Euphytica (2024) 220:73
https://doi.org/10.1007/s10681-024-03333-2

RESEARCH

Development of new high-yielding planting material based on performance of 38 oil palm (*Elaeis guineensis* Jacq.) *Dura* × *Pisifera* families

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Received: 17 June 2023 / Accepted: 27 March 2024 / Published online: 8 April 2024

Abstract Due to the narrow genetic base of both Deli and AVROS populations used in Malaysian commercial planting materials, exotic germplasm from Nigeria has been introduced into existing breeding populations. This study was conducted to select the best families from 38 *dura* × *pisifera* (D × P) families for the development of new high-yielding planting materials. The families were planted at the MPOB Research Station Hulu Paka, Terengganu, Malaysia, in 2007, in a randomised complete block design with three replications. Bunch yield recording, bunch quality components estimations, and vegetative measurements were analysed using analysis of variance, followed by comparisons between family means, heritability estimates, and cluster analysis. Highly significant genetic variation was observed for all traits among the 38 D × P families. Families PK 4044, ECP HP 496, ECP HP 500, and ECP HP 502 exhibited excellent yield-related traits such as fresh fruit bunch (FFB) yield, bunch number (BNO), oil yield (OY), total economic product (TEP), and total oil content (TOT). Although the broad-sense heritability estimates were low for FFB yield (15.8%), moderate for TEP (53.8%) and TOT (55.2%), the estimates were high for BNO (80.9%) and OY (62.7%). The families clustered into three main clusters with several sub-clusters, whereby the high-yielding four families (PK 4044, ECP HP 496, ECP HP 500, and ECP HP 502) were clustered together. Using these families as commercial planting materials may potentially increase the national oil yield, which has stagnated for a few decades, and subsequently contribute to the advancement of the oil palm industry in the future.

Keywords Bunch yield · Cluster analysis · Heritability · Genetic variation · Oil yield

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Introduction

In 2021, oil palm (*Elaeis guineensis* Jacq.) was the main contributor from the agriculture sector to Malaysia's Gross Domestic Product (GDP) at 35.2%, followed by other agriculture (29.3%), livestock (16.7%), fisheries (11.3%), forestry and logging (5.2%), as well as rubber (2.3%) (DOSM 2022). In the same year, the area of oil palm plantations in Malaysia reached 5.7 million hectares, an increase of 54,000 hectares from 1960 (MPOB 2022), indicating the remarkable growth of the industry. Moreover, global demand for vegetable oils is expected to increase to 240 million tonnes by 2050 (Barcelos et al. 2015). As the highest productivity oil crop among cultivated oil crops, the oil palm industry worldwide strives to meet this increasing demand.

The *dura* fruit form from the Deli breeding stock was the first commercial oil palm planting material in Malaysia in 1917. Discovery of the monogenic shell thickness by Beirnaert and Vanderweyen (1941) showed the importance of the *tenera* fruit form of the *dura* × *pisifera* (D × P) hybrid. Compared to the *dura*, the *tenera* contains a higher proportion of oil-bearing mesocarp, which results in a higher oil yield. Thus, the Malaysian Department of Agriculture (DOA) began production of the country's first D × P planting material in 1953, and the oil palm industry responded by switching to D × P planting materials a few years later (Kushairi et al. 1999). Switching from the *dura* to the *tenera* (D × P) planting materials improved yields by up to 30% in the country (Kushairi 2009).

Since the *Algemene Vereniging van Rubberplanters ter Oostkut van Sumatra* (AVROS) *pisifera* has shown good general combining ability (GCA) with the Deli *dura*, the Deli *dura* × AVROS *pisifera* (D × P) has been the common commercial planting material in Malaysia and worldwide (Kushairi et al. 1999). The Deli populations in Malaysia are descended from four *dura* seedlings planted in Bogor Botanical Garden, Indonesia in 1848, while AVROS *pisifera* originated from the "Djongo" palm found in Eala Botanical Garden, Zaire. Although, the performance of Deli *dura* × AVROS *pisifera* families has been extensively studied to identify superior families in order to increase oil productivity (Noh et al. 2010), the narrow genetic base of the existing Deli and AVROS populations would be a setback for yield improvement, as both populations are descended from a limited number of palms. This drawback led to a series of expeditions conducted in Africa and Latin America to search for *E. guineensis* and *E. oleifera* genetic materials, respectively (Rajanaidu 1994; Rajanaidu et al. 2017; Rajanaidu and Rao 1988). These germplasm collections were then field-planted, evaluated, and utilised in several ways for crop improvement. One of them is to develop elite D × P planting materials through the introgression of elite palms from the germplasm collections into current breeding material (Rajanaidu et al. 2017).

Development of new high-yielding planting materials is much needed as the national yield performance has stagnated at 3.7 t ha^{-1} for a few decades (Parveez 2019). Due to land scarcity, increasing plantation areas is not an option to boost yields. Therefore, the most effective and sustainable way to increase oil yield is by utilising planting materials from high-yielding genetic bases. Generally, development of new and improved planting materials relies greatly on populations of *dura* and *pisifera*. In Malaysia, the modified recurrent selection (MRS) is the most widely practised scheme by oil palm breeders, involving inter-crossing between selected parents from both *dura* and *pisifera* populations with the aim to exploit heterosis (Kushairi and Mohd Din 2020). Selected families derived from the inter-crosses would be planted to improve bunch and oil yields. Hence, the objective of this study was to select the best families from a set of 38 *dura* × *pisifera* crosses for the development of new high-yielding planting materials.

Materials and methods

Materials

A total of 38 D × P families were derived from inter-crosses between 31 Deli *dura* palms and 11 *pisifera* palms (four AVROS, four MPOB-Nigeria and three MPOB-Nigeria × United Plantations) (Table 1). The Deli *dura* palms were from several sub-populations, such as Banting, Highlands Estate, Ulu Remis, Johor Labis, Highlands Estate × Elmina, Ulu Remis × Highlands Estate, and Ulu Remis × Elmina. The AVROS *pisifera* male parents were from the fifth cycle of MPOB's *tenera/pisifera* breeding populations, which is the descendant of BM 119 from Oil Palm Research Station (OPRS), Banting. The MPOB-Nigeria *pisifera* palms were from the second generation of Nigeria germplasm in MPOB, while the MPOB-Nigeria × United Plantations *pisifera* palms were derived from a collaborative crossing programme with the industry known as BK 20: United Plantations (UP) Nigeria Crossing Programme. The 38 D × P families were planted in Trial 0.491 at MPOB Research Station Hulu Paka, Terengganu, in 2007 in a randomised complete block design (RCBD), in three replications, with 16 palms per family per replicate at a planting density of 148 palms ha^{-1}. Annual rainfall ranged from 2,545 to 6,176 mm $year^{-1}$, with a mean rainfall of 3,948 mm $year^{-1}$ from 2007 to 2018.

Table 1 *Dura* × *pisifera* families in Trial 0.491, MPOB Research Station Hulu Paka

No	*Dura* × *Pisifera* Origin	Family	Pedigree (Female × Male)
1	Deli Banting × AVROS	ECP HP 414	0.279/242 × 0.394/456
2	Deli Banting × AVROS	ECP HP 415	0.279/24 × 0.394/456
3	Deli Banting × AVROS	ECP HP 550	0.279/24 × 0.337/147
4	Deli Banting × AVROS	ECP HP 617	0.281/74 × 0.394/24
5	Deli Banting × MPOB-Nigeria	ECP HP 626	0.279/48 × 0.337/535
6	Deli Banting × MPOB-Nigeria	ECP HP 633	0.279/26 × 0.337/94
7	Deli Banting × MPOB-Nigeria	ECP HP 635	0.281/74 × 0.337/94
8	Deli Banting × (MPOB-Nigeria × UP)	PK 4039	0.212/101 × 0.292/353
9	Deli Banting × (MPOB-Nigeria × UP)	PK 4152	0.212/444 × 0.292/1218
10	Deli Banting × (MPOB-Nigeria × UP)	PK 4159	0.212/438 × 0.292/1218
11	Deli Banting × (MPOB-Nigeria × UP)	PK 4160	0.212/441 × 0.292/1218
12	Deli Banting × (MPOB-Nigeria × UP)	PK 4169	0.212/441 × 0.292/1250
13	Deli Banting × (MPOB-Nigeria × UP)	PK 4176	0.212/39 × 0.292/1250
14	Deli H. Est. × (MPOB-Nigeria × UP)	PK 4044	0.212/6 × 0.292/353
15	Deli H. Est. × (MPOB-Nigeria × UP)	PK 4161	0.212/466 × 0.292/1218
16	Deli H. Est. × (MPOB-Nigeria × UP)	PK 4181	0.212/466 × 0.292/1250
17	Deli Johor Labis × AVROS	ECP HP 428	0.278/318 × 0.394/24
18	Deli Johor Labis × AVROS	ECP HP 437	0.281/57 × 0.394/222
19	Deli Ulu Remis × AVROS	ECP HP 423	0.338/304 × 0.394/24
20	Deli Ulu Remis × AVROS	ECP HP 425	0.338/56 × 0.394/24
21	Deli Ulu Remis × AVROS	ECP HP 449	0.338/373 × 0.394/222
22	Deli Ulu Remis × AVROS	ECP HP 450	0.338/389 × 0.394/222
23	Deli Ulu Remis × AVROS	ECP HP 452	0.338/264 × 0.394/222
24	Deli Ulu Remis × AVROS	ECP HP 456	0.338/84 × 0.394/222
25	Deli Ulu Remis × AVROS	ECP HP 466	0.338/422 × 0.394/234
26	Deli Ulu Remis × MPOB-Nigeria	ECP HP 496	0.338/360 × 0.337/552
27	Deli Ulu Remis × MPOB-Nigeria	ECP HP 500	0.338/361 × 0.337/552
28	Deli Ulu Remis × MPOB-Nigeria	ECP HP 502	0.280/65 × 0.337/552
29	Deli Ulu Remis × MPOB-Nigeria	ECP HP 504	0.338/89 × 0.337/552
30	Deli Ulu Remis × MPOB-Nigeria	ECP HP 519	0.338/300 × 0.337/147
31	Deli Ulu Remis × MPOB-Nigeria	ECP HP 529	0.338/84 × 0.337/147
32	Deli Ulu Remis × MPOB-Nigeria	ECP HP 531	0.338/360 × 0.337/147
33	Deli Ulu Remis × MPOB-Nigeria	ECP HP 630	0.338/427 × 0.337/535
34	Deli (H. Est. × Elmina) × (MPOB-Nigeria × UP)	PK 4032	0.212/714 × 0.292/353
35	Deli (H. Est. × Elmina) × (MPOB-Nigeria × UP)	PK 4144	0.212/273 × 0.292/1218
36	Deli (Ulu Remis × Elmina) × AVROS	ECP HP 593	0.281/44 × 0.394/234
37	Deli (Ulu Remis × Elmina) × AVROS	ECP HP 618	0.281/44 × 0.394/234
38	Deli (Ulu Remis × H. Est.) × (MPOB-Nigeria × UP)	PK 4189	0.212/496 × 0.292/1218

H. Est. = Highlands Estate, *UP* = United Plantations

Data collection

Data collection from the 38 D × P families was carried out for vegetative measurements, bunch yield, and bunch quality components. Bunch yield was recorded for each palm at two harvest rounds per month starting at 36 months after field planting by recording the bunch weight (BWT) and bunch number (BNO). Fresh fruit bunch (FFB) yield, BNO and average bunch weight (ABW) were calculated based on the following formulae;

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

$$\text{BNO (no. palm}^{-1}\text{ year}^{-1}) = \sum_{i=1}^{n} \text{BNOi}$$

$$\text{ABW (kg)} = \text{FFB/BNO}$$

where n is the number of harvest rounds, and i is the number of palm.

The bunch yield record between January and December was summarised for each year, and the average over four consecutive recording years (2014–2017) was used for data analysis. In addition, two to five bunches from each palm were sampled from 2011 to 2018 to determine the bunch quality components using the bunch analysis method (Blaak et al. 1963; Rao et al. 1983). The bunch quality components include bunch weight (BWT), mean fruit weight (MFW), mean nut weight (MNW), parthenocarpic to bunch (P/B), mesocarp to fruit (M/F), kernel to fruit (K/F), shell to fruit (S/F), oil to dry mesocarp (O/DM), oil to wet mesocarp (O/WM), fruit to bunch (F/B), oil to bunch (O/B), kernel to bunch (K/B), moisture content (MC), oil to fibre (O/F), oil yield (OY), kernel yield (KY), total economic product (TEP), and total oil (TOT). In 2015, one round of vegetative measurements using the non-destructive method by Corley and Breure (1981) was carried out for each palm. The vegetative characters measured were frond production (FP), petiole cross-section (PCS), rachis length (RL), leaflet length (LL), leaflet width (LW), leaflet number (LN), trunk height (HT), leaf area (LA), leaf area index (LAI), and trunk diameter (DIA). In terms of height, the oil palm stem is not visibly apparent in the first two years of growth and is not considered in the annual trunk height increment (HTi) estimation (Breure and Powell 1988). Therefore, the annual HTi in this study is the height of the palm at year eight after field planting, divided by six. Physiological traits such as vegetative dry matter (VDM), bunch dry matter (BDM), total dry matter (TDM), and bunch index (BI) were derived using bunch yield and vegetative measurements (Table 2).

