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EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN FERTILISER ON OIL PALM PERFORMANCE ON ALLUVIAL SOIL

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ABSTRACT

The primary objective for many oil palm growers has been to enhance crop yield, which can be achieved through the cultivation of more productive varieties. Therefore, there is a need to study new planting materials to find the optimum planting density in oil palm plantations. Oil palm growth and yield performance of two planting materials (PS1 and DxP) were determined using four planting densities and three nitrogen fertiliser rates. The analysis of variance for fresh fruit bunch (FFB) and its components over 17 years of recording show no significant interaction between planting density, progeny lineage and nitrogen (N). The N had a significant effect on FFB yield where N1 rate was a significant difference in average FFB yield by 0.89 t ha^{-1} as compared to the control. However, a higher rate of N (N2) did not significantly increase FFB yield since the difference is only 0.09 t ha^{-1}. The standard rate of N fertiliser significantly produces maximum cumulative yields over 17 years of harvesting. Vegetative growth shows that higher planting density increased rachis length, frond length, height, leaf area and leaf area index. PS1 exhibited a significantly shorter rachis length measuring 3.08% less at 6.18 m, in comparison to DxP which measured 6.33 m. Over 17 years of harvesting, a planting density of 140 palms ha^{-1} yielded the highest cumulative and average FFB yield amounting to 426.96 and 24.19 t ha^{-1} yr^{-1} respectively. However, it was not significantly different to the yield achieved at a density of 160 palms ha^{-1}, which yielded cumulatively at 425.68 t ha^{-1} yr^{-1} and average of 24.12 t ha^{-1} yr^{-1}. The study shows that the standard practice of 140 palms ha^{-1} continues to be the preferred agronomic optimum planting density.

Keywords: density, *Elaeis guineensis*, nitrogen, progeny, yield.

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INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) maintains its position as the predominant commodity crop in Malaysia, leading in terms of planted area, production, and export earnings. In 2022, the overall oil palm planted area reached 5.67 million hectares, which slightly declined by 1.1% from the previous year due to the improvement in MPOB renewal licensing procedures for independent smallholders (Parveez et al., 2023). The palm oil sector contributed RM48 billion to the gross domestic product (GDP), accounting for 3.6% of Malaysia's total GDP in 2020, making it the foremost contributor among all commodity crops (Ministry of Plantation Industries and Commodities, 2021).

Oil palm plantations are usually found on alluvial and inland soils (Sergieieva, 2023). In Malaysia, there are around 500 distinct soil types, with residual soils and alluvial soils emerging as the most common, including in Northern Borneo (Ashraf et al., 2017; Sellan et al., 2021). The alluvial soils originate from the weathering of hills composed of mudstone and sandstone and they are considered as types of soils which are suitable for oil palm plantations. These soils can vary from clayey and silty to sandy, and they are rich in organic matter with a pH range of 4.0-6.8 (Din et al., 2021; Sellan et al., 2021).

The fertilisation process plays a significant role throughout the majority of the oil palm's life cycle (Darras et al., 2019). Nitrogen (N) fertiliser is frequently employed in oil palm plantations as one

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of the commonly used chemical fertilisers (Azahari & Sukarman, 2023). The suggested application rate for N fertiliser in oil palm varies from 48-260 kg N ha^{-1} yr^{-1}, with options for either split rates every six months or a single annual dose (Skiba et al., 2020).

Nitrogren fertiliser problems on alluvium soils in Malaysia are not clearly mentioned. However, N fertiliser management is a common issue in oil palm plantations. According to Sugianto et al. (2023), a substantial portion of the 973 fields, each averaging 2 ha, exhibited insufficient N levels, accounting for approximately two-thirds of the total. N losses are the most uncertain aspects of N fluxes. Hence, additional investigation into N losses is essential to enhance understanding of minimising environmental impacts and enhancing the economic and agro-ecological efficiency of management practices (Pardon et al., 2016).

Increasing crop yield has been the priority for most planters and can be accomplished by planting more productive varieties. Most breeding programmes are industry-driven, therefore aside from focusing on producing high oil-yielding planting materials, efforts are also channelled towards developing dwarfed planting materials to address harvesting issues. The new generation of oil palm planting materials based on MPOB-Nigerian *dura* x AVROS *pisifera* (PS1) was introduced to reduce the palm height of the standard (DxP) planting material from the current 45-75 cm yr^{-1} to an average height increment of 40 cm yr^{-1} (Kushairi et al., 2003; Rajanaidu et al., 1999). The PS1 was developed by MPOB to address harvesting issues that become more challenging as the palms mature. Despite the slow growth, PS1's FFB yields were not compromised as it is able to produce about 30.0-33.0 t ha^{-1} yr^{-1} with high oil content, high percentage of oil to bunch (O/B) and potentially increased oil yield of 7.7 t ha^{-1} yr^{-1} (Wahid et al., 2005). According to Hafiz and Rashid (2011), PS1 produces lighter fruitlets per bunch but records higher bunch weight compared to other standard planting materials.

Planting density in oil palm refers to the number of oil palm trees planted per hectare in a plantation. Typically, oil palm (*E. guineensis* Jacq.) is commonly planted in a triangular pattern (Bonneau et al., 2018; Van Leeuwen, 2019), at a density of 130-160 palms ha^{-1} with a spacing of 8.50-9.42 m depending on the soil type and environmental conditions. Studies on planting density and its effect on oil palm yield have been extensively explored (Barcelos, et al., 2015; Bonneau et al., 2018; Korol et al., 2021; Woittiez et al., 2017). Increasing the number of productive oil palm trees per hectare is one feasible strategy to increase palm oil productivity. However, this is deemed a simplistic solution as there are other factors i.e., environmental, that need consideration.

