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Effect of residual frond number and NPK fertilization on yield components of oil palm (*Elaeis guineensis* Jacq)

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Abstract: Optimizing agronomic practices, such as frond management and NPK fertilizer application, is crucial for enhancing the productivity of oil palm (*Elaeis guineensis* Jacq). This study aimed to evaluate the effects of retained frond number and NPK fertilizer rate on key production traits of oil palm. A factorial experiment was conducted using a Completely Randomized Design (CRD) with two factors: frond number (48, 40, and 32 fronds per plant) and NPK fertilizer rates (0.5, 1.75, 3.0, and 4.25 kg per plant). The research was conducted from May to November 2023 in Bencah Kelubi Village, Riau Province, Indonesia, on a 12-year-old DxP Marihat oil palm (hybrid variety). Parameters measured included sex ratio, number and weight of fresh fruit bunches (FFB), fresh fruit (FF) weight and volume, and mesocarp thickness. Results showed that both frond number and fertilizer rate significantly affected all yield components except sex ratio. The treatment of 40 retained fronds combined with 4.25 kg NPK fertilizer per plant produced the highest FFB number (3.16 bunches), FFB weight (16.42 kg), FF weight (9.45 g), FF volume (9.35 L), and mesocarp thickness (4.35 mm). These findings demonstrate that moderate pruning combined with optimal nutrient application improves physiological performance and yield components, supporting more sustainable and efficient oil palm cultivation practices.

Keywords: fertilizer application, frond retention, NPK fertilizer, oil palm yield, sustainable cultivation.
Abbreviations: Anova_Analysis of variance; Ca_Calcium; CPO_Crude palm oil; CRD_Completely Randomized Design; Cu_Copper; DNMRT_Duncan's multiple range test; Fe_Iron; FF_Fresh fruit: FFB_Fresh fruit bunches; g_gram; K_Potassium; kg_kilogram; mL_mililiter; mm_milimeter; N_Nitrogen; P_phosphorus.

Introduction

The cultivation of oil palm (*Elaeis guineensis* Jacq) is a significant agricultural activity that plays a critical role in the economies of many tropical countries. The key to improving the productivity of oil palm is optimizing growth conditions through agronomic practices, notably the management of fronds and the application of fertilizers. Given the increasing importance of the crop for edible oil production, understanding the factors that enhance its yield is essential.

One critical aspect affecting oil palm productivity is the number of fronds which plays a significant role in the photosynthetic capacity and overall vigor of oil palm plants. Greater frond numbers generally boost photosynthetic efficiency, thereby enhancing fruit production components such as the number of fruit bunches per palm and the overall biomass yield (Pato et al., 2023). Previous studies have shown that fronds contribute to the plant's capacity to store carbohydrates, which are essential for fruit development (Hapsoh et al., 2020). Increased frond numbers also improves light interception and, consequently, fruit yield (Hapsoh et al., 2020), supporting the idea that both frond retention and fertilizer application act synergistically to optimize oil palm production.

The application of fertilizers, particularly NPK (Nitrogen, Phosphorus, and Potassium) fertilizers, is known to influence growth parameters, including the sex ratio of flowers, the number of fruit bunches, and the weight and volume of fruit produced. Studies have demonstrated that appropriate NPK fertilizer application can substantially improve growth metrics by supplying essential nutrients that enhance metabolic processes in the plant (Ayeni et al., 2024; Purnomo et al., 2022). Furthermore, understanding environmental and biological factors, including the number of leaves, interact with fertilizer application is critical for optimizing plant performance and fruit quality (Yi, 2019).

This interaction between frond counts and nutrient application highlights the need for a systematic approach to fertilization and frond management. Understanding these dynamics can provide valuable insights into sustainable practices that minimize external inputs while maximizing both productivity and environmental health in oil palm plantations. This study aims to examine the effects of frond retention and NPK fertilizer application on key production components of oil palm, with the goal of developing actionable strategies to improve yield sustainably.

Results and discussion

Sex ratio in plant

Table 1 shows that neither frond retention nor NPK fertilization, individually or in combination, significantly ($p < 0.05$) affected the sex ratio of oil palm. The values ranged narrowly from 0.51 to 0.61, with no statistical differences detected based on DNMRT at the 5% significance level. These findings indicate that the treatments did not induce sufficient physiological variation to alter the proportion of female inflorescences, a key determinant of yield.