Statistical analysis

All data were analysed on an individual-palm basis, where simple statistics such as mean and coefficient of variation (CV) were determined for each trait. The analysis of variance (ANOVA) for all traits was performed using the Statistical Analysis Software (SAS 9.4) programme, where the general linear model (PROC GLM) was used due to the unequal number of palms from the families studied. The family mean comparison was conducted using Fisher's least significant difference (LSD) at a 5% level of probability. Broad-sense heritability (h^2_B) of all traits in families was estimated using variance components from ANOVA as follows;

$$\text{Broad - sense heritability } \left(h^2_B\right) = 2(\sigma^2_g/\sigma^2_g + \sigma^2_{gr} + \sigma^2_e)$$

where σ^2_g = family variance, σ^2_{gr} = interaction between family and replication variance and σ^2_e = within palms variance. The sum of σ^2_g, σ^2_{gr} and σ^2_e is phenotypic variance (σ^2_p).

The minimum variance method (Ward 1963) was used to cluster the families into groups, which was analysed using SAS 9.4.

Results and discussion

Bunch yield and its components

A previous study by Noh et al. (2010) revealed limited genetic variability among 40 Deli *dura* × AVROS *pisifera* progenies planted in MPOB Research Station Keratong, Pahang, in terms of FFB yield and BNO, which could be a hindrance to future selection and breeding. However, 38 D × P families in this study and 34 D × P families studied by Arolu et al. (2017) proved otherwise, where analysis of variance (ANOVA) showed highly significant differences for bunch yield and its components. A significant difference was also detected for the interaction

Table 2 Mean squares for bunch yield and its components in 38 D × P families

Source of variation	df	FFB	BNO	ABW
Replications (r)	2	114.9^{ns}	105.5**	136.4**
Families (g)	37	10,638.9**	238.4**	190.7**
g × r	74	4432.9**	18.2**	21.4**
Within palms (e)	1452	1513.5	7.0	7.2

**, ns = significant at P ≤ 0.01 and non-significant, respectively. *FFB* = fresh fruit bunch yield, *BNO* = bunch number, *ABW* = average bunch weight effect between family and replicate (g × r), suggesting inconsistencies in bunch yield and its components across the three replicates in this study.

The performance of 38 D × P families in terms of bunch yield and its components is presented in Table 3. Family PK 4044 from the Deli Highlands Estate × (MPOB-Nigeria × UP) cross produced the highest FFB yield at an average of 214.4 kg palm^{-1} year^{-1}. However, no difference was observed in the FFB yields from families PK 4144, PK 4159, PK 4189, ECP HP 496, ECP HP 500, ECP HP 502, ECP HP 504, ECP HP 519, ECP HP 529, and ECP HP 449 based on Fisher's LSD. The majority of these families were from the Deli Ulu Remis × MPOB-Nigeria cross. In contrast, family PK 4039 from the Deli Banting × (MPOB-Nigeria × UP) cross, was ranked the lowest in terms of FFB yield, at 149.4 kg palm^{-1} year^{-1}. Fisher's LSD indicated no significant difference between family PK 4039 and four other families, namely ECP HP 415, ECP HP 617, ECP HP 626 and PK 4169. The results also showed that families with the highest (PK 4044) and lowest (PK 4039) FFB yields had comparable ABW means at 14 kg. However, a higher BNO for family PK 4044 (a mean of 15.3 bunches palm^{-1} year^{-1}) than for family PK 4039 (a mean of 10.6 bunches palm^{-1} year^{-1}) may have contributed to the differences in their FFB yields. Moreover, FFB yield is one of the requirements listed in the Malaysian Standard of Oil Palm Seeds for Commercial Planting (MS 157) by the Department of Standards Malaysia. Based on the current standard, MS 157:2017, the *tenera* in the progeny test should meet the minimum requirement of FFB yield at 170 kg palm^{-1} year^{-1} (DOSM 2017). In this study, the majority of the families, i.e. 33 of 38 families representing 87%, had higher FFB yields than the value listed in the MS 157:2017 standard, demonstrating the effectiveness of the parental selection.

In terms of the number of fruit bunches produced per family, the highest BNO was recorded in family ECP HP 496 from the Deli Ulu Remis × MPOB-Nigeria cross at 20.2 bunches palm^{-1} year^{-1}, though it had the lowest ABW of 10.3 kg. These values were significantly different from the corresponding mean values for BNO and ABW of other families through Fisher's LSD analysis. Conversely, family ECP HP 550 from the Deli Banting × AVROS cross had the lowest BNO but highest ABW at 8.2 bunches palm^{-1} year^{-1} and 22.2 kg, respectively. These observations suggested

Table 3 Family means for bunch yield and its components from the 38 D × P families

No	Family	FFB	BNO	ABW
1	PK 4044	**214.4**^{a}	15.3^{cd}	14.3^{n-q}
2	ECP HP 502	212.6^{ab}	14.6^{c-g}	14.7^{k-p}
3	PK 4144	209.3^{a-c}	13.0^{h-m}	16.5^{e-i}
4	PK 4189	208.1^{a-d}	14.1^{e-i}	15.0^{j-o}
5	ECP HP 496	207.4^{a-d}	**20.2**^{a}	**10.3**^{u}
6	ECP HP 500	205.5^{a-e}	14.8^{c-f}	14.0^{o-r}
7	PK 4159	205.3^{a-e}	13.1^{h-m}	15.9^{f-k}
8	ECP HP 529	204.4^{a-e}	15.0^{c-f}	13.9^{o-r}
9	ECP HP 519	203.7^{a-e}	15.5^{c}	13.2^{q-s}
10	ECP HP 504	199.6^{a-f}	17.0^{b}	11.8^{t}
11	ECP HP 449	197.2^{a-g}	12.0^{m-p}	16.7^{d-g}
12	ECP HP 456	196.2^{b-g}	13.0^{i-n}	15.4^{i-n}
13	ECP HP 531	195.1^{c-g}	13.5^{g-j}	14.7^{l-p}
14	ECP HP 450	192.7^{c-h}	11.8^{n-r}	16.6^{e-h}
15	ECP HP 635	192.6^{c-h}	11.8^{n-r}	16.7^{d-h}
16	PK 4161	192.2^{c-h}	13.8^{f-i}	14.1^{o-q}
17	ECP HP 452	191.7^{d-h}	12.3^{k-p}	15.9^{g-l}
18	PK 4032	191.2^{d-h}	13.3^{h-k}	14.9^{j-o}
19	ECP HP 425	191.1^{d-h}	13.2^{h-l}	14.6^{m-p}
20	PK 4160	189.4^{e-i}	14.2^{d-h}	13.6^{p-r}
21	ECP HP 633	186.3^{f-j}	11.4^{o-s}	16.8^{d-g}
22	ECP HP 593	186.3^{f-j}	10.7^{r-u}	17.7^{c-e}
23	PK 4181	185.7^{f-j}	15.2^{c-e}	12.4st
24	PK 4152	185.4^{f-j}	12.1^{l-p}	15.5^{h-m}
25	ECP HP 466	185.0^{f-j}	10.7^{q-u}	17.6^{c-e}
26	ECP HP 428	184.9^{f-j}	10.3^{s-v}	18.4^{bc}
27	ECP HP 423	184.1^{f-j}	11.7^{o-r}	16.0^{f-j}
28	ECP HP 550	180.9^{g-j}	**8.2**^{x}	**22.2**^{a}
29	ECP HP 437	180.3^{g-k}	10.2^{t-v}	17.9^{b-d}
30	ECP HP 618	177.8^{h-l}	11.3^{p-t}	15.9^{f-l}
31	PK 4176	173.1^{i-m}	11.9^{m-q}	14.8^{j-o}
32	ECP HP 414	171.7^{j-n}	10.1^{uv}	17.6^{c-e}
33	ECP HP 630	170.4^{j-n}	11.4^{o-t}	15.3^{j-n}
34	ECP HP 617	163.2^{k-o}	9.4^{vw}	17.8^{b-d}
35	ECP HP 626	161.0^{l-o}	9.6^{uv}	17.1^{d-f}
36	PK 4169	158.8^{m-o}	12.5^{j-o}	12.8^{r-t}
37	ECP HP 415	155.6^{no}	8.3^{wx}	19.0^{b}
38	PK 4039	**149.4**^{o}	10.6^{r-u}	14.3^{m-q}
	Trial mean	188.8	12.7	15.4
	CV (%)	22.9	28.6	22.8

Means with the same letter are not significantly different at $p \leq 0.05$ based on Fisher's Least Significant Difference (LSD). Figures in bold within the mean column are minimum and maximum values. *FFB* = fresh fruit bunch yield (kg palm^{-1} year^{-1}), *BNO* = bunch number (no. palm^{-1} year^{-1}), *ABW* = average bunch weight (kg), *CV* = coefficient of variation a negative relationship between BNO and ABW. The negative correlation between BNO and ABW in oil palm is widely known (Tanya et al. 2013). As oil yield (OY) is an important trait for productivity improvement, relationships between OY and yield components have been studied. The BNO and ABW exhibited by the MPOB-Senegal germplasm were moderately and positively correlated to OY production, while FFB yield was highly and positively correlated to OY (Myint et al. 2019). Four families derived from the MPOB-Nigeria and MPOB-Nigeria × United Plantations male parents, namely PK 4044, ECP HP 502, PK 4144, and PK 4189 were the top FFB yielders, with comparable ABW (14.3 to 16.5 kg) and higher BNO (13.0 to 15.3 bunches palm^{-1} year^{-1}) than the trial means. The results thus suggest that moderate ABW with high BNO traits should be considered for high FFB yield production. The findings also agreed with Arolu et al. (2016), who suggested that Nigeria *pisifera* male parents may have contributed to higher FFB yield in their 34 Deli *dura* × Nigeria *pisifera* families.

Bunch quality components

There were highly significant differences ($P<0.01$) among the families for all bunch quality component traits (Table 4). As bunch quality components consist of major economic traits such as OY, TEP, and TOT, significant genetic variation detected among families would assist in the selection programme for improvements of these traits. The g × r interaction was also highly significant for the majority traits such as BWT, P/B, K/F, O/DM, O/B, O/F, OY, TEP, and TOT, while significant for MFW and K/B. This suggests inconsistencies in the bunch quality component traits across the replicates. Mhanhmad et al. (2011) found that F/B, K/B, and O/B were significantly higher in the dry season (January to April 2008) compared to the wet season (July to October 2007) in Pathio district, Chumphon province, Thailand. Nevertheless, non-significant differences in the g × r interaction were observed for MNW, M/F, S/F, O/WM, F/B, MC, and KY, implying consistencies in the performance of families for these traits across replicates.

The performance of bunch quality components for 38 D × P families is presented in Table 5. Bunch weight (BWT) ranged from 9.4 kg to 24.7 kg, with a trial mean of 13.2 kg. Family ECP HP 550 from the Deli Banting × AVROS cross with the highest BWT, or 86% higher than the trial mean, was significantly different from all the other families. In contrast, family ECP HP 496 from the Deli Ulu Remis × MPOB-Nigeria cross with the lowest BWT was not significantly different from families PK 4169, PK 4181, ECP HP 500, ECP HP 504, PK 4176, PK 4039, and ECP HP 502. Meanwhile, four families, namely ECP HP 630, ECP HP 425, ECP HP 414, and ECP HP 450, were found to have the highest MFW of 15.2 g, 14.3 g, 14.0 g, and 13.8 g, respectively. Their BWT means were not significantly different based on Fisher's LSD. On the other hand, eight families (PK

Table 4 Mean squares for bunch quality components in 38 D × P families

Source of variation	df	BWT	MFW	MNW	P/B	M/F	K/F	S/F	O/DM	O/WM
Replications (r)	2	158.2**	36.4**	0.3^{ns}	138.8**	16.7^{ns}	10.8*	1.7^{ns}	13.9*	9.6^{ns}
Families (g)	37	123.0**	134.6**	8.4**	81.7**	311.2**	70.4**	137.0**	56.2**	201.0**
g × r	74	23.4**	6.4*	0.3^{ns}	21.7**	21.6^{ns}	4.7**	7.9^{ns}	5.2**	12.1^{ns}
Within palms (e)	791	10.5	4.7	0.3	12.1	16.4	3.1	7.3	3.5	12.3

Source of variation	F/B	O/B	K/B	MC	O/F	OY	KY	TEP	TOT
Replications (r)	55.4^{ns}	11.2^{ns}	8.0**	4.8^{ns}	4476.8^{ns}	227.6^{ns}	16.7^{ns}	240.6^{ns}	237.5^{ns}
Families (g)	149.7**	191.5**	23.2**	172.0**	26,276.0**	1536.1**	75.4**	1375.0**	1398.0**
g × r	18.0^{ns}	12.4**	2.1*	10.4^{ns}	2601.1**	215.6**	7.7^{ns}	219.1**	218.1**
Within palms (e)	16.3	8.1	1.5	11.7	1650.9	107.3	7.5	118.7	116.5

*, **, ns = significant at $P \leq 0.05$, $P \leq 0.01$ and non-significant, respectively. *BWT* = bunch weight, *MFW* = mean fruit weight, *MNW* = mean nut weight, *P/B* = parthenocarpic to bunch, *M/F* = mesocarp to fruit, *K/F* = kernel to fruit, *S/F* = shell to fruit, *O/DM* = oil to dry mesocarp, *O/WM* = oil to wet mesocarp, *F/B* = fruit to bunch, *O/B* = oil to bunch, *K/B* = kernel to bunch, *MC* = moisture content, *O/F* = oil to fiber, *OY* = oil yield, *KY* = kernel yield, *TEP* = total economic product, *TOT* = total oil

