 c	16.6 a	30.12 a
YAP 5	9.18 cd	90.85 ab	74.94 b	51.47 bc	15.61 c	68.51 ab	79.72 b	52.95 c	15.54 ab	31.51 a
YAP 7	11.85 a	89.95 bc	79.48 a	54.48 ab	17.82 b	54.93 d	62.77 e	54.10 c	14.93 b	30.98 a
YAP 9	11.12 ab	89.80 c	80.25 a	56.88 a	20.86 a	63.62 bc	70.38 cd	58.16 a	11.96 c	29.87 a
Y.A.P. 11	10.21 bc	90.71 abc	79.23 a	52.89 bc	18.96 ab	68.51 ab	73.32 bc	54.71 bc	14.66 b	30.63 a
YAP 14	8.25 d	90.05 bc	78.57 a	52.32 bc	18.31 b	60.33 cd	64.75 de	57.37 ab	15.52 ab	27.11 b
Trial mean	9.89	90.48	78.67	53.23	18.25	65.13	73.01	55.10	14.87	30.04
CV (%)	14.35	0.72	2.43	3.98	9.36	10.79	12.62	3.94	10.55	5.15

Where; M/FW.: Mean fruit weight (gr), S.B.: Spikes bunch ratio (%), ODM: Oil-to-dry mesocarp ratio (%), O/FM: Oil-to-fresh mesocarp ratio (%), O/B: Oil-to-bunch ratio (%), NF/B: Normal fruit-to-bunch ratio (%), FS: fruit set (%), M/F: Mesocarp-to-fruit ratio (%), K/F: kernel to fruit ratio (%), S/F: Shell-to- fruit ratio (%), CV: coefficient of variation. Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey ($n = 252$).

The Tukey test did not show significant differences for the NF/B and FS traits. Their values were found in 65.13% for NF/B, and 73.01% for FS These characteristics define the efficiency of entomophilous pollination, where the insect *Elaeidobius kamerunicus* is the most efficient pollinator in the cultivation of oil palm. Studies carried out by Swaray et al. [26] in different *dura* × *pisifera* progenies show the population dynamics of these insects between different cultivars, with good percentages of FS that ranged between 70% and 75%. The M/F trait showed the highest values in the P7 progeny with 59.04%, followed by the P1 and P2 progeny with 57.30% and 56.04%, the P6 progeny with 51.87% presented the lowest value for this trait.

M/F is one of the most desirable traits to be introgressed in breed progenies of oil palm. Since the oil is stored in the fruit's mesocarp, the genetic variability found in this study will allow breeding and advancement in selecting good female progenitors that present this characteristic. In dura progenies of Nigerian origin, M/F values between 52.5% and 61.2% have been reported [9], which coincide with the values found in this research. M/F, K/F, and S/F define the composition of the fruits, and the P7 progeny presented the lowest values of K/F and S/F with 12.48% and 28.48%, respectively. Additionally, within the best families and later the best individuals, following the F.I.S. strategy, we identify parentals with M/F between 60% and 70% like the values reported in the Deli dura of Southeast Asia that are between 58 and 68% [18].

On the other hand, the P6 progeny showed the highest K/F value with 17.82%, and the P3 progeny had the highest S/F value with 32.42%. These results could be because S/F is reduced at the expense of the M/F when progenies are generated between *dura* and *pisifera*. Therefore, the adequate selection of parents and the evaluation of progenies for their combinatorial ability is decisive in selecting the best progenies.

3.4. Heritability and Genetic Parameters

In general, estimating and finding genetic variability and heritability in oil palm progenies ensures profit in future generations and, therefore, continuous progress in breeding programs [37]. The heritability and genetic parameters of the 25 analyzed traits are presented in Table 8. The highest H^2_B was recorded in HT (71.62%), followed by LN (46.64%) and S.B. with 45.49%. For the K/F trait, H^2_B was 44.47%, for RL 42.25%, and 40.73% for BW Swaray et al. [26] measured 82.56% heritability for height, showing the high heritability of this genetic trait. On the other hand, research conducted by Myint et al. [27] in MPOB-Senegal germplasm planted ex-situ reported values of 22.41% of H^2_B for the genetic trait of HT A record that contrasts with the high values reported in *dura* × *pisifera* and *dura* × *dura* progenies, as in the case of this research.