There are several techniques to define the optimal oil palm planting density as follows:

- Current optimum: The oil palm planting density that provides the highest yield in any given year (Bonneau et al., 2018).
- Agronomic optimum: Oil palm planting density that produces the maximum cumulative FFB output over a specific period (Bonneau et al., 2018).
- Economics optimum: The density of oil palm plantations that produces the maximum accumulated discounted profit over a certain period (Latif et al., 2003).

In mineral soils, commercial DxP is routinely planted at 136-148 palms ha^{-1}. However, with the new and high-yielding variety, PS1, introduced in 1999, the feasibility of higher-density planting was explored. As with most agronomy studies, establishing the optimal planting density requires long-term evaluation. This article reports on the response of the progeny lineage towards higher planting densities and N fertiliser application on alluvial soil.

MATERIALS AND METHODS

The study was conducted at Lahad Datu, Sabah, 05°07′50″N latitude and 118°26′34″E longitude at an elevation of 50 m above sea level. The experimental site was located on the Bengawat family soil series and was classified as Typic Endoaquepts (USDA Soil Taxonomy) or Eutric Gleysols (FAO/UNESCO Legend). The trial was a randomised complete block design (RCBD) with split plot treatments. The RCBD was chosen for its practicality in the field, easy to implement and provide manageable experimental design. The design allows detection of treatment effects with a smaller sample size such as N. It was initiated in May 2000 with the following treatments: Main plot of four densities (D1: 140 palms ha^{-1}, 9.06 m triangular spacing; D2: 160 palms ha^{-1}, 8.50 m triangular spacing; D3: 180 palms ha^{-1}, 8.00 m triangular spacing; and D4: 200 palms ha^{-1}, 7.60 m triangular spacing), replicated thrice.

Two palm progenies (PS1 and commercial DxP) form the subplot treatments and three levels of N fertiliser application (N0 – control, N1 – 0.63 to 0.95 kg N $palm^{-1}$ yr^{-1}, and N2 – 1.26 to 1.89 kg N $palm^{-1}$ yr^{-1}) as the sub-plot treatments. Different varieties of oil palm may have distinct genetic characteristics, growth patterns, and nutrient requirements. The N fertiliser used was sulphate of ammonia (21% N). In addition, muriate of potash (MOP – 60% K_2O), rock phosphate (RP – 30% P_2O_5), kieserite (27% MgO) and borate 48 (48% B_2O) were applied as per normal practice (Nur Zuhaili et al., 2021).

Vegetative measurements were conducted on three to four recording palms per plot using conventional non-destructive techniques on frond 17 from the selected palms. Previous research (Foster, 2003) suggested that frond 17 be used as a reference for leaf analysis due to its midpoint location and the correlation between fruit bunch yield and leaf nutrient levels. Measurements were done once a year to monitor the oil palm vegetative growth in terms of frond production, leaf area, petiole cross-section, trunk height, and diameter. As for the leaf nutrient content, the central leaflets were sampled from frond 17. Calcium (Ca) and magnesium (Mg) content were determined using atomic absorption spectrophotometer (AAS). Colourimetry using the vanadomolybdate yellow method was used to measure phosphorus (P), while potassium (K) content was determined by a flame photometer. Nitrogen content in plant was analysed through wet digestion and titration by observing the colour change to red as endpoint was obtained. Soil samples were taken one year after planting by using a screw auger at three sampling points - the palm circle, frond pile and avenue and at three soil depths at each point, 0-15, 15-30 and 30-60 cm. The soil samples were analysed for pH, organic carbon (C), total N, available P, exchangeable K, Ca, Mg and soil texture.

Fresh fruit bunch (FFB) number and weight of the recording palms of each plot were taken at harvesting rounds every 10-15 days. The effects of the various treatments on palm growth and yield were analysed using analysis of variance (ANOVA) for split-plot design. Significant differences at $P \leq 0.05$ were determined followed by Duncan's test (DMRT) to compare the means of the parameters. All tests were accomplished using the SAS Statistics software program.

RESULTS AND DISCUSSION

Soil Physico-chemical Properties

Results of soil physical analysis of Bengawat Series are shown in *Table 1*. The soil texture analysis revealed that the clay content in the topsoil (0-15 cm) was about 14%, slightly higher to over 17% at 45 cm depth. The topsoil silt content was over 50%, marginally decreasing with depth whereas the fine and coarse sand increased slightly. These soils occurred on a level terrain and were characterised by the gleyic horizon occurring within 50 cm of the soil surface. The gleyic colour (2.5Y7/2-10.0YR7/2) horizon occurs within 50 cm due to poorly drained conditions. The soils were texturally classified as fine sandy clay to heavy clay with moderate medium subangular blocky and slightly sticky.

Most of the chemical parameters were found to be very high compared to the nutrients required by the palms except for available P and organic C. In general, most soil nutrients decreased with depth, especially the mobile nutrients such as N and K. Available P was much higher in the topsoil (11.9 mg kg^{-1}) because P is relatively immobile. Exchangeable Ca and Mg did not change significantly with depth. The presence of high exchangeable Ca [13.68-16.02 cmol (+) kg^{-1}] and Mg [6.04-6.33 cmol (+) kg^{-1}] would most probably affect K and Mg uptake due to the dominance of Ca^{2+} ions in the soil as Ca constitutes over 65% of the total soil exchangeable cations. Exchangeable Ca and Mg in Bengawat family soils are generally higher, especially exchangeable Ca than in other soils.