Sex expression in oil palm is regulated by complex interactions among physiological, nutritional, genetic, and environmental factors. Although greater frond retention can enhance light interception and assimilate production (Corley and Tinker, 2016), the frond range examined in this study (32–48) may not have been broad enough to significantly influence assimilate allocation for female flower formation (Sibarani et al., 2019).

Nutrient availability, particularly phosphorus (P), is essential for flower initiation because of its critical role in energy transfer and meristem development (Johnston and Poulton, 2019). The applied NPK ratio (13:8:27) contained a relatively low proportion of P, which may have limited floral differentiation. Phosphorus has been shown to enhance fresh fruit bunch (FFB) yield and promote female inflorescence development (Viégas et al., 2019). Other nutrients, such as nitrogen (N), potassium (K), and magnesium (Mg), primarily support vegetative growth and photosynthesis, but their effects on sex ratio are largely indirect and mediated through interactions with P.

Environmental and hormonal factors also play a crucial role. Stress conditions, such as drought or defoliation, can shift sex expression toward male flowers as a survival mechanism (Ithnin et al., 2022), while internal hormonal balances influenced by environmental cues that regulate floral development at the molecular level (Adam et al., 2011).

In summary, the limited impact of frond retention and NPK fertilization on sex ratio suggests that phosphorus nutrition, environmental stimuli, and hormonal regulation are likely more decisive factors. Future studies should consider the roles of micronutrients, hormonal profiling, and genotype–environment interactions to better understand and manage sex ratio variability in oil palm.

Number of fresh fruit bunches (FFB) per plant

Table 2 indicates that both frond retention and NPK fertilizer rate significantly influenced the number of FFBs per oil palm plant. Frond retention refers to the number of oil palm fronds intentionally left attached to the trunk after harvesting or pruning to maintain an optimal leaf area for photosynthesis, carbohydrate production, and fresh fruit bunch (FFB) development. The number of fronds retained is typically determined by agronomic standards or specific research objectives, as achieving the right balance between canopy size and harvesting accessibility is essential for maximizing oil palm productivity.

Although no significant interaction was detected, consistent trends suggest physiological synergy. Plants with 40 retained fronds produced the highest average FFBs (2.92), followed by 48 (2.79) and 32 (2.75). These results highlight the importance of maintaining an adequate canopy size for photosynthesis and carbohydrate supply during inflorescence differentiation and fruit filling (Corley and Tinker, 2016; Kii et al., 2020). Insufficient frond retention may reduce assimilate availability, leading to inflorescence abortion or underdeveloped bunches (Ardiyanto et al., 2021). LAI values below 3.5 have been associated with poor radiation interception and reduced reproductive output (Röll et al., 2015).

Across all frond levels, higher NPK rates led to increased FFB production, rising from 2.61 at 0.5 kg to 3.05 at 4.25 kg plant^{-1}, confirming the role of a balanced macronutrient supply in enhancing yield potential (Viegas et al., 2023). Nitrogen promotes cell division, phosphorus supports energy transfer and root growth, and potassium enhances enzyme activity, carbohydrate transport, and fruit development (Tao et al., 2018). Potassium deficiency, in particular, has been associated with smaller and fewer bunches (Cui et al., 2021).

However, the marginal difference between 3.0 and 4.25 kg suggests a yield plateau, indicating a potential threshold beyond which nutrient uptake is no longer limiting. Excessive fertilization without adequate canopy capacity may result in inefficiencies and nutrient losses, particularly in highly weathered tropical soils (Fairhurst and Härdter, 2003). Therefore, integrated management, retaining 40–48 fronds and applying 3.0–4.25 kg NPK per plant, is essential to optimize FFB yield while minimizing input waste and environmental impact. Site-specific strategies remain critical for sustainable intensification.

Weight of FFB per plant

Table 3 shows that both frond retention and NPK fertilizer rate significantly influenced FFB weight per oil palm. Although their interaction was not statistically significant, the additive effect of both factors supports the role of canopy size and nutrient supply in determining reproductive biomass.