Table 8. Variance components and genetic parameters of quantitative traits.

Trait	$\sigma^2 g$	$\sigma^2 ge$	$\sigma^2 e$	$\sigma^2 p$	H^2_B (%)
FFB	231.0452	−13.0404	854.1390	1072.14	21.55
BNO	1.2485	1.9637	3.6625	6.87	18.16
ABW	1.5816	0.2805	2.0212	3.88	40.73
FP	4.5840	-0.3314	23.8800	28.13	16.29
PCS	0.0093	−0.0029	0.0700	0.08	12.20
RL	0.0387	0.0029	0.0500	0.09	42.25
LL	29.6733	8.8229	44.3800	82.88	35.80
LW	0.1493	0.1886	0.1800	0.52	28.83
LN	25.4100	0.2143	28.8600	54.48	46.64
HT	0.0039	0.0000	0.0015	0.01	71.62
LA	0.1164	0.0486	0.2840	0.45	25.93
LAI	0.0609	0.0139	0.2516	0.33	18.65
DI	0.0001	0.0006	0.0004	0.00	12.60
MFW	0.5639	−0.1486	1.9900	2.41	23.44
SB	1.0728	0.2457	1.0400	2.36	45.49
ODM	0.0933	0.7714	4.8400	5.52	1.69
OFM	3.1767	0.0971	11.4400	14.71	21.59
OB	0.7850	0.0629	5.7900	6.64	11.83
NFB	4.0522	7.6657	58.3500	70.07	5.78
FS	2.1433	−2.1457	52.4400	52.44	4.09
MF	5.7050	−0.0143	11.8800	17.57	32.47
KF	2.4656	0.0086	3.0700	5.54	44.47
SF	1.5039	0.1286	5.2200	6.85	21.95

$\sigma^2 g$ = progeny variance, σ^2 = ge progeny by year variance, σ^2 e = error variance, σ^2 *p* = variance phenotypic, H^2_B = Broad sense heritability (%), FFB: fresh fruit bunch (kg/palm^{-1}), BNO: bunch number (bunches/palm^{-1}), ABW: average bunch weight (kg/bunch), FP: frond production (number of leafs palm^{-1}), PCS: petiole cross section (cm^2), RL: Rachis length (cm), LL: leaflet length (cm), LW: leaflet width (cm), LN: Leaflet number, HT: Annual palm height (m year^{-1}), LA: Leaf area (cm^2), LAI: leaf area index, DI: diameter of palm trunk (m), MFW: mean fruit weight (gr), SB: spikes bunch ratio (%), ODM: Oil to dry mesocarp ratio (%), OFM: Oil to fresh mesocarp ratio (%), OB: oil to bunch ratio (%), NFB: normal fruit to bunch ratio (%), FS: fruit set (%), MF: Mesocarp-to-fruit ratio (%), KF: kernel-to-fruit ratio (%), SF: Shell-to-fruit ratio (%).

The value of H^2_B obtained for the HT trait confirms the good selection of the parents that are part of the pedigree of the progenies used in the present study. In addition, this characteristic envisions good results in future breeding cycles. The lowest H^2_B was presented in ODM with 1.69%, followed by FS with a value of 4.09% and NF/B with 5.78%. These last two traits were highly influenced by factors external to the genotype, such as the work of entomophilous pollination [18]. In interspecific OxG hybrid, FS heritability is very low (4.9%) [33], comparable to this study's results.

3.5. Analysis of Agronomic Traits

The correlation analysis for the yield traits was separated by crop development stage, young stage, and adult stage. Similar behaviors in the analysis for the entire crop cycle was observed between the yield traits with high Pearson's correlation between FFB and BN (r = 0.70, $p \leq 0.01$), FFB and BW (−0.41), and a high correlation between BN and BW with a value of −0.86 with a ($p \leq 0.01$). These values suggest that the positive increase in BN and BW will significantly improve the performance of FFB (Figure 2). Marhalil et al. [35], in different genetic genotypes derived from Nigeria, Congo (Zaire), and Cameroon, found similar correlations to those in this study for FFB and BN (r = 0.58) and FFB and BW (r = 0.21). In *dura*-type accessions of the *E. guineensis* germplasm of Embrapa (Brazil), phenotypic correlation analyses showed high and positive values for the FFB and BN traits, with r = 0.78 at $p \leq 0.01$ [38].