Table 5 Family means for bunch quality components from the 38 D×P families

No	Family	BWT	MFW	MNW	P/B	M/F	K/F	S/F	O/DM	O/WM
1	ECP HP 550	**24.7^{a}**	10.6^{i-k}	2.2^{i-m}	5.1^{e-l}	78.0^{k-m}	9.5^{a-c}	12.5^{e-l}	77.9^{l-p}	46.8^{m-o}
2	PK 4152	19.8^{b}	12.0^{e-i}	2.7^{c-g}	3.6^{i-n}	77.3^{l-o}	9.5^{a-c}	13.3^{d-i}	75.8^{s}	46.2^{no}
3	ECP HP 626	17.6^{c}	13.3^{b-e}	2.3^{i-m}	4.6^{g-n}	82.8^{b-f}	6.8^{k-o}	10.5^{m-o}	**74.0^{t}**	**41.4^{p}**
4	ECP HP 452	16.2^{cd}	12.7^{c-g}	3.0^{a-c}	5.1^{e-k}	75.7^{m-p}	9.9^{ab}	14.5^{b-d}	78.5^{h-n}	49.4^{i-l}
5	ECP HP 415	15.9^{c-e}	13.0^{b-f}	2.5^{f-j}	9.4^{ab}	79.7^{g-l}	8.4^{c-g}	11.9^{g-m}	78.5^{h-n}	49.4^{i-l}
6	ECP HP 617	15.6^{c-f}	12.9^{b-f}	**3.3^{a}**	6.4^{c-h}	**73.5^{p}**	**10.6^{a}**	15.9^{ab}	76.8^{p-s}	47.2^{l-o}
7	ECP HP 593	15.4^{c-f}	13.3^{b-e}	2.3^{i-l}	7.2^{b-e}	81.9^{c-h}	7.4^{g-m}	10.8^{l-o}	79.8^{c-g}	48.9^{j-m}
8	ECP HP 428	15.3^{d-f}	12.3^{d-h}	2.3^{h-l}	6.7^{c-g}	80.5^{e-k}	8.3^{d-h}	11.2^{k-n}	78.4^{i-o}	50.1^{f-k}
9	ECP HP 618	15.1^{d-g}	11.2^{h-j}	1.8^{n-p}	5.3^{d-k}	82.8^{b-f}	7.4^{g-l}	9.8^{no}	79.5^{c-j}	49.3^{i-l}
10	ECP HP 437	15.0^{d-h}	11.7^{f-i}	2.6^{f-j}	7.4^{b-e}	77.4^{l-o}	9.1^{b-e}	13.5^{d-h}	77.4^{n-q}	48.1^{k-n}
11	ECP HP 633	14.8^{d-h}	11.3^{h-j}	2.3^{i-l}	4.5^{g-n}	79.5^{g-l}	7.0^{i-n}	13.5^{d-h}	78.1^{k-o}	51.1^{d-j}
12	ECP HP 449	14.7^{d-i}	11.4^{g-i}	2.5^{f-j}	4.8^{f-m}	77.9^{k-m}	9.6^{a-c}	12.5^{e-l}	78.7^{g-m}	49.5^{i-l}
13	ECP HP 466	14.4^{d-j}	13.6^{b-d}	2.6^{e-i}	5.8^{c-i}	80.8^{d-j}	7.2^{h-m}	12.0^{f--m}	80.5^{a-c}	52.6^{b-e}
14	ECP HP 630	14.1^{e-k}	**15.2^{a}**	2.9^{b-e}	7.9^{bc}	80.4^{f-k}	6.5^{l-p}	13.1^{d-j}	76.2^{q-s}	45.6^{o}
15	ECP HP 450	13.9^{e-l}	13.8^{a-c}	2.4^{g-k}	**10.8^{a}**	82.1^{c-g}	6.7^{l-p}	11.2^{k-n}	80.2^{a-f}	51.9^{c-h}
16	ECP HP 456	13.7^{f-l}	13.2^{b-e}	2.7^{b-f}	8.0^{bc}	78.7^{j-l}	7.6^{f-l}	13.7^{d-g}	79.2^{d-k}	52.0^{c-g}
17	ECP HP 423	13.6^{f-m}	13.4^{b-e}	2.7^{d-h}	7.1^{c-f}	79.6^{g-l}	8.1^{e-i}	12.3^{e-l}	81.1^{ab}	52.3^{b-f}
18	PK 4189	13.6^{f-m}	8.2^{n-q}	2.0^{l-n}	3.8^{i-n}	75.1^{n-p}	7.8^{f-k}	17.1^{a}	77.6^{m-p}	49.7^{g-k}
19	PK 4144	13.6^{f-m}	7.9^{o-q}	2.0^{l-n}	3.0^{k-n}	74.8^{op}	7.9^{e-k}	**17.3^{a}**	77.2^{o-r}	47.9^{k-o}
20	ECP HP 414	13.1^{g-n}	14.0^{a-c}	3.1^{ab}	7.6^{b-d}	77.3^{l-o}	9.4^{a-d}	13.3^{d-i}	78.4^{i-o}	50.4^{e-j}
21	ECP HP 635	12.8^{h-o}	9.9^{j-l}	2.2^{j-m}	**2.3^{n}**	77.6^{l-n}	8.6^{c-f}	13.8^{c-f}	76.1^{rs}	47.8^{k-o}
22	ECP HP 425	12.7^{i-o}	14.3^{ab}	3.0^{b-d}	5.3^{d-k}	79.1^{i-l}	8.1^{e-i}	12.8^{d-k}	79.2^{d-k}	52.4^{b-f}
23	ECP HP 519	12.5^{j-p}	11.4^{g-i}	**1.1^{s}**	4.2^{h-n}	**90.0^{a}**	3.8^{t}	**6.2^{p}**	**81.1^{a}**	53.6^{a-c}
24	PK 4159	12.4^{j-p}	8.1^{n-q}	1.6^{o-q}	4.9^{f-m}	79.8^{g-l}	6.5^{l-p}	13.7^{d-f}	79.1^{e-l}	51.3^{d-i}
25	ECP HP 529	12.4^{j-p}	11.2^{h-j}	1.8^{n-p}	5.5^{d-j}	83.8^{bc}	5.8^{o-r}	10.4^{m-o}	80.0^{a-f}	53.1^{a-d}
26	PK 4032	12.3^{j-p}	9.3^{k-o}	1.8^{n-p}	3.0^{k-n}	80.3^{f-k}	5.9^{n-r}	13.8^{c-f}	79.6^{c-i}	53.2^{a-d}
27	PK 4160	12.3^{j-p}	**6.8^{q}**	1.4^{q-s}	3.0^{k-n}	79.2^{h-l}	7.0^{i-n}	13.7^{d-f}	77.4^{m-p}	49.0^{i-m}
28	PK 4044	12.1^{k-q}	7.0^{pq}	1.4^{q-r}	2.3^{n}	79.9^{g-l}	6.2^{m-q}	13.9^{c-e}	79.3^{c-k}	52.8^{a-d}
29	PK 4161	12.0^{k-q}	8.0^{n-q}	1.9^{m-o}	3.2^{j-n}	75.7^{m-p}	7.6^{f-l}	16.6^{a}	78.4^{i-o}	51.0^{d-j}
30	ECP HP 531	11.7^{l-q}	12.4^{d-h}	1.8^{n-p}	5.4^{d-j}	85.4^{b}	5.5^{p-r}	9.0^{o}	80.1^{a-f}	54.2^{a-c}
31	ECP HP 502	11.5^{m-r}	7.9^{n-q}	1.3^{rs}	2.8^{l-n}	84.1^{bc}	4.3^{st}	11.6^{i-m}	79.0^{f-l}	52.0^{c-g}
32	PK 4039	11.4^{n-r}	8.4^{m-p}	2.0^{k-n}	2.7^{mn}	75.0^{n-p}	8.0^{e-j}	17.0^{a}	78.3^{j-o}	49.6^{h-k}
33	PK 4176	10.8^{o-r}	8.4^{m-p}	1.5^{p-q}	3.2^{j-n}	81.5^{c-i}	5.9^{n-r}	12.5^{e-l}	80.4^{a-d}	54.2^{a-c}
34	ECP HP 504	10.7^{o-r}	8.5^{m-p}	1.4^{q-s}	3.7^{i-n}	83.5^{bc}	5.2^{q-s}	11.3^{j-n}	80.3^{a-e}	54.7^{ab}
35	ECP HP 500	10.5^{p-r}	9.8^{k-m}	1.6^{o-q}	4.6^{g-n}	83.4^{b-d}	**3.7^{t}**	12.9^{d-k}	79.7^{c-h}	**55.0^{a}**
36	PK 4181	10.5^{p-r}	9.1^{l-o}	2.0^{k-n}	3.6^{i-n}	77.6^{l-n}	6.9^{j-o}	15.6^{a-c}	79.8^{b-g}	52.6^{a-e}
37	PK 4169	9.9^{qr}	7.2^{pq}	1.3^{q-s}	2.7^{mn}	81.9^{c-h}	5.9^{n-r}	12.2^{e-m}	79.2^{d-k}	52.1^{c-f}
38	ECP HP 496	**9.4^{r}**	9.4^{k-n}	1.5^{p-r}	3.6^{i-n}	83.2^{b-e}	5.0^{rs}	11.8^{h-m}	78.5^{h-n}	52.4^{b-f}
	Trial mean	13.2	10.9	2.1	4.9	80.2	7.0	12.8	78.8	50.8
	CV (%)	30.6	29.3	37.0	80.8	6.7	34.7	27.8	3.0	8.8

No	Family	F/B	O/B	K/B	MC	O/F	OY	KY	TEP	TOT
1	ECP HP 550	64.4^{e-l}	23.4^{j-m}	5.8^{a}	40.0^{b}	358.6^{k-n}	49.0^{f-m}	11.9^{ab}	56.2^{f-m}	55.0^{-m}
2	PK 4152	64.2^{f-n}	22.9^{k-m}	5.8^{ab}	39.2^{bc}	316.0^{pq}	48.4^{g-n}	12.3^{a}	55.7^{g-m}	54.5^{g-n}
3	ECP HP 626	63.1^{i-p}	21.6^{m}	4.0^{h-l}	**44.3^{a}**	**291.6^{q}**	**35.4^{q}**	6.6^{h-n}	**39.4^{s}**	**38.7^{r}**
4	ECP HP 452	64.1^{g-n}	24.0^{i-l}	5.9^{a}	37.2^{c-f}	371.9^{g-m}	47.1^{i-o}	11.3^{a-c}	53.9^{j-p}	52.8^{h-o}

Table 5 (continued)