Palms with 40 retained fronds produced the highest mean FFB weight (15.76 kg), slightly higher than those with 48 fronds (15.53 kg), and significantly greater than palms with 32 fronds (15.00 kg). This finding aligns with previous studies indicating that 35–40 healthy fronds are optimal for balancing photosynthesis and fruit development (Henson, 2009; Lamade and Bouillet, 2005; Ardiyanto et al., 2021). The FFB weight increased consistently with higher NPK rates, rising from 14.44 kg at 0.5 kg plant^{-1} to 16.25 kg at 4.25 kg plant^{-1}. The highest value (16.42 kg) was recorded in the 40 frond + 4.25 kg NPK treatment, underscoring the importance of macronutrients in enhancing fruit set and bunch biomass (Viegas et al., 2023).

Nitrogen supports vegetative growth and chlorophyll synthesis, phosphorus promotes root development and energy transfer, and potassium regulates carbohydrate transport and fruit filling (Cui et al., 2021). However, yield gains plateaued beyond 3.0 kg NPK, indicatied diminishing returns due to nutrient saturation (Corley and Tinker, 2016).

Excessive fertilization, particularly in tropical soils, leads to inefficiency and nutrient losses. Therefore, nutrient use efficiency (NUE) should guide fertilization strategies by integrating frond management, soil properties, and plant nutrient demand (Fairhurst and Härdter, 2003; Tao et al., 2018; Röll et al., 2015; Viegas et al., 2023). In conclusion, retaining 40–48 fronds combined with applying 3.0–4.25 kg NPK plant^{-1} ensures optimal FFB weight while promoting efficient resource use and sustained yield improvement in oil palm systems.

The weight of fresh fruit (FF) per plant

Table 4 presents the effects of frond retention and NPK fertilizer application on fresh fruit (FF) weight per oil palm plant. Both factors significantly influenced FF production. The highest mean FF weight (9.07 kg plant^{-1}) was achieved with 40 retained fronds, suggesting

Table 1. Sex ratio per plant (%) as affected by the number of retained fronds and NPK fertilizer application.

Number of retained frond	NPK fertilizer (kg per plan)				Mean
	0.5	1.75	3	4.25	
48	0.54 a	0.55 a	0.57 a	0.60 a	0.57 a
40	0.55 a	0.57 a	0.60 a	0.61 a	0.58 a
32	0.51 a	0.54 a	0.55 a	0.58 a	0.55 a
Mean	0.53 a	0.55 a	0.57 a	0.60 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

Table 2. Number of FFB per plant (bunch) as affected by the number of retained fronds and NPK fertilizer application.

Number of Retained Fronds	NPK Fertilizer (kg per plant)				Mean
	0.5	1.75	3	4.25	
48	2.67 a	2.67 a	2.83 a	3.00 a	2.79 a
40	2.67 a	2.83 a	3.00 a	3.16 a	2.92 a
32	2.49 b	2.67 a	2.83 a	3.00 a	2.75 a
Mean	2.61 a	2.72 a	2.89 a	3.05 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

Table 3. The weight of FFB (kg) per oil palm plant as affected by the number of retained fronds and NPK fertilizer application**.**

Number of Retained Fronds	NPK Fertilizer (kg per plant)				Mean
	0.5	1.75	3	4.25	
48	14.34 c	15.36 ab	16.06 ab	16.35 ab	15.53 ab
40	14.77 b	15.58 ab	16.25 ab	16.42 a	15.76 a
32	14.21 c	14.69 b	15.12 ab	15.97 ab	15.00 b
Mean	14.44 c	15.21 b	15.81 ab	16.25 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

Table 4. The weight of fresh fruit (FF***)*** per oil palm plant (gram) as affected by the number of retained fronds and NPK fertilizer application.

Number of Retained Fronds	NPK Fertilizer (kg per plant)				Mean
	0.5	1.75	3	4.25	
48	8.29 bc	8.54 bc	9.06 ab	9.32 ab	8.80 ab
40	8.42 bc	9.08 ab	9.33 ab	9.45 a	9.07 a
32	8.21 c	8.44 bc	8.60 ab	9.16 ab	8.60 b
Mean	8.31 c	8.69 b	9.00 ab	9.31 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

Table 5. The volume of fresh fruit (FF) per oil palm plant (L) as affected by the number of retained fronds and NPK fertilizer application.