TABLE 1. SOIL PHYSICAL ANALYSIS OF BENGAWAT SOIL

Soil texture (%)	Soil depth (cm)		
	0-15	15-30	30-45
	Mean ± SE	Mean ± SE	Mean ± SE
Clay	13.99 ± 1.18	15.51 ± 1.49	17.88 ± 1.46
Silt	51.26 ± 2.55	49.46 ± 2.73	45.27 ± 2.64
Fine sand	29.56 ± 1.28	29.35 ± 1.25	30.74 ± 1.31
Coarse sand	5.23 ± 0.72	5.68 ± 0.90	6.11 ± 0.89

Note: Values are the means from 48 samples; SE - standard error.

Effect of Nitrogen (N) and Vegetative Growth

The analysis of variance shows N had a significant effect on FFB yield as early as the sixth-year harvest. Over 17 years of harvest, there was a significant difference in average FFB yield by 0.89 t ha^{-1} at the N1 rate as compared to the control plot (N0). Application of N at a higher rate (N2) did not significantly increase FFB yield and its components, the difference was only 0.09 t ha^{-1}. The results show that the N requirement for oil palm on alluvial soils was between 3-6 kg sulphate of ammonia (SOA) palm^{-1} yr^{-1} and it was in line with previous studies (Chang et al., 2022) which reported that the N requirement was about 4.2 kg SOA palm^{-1} yr^{-1} to meet the FFB yield of 30 t ha^{-1} yr^{-1}. Meanwhile, the low level of leaf K in the entire plot was due to the imbalance effect of Mg and Ca on the soil cation exchange site. The leaf K ranged between 0.47% to 0.53% which was significantly low compared to the standard K values. The high values of exchangeable Mg and Ca in Bengawat soils contributed to the low uptake of K due to the dominance of Mg and Ca ion in the soil.

The summarised vegetative parameters in the ninth year of planting are in *Table 2*. Between the period of 7th-10th year after planting, increased planting density resulted in high leaf area index (LAI) values. The LAI greater than six indicates high inter-plant competition for light, water, and nutrients, subsequently affecting both bunch number and bunch weight. Aside from that, LAI above six also contributed to higher total dry weight production caused solely by better vegetative growth, as yield ha^{-1} declined (Breure, 2003). *Table 2* shows higher planting density has led to an increment in the rachis length, height, leaf area and LAI. Increasing planting density from 140 to 160, 180 and 200 palms ha^{-1} produced longer rachis length by 4.22%, 8.00% and 10.50%, respectively however no significant difference was detected between the density of 140 and 160 palms ha^{-1}. Planting at high density enhanced frond length, thus increasing the LAI values which benefits dry matter production for vegetative growth.

The LAI increased from 4.98-5.52 and 6.42-6.89 with increased planting density from 140-160 and 180-200 palms ha^{-1}, respectively with a decrease in annual frond production. Planting at high density resulted in low frond production and palm trunk diameter. Meanwhile, planting at 160 palms ha^{-1} with an index less than 5 affected the average bunch numbers. The LAI was expected to increase consistently with increasing palm age, especially at higher density. The frond production was about 4.30% and 8.12% lower at 180 and 200 palms ha^{-1} as compared to 140 palms ha^{-1}. The palm girth diameter was 5.97% and 10.45% lower at 180 and 200 palms ha^{-1}, respectively than 140 palms ha^{-1}. The palm height increment was between 0.44 to 0.46 m yr^{-1} without any significant difference at various densities. The results show that PS1 has a significantly shorter rachis length of 0.02 m or 3.08% compared to DxP. Indirectly, this variety is suitable for denser than the usual planting density. In the ninth year of planting, the height increment of PS1 in N1 plots ranged from 0.41-0.49 m yr^{-1}, while the DxP is between 0.44-0.47 m yr^{-1}, without significant difference.

Oil Palm Fresh Fruit Bunches (FFB) Yield and Bunch Components

The analysis of variance for FFB yield and components over 17 years of recording shows no significant interaction between planting density, progeny and N. FFB and its components were significantly affected by density, however, it was only FFB that varied with N. The application of fertiliser can affect FFB yield, but the relationship between density and fertiliser is not straightforward. According to Prabowo et al. (2023), the response of yield, nutrient uptake, and recovery efficiency (RE) to fertiliser application was significantly correlated with several factors, but the maximum yield response was negatively correlated with nutrient uptake. The mean and cumulative FFB yield and bunch components over 17 years were summarised in *Table 3*, except for density at 200 palms ha^{-1}. Data recording for the latter planting design was taken only for nine years because of a drastic decline in yield in the 10th year of harvest due to the etiolation of the palms. Over 17 years of harvesting, it was the planting density at 140 palms ha^{-1} that gave the highest cumulative and average FFB yields but with no significant difference when compared to 160 palms ha^{-1} planting density.

An increase in planting density from 140 to 160 and 180 palms ha^{-1} had resulted in significantly decreased cumulative bunch production from 213.64 to 188.09 (11.95%) and 167.51 (21.59%) bunches $palm^{-1}$, respectively. These results were similar to previous studies. According to Bonneau et al. (2018) and Romero et al. (2022), higher planting density resulted in lower cumulative FFB production. The cumulative average bunch weight was slightly higher from 276.27-280.11 (1.37%) although negligible, at a density of 140-160 palms ha^{-1}, respectively. However, it significantly decreased from 276.27-262.59 (5.21%) with planting density from 140-180 palms ha^{-1}. The decrease in bunch weight is visible with the increase in density.