No	Family	F/B	O/B	K/B	MC	O/F	OY	KY	TEP	TOT
5	ECP HP 415	69.2^{ab}	27.2^{d-f}	5.1^{a-e}	37.1^{c-f}	368.2^{i-m}	43.2^{l-o}	8.4^{d-h}	48.2^{n-r}	47.4^{n-q}
6	ECP HP 617	61.9^{l-p}	**21.6^{m}**	**5.9^{a}**	38.7^{b-d}	337.6^{n-p}	36.2^{pq}	10.0^{c-e}	42.2^{rs}	41.2^{q-r}
7	ECP HP 593	64.3^{e-l}	25.8^{f-i}	4.3^{f-k}	38.9^{b-d}	402.3^{c-f}	51.4^{e-k}	8.7^{d-g}	56.6^{e-l}	55.7^{f-l}
8	ECP HP 428	65.8^{c-h}	26.5^{e-g}	5.0^{c-f}	36.1^{e-h}	367.8^{i-m}	50.4^{e-k}	9.3^{d-f}	56.0^{g-m}	55.1^{g-m}
9	ECP HP 618	64.6^{d-k}	26.4^{e-g}	4.4^{e-j}	38.0^{b-e}	393.4^{c-i}	50.0^{e-l}	8.7^{d-g}	55.2^{h-n}	54.4^{g-n}
10	ECP HP 437	65.9^{c-h}	24.5^{h-k}	5.4^{a-c}	38.0^{b-e}	347.4^{m-o}	45.4^{k-o}	10.0^{c-e}	51.4^{k-q}	50.4^{l-p}
11	ECP HP 633	62.8^{j-p}	25.5^{f-i}	4.1^{h-l}	34.7^{g-l}	361.2^{j-n}	48.9^{g-m}	7.9^{f-l}	53.6^{j-p}	52.8^{h-o}
12	ECP HP 449	64.6^{d-k}	24.9^{g-j}	5.8^{ab}	37.2^{c-f}	374.7^{g-l}	54.6^{c-h}	**12.4^{a}**	62.1^{b-i}	60.8^{b-g}
13	ECP HP 466	66.9^{b-f}	28.4^{cd}	4.5^{e-j}	34.8^{g-l}	419.9^{a-c}	53.5^{d-j}	8.4^{d-i}	58.5^{d-k}	57.6^{d-k}
14	ECP HP 630	65.2^{d-j}	24.0^{i-l}	3.8^{i-m}	40.2^{b}	324.8^{op}	41.8^{n-q}	6.6^{i-o}	45.7^{q-s}	45.0^{p-r}
15	ECP HP 450	63.7^{g-n}	27.3^{d-f}	3.6^{k-m}	35.4^{f-k}	415.0^{a-d}	59.8^{b-d}	8.0^{f-l}	64.5^{b-d}	63.7^{b-d}
16	ECP HP 456	66.9^{b-f}	27.4^{d-f}	4.5^{d-i}	34.4^{h-m}	386.6^{e-j}	55.1^{c-g}	9.0^{d-f}	60.5^{c-j}	59.6^{c-h}
17	ECP HP 423	69.7^{a}	29.1^{b-d}	5.1^{a-e}	35.5^{f-j}	**440.3^{a}**	56.4^{c-e}	9.7^{c-f}	62.2^{b-h}	61.3^{b-g}
18	PK 4189	61.0^{o-q}	22.9^{k-m}	4.5^{e-j}	36.2^{e-h}	354.2^{l-n}	47.7^{h-o}	9.3^{d-f}	53.3^{j-p}	52.4^{h-o}
19	PK 4144	61.6^{m-q}	22.2^{lm}	4.6^{c-h}	38.1^{b-e}	346.7^{m-o}	45.1^{k-o}	9.5^{d-f}	50.8^{l-q}	49.8^{l-p}
20	ECP HP 414	63.7^{g-o}	24.7^{g-k}	5.4^{a-c}	35.9^{e-i}	369.9^{h-m}	43.5^{l-o}	9.3^{d-f}	49.1^{m-r}	48.2^{m-q}
21	ECP HP 635	**59.1^{q}**	21.9^{m}	4.9^{c-g}	37.3^{c-f}	324.4^{op}	41.2^{o-q}	9.2^{d-f}	46.7p-r	45.8^{o-r}
22	ECP HP 425	**69.7^{a}**	28.9^{cd}	5.3^{a-d}	34.0^{h-n}	386.7^{e-j}	54.0^{d-i}	10.1^{b-d}	60.0^{c-j}	59.0^{c-j}
23	ECP HP 519	64.0^{g-n}	30.9^{ab}	**2.3^{p}**	33.9^{h-n}	438.2^{ab}	63.6^{ab}	**4.8^{o}**	66.5^{a-c}	66.0^{a-c}
24	PK 4159	62.2^{k-p}	25.5^{f-i}	3.8^{i-m}	35.3^{f-k}	386.4^{e-j}	53.7^{d-j}	8.0^{f-k}	58.5^{d-k}	57.7^{d-k}
25	ECP HP 529	66.3^{c-g}	29.5^{a-c}	3.5^{k-m}	33.7^{i-n}	406.0^{c-f}	58.7^{b-d}	7.1^{g-m}	63.0^{b-g}	62.3^{b-f}
26	PK 4032	60.5^{pq}	25.8^{f-i}	3.4^{l-n}	33.2^{k-o}	396.2^{c-h}	50.9^{e-k}	6.8^{h-n}	55.0^{i-o}	54.3^{g-n}
27	PK 4160	61.5^{n-q}	24.0^{i-l}	4.1^{g-l}	36.8^{d-g}	348.9^{l-o}	46.9^{j-o}	8.1^{f-k}	51.7^{k-q}	50.9^{k-p}
28	PK 4044	61.6^{m-q}	26.0^{f-h}	3.7^{j-m}	33.5^{j-n}	388.3^{d-j}	58.8^{b-d}	8.3^{d-j}	63.8^{b-e}	63.0^{b-e}
29	PK 4161	61.9^{l-p}	24.0^{i-l}	4.5^{d-i}	35.1^{f-k}	371.4^{h-m}	47.8^{h-o}	9.1^{d-f}	53.3^{j-p}	52.4^{i-o}
30	ECP HP 531	67.0^{b-e}	31.0^{a}	3.4^{l-n}	32.4^{m-o}	409.3^{c-f}	60.3^{b-d}	6.5^{j-o}	64.2^{b-d}	63.5^{b-d}
31	ECP HP 502	65.6^{c-i}	28.7^{cd}	2.7^{n-p}	34.3^{h-m}	382.7^{f-k}	61.2^{bc}	5.7^{m-o}	64.3^{b-d}	64.0^{b-d}
32	PK 4039	65.3^{d-j}	24.4^{h-k}	5.0^{b-f}	36.8^{d-g}	369.1^{i-m}	42.6^{m-p}	8.7^{d-g}	47.8^{o-r}	46.9^{o-q}
33	PK 4176	67.2^{a-d}	29.7^{a-c}	3.8^{i-m}	32.7^{l-o}	417.0^{a-c}	55.8^{c-f}	7.2^{g-m}	60.1^{c-j}	59.4^{c-i}
34	ECP HP 504	64.3^{f-m}	29.4^{a-c}	3.2^{m-o}	32.0^{no}	412.4^{b-e}	59.7^{b-d}	6.1^{l-o}	63.3^{b-f}	62.7^{b-f}
35	ECP HP 500	68.1^{a-c}	**31.2^{a}**	2.4^{op}	**31.1^{o}**	398.8^{c-g}	**70.0^{a}**	5.2^{no}	**73.1^{a}**	**72.6^{a}**
36	PK 4181	63.6^{h-o}	25.9^{f-h}	4.2^{f-l}	34.1^{h-n}	402.8^{c-f}	51.8^{e-k}	8.3^{e-j}	56.7^{e-l}	55.9^{e-l}
37	PK 4169	65.5^{c-i}	28.0^{c-e}	3.7^{j-m}	34.3^{h-m}	385.8^{e-j}	48.9^{f-m}	6.4^{k-o}	52.8^{k-q}	52.1^{j-p}
38	ECP HP 496	66.0^{c-h}	28.8^{cd}	3.1^{m-o}	33.3^{j-o}	369.8^{h-m}	64.5^{ab}	7.0^{g-n}	68.6^{ab}	67.9^{ab}
	Trial mean	64.6	26.4	4.2	35.6	379.8	52.0	8.2	57.0	56.1
	CV (%)	7.3	15.1	36.9	12.0	13.8	25.4	39.3	23.4	23.7

Means with the same letter are not significantly different at $p \leq 0.05$ based on Fisher's Least Significant Difference (LSD). Figures in bold within the mean column are minimum and maximum values. *BWT* = bunch weight (kg), *MFW* = mean fruit weight (g), *MNW* = mean nut weight (g), *P/B* = parthenocarpic to bunch (%), *M/F* = mesocarp to fruit (%), *K/F* = kernel to fruit (%), *S/F* = shell to fruit (%), *O/DM* = oil to dry mesocarp (%), *O/WM* = oil to wet mesocarp (%), *F/B* = fruit to bunch (%), *O/B* = oil to bunch (%), *K/B* = kernel to bunch (%), *MC* = moisture content (%), *O/F* = oil to fiber (%), *OY* = oil yield (kg palm^{-1} year^{-1}), *KY* = kernel yield (kg palm^{-1} year^{-1}), *TEP* = total economic product (kg palm^{-1} year^{-1}), *TOT* = total oil (kg palm^{-1} year^{-1}), *CV* = coefficient of variation

4160, PK 4044, PK 4169, PK 4144, ECP HP 502, PK 4161, PK4159, and PK 4189) had the lowest MFW and were not significantly different from each other. Families ECP HP 617 (Deli Banting × AVROS) and ECP HP 519 (Deli Ulu Remis × MPOB-Nigeria) had contrasting results in terms of MNW, M/F, and

K/B. Family ECP HP 617 had the highest MNW (3.3 g) and K/B (5.9%), while having the lowest M/F (73.5%). On the contrary, due to its lowest MNW (1.1 g) and K/B (2.3%), family ECP HP 519 had the highest M/F at 90.0%, or 12% higher than the trial mean, with significant variation from the other families. Some 17 families representing 45%, had a higher M/F than the trial mean and were mostly from the Deli Ulu Remis × MPOB-Nigeria cross. Shell to fruit (S/F) ranged from 6.2% to 17.3%, with a trial mean of 12.8%. Family PK 4144 from the Deli (H. Est. × Elmina) × (MPOB-Nigeria × UP) had the highest S/F and was not significantly different from families PK 4189, PK 4039, PK 4161, ECP HP 617, and PK 4181. The lowest S/F, which was 48% lower than the trial mean, was recorded by family ECP HP 519, with significant variation from all the other families. Kushairi et al. (2003) suggested that high M/F and low S/F determine a high O/B, whereby an increase in mesocarp content would reduce the shell content without changing the kernel size. Family ECP HP 519 had a mean O/B of 30.9%, the third highest after families ECP HP 500 and ECP HP 531. These three families were from the Deli Ulu Remis × MPOB-Nigeria cross and were not significantly different for O/B. Kernel to fruit (K/F) ranged from 3.70% by family ECP HP 500 to 10.6% by family ECP HP 617, where both families also showed contrasting results for O/B at 31.2% and 21.6%, respectively.

Meanwhile, P/B varied from 2.3% for family ECP HP 635 (Deli Banting × MPOB-Nigeria) to 10.8% for family ECP HP 450 (Deli Ulu Remis × AVROS). Family ECP HP 635 also had the lowest F/B at 59.1%. However, its lowest P/B and F/B means were not significantly different from families PK 4032, PK 4189, PK 4160, PK 4144, and PK 4044, derived from the MPOB-Nigeria × UP male parents. Family ECP HP 626 (Deli Banting × MPOB-Nigeria) had the lowest O/DM (74.0%) and O/WM (41.4%), which were 6% and 19% lower than the trial means, respectively, with significant variation from the other families based on Fisher's LSD. On the contrary, the highest O/DM was found for family ECP HP 519 at 81.1%, while family ECP HP 500 had the highest O/WM of 55.0%. Moisture content (MC) varied from 31.1% to 44.3%, with a trial mean of 35.6%. Family ECP HP 626 with the highest MC (or 24% higher than the trial mean) showed no significant difference from the other families. The high MC reflected a negative influence on the oil-related traits such as O/F (291.6%), OY (35.4 kg palm^{-1} year^{-1}), TEP (39.4 kg palm^{-1} year^{-1}), and TOT (38.7 kg palm^{-1} year^{-1}). Meanwhile, family ECP HP 500 with the lowest MC had the highest OY (70.0 kg palm^{-1} year^{-1}), TEP (73.1 kg palm^{-1} year^{-1}), and TOT (72.6 kg palm^{-1} year^{-1}). Oil yield (OY) is a derived trait, of which O/B and FFB yield are its main components. Thus, the high OY of family ECP HP 500 was associated with the highest mean of O/B. Based on Fisher's LSD, OY, TEP, and TOT means of family ECP HP 500 did not differ significantly from ECP HP 519, with the highest M/F and the lowest S/F. This suggests that the selection of palms for high oil production should also consider the M/F and S/F traits as selection criteria. KY varied from 4.8 kg palm^{-1} year^{-1} to 12.4 kg palm^{-1} year^{-1}, with a trial mean of 8.2 kg palm^{-1} year^{-1}. Family ECP HP 449 from the Deli Ulu Remis × AVROS had the highest KY and was not significantly different from families PK 4152, ECP HP 550, and ECP HP 452. These progenies, with KY at least 38% higher than the trial mean are potential candidate for multi-location evaluation in efforts to develop varieties with kernel oil.

Family ECP HP 626 displayed the worst performance in bunch quality components, having the lowest means of O/DM, O/WM, O/F, OY, TEP, and TOT. However, all 38 D × P families in this study had OY exceeding 35 kg palm^{-1} year^{-1} or 5 t ha^{-1} year^{-1}, which is above the 2021 average national OY of 3.1 t ha^{-1} (MPOB 2022). This suggests the potential use of these families in this study to improve the performance of national oil production. In the meantime, factors underlying the gap between potential and actual results are important to understand. According to Woittiez et al. (2017), yield-reducing factors such as unsuitable cropland as well as pests and disease infections have an impact on actual yields. Besides that, factors underlying bunch production would require further studies, especially regarding sex determination and the failure of bunches to form. In the current Malaysian Standard, MS 157:2017, the minimum requirements for bunch quality components for the *tenera* in progeny tests are an O/B of 25%, K/B of 3%, and OY of 42.5 kg palm^{-1} year^{-1} (DOSM 2017). A total of 18 families representing 47%, namely ECP HP 423, ECP HP 425, ECP HP 428, ECP HP 450, ECP HP 456, ECP HP 466, ECP HP 593, ECP HP 618, ECP HP 496, ECP HP 504, ECP HP 529, ECP

HP 531, ECP HP 633, PK 4032, PK 4044, PK 4159, PK 4176, and PK 4181, fulfilled these minimum requirements, including FFB yields of more than 170 kg palm^{-1} year^{-1}. Half of these families were from the Deli Ulu Remis female parents, which could be selected for future breeding programmes.