Number of Retained Fronds	NPK Fertilizer (kg per plant)				Mean
	0.5	1.75	3	4.25	
48	8.14 bc	8.40 ab	8.93 ab	9.20 ab	8.67 ab
40	8.29 b	8.96 ab	9.21 ab	9.35 a	8.95 a
32	8.08 c	8.30 b	8.49 ab	9.06 ab	8.48 b
Mean	8.17 bc	8.55 ab	8.88 ab	9.20 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

Table 6. The thickness of mesocarp per oil palm plant (mm) as affected by the number of retained fronds and NPK fertilizer application.

Number of Retained Fronds	NPK Fertilizer (kg per plant)				Mean
	0.5	1.75	3	4.25	
48	3.55 c	3.73 b	3.97 ab	4.23 ab	3.87 ab
40	3.60 bc	3.88 ab	4.08 ab	4.35 a	3.98 a
32	3.49 c	3.68 bc	3.80 ab	4.02 ab	3.75 b
Mean	3.55 c	3.76 b	3.95 ab	4.20 a	

Note: Numbers in the same row and column followed by the same letter are not significantly different according to the DNMRT test at the 5% level.

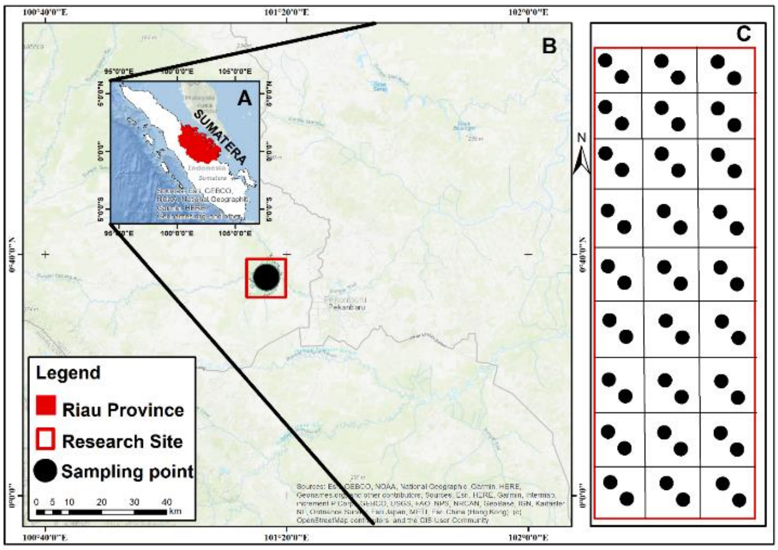

Figure 1. A (inset): Riau Province. B: Location of oil palm plantation.
C: Plant sampling distribution scheme.

this level optimally balances photosynthetic capacity and assimilate allocation for fruit development. Frond number directly affects nutrient dynamics and growth conditions, thereby influencing fruit weight (Greenshields et al., 2023).

In contrast, the lowest FF weight (8.60 kg plant^{-1}) occurred with 32 fronds, indicating that excessive pruning may reduce assimilate availability and limit the yield. Conversely, retaining too many fronds can restrict air circulation and increase pest incidence, adversely affecting fruit production (Sun, 2023). Hence, maintaining an optimal frond balance is critical, where too few fronds limit photosynthetic output, and excessive fronds complicate orchard management.

Across all frond levels, increasing NPK rates consistently enhanced FF weight, from 8.31 kg plant^{-1} at 0.5 kg to 9.31 kg plant^{-1} at 4.25 kg. Appropriate NPK application improves crop coefficients, water use efficiency, and yield performance in oil palm (Sigalingging et al., 2024). Potassium is particularly important because large quantities are removed during harvest, making it essential for sustaining fruit weight and productivity (Ardian et al., 2022; Cui et al., 2021).

The combination of 40 fronds with 4.25 kg NPK produced the highest individual FF weight (9.45 kg plant^{-1}), significantly outperforming most other treatments. This indicates a synergistic effect between optimal canopy size and adequate nutrient supply in enhancing productivity.

Overall, these findings highlight the importance of integrated crop management, where balanced frond retention and sufficient nutrient input are both essential for maximizing fresh fruit yield, especially in nutrient-demanding tropical soils.