The optimum yield was obtained at a density of 140 palms ha^{-1}. Without any thinning practices at the early stages, planting density at 180 palms ha^{-1} was not advantageous for both progenies on alluvial soils. An increase in planting density from 140-180 and 160-180 palms ha^{-1} significantly decreased cumulative FFB yield by 17.49 t ha^{-1} (4.10%) and 16.21 t ha^{-1} yr^{-1} (3.80%), respectively. Both progenies had no significant effect on FFB yield and bunch components. The PS1 produced a balanced cumulative bunch number and bunch weight; 171.99 bunches and 223.71 kg as compared to 165.32 bunches and 233.75 kg of DxP. Meanwhile, an increased rate of double N application from the recommended estate rate did not significantly increase the FFB yield and bunch components. A significant difference was found only in the control plot. The effects of planting density, progeny lineage and N on annual FFB yield t ha^{-1} yr^{-1} were summarised in *Table 4* and *5*, average bunch weight (kg $bunches^{-1}$) (*Table 6* and *7*) and average bunch number (no $palm^{-1}$ yr^{-1}) in *Table 8* and *9*. *Table 4* and *5* show that the current optimum planting density for the first four years of cropping was 200 palms ha^{-1}, then reduced to between 160 and 140 palms ha^{-1} on the fifth year onwards. The results suggested that both lineages can be planted at a higher density for the first four years of cropping on alluvial soils. A planting density of 160-200 palms ha^{-1} gave an advantage of higher early yields which was similar to a study conducted by Latif et al. (2003).

As shown in *Table 3*, the cumulative yield of 140 and 160 palms ha^{-1} was not significantly different, whereby the extra palms in the latter planting gave no advantage on cumulative yields beyond the 10th year of harvesting onwards. The study showed a significant effect of progeny lineage on average bunch weight and bunch number. PS1 had a significantly higher bunch number with a lower bunch weight compared to DxP. This difference was noticeable in the fourth year of harvest. However, over 17 years of harvesting, both bunch characters were not significantly different. A similar trend was observed i.e., a higher bunch number with lighter bunch weight, which was the preferable bunch characteristic for the field workers.

TABLE 2. VEGETATIVE GROWTH OF OIL PALMS IN RESPONSE TO VARIOUS TREATMENTS

Planting density (palms ha^{-1})	Frond production	Rachis length (m)	Height (m)	Diameter (m)	Relative leaf area (m^2)	Frond dry weight (kg)	Petiole cross-section (cm^2)	Leaf area index	Height increment
140	24.11a	5.89c	3.13b	0.67a	16.18a	3.67a	33.89a	4.98d	0.45a
160	23.74a	6.15b	3.22b	0.67a	16.46a	3.85a	35.62a	5.52c	0.46a
180	23.07b	6.41a	3.08b	0.63b	16.20a	4.01a	37.19a	6.42b	0.44a
200	22.16c	6.58a	3.98a	0.60c	16.71a	3.62a	33.38a	6.89a	0.44a
LSD $_{(0.05)}$	0.6479	0.2042	0.2466	0.0185	0.7687	0.4490	4.3870	0.3429	0.0355
MSE	3.4943	0.3983	0.3566	0.0033	3.3134	0.7338	70.1861	1.9766	0.0072
CV (%)	4.13	4.84	11.81	4.29	7.07	17.59	18.59	8.55	11.91

Progenies	Frond production	Rachis length (m)	Height (m)	Diameter (m)	Relative leaf area (m^2)	Frond dry weight (kg)	Petiole cross-section (cm^2)	Leaf area index	Height increment
PS1	23.46a	6.18b	3.10a	0.65a	16.07a	3.58b	32.93b	5.92a	0.44a
DxP	23.08a	6.33a	3.09a	0.63b	16.20a	4.00a	37.11a	5.99a	0.44a
LSD $_{(0.05)}$	0.4582	0.1444	0.1744	0.0131	0.5435	0.3175	3.1020	0.2425	0.0251

Nitrogen level	Frond production	Rachis length (m)	Height (m)	Diameter (m)	Relative leaf area (m^2)	Frond dry weight (kg)	Petiole cross-section (cm^2)	Leaf area index	Height increment
N0	22.43b	6.23a	3.01a	0.64a	15.93a	3.76a	34.72a	5.83b	0.43a
N1	23.74a	6.26a	3.13a	0.64a	15.95a	3.78a	34.94a	5.83b	0.45a
N2	23.65a	6.27a	3.16a	0.65a	16.53a	3.83a	35.41a	6.20a	0.45a
LSD $_{(0.05)}$	0.5611	0.1768	0.2136	0.0161	0.6657	0.3888	3.7990	0.2970	0.0308

Note: Values are mean of three replications in the ninth year of recording. Means with different alphabets in the same column are significantly different at 5% level with DMRT (Duncan Multiple Range Test).

TABLE 3. MEAN AND CUMULATIVE OF FFB YIELD AND BUNCH COMPONENTS OVER 17 YEARS OF HARVESTING

Planting density (palms ha^{-1})	ABNO (palm^{-1})		ABWT (kg bunch^{-1})		FFB (t ha^{-1} yr^{-1})	
	Mean	Cumulative	Mean	Cumulative	Mean	Cumulative
140	12.80a	213.25a	15.55a	276.27a	24.19a	426.96a
160	11.31b	188.09b	15.75a	280.11a	24.12ab	425.68a
180	10.20c	167.51c	14.79b	262.59b	23.31b	409.47b
200*	12.79a	115.08d	10.43c	100.81c	23.38b	222.83c
LSD $_{(0.05)}$	0.644	9.35	0.729	11.34	0.747	10.83
CV (%)	8.12	7.95	7.66	8.94	4.68	4.51

Progenies	ABNO (palm^{-1})		ABWT (kg bunch^{-1})		FFB (t ha^{-1} yr^{-1})	
	Mean	Cumulative	Mean	Cumulative	Mean	Cumulative
PS1	10.45a	171.99a	12.62a	223.71a	20.91a	366.77a
DxP	10.09a	165.32a	13.18a	233.75a	20.97a	368.15a
LSD $_{(0.05)}$	0.455	6.614	0.515	8.022	0.528	7.655