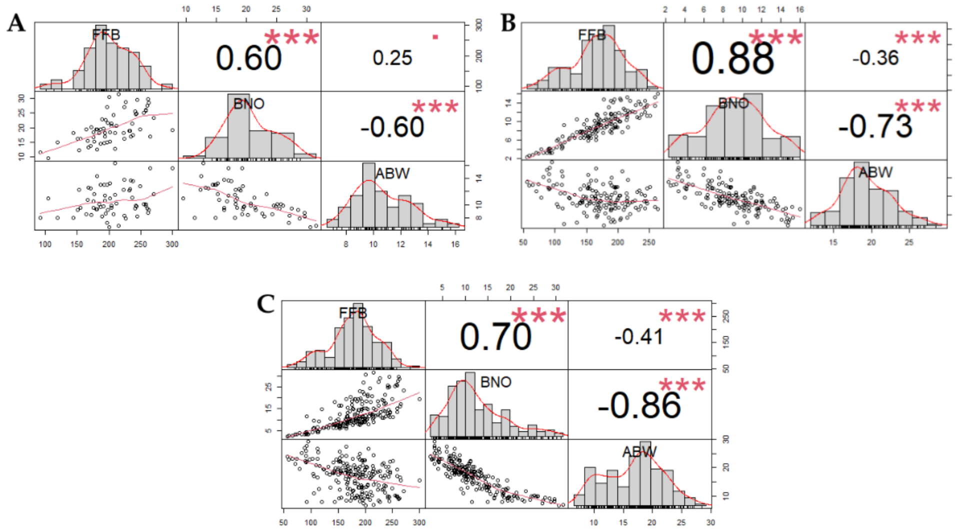

Figure 2. Pearson correlations for yield traits in *dura* × *dura* progenies. (**A**): Young stage. (**B**): Adult stage and (**C**): All crop cycle. FFB: Fresh Fruit Bunches, BN: Bunch Number, and BW: Average bunch weight. *** Highly significant correlations ($p \leq 0.01$).

For the main vegetative traits of interest, the Pearson correlation coefficients showed correlation values of (r = 0.10, $p \leq 0.01$) between HT and LA, and a low association between HT and LAI with 0.13 ($p \leq 0.01$). In contrast, a significant correlation between LA and LAI with r = 0.54, $p \leq 0.01$ was achieved (Figure 3). Thus, the knowledge of the association of the different genetic traits in oil palm is fundamental for the selection of progenies with direct genetic gains [39].

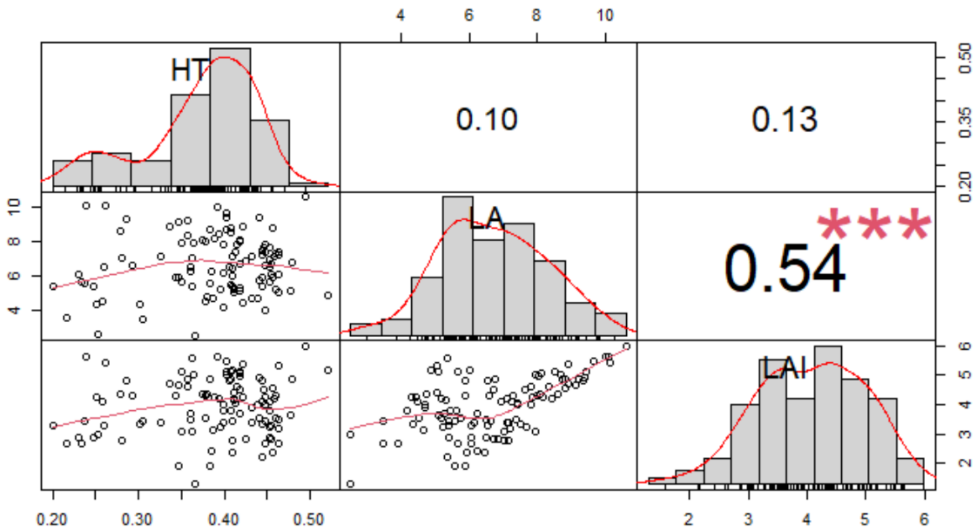

Figure 3. Pearson correlations for vegetative traits in *Dura* × *Dura* progenies. HT: Annual palm height (m $year^{-1}$), LA: Leaf area (cm^2), LAI: leaf area index. *** Highly significant correlations ($p \leq 0.01$).