Vegetative and physiological traits

ANOVA results showed highly significant differences between families for all vegetative and physiological traits (Table 6), demonstrating the presence of variability in these traits. In addition, the ANOVA also revealed that the performance in the vegetative and physiological traits was inconsistent across the replicates. This was supported by the significant g × r interaction effect obtained. Frond production (FP) ranged from 21.7 fronds palm^{-1} year^{-1} to 29.1 fronds palm^{-1} year^{-1}, with a trial mean of 24.8 fronds palm^{-1} year^{-1} (Table 7). Family ECP HP 502 from the Deli Ulu Remis × MPOB-Nigeria cross had the highest means of FP, or 17% higher than the trial mean. It was significantly different from all the other families. Typically, palms with a high number of fronds would potentially produce a higher FFB yield as bunches are produced at the frond axils (Noh et al. 2010). This study has also proven this assertion where family ECP HP 502 was the second highest FFB yielder after family PK 4044 (Table 3) with an FP of 26.9 fronds palm^{-1} year^{-1}. As such, FP should be considered in the selection of high-yielding planting materials. Family ECP HP 437 from the Deli Johor Labis × AVROS cross had the highest PCS (35.8 cm^2), while family ECP HP 496 had the lowest PCS (23.8 cm^2). This is advantageous because palms with narrow PCS allow for easier frond cutting during FFB harvesting. On the other hand, short RL is a selected trait for high-density planting at 180–200 palms ha^{-1} (Barcelos et al. 2015), compared to 136–160 palms ha^{-1} in standard commercial plantings. For breeding for compactness, palms with an RL shorter than 5 m are desirable (Norziha et al. 2020). In this study, PK 4144 was the only family with an RL less than 5 m. It was however, not significantly different from three other families from the Deli Ulu Remis × AVROS cross, namely ECP HP 450 (5.1 m), ECP HP 449 (5.1 m), and ECP HP 452 (5.0 m). Family PK 4169 from the Deli Banting × (MPOB-Nigeria × UP) cross had the highest RL at 5.9 m, with no significant difference from families ECP HP 633 (5.8 m) and ECP HP 529 (5.8 m). Trunk height (HT) varied from 1.7 m (PK 4039) to 2.6 m (ECP HP 500), with a trial mean of 2.2 m. HT of less than 1.8 m (or HTi lower than 0.3 m year^{-1}) is also a selection criterion for compactness besides RL (Norziha et al. 2020). Furthermore, low HT is a critical trait of interest for oil palm breeders as it increases the ease of FFB harvesting and the economic lifespan (Marhalil et al. 2014). In this study, families PK 4039, ECP HP 496, and ECP HP 504 had the lowest HT (or an average HTi of 0.3 m year^{-1}), with no significant

Table 6 Mean squares for vegetative and physiological traits in 38 D × P families

Source of variation	df	FP	PCS	RL	LL	LW	LN	HT	LA
Replications (r)	2	368.4**	2256.0**	4.4**	338.7**	14.5**	2133.2**	16.8**	57.2**
Families (g)	37	101.8**	459.0**	2.1**	607.7**	3.0**	671.0**	2.3**	19.5**
g × r	74	8.9**	123.8**	0.7**	110.1**	0.7**	295.2**	0.7**	7.2**
Within palms (e)	1476	4.7	33.5	0.2	57.3	0.3	72.6	0.2	2.2

Source of variation	LAI	DIA	VDM	df	BDM	TDM	BI
Replications (r)	20.1**	0.1**	697.4**	2	33.8^{ns}	1002.5**	0.1**
Families (g)	6.8**	0.0**	100.3**	37	69.7**	193.6**	0.1**
g × r	2.5**	0.0**	23.5**	74	61.7**	127.4**	0.0**
Within palms (e)	0.8	0.0	7.3	1473	21.5	35.9	0.0

**, ns=significant at $P \leq 0.01$ and non-significant, respectively. *FP* = frond production, *PCS* = petiole cross-section, *RL* = rachis length, *LL* = leaflet length, *LW* = leaflet width, *LN* = leaflet number, *HT* = trunk height, *LA* = leaf area, *LAI* = leaf area index, *DIA* = trunk diameter, *VDM* = vegetative dry matter, *BDM* = bunch dry matter, *TDM* = total dry matter, *BI* = bunch index

Table 7 Family means for vegetative and physiological traits from the 38 D × P families

No	Family	FP	PCS	RL	LL	LW	LN	HT	LA
1	ECP HP 502	**29.1^{a}**	30.3^{d-g}	5.7^{b-e}	85.6^{h-m}	5.4^{c-g}	172.1^{c-j}	2.3^{c-g}	9.2^{d-j}
2	ECP HP 496	27.5^{b}	**23.8^{o}**	5.2^{m-p}	81.3^{pq}	**4.7^{s}**	166.4^{o-t}	1.7^{mn}	**7.3^{r}**
3	ECP HP 500	27.2^{bc}	26.7^{i-n}	5.7^{b-d}	90.9^{a-e}	4.9^{p-s}	171.4^{c-l}	**2.6^{a}**	8.8^{f-o}
4	PK 4044	26.9^{b-d}	30.0^{f-h}	5.6^{d-g}	86.1^{g-l}	5.7^{a-c}	173.9^{b-g}	2.0^{h-k}	9.7^{a-e}
5	ECP HP 504	26.6^{b-e}	25.5^{j-o}	5.6^{d-g}	82.6^{m-q}	4.8^{s}	171.7^{c-k}	1.8^{l-n}	7.7^{qr}
6	ECP HP 452	26.4^{c-e}	26.7^{i-n}	5.0^{qr}	85.5^{h-m}	4.9^{rs}	165.5^{p-t}	2.1^{f-i}	7.8^{p-r}
7	ECP HP 519	26.0^{d-f}	28.0^{g-j}	5.5^{e-j}	**80.8^{q}**	5.3^{f-o}	170.5^{f-n}	2.3^{b-e}	8.2^{o-q}
8	ECP HP 550	26.0^{d-g}	34.7^{ab}	5.5^{f-k}	86.4^{g-k}	5.2^{i-p}	168.3^{k-s}	2.3^{b-e}	8.6^{i-o}
9	ECP HP 415	25.9^{e-h}	33.3^{a-c}	5.7^{b-d}	81.8^{n-q}	5.1^{l-r}	171.5^{c-l}	2.5^{ab}	8.2^{o-q}
10	ECP HP 450	25.7^{e-i}	27.0^{i-l}	5.1^{p-r}	90.1^{c-f}	5.1^{k-q}	164.8st	2.2^{e-h}	8.7^{g-o}
11	ECP HP 414	25.4^{f-j}	31.5^{c-f}	5.2^{n-p}	85.4^{h-m}	5.1^{m-r}	169.2^{i-p}	2.4^{bc}	8.5^{l-p}
12	PK 4152	25.3^{f-k}	30.1^{e-h}	5.5^{g-k}	88.6^{d-h}	5.3^{f-n}	174.0^{b-g}	2.2^{c-g}	9.3^{d-h}
13	ECP HP 423	25.2^{f-l}	27.7^{h-k}	5.4^{h-m}	85.4^{h-m}	5.3^{e-l}	170.9^{e-m}	2.4^{b-e}	8.9^{f-n}
14	PK 4039	25.1^{f-m}	23.8^{o}	5.3^{m-p}	84.5^{j-p}	5.2^{g-o}	165.3^{q-t}	**1.7^{n}**	8.3^{n-q}
15	PK 4159	25.1^{g-n}	25.7^{j-o}	5.4^{i-m}	89.0^{c-g}	5.6^{a-d}	170.4^{g-n}	2.2^{c-g}	9.7^{a-e}
16	ECP HP 449	25.0^{h-n}	26.2^{i-o}	5.1^{qr}	90.6^{b-e}	4.9^{q-s}	165.2^{r-t}	2.2^{c-g}	8.5^{k-o}
17	PK 4032	25.0^{h-o}	28.7^{g-i}	5.6^{d-j}	83.9^{k-q}	5.4^{c-h}	168.5^{j-s}	2.0^{i-k}	8.8^{g-o}
18	ECP HP 529	24.9^{i-p}	28.0^{g-k}	5.8^{a-c}	84.4^{j-p}	5.6^{a-d}	**179.9^{a}**	2.3^{c-f}	9.7^{a-e}
19	ECP HP 428	24.8^{j-p}	32.7^{b-d}	5.6^{d-i}	91.5^{a-e}	5.2^{h-o}	172.5^{c-i}	2.6^{a}	9.4^{b-f}
20	PK 4176	24.6^{j-p}	26.0^{j-o}	5.6^{d-i}	91.5^{a-d}	5.2^{g-o}	167.8^{l-s}	2.0^{i-l}	9.2^{d-i}
21	PK 4160	24.6^{j-p}	24.7^{l-o}	5.5^{g-k}	84.5^{j-p}	5.1^{k-q}	168.9^{i-r}	1.9^{j-l}	8.4^{m-q}
22	PK 4161	24.4^{j-p}	25.4^{k-o}	5.4^{j-n}	89.9^{c-f}	5.0^{n-r}	174.2^{b-e}	2.0^{h-k}	9.0^{f-l}
23	ECP HP 425	24.4^{k-p}	26.9^{i-m}	5.3^{l-p}	92.1^{a-c}	5.0^{n-r}	166.7^{n-t}	2.4^{bc}	8.9^{f-o}
24	PK 4181	24.3^{l-p}	24.3^{no}	5.4^{j-n}	88.2^{d-i}	5.3^{e-m}	167.5^{m-s}	2.1^{g-j}	8.9^{f-m}
25	ECP HP 617	24.3^{m-p}	33.2^{bc}	5.5^{d-j}	91.2^{a-e}	5.7^{a-c}	172.0^{c-k}	2.3^{b-e}	**10.2^{a}**
26	ECP HP 531	24.2^{m-q}	31.9^{c-f}	5.5^{d-j}	83.1^{l-q}	5.7^{ab}	175.0^{b-d}	2.2^{c-g}	9.4^{b-f}
27	PK 4144	24.1^{n-q}	26.0^{j-o}	**5.0^{r}**	88.2^{e-i}	5.3^{e-m}	**163.1^{t}**	2.2^{c-g}	8.7^{h-o}
28	ECP HP 633	24.1^{n-r}	33.1^{bc}	5.8^{ab}	84.7^{j-o}	5.4^{d-h}	175.1^{bc}	2.5^{ab}	9.2^{d-j}
29	PK 4189	24.0^{o-s}	27.7^{h-k}	5.2^{o-q}	91.4^{a-e}	5.2^{j-p}	167.9^{l-s}	2.2^{c-g}	9.1^{e-l}
30	ECP HP 618	24.0^{p-s}	33.4^{a-c}	5.3^{k-o}	81.5^{o-q}	5.4^{d-i}	169.1^{i-q}	2.6^{a}	8.5^{k-o}
31	ECP HP 456	24.0^{p-s}	27.2^{i-k}	5.5^{e-j}	90.3^{b-f}	5.2^{g-o}	169.0^{i-q}	2.4^{b-d}	9.1^{e-k}
32	PK 4169	23.3^{q-t}	26.6^{i-n}	**5.9^{a}**	89.9^{c-f}	5.5^{b-f}	174.2^{b-f}	2.4^{bc}	9.8^{a-d}
33	ECP HP 593	23.2^{r-t}	31.6^{c-f}	5.4^{h-l}	82.3^{m-q}	5.4^{d-j}	168.9^{i-r}	2.6^{a}	8.6^{j-o}
34	ECP HP 635	23.1st	32.6^{b-e}	5.5^{d-j}	84.9^{i-n}	**5.8^{a}**	177.0^{ab}	2.2^{d-h}	10.0^{a-c}
35	ECP HP 466	22.7^{tu}	31.3^{c-f}	5.6^{d-h}	87.2^{f-j}	5.3^{e-k}	171.3^{d-l}	2.5^{ab}	9.1^{e-k}
36	ECP HP 437	22.7^{tu}	**35.8^{a}**	5.5^{d-j}	**94.0^{a}**	5.5^{b-e}	170.0^{h-o}	2.3^{b-e}	10.1^{a}
37	ECP HP 630	21.9^{uv}	24.4^{m-o}	5.5^{f-k}	93.6^{ab}	5.0^{o-r}	173.1^{c-h}	2.1^{f-j}	9.3^{c-g}
38	ECP HP 626	**21.7^{v}**	30.1^{e-h}	5.6^{c-f}	93.6^{ab}	5.2^{i-p}	179.4^{a}	1.9^{k-m}	10.0^{ab}
	Trial mean	24.8	28.6	5.5	87.4	5.3	170.6	2.2	9.0
	CV (%)	11.2	24.8	9.0	9.8	12.1	5.9	22.7	18.9

No	Family	LAI	DIA	VDM	BDM	TDM	BI
1	ECP HP 502	5.4^{d-j}	**0.8^{a}**	**17.5^{a}**	16.4^{a-e}	**33.9^{a}**	0.5^{j-n}
2	ECP HP 496	**4.3^{r}**	0.7^{g-n}	12.8^{l-p}	16.3^{a-e}	29.1^{e-k}	0.6^{a}
3	ECP HP 500	5.2^{g-o}	0.8^{ab}	15.7^{b-d}	16.3^{a-e}	32.0^{a-d}	0.5^{h-k}
4	PK 4044	5.7^{a-f}	0.8^{ab}	15.8^{b-d}	17.4^{ab}	33.2^{ab}	0.5^{e-i}

Table 7 (continued)