Nitrogen level	ABNO (palm^{-1})		ABWT (kg bunch^{-1})		FFB (t ha^{-1} yr^{-1})	
	Mean	Cumulative	Mean	Cumulative	Mean	Cumulative
N0	10.26a	168.19a	12.39b	219.73b	20.32b	356.18b
N1	10.39a	171.61a	12.98ab	230.28ab	21.21a	372.80a
N2	10.16a	166.27a	13.32a	238.18a	21.30a	373.33a
LSD $_{(0.05)}$	0.558	8.101	0.631	9.82a	0.647	9.376

Note: Mean and cumulative values over ninth of years recording; ABNO - average bunch number; ABWT - average bunch weight; FFB - fresh fruit bunch. Figures are the mean and cumulative of three replications over 17 continuous years of recording. Means with different alphabets in the same columns are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 4. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL FFB YIELD (YEAR 1 TO 9)

Planting density (palms ha^{-1})	Year of harvesting									Average (t ha^{-1} yr^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
140	8.52b	19.98b	27.94b	24.86b	27.96ab	30.21a	28.16a	29.97a	27.49a	25.01a
160	8.56b	20.48ab	30.69a	25.79ab	29.03a	29.02ab	27.64ab	27.96b	26.72a	25.09a
180	10.17a	20.02b	29.97ab	26.47a	28.52ab	28.20b	26.31b	26.54b	25.15ab	24.59a
200	10.93a	21.76a	29.97ab	26.67a	26.84b	25.11c	22.59c	23.31c	23.21b	23.38b
LSD $_{(0.05)}$	1.069	1.540	1.967	1.323	1.804	1.605	1.437	1.976	2.394	0.748
CV (%)	16.63	11.12	9.85	7.57	9.53	8.47	8.15	10.89	13.86	4.53
Current optimum density (palms ha^{-1})	200	200	160	200	160	140	140	140	140	

Progenies	Year of harvesting									Average (t ha^{-1} yr^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
PS1	9.62a	20.89a	29.68a	26.07a	28.07a	28.00a	26.33a	27.45a	25.93a	24.67a
DxP	9.47a	20.24a	29.61a	25.83a	28.11a	28.27a	26.02a	26.44a	25.36a	24.37a
LSD $_{(0.05)}$	0.756	1.089	1.391	0.936	1.276	1.135	1.016	1.397	1.693	0.518

Nitrogen Level	Year of harvesting									Average (t ha^{-1} yr^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
N0	9.53ab	20.71a	29.16a	26.01a	27.74a	27.40b	25.24b	25.53b	25.23a	24.06b
N1	9.04b	20.36a	30.29a	25.84a	28.78a	28.05ab	26.63a	28.00a	25.71a	24.74a
N2	10.08a	20.63a	29.48a	25.99a	27.75a	28.95a	26.65a	27.30a	25.99a	24.76a
LSD $_{(0.05)}$	0.926	1.334	1.703	1.146	1.562	1.390	1.245	1.711	2.073	0.648

Note: Values are mean of three replications in the ninth year of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 5. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL FFB YIELD (YEAR 10 TO 17)

Planting density (palms ha^{-1})	Year of harvesting								Average (t ha^{-1} yr^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
140	20.52a	21.81a	24.04a	23.22a	24.35a	21.88ab	26.04a	24.34b	23.27a
160	18.67a	21.54ab	26.21a	23.40b	22.89a	22.82a	24.28b	24.42a	23.03ab
180	20.45a	21.00b	24.35a	18.12c	23.17a	20.23a	23.28b	24.38a	21.87b
LSD $_{(0.05)}$	2.183	1.606	2.390	1.805	1.787	1.917	1.540	1.713	1.231
CV (%)	21.73	15.05	19.02	17.36	15.07	17.53	12.42	13.91	8.16
Current optimum density (palms ha^{-1})	140	140	160	160	140	160	140	160	

Progenies	Year of harvesting								Average (t ha^{-1} yr^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
PS1	14.69a	15.77a	18.51a	15.46a	17.20a	15.93a	18.33a	17.55b	16.68a
DxP	15.14a	15.91a	18.79a	15.41a	18.01a	16.54a	18.47a	19.02a	17.16a
LSD $_{(0.05)}$	1.543	1.135	1.690	1.276	1.264	1.356	1.089	1.211	1.018

Nitrogen level	Year of harvesting								Average (t ha^{-1} yr^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
N0	14.29a	14.95a	16.42b	14.02b	17.18a	15.64a	18.25a	18.10a	16.10b
N1	15.12a	16.05ab	19.15a	15.89a	17.85a	16.50a	18.52a	18.85a	17.24a
N2	15.32a	16.52a	20.39a	16.39a	17.77a	16.56a	18.43a	17.91a	17.41a
LSD $_{(0.05)}$	1.890	1.391	2.070	1.563	1.548	1.660	1.334	1.484	1.244

Note: Values are mean of three replications in the eighth years of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 6. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL BUNCH WEIGHT (YEAR 1 TO 9)

Planting density (palms ha^{-1})	Year of harvesting									Average (kg bunch^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
140	3.56a	6.84a	9.26a	9.88a	13.12a	12.77ab	14.08ab	17.27a	17.50a	11.59a
160	3.54a	6.60ab	9.21a	9.52ab	12.72a	12.69ab	14.20a	16.46ab	16.86a	11.31a
180	3.49a	6.51ab	9.14a	9.31ab	12.39ab	12.98a	13.50ab	15.59bc	16.61a	11.07a
200	3.40a	5.81b	8.43b	8.85b	11.45b	11.72b	12.93b	14.67c	16.53a	10.43b
LSD $_{(0.05)}$	0.299	0.797	0.585	0.714	1.029	1.042	1.137	1.269	1.212	0.618
CV (%)	12.72	18.39	9.63	11.28	12.3	12.33	12.34	11.77	10.66	8.32