For the oil characteristics, strong and positive correlation coefficients were presented between ODM and OB (r = 0.61, $p \leq 0.01$), followed by the correlation between MF and OB (r = 0.51, $p \leq 0.01$) and between OB and SF, (r = −0.41, $p \leq 0.01$) and between OB and NFB (r = 0.18, $p \leq 0.01$). Finally, between M/F and S/F, there was a correlation coefficient of r = −0.84 ($p \leq 0.05$), it was the highest found between the different comparisons analyzed

(Figure 4). The high and positive correlations found for O/B with other genetic traits of interest increase the possibility of increasing the oil contents in the next breeding progenies.

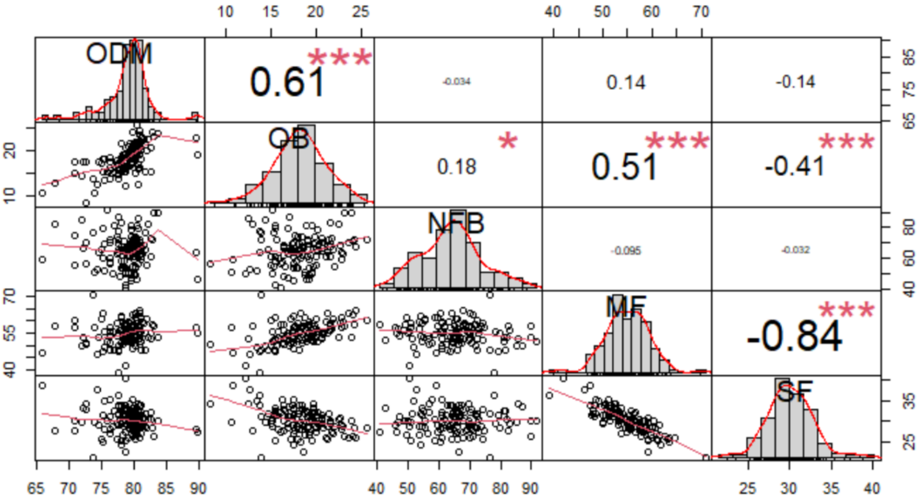

Figure 4. Pearson correlations for bunch quality traits in *Dura* × *Dura* progenies. Where: ODM: Oil to dry mesocarp ratio (%), O/B: oil to bunch ratio (%), NF/B: normal fruit to bunch ratio (%), M/F: Mesocarp-to-fruit ratio (%), S/F: Shell-to-fruit ratio (%). * Significant correlations ($p \leq 0.05$). *** Highly significant correlations ($p \leq 0.01$).

Research carried out in different materials derived from Nigeria, Congo (Zaire), and Cameroon showed the advantages and perspectives of having these high correlations in genetic traits that strengthen oil palm selection and genetic progress [35].

4. Conclusions

The development of commercial oil palm cultivars with a productive and economic life of more than 35 years is possible by identifying *dura* dwarf progenies with high yields, allowing increased profitability and the sustainability of oil palm crops.

According to the results obtained for the genetic traits of yield, vegetative parameters, and bunch components, there is wide variability in the progenies of the studied Cenipalma slow-growth population, which will direct an adequate selection of female parents in oil palm. For the trait of increase in height, the P6 progeny stands out with the lowest annual growth rate of 0.29 m year^{-1}, positioning it as one of the selected candidates for the production of commercial cultivars. On the other hand, the heritability in the broad sense for this trait was the highest, with 72% being a trait with low environmental influence, allowing the future development of dwarf progenies in different environments. On the other hand, the LAI found in the P1 progeny with 5.49 and in the P6 progeny with 5.43 highlight other genetic traits of interest in palm cultivation for future improved progenies. The yield of FFB in the evaluated progenies ranged between 165 and 208 kg per palm per year. The latter value identified in the P3 progeny makes it a candidate to increase the selection of plants with high yields that can be combined with other genetic traits. In general, the yield performance of these progenies was similar to cultivars improved from Deli *dura* with values for the FFB and BN that ranged between 180 and 210 kg per palm per year and 6 to 11 bunches per palm per year [9].

