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Effect of Over-Pruning and NPKMg Fertilization on the Yield Components and Productivity of Oil Palm (*Elaeis guineensis* Jacq.)

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Abstract: This study aimed to evaluate the effects of N, P, K, and Mg fertilization on improving growth parameters and productivity of oil palm plants subjected to over-pruning. The experiment was conducted using a completely randomized split-plot design with two factors: pruning treatment as the main factor and N, P, K, and Mg fertilization as the second factor. The observed parameters included the number of female inflorescences, number of male inflorescences, sex ratio, number of fruit bunches, bunch weight, fresh fruit weight, fresh fruit volume, mesocarp thickness, and fruit lipid content. The data obtained were statistically analyzed using analysis of variance, followed by Duncan's New Multiple Range Test (DNMRT) at the 5% significance level. The results showed that the P1 treatment, representing normal pruning, combined with the N3 fertilization treatment improved several growth and productivity parameters, including the number of female inflorescences (5.02), number of fruit bunches (5.83), sex ratio (60.12%), fruit bunch weight (20.40 kg), fresh fruit weight (12.43 g), mesocarp thickness (3.93 mm), fresh fruit volume (12.59 mL), and fresh fruit lipid content (20.21%). In contrast, over-pruning tended to increase the number of male inflorescences (4.00), indicating a decline in the reproductive performance of the plants. In conclusion, normal pruning and the application of N, P, K, and Mg fertilizers significantly improved the growth and productivity of oil palm plants affected by over-pruning, particularly by increasing the number of female inflorescences, number of fruit bunches, sex ratio, fruit bunch weight, fresh fruit weight, mesocarp thickness, fresh fruit volume, and fresh fruit lipid content.
Keywords: NPK fertilization; over-pruning; oil palm productivity; number of inflorescences; normal pruning

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INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is an important source of edible vegetable oil and one of Indonesia's strategic plantation commodities. Crude palm oil is widely used in the food, cosmetics, and alternative energy industries, thereby contributing substantially to the national economy and foreign exchange earnings (Ramadhan & Nasrul, 2022). Riau Province is one of the main centers of oil palm production in Indonesia, with a planted area of 3,401,607 ha and total production of 9,222,465 tons in 2023. Smallholder plantations account for 2,288,586 ha, with an average productivity of 3,183 kg/ha (BPS, 2025). However, smallholder oil palm productivity in Riau remains relatively low, reaching only 3,461 kg/ha, compared with Papua Province, where productivity reaches 5,076 kg/ha (BPS Provinsi Riau, 2024). These figures indicate that oil palm productivity in Riau has not yet reached its optimal level despite the continued expansion of planted areas. This condition reflects a gap between the genetic potential of oil palm and the actual yield achieved under field conditions.

Low productivity in smallholder oil palm plantations is commonly associated with suboptimal agronomic management, including inadequate harvest practices, nutrient imbalance, and poor implementation of field maintenance standards. Previous studies have shown that Indonesian smallholder oil palm yields remain below attainable levels and that improved agronomic practices can increase fresh fruit bunch (FFB) yield and profitability (Woittiez et al., 2019; Sugianto et al., 2025). Among these agronomic practices, pruning plays an important role because it regulates canopy structure, facilitates harvesting, maintains an adequate leaf area, and supports efficient assimilate production and distribution. However, inappropriate pruning, particularly over-pruning, is still frequently observed in smallholder plantations. Over-pruning occurs when the number of fronds removed exceeds the optimum threshold recommended according to plant age and physiological condition. This practice reduces the number of functional leaves, limits photosynthetic capacity, disrupts assimilate production, and ultimately decreases FFB yield. Marcelino & Diaz (2016) reported that frond retention significantly affects bunch number and bunch weight, and that excessive pruning below the optimum frond number can reduce oil palm yield.

Fertilizer management is a key agronomic strategy for maintaining vegetative growth and sustaining FFB production, particularly in plants experiencing physiological disturbance due to over-pruning (Hamidi et al., 2024). Nutrient limitation and nutrient imbalance have been widely reported as major constraints in smallholder oil palm systems. Woittiez et al. (2019) found widespread deficiencies of N, P, and K in Indonesian smallholder plantations, while Lim et al. (2023) reported that nutrient inputs in smallholder fields were often insufficient and imbalanced, particularly for K and Mg. These findings indicate that balanced fertilization is essential for narrowing yield gaps and improving productivity in smallholder plantations.

Nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) are essential nutrients that play complementary roles in supporting oil palm growth, physiological recovery, and productivity. Nitrogen contributes to protein and chlorophyll formation, thereby supporting leaf development and photosynthetic activity. Phosphorus is involved in energy metabolism and root growth, while potassium plays an important role in carbohydrate transport, sugar accumulation, water regulation, and fruit development. Magnesium is a central component of chlorophyll and is therefore essential for maintaining photosynthetic performance. Yadav et al. (2017) reported that nitrogen plays a vital role in improving nutrient-use efficiency and accelerating biomass recovery in plants under stress or disturbance. In mature oil palm, complete NPK fertilization has been shown to improve foliar nutrient status and increase FFB yield (Arifin et al., 2022). In addition, K and Mg application can significantly increase FFB yield, vegetative growth, and nutrient uptake under contrasting environmental conditions in Sumatra (Prabowo et al., 2023). Magnesium application has also been shown to increase leaf Mg content, improve K–Mg nutrient balance, and support yield performance, particularly on marginal soils such as Ultisols and acidic soils (Sahibin et al., 2019; Viégas et al., 2023).

The interaction between fertilization and pruning intensity is closely related to the balance between assimilate production and assimilate allocation. Under moderate pruning conditions, sufficient leaf area can be maintained to support photosynthesis, while adequate N, P, K, and Mg availability enhances nutrient uptake, physiological function, and assimilate translocation to developing fruit bunches. Conversely, excessive frond removal may weaken source capacity and reduce the plant's ability to support reproductive growth. Therefore, appropriate nutrient management is needed to minimize the negative effects of over-pruning and to support the recovery of mature oil palm plants.

Despite the importance of pruning and fertilization in oil palm cultivation, limited studies have specifically examined the role of N, P, K, and Mg fertilization in restoring the physiological condition and productivity of mature oil palm plants affected by over-pruning, particularly in smallholder plantations in Riau Province. This study therefore aims to evaluate the effects of N, P, K, and Mg fertilization on over-pruned mature oil palm plants, with emphasis on physiological recovery and productivity improvement. In addition, this study seeks to identify the most effective fertilizer combination for reducing the adverse effects of over-pruning and restoring crop performance. The findings are expected to provide a scientific basis for improved fertilization management and to serve as a practical reference for enhancing the productivity of over-pruned oil palm (*Elaeis guineensis* Jacq.) in smallholder plantation systems.

METHOD

This study was a field experiment designed to evaluate the effects of pruning condition and N, P, K, and Mg fertilizer dosage on flowering, fruit bunch production, and fruit quality of mature oil palm grown on sapric peat soil. The experiment used a split-plot design, with pruning condition as the main plot and fertilizer dosage as the subplot, to assess both individual and interactive treatment effects under field conditions.

Study Site and Period

This study was conducted in Kepau Jaya Village, Siak Hulu District, Kampar Regency, Riau Province, Indonesia. The experimental site was characterized by a flat land surface. The soil in Kepau Jaya Village is classified as sapric peat, with a peat depth of >2 m and a soil pH of 4–5. The study was carried out over seven months, from November 2025 to May 2026.

Tools and Materials

The tools used in this study included machetes, hoes, an analytical balance, an analog scale, vernier calipers, measuring cylinders, wheelbarrows, harvesting sickles, rulers, stationery, and documentation equipment. The materials used were 21-year-old mature oil palm plants of the DxP Simalungun variety and N, P, K, and Mg fertilizers, namely ZA, TSP, KCl, and dolomite.

Experimental Design

The study employed a split-plot design arranged in a completely randomized pattern. The main plot consisted of pruning condition, while the subplot consisted of N, P, K, and Mg fertilizer dosage. A split-plot design was selected because it can accommodate treatments that differ in operational difficulty, where pruning requires a larger treatment area, whereas fertilizer dosages are relatively easier to apply. This design is also effective for controlling field variation in oil palm plantations.