The volume of fresh fruit (FF) per plant

Table 5 presents the interaction effects of frond retention and NPK fertilizer rates on fresh fruit (FF) volume per oil palm plant. The highest mean FF volume (8.95 L plant^{-1}) was recorded with 40 retained fronds, followed closely by 48 fronds (8.67 L plant^{-1}). Proper frond management supports palm vegetative growth, such as leaf area and green frond count, thereby improving nutrient uptake, photosynthetic capacity, and ultimately fruit production (Anggoro and Sugandi, 2024; Atnaw et al., 2014).

By contrast, retaining only 32 fronds significantly reduced FF volume (8.48 L plant^{-1}), indicating that excessive pruning limits assimilate production and fruit filling. Previous studies show that frond loss or desiccation negatively correlates with palm growth metrics, including petiole size and leaf area, leading to lower fresh fruit bunch (FFB) yields (Irvanto et al., 2022).

However, excessive frond accumulation can also be detrimental. Overabundant fronds may cause shading and resource competition in the lower canopy, while decomposing frond piles can restrict soil aeration and root activity, ultimately reducing fruit yield (Ooi et al., 2017; Greenshields et al., 2023).

Regarding fertilizer rates, FF volume increased steadily with higher NPK application, from 8.17 L plant^{-1} at 0.5 kg to 9.20 L plant^{-1} at 4.25 kg, confirming the positive role of nutrient supply in fruit development. The combination of 40 fronds with 4.25 kg NPK produced the highest individual FF volume (9.35 L plant^{-1}), significantly outperforming most other treatments according to the DNMRT test. These findings emphasize the need for integrated canopy and nutrient management to optimize fresh fruit volume in oil palm systems, particularly in nutrient-demanding tropical soils.

The thickness of mesocarp per plant

Table 6 shows the effects of frond retention and NPK fertilizer rates on mesocarp thickness in oil palm fruit. Retaining 40 fronds produced the highest mean mesocarp thickness (3.98 mm), significantly greater than the 32-frond treatment (3.75 mm). Optimal frond management, including timely pruning, enhanced light penetration and nutrient availability, thereby promoting healthier mesocarp development. Ooi et al. (2017) highlighted that proper frond management contributes to biomass production and overall plant health, leading to improved mesocarp characteristics. Similarly, Ngalle et al. (2013) reported that well-maintained fronds positively influence mesocarp cellular structure, resulting in thicker and healthier tissues.

The 48-frond treatment yielded an intermediate mesocarp thickness (3.87 mm), suggesting that 40 fronds may provide the optimal balance between vegetative and reproductive growth. Excess frond material, if unmanaged, can create competition for light and nutrients, potentially limiting photosynthesis in younger leaves and reducing mesocarp thickness. Irvanto et al. (2022) found that higher frond desiccation scores correlate with reduced vegetative growth, likely affecting mesocarp development as well.

A consistent trend was observed with increasing NPK fertilizer application: mesocarp thickness increased from 3.55 mm at 0.5 kg to 4.20 mm at 4.25 kg NPK per plant. Nitrogen plays a critical role on vegetative growth, influencing cell division and root development, which improve nutrient uptake and ultimately enhance mesocarp thickness (Hapsoh et al., 2020; Purnomo et al., 2022). Jamidi et al. (2023) also reported that specific NPK doses (2.25 g per seedling) significantly improved oil palm growth, indicating a positive relationship between fertilization and mesocarp development.

Phosphorus supports energy transfer and photosynthesis, accelerating mesocarp tissue growth and promoting oil accumulation during the final maturation stages, a key determinant of fruit quality (Lopes et al., 2021). Potassium, essential for regulating stomatal conductance and photosynthetic efficiency, further contributes to mesocarp thickening as oil content increases (Hapsoh et al., 2020).

The highest mesocarp thickness (4.35 mm) was recorded in the treatment combining 40 fronds with 4.25 kg NPK per plant, suggesting a synergistic effect between adequate canopy retention and nutrient availability. Statistical analysis using the DNMRT test confirmed significant differences ($p < 0.05$) across frond retention and fertilizer levels, particularly between the lowest and highest treatments. These findings indicate that maintaining sufficient photosynthetic capacity alongside with optimal nutrient supply is essential for improving mesocarp thickness, a key trait influencing both oil yield and quality in oil palm production.