New populations of female parents, developed from the R.R.S., will allow the introgression of genetic traits of interest to add value to the new cultivars. This is the case of the dwarf *dura* population of Cenipalma, which would be used to advance in new breeding cycles, maximizing the genetic gains. In addition to dwarf and highly productive palms, traits such as disease resistance, tolerance to abiotic factors, and improvement of oil quality could be introgressed to generate differentiated cultivars in the subsequent crop breeding cycles.

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References

1. Fedepalma. *Anuario estadístico 2020. Principales cifras de la agroindustria de la palma de aceite en Colombia y en el mundo*; Fedepalma: Bogotá, Colombia, 2020; p. 238.
2. Tabi, K.M.A. Effect of dry heat treatment along with some dormancy breaking chemicals on oil palm seed germination. *S. Afr. J. Bot.* **2017**, *112*, 489–493. [CrossRef]
3. Beirnaert, A.D.F.; Vanderweyen, R. *Contribution À L'étude Génétique et Biométrique des Variétés D' Elaeis Guineensis Jacquin*; East African Standard: Nairobi, Kenya, 1941; p. 27.
4. Reyes, P.A.; Ochoa, J.C.; Montoya, C.; Daza, E.; Ayala, I.M.; Romero, H.M. Development and validation of a bi-directional allele-specific PCR tool for differentiation in nurseries of dura, tenera and pisifera oil palms. *Agron. Colomb.* **2015**, *33*, 5–10. [CrossRef]
5. Singh, R.; Low, E.-T.L.; Ooi, L.C.-L.; Ong-Abdullah, M.; Ting, N.-C.; Nagappan, J.; Nookiah, R.; Amiruddin, M.D.; Rosli, R.; Manaf, M.A.A. The oil palm SHELL gene controls oil yield and encodes a homologue of SEEDSTICK. *Nature* **2013**, *500*, 340–344. [CrossRef] [PubMed]
6. Babu, B.K.; Mathur, R.; Kumar, P.N.; Ramajayam, D.; Ravichandran, G.; Venu, M.; Babu, S.S. Development, identification and validation of CAPS marker for SHELL trait which governs dura, pisifera and tenera fruit forms in oil palm (*Elaeis guineensis* Jacq.). *PLoS ONE* **2017**, *12*, e0171933. [CrossRef]
7. Mondragon-Serna, A.; Baena-Snata, M.A.; González-Díaz, A.; García-Nuñez, J.A.; Ayala-Diaz, I.M.; Romero, H.M. The Oil Palm. In *Oil Crops. Growth, Uses, and Toxicity*; Perea-Flores, M.J., Camacho-Díaz, B.H., Quintanilla-Carvajal, M.X., Eds.; Nova Science Publishers, Inc.: New York, NY, USA, 2021; pp. 105–146.
8. Rajanaidu, N. A Review of Oil Palm Breeding for the Past 50 Years. *Rev. Palmas* **2016**, *37*, 190–202.
9. Noh, A.; Rafii, M.Y.a. Variability and performance evaluation of introgressed Nigerian dura x Deli dura oil palm progenies. *Genet. Mol. Res.* **2014**, *13*, 2426–2437. [CrossRef]