Progenies	Year of harvesting									Average (kg bunch^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
PS1	3.54a	6.38a	8.86a	9.09b	12.22a	11.95b	13.26b	15.45b	16.70a	10.83b
DxP	3.45a	6.49a	9.16a	9.69a	12.63a	13.14a	14.09a	16.55a	17.06a	11.36a
LSD $_{(0.05)}$	0.211	0.564	0.413	0.504	0.728	0.736	0.804	0.897	0.857	0.439

Nitrogen level	Year of harvesting									Average (kg bunch^{-1})
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
N0	3.41a	6.70a	8.83a	9.03b	12.06a	12.03b	12.90b	15.48b	16.49a	10.77b
N1	3.48a	6.28a	8.93a	9.21b	12.46a	12.33b	13.49b	15.72ab	16.94a	10.98b
N2	3.59a	6.34a	9.27a	9.93a	12.76a	13.27a	14.63a	16.80a	17.20a	11.53a
LSD $_{(0.05)}$	0.259	0.691	0.506	0.618	0.892	0.902	0.985	1.099	1.05	0.538

Note: Values are mean of three replications in the ninth year of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 7. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL BUNCH WEIGHT (YEAR 10 TO 17)

Planting density (palms ha^{-1})	Year of harvesting								Average (kg bunch^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
140	17.94a	18.24b	20.22a	19.57ab	20.31a	21.80b	21.41ab	20.52a	20.00a
160	18.03a	19.34a	20.62a	20.53a	20.67a	23.11a	22.15a	21.64a	20.76a
180	16.72b	17.15c	18.60b	18.50b	19.44a	20.34c	20.49b	20.54a	18.97b
LSD $_{(0.05)}$	0.898	0.905	1.177	1.490	1.419	1.176	1.117	1.468	0.831
CV (%)	10.12	9.82	11.75	15.09	13.94	10.70	10.35	13.89	10.12

Progenies	Year of harvesting								Average (kg bunch^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
PS1	12.97a	13.41a	14.58a	14.21a	14.73a	16.05a	15.96a	15.26a	14.65a
DxP	13.37a	13.95a	15.14a	15.09a	15.48a	16.57a	16.07a	16.09a	15.22a
LSD $_{(0.05)}$	0.635	0.640	0.832	1.054	1.004	0.831	0.790	1.038	0.760

Nitrogen level	Year of harvesting								Average (kg bunch^{-1})
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
N0	12.50b	12.65b	13.75b	13.99a	14.17b	15.60b	15.79a	15.37a	14.23b
N1	13.44a	14.29a	15.21a	15.20a	15.36ab	16.44ab	16.02a	15.97a	15.24a
N2	13.58a	14.11a	15.62a	14.75a	15.79a	16.90a	16.23a	15.68a	15.33a
LSD $_{(0.05)}$	0.778	0.784	1.019	1.291	1.229	1.018	0.968	1.271	1.008

Note: Values are mean of three replications in the eighth years of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 8. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL BUNCH NUMBER (YEAR 1 TO 9)

Planting density (palms ha^{-1})	Year of harvesting									Average
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
140	17.18a	21.93a	21.59a	18.27a	15.51a	17.25a	14.55a	12.60a	11.37a	16.69a
160	15.41a	20.51ab	21.15a	17.20ab	14.52a	14.57b	12.28b	10.70b	10.01b	15.15b
180	16.05a	17.43c	18.19b	16.16bc	12.89b	12.27c	10.99c	9.62c	8.53c	13.57c
200	16.15a	18.96bc	17.88b	15.22c	11.95b	10.80d	8.95d	8.06d	7.09d	12.79c
LSD $_{(0.05)}$	1.867	2.312	1.137	1.374	1.546	1.437	0.959	0.943	1.055	0.787
CV (%)	17.11	17.41	8.57	12.2	16.73	15.54	12.17	13.67	16.93	8.03

Progenies	Year of harvesting									Average
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
PS1	16.04a	19.53a	20.02a	17.32a	13.92a	14.39a	12.16a	10.78a	9.52a	14.86a
DxP	16.35a	19.88a	19.38a	16.11b	13.51a	13.05b	11.23b	9.71b	8.98a	14.24b
LSD $_{(0.05)}$	1.32	1.635	0.804	0.972	1.093	1.016	0.678	0.667	0.746	0.556

Nitrogen level	Year of harvesting									Average
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
N0	16.54a	19.35a	19.85ab	17.44a	13.94a	13.88a	11.84a	9.98b	9.32a	14.68a
N1	15.46a	19.93a	20.28a	17.01a	14.08a	13.86a	11.99a	10.81a	9.20a	14.73a
N2	16.60a	19.85a	18.97b	15.71b	13.12a	13.43a	11.25a	9.95b	9.23a	14.24a
LSD $_{(0.05)}$	1.617	2.002	0.985	1.19	1.339	1.245	0.83	0.817	0.913	0.682

Note: Values are mean of three replications in the ninth year of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

TABLE 9. THE EFFECT OF PLANTING DENSITY, PROGENY LINEAGE AND NITROGEN ON ANNUAL BUNCH NUMBER (YEAR 10 TO 17)