The pruning treatment was coded as P and assigned as the main plot, consisting of two levels:

P1 = Plants under normal pruning conditions
P2 = Plants under over-pruning conditions

The N, P, K, and Mg fertilizer dosage treatment was coded as N and consisted of four levels:

N0 = 0 kg N, P, and K per plant + 0 kg Mg per plant
N1 = 0.345 kg N + 0.27 kg P_2O_5 + 0.375 kg K_2O + 0.75 kg MgO
= 1.64 kg urea + 0.56 kg TSP + 0.625 kg KCl + 2.75 kg dolomite
N2 = 0.69 kg N + 0.54 kg P_2O_5 + 0.75 kg K_2O + 1.50 kg MgO
= 3.28 kg urea + 1.125 kg TSP + 1.25 kg KCl + 5.50 kg dolomite
N3 = 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO
= 4.92 kg urea + 1.69 kg TSP + 1.875 kg KCl + 8.25 kg dolomite

Each treatment combination was replicated three times, resulting in 24 experimental units and 48 sample palms. The number of replications was determined based on the fundamental principles of agricultural experimental design, in which replication is essential for estimating experimental error and improving the precision of the results. Ideally, the number of replications should be determined through statistical power analysis. However, because preliminary data on variability and effect size were limited, power analysis could not be fully applied in this study. Therefore, the number of replications was determined based on common practice in field-based agronomic research, while considering the balance between data precision and resource availability.

Observation Parameters

1. **Number of female inflorescence bunches per plant:** The number of emerging female inflorescence bunches was recorded based on the criterion that the spathe enclosing the inflorescence had fully opened. Observations were conducted by counting the number of female inflorescence bunches once each month for six months, on the second week of each month. Environmental factors, including rainfall, temperature, and humidity, were recorded as supporting data, while crop maintenance conditions were kept uniform across all experimental units. This was done to minimize the influence of external factors on the study results. The observed number of female inflorescence bunches was averaged for each treatment unit.
2. **Number of male inflorescence bunches per plant:** The number of emerging male inflorescence bunches was recorded based on the criterion that the spathe enclosing the inflorescence had fully opened. Observations were conducted by counting the number of male inflorescence bunches once each month for six months. The observed number of male inflorescence bunches was averaged for each treatment unit.
3. **Sex ratio per plant (%):** Sex ratio was defined as the ratio of the number of female inflorescence bunches to the total number of inflorescences, consisting of both male and female inflorescences. Sex ratio was calculated at the end of the study for each treatment unit. In oil palm, sex ratio is influenced not only by genetic factors but also by environmental conditions and cultivation practices. Factors that may affect sex ratio include rainfall, water availability, temperature, nutrient status, and over-pruning. The sex ratio was calculated using the following formula:

$$\text{Sex ratio} = \frac{\text{JBB}}{\text{JBB} + \text{JBJ}} \times 100\%$$

   Note:
   JBB = Number of emerging female inflorescence bunches
   JBJ = Number of emerging male inflorescence bunches

4. **Number of fruit bunches per plant:** The number of fruit bunches was observed from mature fruit bunches harvested during the study. Observations were conducted by counting the number of mature fruit bunches at each harvest. The average number of harvested mature fruit bunches was then calculated for each treatment unit.
5. **Fruit bunch weight (kg):** Fruit bunch weight was measured from mature fruit bunches harvested during the study. Each mature bunch was weighed using a platform scale. The average fruit bunch weight was calculated by dividing the total fruit bunch weight by the number of harvested fruit bunches in each treatment unit.

6. **Fresh fruit weight (g):** Fresh fruit weight was measured by collecting fresh fruits from the lower, middle, and upper spikelet sections of harvested mature fruit bunches. Five fresh fruits were taken from each section and weighed using an analytical balance. The average fresh fruit weight was calculated based on the total weight of the observed fresh fruit samples in each treatment unit.
7. **Fresh fruit volume (mL):** Fresh fruit volume was measured using fresh fruits collected from the lower, middle, and upper spikelet sections of harvested mature fruit bunches. Five fresh fruits from each section were measured using a measuring cylinder containing 100 mL of water. Fruit volume was determined based on the difference between the final and initial water volumes. The average fresh fruit volume was calculated for each treatment unit based on the observed fruit samples.
8. **Mesocarp thickness (mm):** Mesocarp thickness was measured using fresh fruits collected from the lower, middle, and upper spikelet sections of harvested mature fruit bunches. Five fresh fruits were cut horizontally using a machete, and mesocarp thickness was measured on four sides using vernier calipers. The average mesocarp thickness was calculated for each treatment unit.
9. **Fresh fruit fat content:** Oil palm fruit fat content was determined using the Soxhlet method, which is a repeated extraction method using an organic solvent to dissolve fat components. Fat content was calculated using the following formula:

$$\text{Fat content} = \frac{\text{Oil weight}}{\text{Dry sample weight}} \times 100\%$$