10. Bastidas, S. Genealogíaa del germoplasma de palma de aceite (*Elaeis guineensis* Jacq.) del proyecto de mejoramiento genético de Corpoica. *Rev. Palmas* **2003**, *24*, 21–29.
11. Ishak, Z.; Hashim, A.T.; Rosli, S.K.; Bakar, D.A.; Ooi, S.E.; Mohd, N.; Ong-Abdullah, M. Oil Palm Tissue Culture: Fast Tracking Elite Commercial Lines. In *The Oil Palm Genome*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 47–68.
12. Domiciano, G.P.; Alves, A.A.; Laviola, B.G.; da Conceio, L.D.H.C.S. Parámetros genéticos e diversidade em progenies de macauba com base em características morfológicas e fisiológicas. *Cienc. Rural* **2015**, *45*, 1599–1605. [CrossRef]
13. Hefena, A.; Sultan, M.; Abdel-Moneam, M.; Hammoud, S.; Barutular, C.; El-Sabagh, A. Assessment of Genetic Variability and Correlation Coefficient to Improve Some Agronomic Traits in Rice. *J. Exp. Agric. Int.* **2016**, *14*, 1–8. [CrossRef]
14. Machado, E.L.; Silva, S.A.; Fernandes, L.d.S.; Brasileiro, H.S. Genetic variability and homozygosity in a F4 castor bean population by microsatellite markers. *Bragantia* **2016**, *75*, 307–313. [CrossRef]
15. Shafique, M.S.; Ahsan, M.; Mehmood, Z. Genetic variability and interrelationship of various agronomic traits using correlation and path analysis in chickpea (*Cicer arietinum* L.). *Acad. J. Agric. Res.* **2016**, *4*, 82–85. [CrossRef]
16. Ayala, I.; Romero, H.M.; Tupaz, A.; Daza, E.; Rincón, A.; Caicedo, A.; Fontanilla, C.; Mosquera, M. *Comportamiento Agronómico de Cultivares Comerciales de Palma de Aceite en el Campo Experimental Palmar de la Vizcaína*; Cenipalma: Bogotá, Colombia, 2017; p. 138.
17. Corley, R.H.V.; Breure, C.J. *Measurements in Oil Palm Experiments*; Internal Report; Unilever Plantations: London, UK, 1981.
18. Hardon, J.J.; Williams, C.N.; Watson, I. Leaf area and yield in the oil palm in malaya. *Exp. Agric.* **1969**, *5*, 25–32. [CrossRef]
19. Corley, R.H.V.; Tinker, P.B. *The Oil Palm*, 5th ed.; Wiley Blackwell: Oxford, UK, 2016; p. 650.
20. Blaak, G.; Sparnaaij, L.; Menedez, T. Breeding and inheritance in the oil palm (*Elaeis guineensis* Jacq.) II. Methods of bunch quality analysis. *J.W. Afr. Inst. Oil Palm Res.* **1963**, *4*, 146–155.
21. Prada, F.; Romero, H.M. *Muestreo y Analisis de Racimos en el Cultivo de la Palma de Aceite. Tecnologías para la Agroindustria de la Palma de Aceite, Guia de Facilitadores*; Cenipalma: Bogotá, Colombia, 2012; p. 158.
22. Falconer, D.; Mackay, T. *Introduction to Quantitative Genetics*; Longman Group: Essex, UK, 1996.