Planting density (palms ha^{-1})	Year of harvesting								Average
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
140	8.25a	9.02a	8.81a	8.79a	8.64a	7.06a	8.26a	8.55a	8.42a
160	6.72b	7.08b	8.21a	6.42b	6.96b	6.16b	6.97b	7.33b	6.99b
180	6.48b	6.06c	7.45b	5.93b	6.59b	5.68b	6.28b	6.76b	6.40c
LSD $_{(0.05)}$	0.701	0.756	0.698	0.786	0.714	0.593	0.767	0.737	0.531
CV (%)	19.40	20.19	16.93	22.09	19.10	18.63	21.17	19.33	10.72

Progenies	Year of harvesting								Average
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
PS1	5.38a	5.61a	6.14a	5.40a	5.65a	4.67a	5.47a	5.59a	5.48a
DxP	5.35a	5.52a	6.10a	5.17a	5.44a	4.78a	5.29a	5.73a	5.42a
LSD $_{(0.05)}$	0.495	0.535	0.493	0.556	0.504	0.419	0.542	0.521	0.412

Nitrogen level	Year of harvesting								Average
	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	
N0	5.13a	5.37a	5.69b	4.71b	5.71a	4.68a	5.35a	5.69a	5.29a
N1	5.51a	5.59a	6.22ab	5.43a	5.52a	4.72a	5.30a	5.77a	5.51a
N2	5.45a	5.73a	6.45a	5.72a	5.41a	4.78a	5.49a	5.53a	5.57a
LSD $_{(0.05)}$	0.607	0.655	0.604	0.681	0.618	0.514	0.664	0.638	0.438

Note: Values are mean of three replications in the eighth years of recording. Means with different alphabets in the same column are significantly different at a 5% level with DMRT (Duncan Multiple Range Test).

CONCLUSION

Non-destructive vegetative measurements, leaf nutrient content, soil sampling, and FFB counts are parameters that are commonly used for long-term study to gather reliable data without destroying the main palms. The FFB yield profile over 17 years of cropping was sufficient for a suitable recommendation towards an optimum agronomic planting density for PS1. Growth characteristics of PS1 such as shorter rachis length and lower height increment are ideal characteristics for planting at higher densities of 160 palms ha^{-1}. However, upon long-term evaluation, the FFB yield at 140 palms ha^{-1} densities gave better cumulative results. The study shows that the standard practice of 140 palms ha^{-1} is still the preferred agronomic optimum planting density. The finding of this study has demonstrated the importance of long-term evaluation of planting material testing at different planting densities for not less than the tenth year of harvest. The optimum agronomic density of 140 palms ha^{-1} can be achieved without a need for thinning and the extra palms in 160 palms ha^{-1} planting gave no advantage on cumulative yields.

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REFERENCES

Ashraf, M. A., Othman, R., & Ishak, C. F. (Eds.). (2017). *Soils of Malaysia*. CRC Press.

Azahari, D. H., & Sukarman. (2023). Impact of chemical fertilizer on soil fertility of oil palm plantations in relation to productivity and environment. *IOP Conference Series: Earth and Environmental Science*, *1243*(1), 012020. https://doi.org/10.1088/1755-1315/1243/1/012020

Azman, H. M. Y., Lee, C. H., & Razak, I. A. (1996). Oil and kernel of oil palm in relation to planting densities, materials, and fertilizer rates. In N. Rajanaidu, I. E. Henson, & B. S. Jalani (Eds.), *Proceedings of the International Conference on Oil and Kernel Production in Oil Palm - A Global Perspective* (pp. 109–119). PORIM.

Barcelos, E., Rios, S. A., Cunha, R. N. V., Lopes, R., Motoike, S. Y., Babiychuk, E., Skirycz, A., & Kushnir, S. (2015). Oil palm natural diversity and the potential for yield improvement. *Frontiers in Plant Science*, *6*, 190. https://doi.org/10.3389/fpls.2015.00190

Bonneau, X., Impens, R., & Buabeng, M. (2018). Optimum oil palm planting density in West Africa. *OCL – Oilseeds and Fats, Crops and Lipids*, *25*(2), A201. https://doi.org/10.1051/ocl/2017060

Breure, C. J. (1976). Preliminary results from an oil palm density × fertilizer experiment on young volcanic soils in west Britain. In D. A. Earp & W. Newall (Eds.), *International developments in oil palm* (pp. 192–207). ISP.

Breure, C. J. (2003). The search for yield in oil palm basic principles. In T. Fairhurst & R. Hardter (Eds.), *Oil palm management for large and sustainable yields* (pp. 59–98). IPNI.

Breure, C. J., Menendez, T., & Powell, M. S. (1990). The effect of planting density on the yield components of oil palm. *Experimental Agriculture*, *26*, 117–124. https://doi.org/10.1017/s0014479700015453

Chang, Y. Y., Abd Wahid, S. A., & Sim, C. C. (2022). Nitrogen and potassium fertiliser requirement optimisation for high-density planting in oil palm (*Elaeis guineensis*) under coastal environment of Peninsular Malaysia. *International Journal of Agricultural Technology*, *18*(5), 1937–1948.

Darras, K. F. A., Corre, M. D., Formaglio, G., Tjoa, A., Potapov, A., Brambach, F., Sibhatu, K. T., Grass, I., Rubiano, A. A., Buchori, D., Drescher, J., Fardiansah, R., Hölscher, D., Irawan, B., Kneib, T., Krashevska, V., Krause, A., Kreft, H., Li, K., ... Veldkamp, E. (2019). Reducing fertilizer and avoiding herbicides in oil palm plantations: Ecological and economic valuations. *Frontiers in Forests and Global Change*, *2*, 65. https://doi.org/10.3389/ffgc.2019.00065

Din, R. D. R., Ishar, S. M., & Naganathan, H. (2021). Physical and chemical characteristics of oil palm plantation soil: A new lead in forensic investigation. *Jurnal Sains Kesihatan Malaysia (Malaysian Journal of Health Sciences)*, *19*(1), 97–105. https://doi.org/10.17576/jskm-2021-1901-11

Foster, H. (2003). Assessment of oil palm fertilizer requirement. In T. Fairhurst & R. Hardter (Eds.), *Oil palm management for large and sustainable yields* (pp. 231–257). IPNI.