Note:
Oil weight = Weight of oil obtained from extraction
Dry sample weight = Weight of the dried fruit sample used for extraction

Data Analysis

The data obtained from the study were analyzed statistically using analysis of variance. The linear model used was as follows:

$$Y_{ijk} = \mu + \alpha_i + \delta_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$$

Note:
Y_{ijk} : Observation for the i-th pruning condition, the j-th N, P, K, and Mg fertilizer dosage, and the k-th replication
μ : Overall mean
α_i : Effect of the i-th pruning condition
δ_{ik} : Main-plot experimental error associated with pruning condition
β_j : Effect of the j-th N, P, K, and Mg fertilizer dosage
$(\alpha\beta)_{ij}$: Interaction effect between pruning condition and fertilizer dosage
ε_{ijk} : Subplot experimental error associated with fertilizer dosage

When the analysis of variance indicated significant treatment effects, the means were further compared using Duncan's New Multiple Range Test (DNMRT) at the 5% significance level. Data were analyzed using SAS System Version 9.0. The linear ANOVA model was selected because it is appropriate for a split-plot design and enables the evaluation of the main plot effect, subplot effect, and their interaction. Model validity was assessed by testing the assumptions of normality, homogeneity of variance, and independence of errors. When these assumptions were not met, data transformation was performed before further analysis using DNMRT.

RESULTS AND DISCUSSION

Number of Female Inflorescence Bunches

Based on the data presented in Table 1, an interaction was observed between pruning treatment and fertilizer dose. In general, the over-pruning treatment, P2, produced a lower value of female inflorescence bunches, with a mean of 4.16, compared with normal pruning, P1, which produced a mean of 5.02. This finding indicates that excessive pruning tends to reduce the physiological performance of oil palm plants, thereby affecting the observed yield components. Meanwhile, differences among fertilizer levels, N0–N3, showed an increasing trend up to a certain dose, as presented in Table 1. Treatments N2 and N3 generally produced higher values than N0 and N1, suggesting that nutrient availability plays an important role in supporting plant growth and productivity.

Table 1. Research parameter values for female inflorescence bunches under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning (P1)	Over-pruning (P2)	Mean
N0	4.16 b	3.33 d	3.75 c
N1	4.66 ab	3.67 cd	4.16 b
N2	4.83 Ab	3.80 bcd	4.32 ab
N3	5.02 A	4.16 b	4.67 A
Mean	**4.66 A**	**3.74 B**	

Nitrogen, phosphorus, potassium, and magnesium play important roles in supporting photosynthesis and plant metabolism. Nitrogen and magnesium are involved in chlorophyll formation, phosphorus supports energy transfer, and potassium facilitates the translocation of photosynthates to generative organs. Together, these nutrients contribute to the formation of female inflorescences in oil palm (Woittiez et al., 2017). In contrast, over-pruning reduces leaf area and disrupts the source–sink balance within the plant. This condition decreases photosynthate production, limits energy supply for flower formation, and induces physiological stress due to metabolic and hormonal imbalance, ultimately reducing plant productivity. The application of high doses of N, P, K, and Mg does not always produce an optimal plant response when photosynthate supply is limited, because the reduced source capacity restricts nutrient utilization for the formation of female inflorescences (Sibarani et al., 2023; Mondragón-Serna et al., 2021).

Number of Male Inflorescence Bunches

As shown in Table 2, the number of male inflorescence bunches was lower under normal pruning, P1, combined with N3, with a value of 3.33, compared with over-pruning, P2, combined with N3, which produced a value of 4.00. The increase in male inflorescence formation under over-pruning, despite fertilizer application, may be attributed to reduced photosynthetic capacity caused by leaf removal. Although nutrients are available, the plant is unable to allocate assimilates optimally for female inflorescence formation. As a result, assimilate allocation shifts toward the formation of male inflorescences, which require relatively less energy. This indicates that sufficient nutrient availability cannot fully compensate for the negative effects of reduced photosynthetic organs. In other words, the effectiveness of fertilization strongly depends on canopy condition, which determines the plant's photosynthetic capacity (Alhafiz et al., 2020).