No	Family	LAI	DIA	VDM	BDM	TDM	BI
5	ECP HP 504	4.6^{qr}	0.7^{g-n}	13.3^{i-n}	16.4^{a-d}	29.7^{d-i}	0.6^{a-e}
6	ECP HP 452	4.6^{p-r}	0.7^{o-r}	13.7^{g-l}	14.9^{d-j}	28.6^{f-k}	0.5^{g-k}
7	ECP HP 519	4.9^{o-q}	0.7^{d-h}	14.7^{d-h}	16.2^{a-f}	30.9^{b-f}	0.5^{d-i}
8	ECP HP 550	5.1^{i-o}	0.7^{d-i}	17.3^{a}	15.2^{d-j}	32.5^{a-c}	0.5^{mn}
9	ECP HP 415	4.9^{o-q}	0.7^{j-o}	16.7^{ab}	**12.2**^{m}	28.9^{e-k}	**0.4**^{o}
10	ECP HP 450	5.2^{h-o}	0.7^{h-n}	13.9^{f-l}	14.8^{d-k}	28.7^{e-k}	0.5^{h-k}
11	ECP HP 414	5.0^{l-p}	0.7^{g-m}	15.7^{b-d}	14.8^{d-k}	30.4^{c-f}	0.5^{k-n}
12	PK 4152	5.5^{d-h}	0.7^{d-g}	15.0^{c-f}	14.9^{d-j}	29.9^{c-i}	0.5^{h-k}
13	ECP HP 423	5.3^{g-n}	0.7^{k-o}	14.0^{f-k}	15.3^{c-j}	29.3^{e-j}	0.5^{d-i}
14	PK 4039	4.9^{n-q}	0.7^{c-f}	11.8^{pq}	12.8^{k-m}	**24.7**^{o}	0.5^{h-k}
15	PK 4159	5.7^{a-e}	0.7^{j-o}	13.0^{j-p}	16.0^{a-f}	29.0^{e-k}	0.5^{a-g}
16	ECP HP 449	5.0^{k-o}	**0.6**^{r}	12.9^{k-p}	**17.6**^{a}	30.8^{b-f}	**0.6**^{a}
17	PK 4032	5.2^{h-o}	0.7^{cd}	14.1^{f-j}	14.6^{d-k}	28.8^{e-k}	0.5^{g-k}
18	ECP HP 529	5.7^{a-e}	0.7^{d-j}	14.0^{f-k}	17.3^{a-c}	31.3^{a-e}	0.6^{a-f}
19	ECP HP 428	5.6^{b-g}	0.7^{d-k}	16.1^{bc}	14.4^{e-l}	30.4^{c-f}	0.5^{l-n}
20	PK 4176	5.5^{d-i}	0.7^{g-n}	12.7^{l-p}	13.9^{h-m}	26.6^{k-o}	0.5^{f-j}
21	PK 4160	4.9^{m-q}	0.7^{n-r}	12.0^{o-q}	15.3^{c-j}	27.3^{i-o}	0.6^{a-d}
22	PK 4161	5.3^{f-l}	0.7^{k-o}	12.4^{n-p}	16.0^{a-g}	28.3^{f-l}	0.6^{ab}
23	ECP HP 425	5.2^{g-o}	0.7^{i-o}	13.3^{i-n}	14.2^{f-m}	27.5^{h-n}	0.5^{h-k}
24	PK 4181	5.3^{g-m}	0.7^{k-p}	12.0^{o-q}	14.0^{g-m}	25.9^{l-o}	0.5^{a-h}
25	ECP HP 617	**6.0**^{a}	0.7^{e-k}	15.8^{b-d}	13.5^{i-m}	29.3^{e-j}	0.5^{mn}
26	ECP HP 531	5.6^{b-g}	0.7^{n-r}	14.7^{d-h}	15.5^{b-i}	30.3^{c-g}	0.5^{f-j}
27	PK 4144	5.1^{h-o}	0.6^{qr}	12.4^{m-p}	15.3^{c-j}	27.7^{g-l}	0.6^{a-f}
28	ECP HP 633	5.4^{d-j}	0.7^{f-k}	15.6^{b-d}	13.4^{j-m}	29.0^{-k}	0.5^{no}
29	PK 4189	5.4^{e-l}	0.7^{d-h}	13.6^{h-m}	16.3^{a-e}	29.9^{d-i}	0.5^{a-g}
30	ECP HP 618	5.0^{k-o}	0.6^{p-r}	15.5^{c-e}	15.4^{c-j}	30.9^{b-f}	0.5^{i-m}
31	ECP HP 456	5.4^{e-k}	0.7^{n-r}	13.1^{j-o}	15.6^{a-h}	28.7^{e-k}	0.5^{a-h}
32	PK 4169	5.8^{a-d}	0.7^{l-p}	12.7^{l-p}	12.5^{lm}	25.1^{m-o}	0.5^{i-m}
33	ECP HP 593	5.1^{j-o}	0.7^{l-p}	14.6^{d-h}	16.2^{a-f}	30.8^{b-f}	0.5^{c-i}
34	ECP HP 635	5.9^{a-c}	0.7^{c-e}	14.8^{d-g}	15.8^{a-h}	30.6^{b-f}	0.5^{g-k}
35	ECP HP 466	5.4^{e-k}	0.7^{g-l}	14.3^{e-i}	16.0^{a-g}	30.3^{c-g}	0.5^{b-i}
36	ECP HP 437	6.0^{a}	0.7^{l-q}	15.6^{b-d}	14.4^{e-l}	30.0^{c-h}	0.5^{k-n}
37	ECP HP 630	5.5^{c-h}	0.7^{m-q}	**11.0**^{q}	13.9^{g-m}	24.9^{no}	0.6^{a-c}
38	ECP HP 626	5.9^{ab}	0.7^{bc}	13.0^{j-p}	13.8^{h-m}	26.8^{j-o}	0.5^{-l}
	Trial mean	5.3	0.7	14.1	15.2	29.2	0.5
	CV (%)	18.9	10.2	23.7	32.6	23.0	18.2

Means with the same letter are not significantly different at $p \leq 0.05$ based on Fisher's Least Significant Difference (LSD). Figures in bold within the mean column are minimum and maximum values. *FP* = frond production (no. palm^{-1} year^{-1}), *PCS* = petiole cross-section (cm^2), *RL* = rachis length (m), *LL* = leaflet length (cm), *LW* = leaflet width (cm), *LN* = leaflet number (no.), *HT* = trunk height (m), *LA* = leaf area (m^2), *LAI* = leaf area index, *DIA* = trunk diameter (m), *VDM* = vegetative dry matter (t ha^{-1} year^{-1}), *BDM* = bunch dry matter (t ha^{-1} year^{-1}), *TDM* = total dry matter (t ha^{-1} year^{-1}), *BI* = bunch index, *CV* = coefficient of variation

variation among them. Compared to current planting materials with HTi between 0.40 m year^{-1} and 0.75 m year^{-1} (Kushairi et al. 1999; Kushairi and Mohd Din 2020), these two families were approximately 28% shorter and can be considered in breeding for shorter palms.

In terms of LL and LW, they ranged from 80.8 cm (ECP HP 519) to 94.0 cm (ECP HP 437) and 4.7 cm (ECP HP 496) to 5.8 cm (ECP HP 635), respectively. Family ECP HP 496 not only exhibited the lowest LW but also recorded the smallest LA, measuring 7.3 m^2, and the lowest LAI at 4.3. Breure (2010) stated that yields are likely to decrease when the LAI is higher than 6, due to competition among palms. All families in this study had LAI of below 6 except for ECP HP 617, but this was not significantly different from the LAI values of ECP HP 437 (6.0), ECP HP 626 (5.9), ECP HP 635 (5.9), PK 4169 (5.8), PK 4159 (5.7), ECP HP 529 (5.7), and PK 4044 (5.7) based on Fisher's LSD. Three of them, namely ECP HP 617, ECP HP 626, and PK 4169, from Banting female parents, were among the five lowest FFB yielders, which is in line with observations by Breure (2010). However, other traits may contribute to better FFB yield, such as high PCS and LL for ECP HP 437, high LW for ECP HP 635, and high LN for ECP HP 529. The leaflet number (LN) varied from 163.1 (PK 4144) to 179.9 (ECP HP 529), with a trial mean of 170.6. Trunk diameter (DIA), ranging from 0.6 m to 0.8 m. Family ECP HP 502, with the highest DIA, had the highest VDM and TDM at 17.5 t ha^{-1} $year^{-1}$ and 33.9 t ha^{-1} $year^{-1}$, respectively.

For physiological traits, the bunch index (BI) is one of the selection criteria for *pisifera* male and *dura* female parents (Breure 1986). Increasing BI, or the proportion of BDM to TDM, is one of the strategies to boost oil production (Hardon et al. 1972; Breure and Corley 1983). In this study, family ECP HP 449 had the highest BI (0.6) and BDM (17.6 t ha^{-1} $year^{-1}$), with no significant difference from families ECP HP 496, ECP HP 456, PK 4161, ECP HP 529, ECP HP 504, PK 4189, and PK 4159. In contrast, family ECP HP 415 from the Deli Banting × AVROS cross had the lowest BI and BDM means, measuring 0.4 and 12.2 t ha^{-1} $year^{-1}$, respectively. These values did not differ significantly from those of family ECP HP 633 from the Deli Banting × MPOB-Nigeria cross. Strong positive correlations between BI and FFB yield have been reported by Junaidah et al. (2004) and Fadila et al. (2016). Thus, BI should not be neglected in the selection of high-yielding materials.

Heritability estimates for D × P families

Statistically, the heritability estimate is used to describe the percentage of phenotypic variation that can be attributed to genetic variation. It indicates the reliability of the phenotype as an indicator of genotype, with possible values between 0% (all environmental variation) and 100% (all genetic variation). Heritability estimates can be categorised as low (less than 30%), moderate (30% to 60%) or high (more than 60%) (Johnson et al. 1955). Variance components and broad-sense heritability (h^2_B) estimates for bunch yield and its components, bunch quality components, as well as vegetative and physiological traits were calculated for the 38 D × P families (Table 8). Broad-sense heritability (h^2_B) estimates were low for FFB yield (15.8%) but high for BNO (80.9%) and ABW (66.5%). These results are expected as the h^2_B estimate for FFB yield is usually low but high for both BNO and ABW (Corley and Tinker 2016). High h^2_B estimates for FFB yield, BNO, and ABW ranging from 88% to 94% were observed among 42 *E. oleifera* × *E. guineensis* progenies in Brazil (Gomes Junior et al. 2016). This was attributed to the high genetic variability among the evaluated progenies, mainly from male and female parents from natural populations in America. Thus, introduction of new materials should always be a priority to increase genetic variability in developing new varieties with selected traits, especially high yield.

The variance for family, family by replication, within palms, and phenotype are presented in Table 8. The results showed that family variance (σ^2_g) for FFB was lower than the family × replication variance (σ^2_{gr}), suggesting a higher influence of local environmental factors on FFB than the family genotype. A few studies reported that the magnitude and dimensions of environmental effects are different for each genotype (Okoye et al. 2009; Rafii et al. 2001). Therefore, studying the interaction of genotypes with the environment is essential to evaluate specific genotypes, especially in terms of FFB. Meanwhile, σ^2_g for BNO and ABW were higher than σ^2_{gr}, indicating the superior effect of genotype in the expression of both traits. In terms of bunch quality components, σ^2_g estimates were higher than σ^2_{gr} for all traits. Therefore, most traits can serve as selection criteria because family genotypes contribute more variation to bunch quality components

Table 8 Variance components and heritability estimates for bunch yield and its components, bunch quality components, vegetative and physiological traits

	Trait	σ^2_g	σ^2_{gr}	σ^2_e	σ^2_p	h^2_B (%)
Bunch yield and its components	FFB	148.5	215.1	1513.5	1877.0	15.8
	BNO	5.3	0.8	7.0	13.2	80.9
	ABW	4.1	1.1	7.2	12.3	66.5
Bunch quality components	BWT	4.1	1.6	10.5	16.2	50.9
	MFW	5.4	0.2	4.7	10.3	100.0
	MNW	0.3	0.0	0.3	0.6	100.0
	P/B	2.5	1.2	12.1	15.8	31.5
	M/F	12.2	0.7	16.4	29.3	83.4
	K/F	2.8	0.2	3.1	6.0	91.9
	S/F	5.5	0.1	7.3	12.8	85.2
	O/DM	2.2	0.2	3.5	5.9	73.5
	O/WM	8.0	*0.0*	12.3	20.3	78.8
	F/B	5.6	0.2	16.3	22.1	50.3
	O/B	7.5	0.5	8.1	16.2	93.2
	K/B	0.9	0.1	1.5	2.4	73.3
	MC	6.9	*0.0*	11.7	18.5	73.9
	O/F	994.7	118.4	1650.9	2764.0	72.0
	OY	55.2	13.5	107.3	175.9	62.7
	KY	2.9	0.0	7.5	10.4	55.0
	TEP	48.3	12.5	118.7	179.5	53.8
	TOT	49.3	12.7	116.5	178.4	55.2
Vegetative and physiological traits	FP	2.2	0.3	4.7	7.2	61.3
	PCS	8.0	6.6	33.5	48.0	33.1
	RL	0.0	0.0	0.2	0.2	26.1
	LL	11.9	3.8	57.3	73.0	32.5
	LW	0.1	0.0	0.3	0.4	25.6
	LN	8.8	16.1	72.6	97.6	18.1
	HT	0.0	0.0	0.2	0.2	33.3
	LA	0.3	0.4	2.2	2.8	20.5
	LAI	0.1	0.1	0.8	1.0	20.2
	DIA	0.0	0.0	0.0	0.0	0.0
	VDM	1.8	1.5	7.3	10.3	35.2
	BDM	0.2	2.9	21.5	24.6	1.3
	TDM	1.5	6.7	35.9	44.0	6.9
	BI	0.0	0.0	0.0	0.0	0.0

σ^2_g = family variance, σ^2_{gr} = family by replication variance, σ^2_e = within palms variance, σ^2_p = phenotypic variance, h^2_B = broad sense heritability, *FFB* = fresh fruit bunch yield, *BNO* = bunch number, *ABW* = average bunch weight, *BWT* = bunch weight, *MFW* = mean fruit weight, *MNW* = mean nut weight, *P/B* = parthenocarpic to bunch, *M/F* = mesocarp to fruit, *K/F* = kernel to fruit, *S/F* = shell to fruit, *O/DM* = oil to dry mesocarp, *O/WM* = oil to wet mesocarp, *F/B* = fruit to bunch, *O/B* = oil to bunch, *K/B* = kernel to bunch, *MC* = moisture content, *O/F* = oil to fiber, *OY* = oil yield, *KY* = kernel yield, *TEP* = total economic product, *TOT* = total oil, *FP* = frond production, *PCS* = petiole cross-section, *RL* = rachis length, *LL* = leaflet length, *LW* = leaflet width, *LN* = leaflet number, *HT* = trunk height, *LA* = leaf area, *LAI* = leaf area index, *DIA* = trunk diameter, *VDM* = vegetative dry matter, *BDM* = bunch dry matter, *TDM* = total dry matter, *BI* = bunch index

than environmental factors. On the contrary, most vegetative and physiological traits, such as RL, LN, LA, LAI, BDM, and TDM, had lower σ^2_g estimates than the σ^2_{gr}. Stronger environmental influence on vegetative and physiological traits, compared to bunch yield and its components, as well as bunch quality components, suggests the need for additional studies on the adaptability and stability of the test genotypes in multi-environment trials.