Hafiz, M. H. M., & Rashid, M. S. A. (2011). Oil palm physical and optical characteristics from two different planting materials. *Research Journal of Applied Sciences Engineering and Technology*, *3*(9), 953–962.

Khushairi, A. (2003). Performance of PS1 and PS2 at MPOB. In *Proceedings of the Seminar on PS1 and PS2 Planting Materials and Release of Elite Germplasm to the Industry*. MPOB.

Korol, Y., Khokthong, W., Zemp, D. C., Irawan, B., Kreft, H., & Hölscher, D. (2021). Scattered trees in an oil palm landscape: Density, size and distribution. *Global Ecology and Conservation*, *28*, e01688. https://doi.org/10.1016/j.gecco.2021.e01688

Latif, J., Mohd, N. M., Tayeb, D. M., & Kushairi, D. A. (2003). Economics of higher planting density in oil palm plantations. *Oil Palm Industry Economic Journal*, *3*(2), 32–39.

Ministry of Plantation Industries and Commodities. (2021). *National Agricommodity Policy 2021-2030 (DAKN2030)*.

Nur Zuhaili, H. A. Z. A., Zuraidah, Y., Afandi, A. M., & Hasnol, O. (2021). Fertiliser management. In A. P. G. Kadir, Z. Idris, I. A. Seman, M. S. Rahami, & N. S. K. Khairuddin (Eds.), *Oil Palm Industry and the Environment* (pp. 31–36). MPOB.

Pardon, L., Bessou, C., Nelson, P. N., Dubos, B., Ollivier, J., Marichal, R., Caliman, J.-P., & Gabrielle, B. (2016). Key unknowns in nitrogen budget for oil palm plantations: A review. *Agronomy for Sustainable Development*, *36*(1), 20. https://doi.org/10.1007/s13593-016-0353-2

Parveez, G. K. A., Rasid, O. A., Ahmad, M. N., Taib, H. M., Bakri, M. A. M., Hafid, S. R. A., Ismail, T. N. M. T., Loh, S. K., Meilina, O. A., Zakaria, K., & Idris, Z. (2023). Oil palm economic performance in Malaysia and R&D progress in 2022. *Journal of Oil Palm Research*, *35*(2), 193–216. https://doi.org/10.21894/jopr.2023.0028

Prabowo, N. E., Foster, H. L., & Nelson, P. N. (2023). Potassium and magnesium uptake and fertiliser use efficiency by oil palm at contrasting sites in Sumatra, Indonesia. *Nutrient Cycling in Agroecosystems*, *126*, 263–278. https://doi.org/10.1007/s10705-023-10289-7

Rajanaidu, N., Jalani, B. S., & Kushairi, A. (1999). The development of dwarf (PS1) and high iodine value (PS2) planting materials. In *Proceedings of the 1999 PIPOC International Palm Oil Congress* (pp. 115–123). PORIM.

Romero, H. M., Guataquira, S., & Forero, D. C. (2022). Light interception, photosynthetic performance, and yield of oil palm interspecific OxG hybrid (*Elaeis oleifera* (Kunth) Cortés x *Elaeis guineensis* Jacq.) under three planting densities. *Plants*, *11*(9), 1166. https://doi.org/10.3390/plants11091166

Sellan, G., Brearley, F. Q., Nilus, R., Titin, J., & Majalap-Lee, N. (2021). Differences in soil properties among contrasting soil types in Northern Borneo. *Journal of Tropical Forest Science*, *33*(2), 191–202. https://doi.org/10.26525/jtfs2021.33.2.191

Sergieieva, K. (2023). *Oil palm plantation: Cultivation and management tips for growers*. EOS. Retrieved December 7, 2023, from https://eos.com/blog/oil-palm-plantation/

Skiba, U., Hergoualc'h, K., Drewer, J., Meijide, A., & Knohl, A. (2020). Oil palm plantations are large sources of nitrous oxide, but where are the data to quantify the impact on global warming? *Current Opinion in Environmental Sustainability*, *47*, 81–88. https://doi.org/10.1016/j.cosust.2020.08.019

Sugianto, H., Monzon, J. P., Pradiko, I., Tenorio, F. A., Lim, Y. L., Donough, C. R., Sunawan, N., Rahutomo, S., Agus, F., Cock, J., Amsar, J., Farrasati, R., Iskandar, R., Edreira, J. I. R., Saleh, S., Santoso, H., Tito, A. P., Ulfaria, N., Slingerland, M. A., & Grassini, P. (2023). First things first: Widespread nutrient deficiencies limit yields in smallholder oil palm fields. *Agricultural Systems*, *210*, 103709. https://doi.org/10.1016/j.agsy.2023.103709

Van Leeuwen, S. (2019). *Analysis of a pineapple-oil palm intercropping system in Malaysia* [Master's thesis, Wageningen University].

Wahid, M. B., Abdullah, S. N. A., & Henson, I. E. (2005). Oil palm – Achievements and potential. *Plant Production Science*, *8*(3), 288–297. https://doi.org/10.1626/pps.8.288

Woittiez, L. S., Van Wijk, M. T., Slingerland, M., Van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, *83*, 57–77. https://doi.org/10.1016/j.eja.2016.11.002