Materials and methods

Place and time

This research was carried out in an oil palm plantation in Bencah Kelubi Village, Kampar Regency, Riau province, Indonesia (Figure 1), with an altitude of 20 meters above sea level. The field was characterized by flat topography with a slight slope gradient of 1–3%, on Inceptisol soil type. According to Rahmanto et al. (2022), the area has a wet tropical climate with rainfall of 2,000–3,000 mm yr^{-1} and is classified as type B in the Schmidt-Ferguson classification. The research was conducted from May to November 2023.

Material and tool

The plant material used in this study consisted of 12-year-old oil palm (Elaeis guineensis Jacq.) of the DxP Marihat commercial variety, which had entered the productive phase. DxP Marihat is an F1 hybrid derived from the Deli Dura maternal line and Pisifera male parents (lines 424 and 968). Its fruits are round to oval, with immature fruits showing violet to black coloration and ripening to reddish-yellow. The variety begins fruiting at 14–18 months and reaches harvest maturity at 30 months. By eight years, palms reach a height of approximately 3.2 m with an average growth rate of 53 cm per year. Each palm typically produces 12 fresh fruit bunches (FFBs) annually, averaging 17 kg per bunch, resulting in an oil yield of 6.7 t ha^{-1} $year^{-1}$. Planting is generally conducted at a density of 143 palms ha^{-1}, in areas below 400 m above sea level, with annual rainfall between 1,500 and 3,000 mm (Indonesian Oil Palm Research Institute, 2009). The fertilizer used was a compound NPK formulation (13:8:27). Field operations and data collection employed standard agronomic and harvesting tools, including hoes, machetes, fruit harvest poles, wheelbarrows, and pruning shears. Additional materials included colored marking paint, tarpaulins, jerry cans, large containers, plant labels, weighing scales, calipers, writing instruments, and digital devices for documentation.

Study site and experimental design

This study was conducted as an experimental research using a factorial Completely Randomized Design (CRD) with two factors: (i) the number of retained oil palm fronds and (ii) the dose of NPK fertilization.

Factor I was the number of retained fronds per oil palm plant, consisting of the following levels:

- P0 = 48 fronds retained per plant
- P1 = 40 fronds retained per plant
- P2 = 32 fronds retained per plant

Factor II was the NPK fertilizer dose, consisting of the following levels:

- N0 = 0.5 kg per plant
- N1 = 1.75 kg per plant
- N2 = 3.0 kg per plant
- N3 = 4.25 kg per plant

Each of the 12 treatment combinations was replicated three times, resulting in 36 experimental units. Each unit consisted of two sample of oil palm trees, totaling 72 plants. The experimental layout is illustrated in Figure 2. Fertilizer application was carried out once at the start of the experiment using a localized placement method. For each tree, four application holes were dug at the cardinal points (east, north, west, south) at a radius of 1 meter from the trunk, with each hole measuring 20 cm in both depth and diameter. A compound NPK fertilizer (13:8:27) was used and applied evenly across the four holes.

Observation parameter and statistical analysis

Observations were conducted at the end of the experimental period, and the measured parameters included sex ratio per plant, number of fresh fruit bunches (FFB) per plant, weight of FFB per plant, weight of fresh fruit (FF) per plant, FF volume per plant, and mesocarp thickness per plant. The collected data were analyzed statistically using analysis of variance (ANOVA), and significant differences among treatment means were further tested using Duncan's New Multiple Range Test (DNMRT) at a 5% significance level. The linear model used:

$Y_{ijk} = \mu + P_i + N_j + (PN)_{ij} + \varepsilon_{ijk}$

Y_{ijk} = Observation data on each sample of oil palm plants

μ = Common mean value

P_i = Effect of residual frond number

N_j = Effect of NPK fertilizer dose

$(PN)_{ij}$ = interaction effect of residual frond number and NPKMg fertilizer

ε_{ijk} = Experimental error on observation data on oil palm plants

Conclusion

This study confirms that both frond retention and NPK fertilizer rate significantly (*$p < 0.05$*) affect major yield components of oil palm, except for the sex ratio. The combination of 40 retained fronds and 4.25 kg NPK per plant consistently produced the highest values across all yield parameters, including fresh fruit bunch (FFB) number (3.16 bunches), FFB weight (16.42 kg), fresh fruit (FF) weight (9.45 g), FF volume (9.35 L), and mesocarp thickness (4.35 mm). These results emphasize that optimal frond management coupled with adequate nutrient supply is essential for enhancing oil palm productivity in a sustainable and resource efficient manner.

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