The h^2_B estimates were high for the majority of the bunch quality components, such as MFW (100%), MNW (100%), O/B (93.2%), K/F (91.9%), S/F (85.2%), M/F (83.4%), O/WM (78.8%), MC (73.9%), O/DM (73.5%), K/B (73.3%), O/F (72.0%) and OY (62.7%). Moderate h^2_B estimates were detected for the rest of the traits, namely TOT (55.2%), KY (55.0%), TEP (53.8%), BWT (50.9%), F/B (50.3%), and P/B (31.5%). Analysis of 24 *dura* × *pisifera* progenies from 10 genetic origins showed that the h^2_B estimates for most bunch quality components were moderate, ranging from 30% to 60% (Swaray et al. 2020). Besides the fact that the aforementioned study involved *dura* and *pisifera* parents from more varied backgrounds compared to this study, the difference in the h^2_B estimates could also be due to the different study environment, one of the determining factors for h^2_B estimates (Acquaah 2020). Most of the vegetative and physiological traits, in contrast, had low h^2_B estimates, ranging from 0% (DIA and BI) to 26.1% (RL). This suggest that most vegetative characters are influenced more by the environment. These results were also contrary to observations by Breure and Corley (1983), where heritability was generally high for vegetative characters. In our study, a high h^2_B estimate was only detected for FP (61.3%), while h^2_B estimates were medium for VDM (35.2%), HT (33.3%), PCS (33.1%), and LL (32.5%).

Principal component analysis

Principal component analysis (PCA) is a useful method for variable-reduction when there are many variables. The variables can be reduced to a few principal components that represent the majority of the variance in the observed variables. For specific crucial and practically significant principal components, maintaining an eigenvalue greater than one is recommended as a general guideline (Ekezie 2013; Iezonni and Pritts 1991). In this study, seven components (PC1-PC7) showed an eigenvalue greater than one, accounting for 89.0% of the total variation (Table 9). Studies on some MPOB oil palm germplasm reported between four and six principal components with eigenvalues greater than one, which explained a total variation of over 85% (Li-Hammed et al. 2016; Norziha et al. 2019; Suzana et al. 2016; Wan Nor Salmiah et al. 2022).

The PC1, with an eigenvalue of 12.3, has the highest variance of 35.2%. It exhibited a strong and positive correlation with bunch quality component traits such as OY (0.263), TOT (0.252), TEP (0.250), O/WM (0.244), and O/B (0.237). Simultaneously, it demonstrated the highest negative relationship with K/F (−0.238) and MC (−0.239). Variables with significant positive and negative effects contribute significantly to the diversity, especially those on PC1 (Li-Hammed et al. 2016). Thus, these bunch quality component traits can be considered for selection in breeding programmes. Meanwhile, other components which had eigenvalues from 1.4 to 5.6 and variance between 3.9% and 16.0%, were primarily associated with vegetative and physiological characteristics. The PC2 was associated mainly with VDM (0.351), PCS (0.337), and HT (0.300). Both PC3 and PC5 were characterised by LA (−0.309 and 0.352) and LAI (−0.308 and 0.352), with the addition of LN (−0.321) for PC3 and LL (0.364) for PC5. On the other hand, PC4 and PC6 exhibited high correlations with BDM (0.339 and 0.312), along with FFB (0.330) and TDM (0.387) for PC4. Additionally, PC6 showed correlations with BI (0.317) and S/F (−0.345). The last component, PC7, was primarily associated with LL (0.487), DIA (0.413), and LW (−0.368).

Through multidimensional preference analysis, a PCA biplot was generated to examine the inter-relationship between the D × P families and variables, as well as to determine which variables contributed the most to the families. Traits in the right quadrant, such as O/B, M/F, OY, TEP, and TOT, were positively correlated with PC1, while traits that were negatively correlated with PC1, namely K/B, MNW, K/F, MC, and KY, were located in the left quadrant (Fig. 1). Vegetative and physiological traits such as PCS, LW, LN, VDM, and RL contributed positively to PC2. Contrastingly, BI and S/F correlated negatively with PC2. Positive associations between variables are indicated by their proximity to one another. Thus, TEP and TOT depend positively on OY. Other positive associations were detected between K/B and MNW, as well as K/F and MC. On the contrary, a strong negative correlation can be observed between ABW and BNO, among others. There was a lack of correlation between VDM and BDM as the angle between these two variable vectors is 90 degrees or orthogonal. Families ECP HP 500 and ECP HP 519 were distinctly located in quadrant I, with O/B being the variable that contributed most to these families. Family ECP HP 496 was located furthest in quadrant IV of the plot due to having the highest BNO as well as the lowest means of leaf-related traits such as LW, LA, and LAI. It is suggested that these three families (ECP HP 500, ECP HP 519, and ECP HP 496) are unique and can be selected for the development of new high-yielding planting materials.

Table 9 Variables correlation loading matrix, eigenvalues, variance and cumulative variance of the seven principal components of 38 D×P families

	Trait	Eigenvectors						
		PC1	PC2	PC3	PC4	PC5	PC6	PC7
Bunch yield and its components	FFB	0.175	−0.026	0.009	0.330	0.213	0.180	0.013
	BNO	0.229	−0.167	−0.070	0.099	0.027	0.091	0.058
	ABW	−0.199	0.214	0.126	0.093	−0.003	−0.001	−0.045
Bunch quality components	BWT	−0.189	0.145	0.131	0.154	−0.113	0.179	0.036
	MFW	−0.107	0.180	0.216	−0.211	0.064	0.281	0.086
	MNW	−0.204	0.044	0.216	−0.079	0.154	0.032	0.160
	P/B	−0.075	0.179	0.244	−0.216	0.094	0.158	0.058
	M/F	0.196	0.179	−0.071	−0.149	−0.162	0.288	−0.078
	K/F	−0.238	−0.022	0.182	0.109	0.105	−0.112	−0.054
	S/F	−0.115	−0.249	−0.030	0.142	0.163	−0.345	0.156
	O/DM	0.212	0.093	0.162	−0.103	0.130	−0.206	−0.215
	O/WM	0.244	0.041	0.057	−0.060	0.143	−0.278	−0.042
	F/B	0.070	0.152	0.202	−0.294	0.047	−0.035	0.287
	O/B	0.237	0.147	0.074	−0.197	0.034	−0.047	0.053
	K/B	−0.226	−0.021	0.201	0.087	0.103	−0.139	−0.020
	MC	−0.239	−0.015	−0.008	0.032	−0.140	0.295	−0.034
	O/F	0.211	0.094	0.153	−0.118	0.131	−0.166	−0.221
	OY	0.263	0.078	0.088	0.051	0.098	0.050	0.122
	KY	−0.180	−0.042	0.235	0.213	0.170	−0.071	−0.008
	TEP	0.250	0.076	0.128	0.086	0.129	0.042	0.127
	TOT	0.252	0.077	0.122	0.080	0.123	0.044	0.127
Vegetative and physiological traits	FP	0.165	0.027	0.128	0.249	−0.218	−0.185	0.275
	PCS	−0.122	0.337	−0.008	0.128	−0.065	−0.045	−0.148
	RL	0.044	0.237	−0.288	−0.132	−0.078	−0.089	0.073
	LL	−0.117	−0.049	−0.081	−0.094	0.364	0.064	0.487
	LW	−0.040	0.180	−0.261	0.074	0.220	−0.163	−0.368
	LN	−0.016	0.193	−0.321	−0.036	−0.005	0.167	0.037
	HT	−0.035	0.300	0.114	−0.013	0.203	−0.026	−0.091
	LA	−0.107	0.148	−0.309	−0.022	0.352	−0.016	0.066
	LAI	−0.107	0.149	−0.308	−0.021	0.352	−0.016	0.067
	DIA	0.060	0.127	−0.222	0.192	−0.186	−0.105	0.413
	VDM	−0.018	0.351	0.042	0.239	−0.144	−0.137	0.072
	BDM	0.147	0.001	0.034	0.339	0.198	0.312	−0.090
	TDM	0.076	0.259	0.055	0.387	0.015	0.090	−0.002
	BI	0.118	−0.277	−0.011	0.034	0.245	0.317	−0.120
	Eigenvalue	12.3	5.6	4.5	3.3	2.2	1.9	1.4
	Variance (%)	35.2	16.0	12.9	9.3	6.4	5.4	3.9
	Cumulative variance (%)	35.2	51.2	64.1	73.4	79.8	85.1	89.0

FFB = fresh fruit bunch yield, *BNO* = bunch number, *ABW* = average bunch weight, *BWT* = bunch weight, *MFW* = mean fruit weight, *MNW* = mean nut weight, *P/B* = parthenocarpic to bunch, *M/F* = mesocarp to fruit, *K/F* = kernel to fruit, *S/F* = shell to fruit, *O/DM* = oil to dry mesocarp, *O/WM* = oil to wet mesocarp, *F/B* = fruit to bunch, *O/B* = oil to bunch, *K/B* = kernel to bunch, *MC* = moisture content, *O/F* = oil to fiber, *OY* = oil yield, *KY* = kernel yield, *TEP* = total economic product, *TOT* = total oil, *FP* = frond production, *PCS* = petiole cross-section, *RL* = rachis length, *LL* = leaflet length, *LW* = leaflet width, *LN* = leaflet number, *HT* = trunk height, *LA* = leaf area, *LAI* = leaf area index, *DIA* = trunk diameter, *VDM* = vegetative dry matter, *BDM* = bunch dry matter, *TDM* = total dry matter, *BI* = bunch index

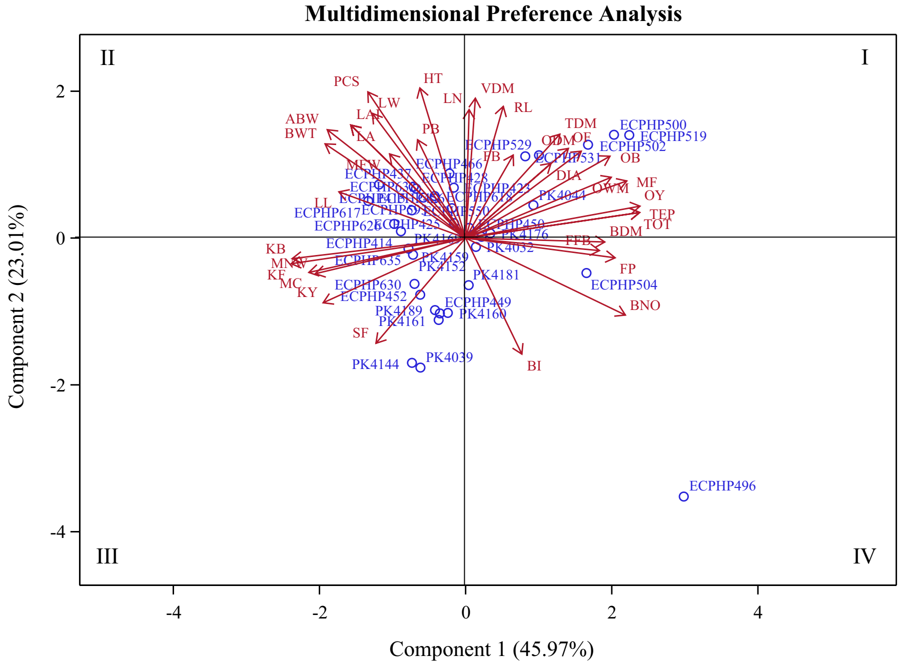

Fig. 1 Biplot based on 35 traits of 38 D × P families on the first and second principal component axes

Cluster analysis

Cluster analysis is a method that uses dendrograms to organise genotypes into groups, which shows how different genotypes might be distinguished. This method has been used to identify unique populations of oil palm germplasm for conservation and utilisation in breeding programmes, such as MPOB-Nigeria (Li-Hammed et al. 2016), MPOB-Sierra Leone (Suzana et al. 2016), MPOB-Guinea (Norziha et al. 2019), and MPOB-Cameroon (Wan Nor Salmiah et al. 2022). The results of those studies also revealed that the grouping of the populations did not associate with their geographical origins. Cluster analysis was also used to evaluate D × P progenies for parental selection in developing new high-yielding planting material (Arolu et al. 2017).