23. Arolu, I.W.; Rafii, M.Y.; Marjuni, M.; Hanafi, M.M.; Sulaiman, Z.; Rahim, H.A.; Abidin, M.I.Z.; Amiruddin, M.D.; Din, A.K.; Nookiah, R. Breeding of high yielding and dwarf oil palm planting materials using Deli *dura* × Nigerian *pisifera* population. *Euphytica* **2017**, *213*, 154. [CrossRef]
24. Sapey, E.; Peprah, B.B.; Adusei-Fosu, K.; Agyei-Dwarko, D. Genetic Variability of Fresh Fruit Bunch Yield (FFB) Yield in Some Dura × Pisifera Breeding Populations of Oil Palm (*Elaeis guineensis* Jacq.). *Am. -Eurasian J. Agric. Environ. Sci.* **2015**, *15*, 1637–1640. [CrossRef]
25. Noh, A.; Rafii, M.Y.; Saleh, G.; Kushairi, A.; Latif, M.A. Genetic performance and general combining ability of oil palm Deli *dura* × AVROS *pisifera* tested on inland soils. *Sci. World J.* **2012**, *2012*, 792601. [CrossRef] [PubMed]
26. Swaray, S.; Amiruddin, M.D.; Rafii, M.Y.; Jamian, S.; Ismail, M.F.; Jalloh, M.; Marjuni, M.; Mohamad, M.M.; Yusuff, O. Influence of parental dura and pisifera genetic origins on oil palm fruit set ratio and yield components in their D × P Progenies. *Agronomy* **2020**, *10*, 1793. [CrossRef]
27. Myint, K.A.; Amiruddin, M.D.; Rafii, M.Y.; Samad, M.Y.A.; Ramlee, S.I.; Yaakub, Z.; Oladosu, Y. Genetic diversity and selection criteria of MPOB-Senegal oil palm (*Elaeis guineensis* Jacq.) germplasm by quantitative traits. *Ind. Crop. Prod.* **2019**, *139*, 111558. [CrossRef]
28. Alvarado, A.; Henry, J. Evolution blue: A new oil palm variety with reduced growth and high oil content. *A.S.D. Oil Palm Pap.* **2015**, *45*, 45.
29. Saldaña-Villota, T.M.; Cotes-Torres, J.M. Radiation interception and leaf area index from foliage cover in diploid potato. *Agron. J.* **2020**, *112*, 2805–2811. [CrossRef]
30. Breure, C.J. Rate of leaf expansion: A criterion for identifying oil palm (*Elaeis guineensis* Jacq.) types suitable for planting at high densities. *NJAS—Wagening. J. Life Sci.* **2010**, *57*, 141–147. [CrossRef]
31. Barcelos, E. Oil palm natural diversity and the potential for yield improvement. *Front. Plant Sci.* **2015**, *6*, 190. [CrossRef]
32. Alvarado, A.; Chinchilla, C.; Rodríguez, J. Desempeño de dos variedades de palma aceitera (Deli × AVROS y Deli × Ghana) plantadas a diferentes densidades en dos sitios en Costa Rica. *ASD Oil Palm Pap.* **2007**, *8*, 35–41.
33. Sunilkumar, K.; Mathur, R.K.; Sparjanbabu, D.S.; Pillai, R.S.N. Evaluation of interspecific oil palm hybrids for dwarfness. *J. Plant. Crop.* **2015**, *43*, 29–34.
34. Donough, C.R. *Breeding Oil Palms for High Oil Yield in I.O.I. Group: 1. First Cycle Development of OPGL-Derived Materials*; MPOB National Seminar: Kuala Lumpur, Malaysia, 2005; p. 125.
35. Marhalil, M.; Zulkifli, Y.; Kushairi, A.; Adura, Z.S.; Nurniwalis, A.; Zubaidah, R. Potential oil palm genetic materials derived from introgression of germplasm (MPOB-Nigeria, MPOB-Zaire and MPOB-Cameroon accessions) to advanced (AVROS) breeding populations. *J. Oil Palm Res.* **2020**, *32*, 569–581.
36. Murugesan, P.; Rani, K.L.M.; Ramajayam, D.; Kumar, K.S.; Mathur, R.K.; Ravichandran, G.; Kumar, P.N.; Arunachalam, V. Genetic diversity of vegetative and bunch traits of African oil palm (*Elaeis guineensis*) germplasm in India. *Indian J. Agric. Sci.* **2015**, *85*, 892–895.
37. Ortega Cedillo, D.; Barrera, C.F.; Ortega Cedillo, J.; Orellana Carrera, J.; Vilela de Resende, M.D.; Damião Cruz, C. Estimates of parameters, prediction and selection of an oil palm population in Ecuador. *Rev. Fac. Nac. Agron. Medellín* **2018**, *71*, 8477–8487. [CrossRef]
38. De Almeida Rios, S.; da Cunha, R.N.V.; Lopes, R.; Barcelos, E.; da Rocha, R.N.C.; de Lima, W.A.A. Correlation and Path analysis for yield components in *dura* oil palm germplasm. *Ind. Crop. Prod.* **2018**, *112*, 724–733. [CrossRef]
39. Cedillo, D.S.O.; Barros, W.S.; Ferreira, F.M.; Dias, L.A.D.S.; Rocha, R.B.; Cruz, C.D. Correlation and repeatability in progenies of African oil palm. *Acta Sci. Agron.* **2008**, *30*, 197–201. [CrossRef]