All 38 D × P families were grouped into three main groups (clusters) with several sub-clusters (Fig. 2). Generally, the grouping of families did not associate with their backgrounds or origins, as crosses from different backgrounds were grouped in the same cluster. Cluster I comprised 13 families, most of which were crosses between Deli (Banting, Johor Labis and Ulu Remis × Elmina) *dura* and AVROS *pisifera*. The second cluster comprised the lowest number of families (nine), with most of them from the Deli Ulu Remis × MPOB-Nigeria cross. On the other hand, Cluster III comprised the highest number of families (16), with families from the Deli *dura* × (MPOB-Nigeria × UP) *pisifera* cross as the majority.

Cluster I consisted of two sub-clusters: I-A and I-B, generally exhibiting large bunch sizes (ABW and BWT), high MC, and wide petioles (PCS) (Table 10). Moreover, sub-cluster I-B, which comprised crosses from all three different *pisifera* male parents (AVROS, MPOB-Nigeria, and MPOB-Nigeria × UP) had the highest values of kernel and leaf-related traits such as K/F (8.6%), K/B (5.1%), LL (90.3 cm), LN (173.4 leaflets), LA (9.6 m^2), and LAI (5.7). However, families within both sub-clusters in Cluster I produced low bunch yield with poor bunch quality, as demonstrated by their low FFB yield (176.3–177.1 kg $palm^{-1}$ $year^{-1}$), BNO (10.3–10.4 bunches $palm^{-1}$ $year^{-1}$), O/WM (46.2–49.9%), OY (42.5–47.9 kg $palm^{-1}$ $year^{-1}$), TEP (48.2–53.1 kg $palm^{-1}$ $year^{-1}$), and TOT (47.2–52.3 kg $palm^{-1}$ $year^{-1}$). The results indicated that families from different genetic backgrounds but exhibiting similar performance for certain traits were clustered together. This was similar to the observations by Arolu et al. (2017), where 34 Deli *dura* × Nigeria *pisifera* progenies were clustered according to the performance of certain characteristics. Conversely, 25

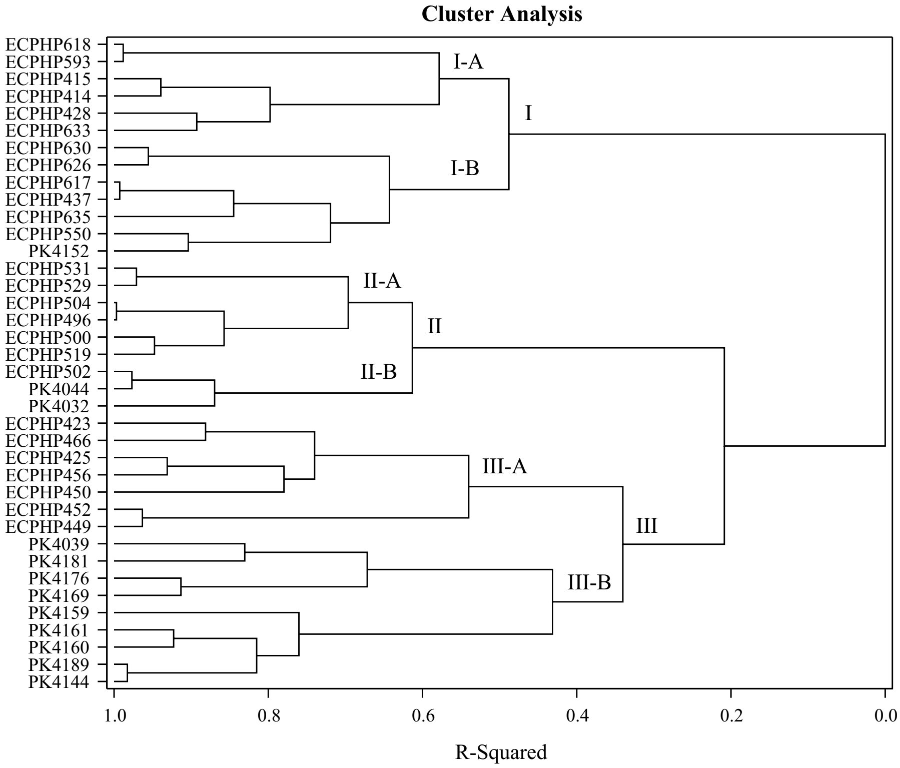

Fig. 2 Dendrogram of the 38 D × P families based on 35 traits evaluated with root mean square distance between observations (R2) = 1.01206

D × P full-sib progenies derived from crosses between Deli *duras* and four different *pisifera* male parents (AVROS, Dumpy AVROS, La Me, and Yangambi) were grouped into various clusters according to their *pisifera* source rather than the morphological performance of the progenies (Junaidah et al. 2011).

Cluster II consisted of families producing more fronds (FP), longer rachis (RL), broader trunk (DIA), and higher dry matter (BDM and TDM) compared to the other two clusters. Both sub-clusters II-A and II-B also demonstrated the best performance in bunch yield and bunch quality components. They had the highest means of FFB yield (202.6–206.1 kg palm^{-1} year^{-1}), BNO (14.4–16.0 bunches palm^{-1} year^{-1}), M/F (81.5–84.9%), O/WM (52.7–53.8%), OY (57.0–62.8 kg palm^{-1} year^{-1}), TEP (61.1–66.5 kg palm^{-1} year^{-1}), and TOT (60.4–65.8 kg palm^{-1} year^{-1}). Furthermore, families within sub-cluster II-A excelled in oil-related traits such as O/DM (80.0%), O/B (30.1%), and O/F (405.7%). Based on the pedigree of the families, sub-cluster II-A consisted of families from Ulu Remis × MPOB-Nigeria crosses. Outstanding bunch yield and bunch quality performance of D × P progenies from the Ulu Remis *dura* has also been reported by Swaray et al. (2020). Among 24 D × P progenies derived from 10 genetic origins, Ulu Remis × Yangambi produced the highest FFB yield, while Ulu Remis × AVROS exhibited higher values of bunch quality components compared to the trial mean.

In this study, families from the Ulu Remis × AVROS cross in sub-cluster III-A produced the highest MNW (2.7 g), F/B (66.5%), and KY (9.8 kg palm^{-1} year^{-1}), while having the lowest values for some vegetative traits such as RL (5.3 m), LW (5.1 cm), LN (167.6 leaflets), and DIA (0.7 m). Interestingly, sub-clusters III-A and III-B consisting of families from the Deli *dura* × (MPOB-Nigeria × UP) *pisifera* cross, had contrasting fruit sizes. On average, the highest MFW was recorded for families within sub-cluster III-A at 13.2 g, while the lowest was recorded in families within sub-cluster III-B at 8.0 g. Besides that, sub-cluster III-B displayed the lowest M/F (77.9%), PCS (25.6 cm^2), and HT (2.1 m), but produced the highest S/F (15.08%).

Table 10 Performance means for each sub-cluster

Sub-cluster	FFB	BNO	ABW	BWT	MFW	MNW	P/B	M/F	K/F	S/F	O/DM	O/WM	F/B	O/B	K/B	MC	O/F	OY
I-A	177.1	**10.3**	**17.6**	14.9	12.5	2.4	**6.8**	80.3	8.0	11.7	78.8	49.9	65.1	26.0	4.7	36.8	377.1	47.9
I-B	**176.3**	10.4	17.5	**17.1**	12.2	2.6	5.3	78.1	**8.6**	13.2	**76.3**	**46.2**	63.4	**22.9**	**5.1**	**39.7**	**328.6**	**42.5**
II-A	202.6	**16.0**	**13.0**	**11.2**	10.4	1.5	4.5	**84.9**	**4.8**	**10.3**	**80.0**	**53.8**	66.0	**30.1**	**3.0**	**32.7**	**405.7**	**62.8**
II-B	**206.1**	14.4	14.6	12.0	8.1	**1.5**	**2.7**	81.5	5.5	13.1	79.3	52.7	**62.6**	26.9	3.3	33.7	389.1	57.0
III-A	191.1	12.1	16.1	14.2	**13.2**	**2.7**	6.7	79.1	8.2	12.7	79.6	51.4	**66.5**	27.1	5.0	35.5	399.3	54.3
III-B	185.7	13.2	14.4	11.8	**8.0**	1.8	3.3	**77.9**	7.1	**15.1**	78.6	50.8	63.3	25.2	4.3	35.5	375.8	48.9
Sub-cluster	KY	TEP	TOT	FP	PCS	RL	LL	LW	LN	HT	LA	LAI	DIA	VDM	BDM	TDM	BI	
I-A	8.7	53.1	52.3	24.6	**32.6**	5.5	84.5	5.3	171.0	**2.5**	8.7	5.2	0.7	**15.7**	**14.4**	30.1	**0.5**	
I-B	9.5	**48.2**	**47.2**	**23.6**	31.6	5.5	**90.3**	5.4	**173.4**	2.2	**9.6**	**5.7**	0.7	14.6	14.5	29.1	0.5	
II-A	**6.1**	**66.5**	**65.8**	26.1	27.3	5.6	**83.8**	5.2	172.5	2.5	**8.5**	**5.1**	0.7	14.2	**16.3**	30.5	**0.5**	
II-B	6.9	61.1	60.4	**27.0**	29.7	**5.6**	85.2	**5.5**	171.6	2.1	9.2	5.5	**0.7**	15.8	16.2	**32.0**	0.5	
III-A	**9.8**	60.2	59.3	24.8	27.6	**5.3**	88.7	**5.1**	**167.6**	2.3	8.7	5.2	**0.7**	13.6	15.5	29.1	0.5	
III-B	8.3	53.9	53.1	24.4	**25.6**	5.4	88.6	5.3	168.8	**2.1**	9.0	5.3	0.7	**12.5**	14.7	**27.2**	0.5	

Figures in bold within the mean column are minimum and maximum values. *FFB* = fresh fruit bunch yield (kg $palm^{-1}$ $year^{-1}$), *BNO* = bunch number (no. $palm^{-1}$ $year^{-1}$), *ABW* = average bunch weight (kg), *BWT* = bunch weight (kg), *MFW* = mean fruit weight (g), *MNW* = mean nut weight (g), *P/B* = parthenocarpic to bunch (%), *M/F* = mesocarp to fruit (%), *K/F* = kernel to fruit (%), *S/F* = shell to fruit (%), *O/DM* = oil to dry mesocarp (%), *O/WM* = oil to wet mesocarp (%), *F/B* = fruit to bunch (%), *O/B* = oil to bunch (%), *K/B* = kernel to bunch (%), *MC* = moisture content (%), *O/F* = oil to fiber (%), *OY* = oil yield (kg $palm^{-1}$ $year^{-1}$), *KY* = kernel yield (kg $palm^{-1}$ $year^{-1}$), *TEP* = total economic product (kg $palm^{-1}$ $year^{-1}$), *TOT* = total oil (kg $palm^{-1}$ $year^{-1}$), *FP* = frond production (no. $palm^{-1}$ $year^{-1}$), *PCS* = petiole cross-section (cm^2), *RL* = rachis length (m), *LL* = leaflet length (cm), *LW* = leaflet width (cm), *LN* = leaflet number (no.), *HT* = trunk height (m), *LA* = leaf area (m^2), *LAI* = leaf area index, *DIA* = trunk diameter (m), *VDM* = vegetative dry matter (t ha^{-1} $year^{-1}$), *BDM* = bunch dry matter (t ha^{-1} $year^{-1}$), *TDM* = total dry matter (t ha^{-1} $year^{-1}$), *BI* = bunch index

Conclusion

The 38 D×P families examined in this study demonstrated a high level of genetic variability for all traits. High heritability estimates were observed for OY, BNO and FP, which all relates to high FFB yield. Therefore, these traits should be prioritised in selecting high-yielding palms. Four families, namely PK 4044, ECP HP 496, ECP HP 500, and ECP HP 502, were identified to have high FFB yields (205.5 to 214.4 kg palm^{-1} year^{-1}), which could be attributed to their high BNO (14.6 to 20.2 bunches palm^{-1} year^{-1}) and moderate ABW (10.3 to 14.7 kg). Families ECP HP 496 and ECP HP 500 produced the highest OY at an average of more than 9 t ha^{-1} year^{-1}, outperforming the national average of 3.7 t ha^{-1}. Family ECP HP 496 also had an advantage in terms of low HT, which was 38% shorter than current recommended planting material in Malaysia, a characteristic that will help to ease FFB harvesting and extend its economic lifespan. Parental palms of these families will be utilised for breeding of high-yielding planting materials. Additionally, superior individual palms from these families can be selected as ortets for clonal propagation of high-yielding commercial clonal planting material. However, since the present study was carried out in only one location, it is important that the identified high-yielding families undergo multiple location testing to verify their suitability under different environmental conditions prior to being recommended for commercial planting. In the interim, using the high-yielding planting material identified in the present in conjunction with good agricultural practices will help increase the national oil yield and contribute to the advancement of the oil palm industry.

Acknowledgements The authors wish to thank the Malaysian Palm Oil Board (MPOB) for providing research materials, facilities, and financial support to carry out this study. We also acknowledge Universiti Kebangsaan Malaysia (UKM) for the research and learning experience.

Author contributions All authors reviewed the manuscript.

Funding The authors have not disclosed any funding.

Declarations

Competing interests The authors declare no competing interests.

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