Table 2. Number of male inflorescence bunches under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning (P1)	Over-pruning (P2)	Mean
N0	4.00 bc	4.50 a	4.25 A
N1	3.67 c	4.33 ab	4.00 Ab
N2	3.33 d	4.16 b	3.75 B
N3	3.33 d	4.00 bc	3.54 b
Mean	**3.58 B**	**4.24 A**	

Fronds retained under normal pruning help plants intercept sunlight and produce sufficient assimilates, which are essential for the development of generative organs (Borghi et al., 2019). Over-pruning reduces active leaf area and consequently decreases photosynthetic capacity. Under such conditions, plants tend to produce more male inflorescences, which require less energy than female inflorescences. The application of N, P, K, and Mg fertilizers can improve nutrient status and photosynthetic activity; however, their effects on male inflorescence formation depend on canopy condition and plant physiological status (Tassinari et al., 2022). Plants maintained under favorable physiological conditions tend to allocate more resources toward female inflorescence formation.

Sex Ratio (%)

Table 3 shows that the main-plot treatment of normal pruning, P1, resulted in a higher sex ratio, with a mean of 60.12%, compared with over-pruning, P2, which produced 50.98%. This result indicates that pruning practices that avoid excessive reduction of leaf area, combined with optimal nutrient availability, can increase the proportion of female inflorescences relative to total inflorescences. This finding is consistent with Mondragón-Serna et al. (2021), who reported that a balanced supply of N and K is important for female inflorescence differentiation in oil palm through improved photosynthesis and assimilate translocation efficiency. Thus, the present results strengthen previous findings that sex ratio is strongly influenced by the interaction between nutrient availability and plant physiological condition. Conversely, under unfertilized conditions, nutrient limitation reduces assimilate production, resulting in a lower proportion of female inflorescences relative to total inflorescences.

Table 3. Sex ratio under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning (P1)	Over-pruning (P2)	Mean
N0	50.98 b	50.24 B	46.75 D
N1	55.94 ab	45.80 c	50.87 C
N2	59.19 ab	47.73 bc	53.45 B
N3	60.12 a	50.98 b	55.55 A
Mean	**57.05 A**	**50.24 B**	

Normal pruning maintains an optimal number of fronds, thereby supporting high photosynthetic activity and ensuring sufficient photosynthate supply for female inflorescence differentiation. In contrast, over-pruning reduces leaf area, causes carbohydrate deficits and physiological stress, promotes male inflorescence formation, and decreases the sex ratio. Under adequate fertilization, the sex ratio tends to remain more stable (Ginting & Panjaitan, 2018). However, under over-pruning, limited resources may constrain the plant response to fertilizer. Environmental factors, particularly rainfall, may also strongly influence sex ratio and obscure the effects of agronomic treatments. Previous studies have shown that rainfall and other abiotic factors may either decrease or increase sex ratio more strongly than nutrient or canopy-management treatments (Syafrizal et al., 2021). In addition to rainfall, other environmental variables, such as temperature, humidity, light intensity, and soil condition, may also affect the results. Variation in these factors can influence physiological processes, including photosynthesis, nutrient uptake, and flower formation, thereby determining plant responses to the applied treatments.

Number of Fruit Bunches

Table 4 shows that the normal pruning treatment, P1, produced a higher number of fruit bunches, with a value of 5.83 bunches, and differed significantly from the unfertilized treatment. Pruning is an important component of oil palm canopy management because it directly affects the active canopy area involved in photosynthesis, which subsequently influences fruit bunch production.

Table 4. Number of fruit bunches under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning (P1)	Over-pruning (P2)	Mean
N0	4.83 b	3.83 d	4.33 C
N1	5.16 ab	4.20 c	4.68 B
N2	5.37 ab	4.67 bc	5.02 Ab
N3	5.83 a	5.00 b	5.41 A
Mean	**5.30 A**	**4.42 B**	

Plants pruned at a moderate level, maintaining approximately 32–40 fronds, produce higher bunch number and bunch weight than plants that are either not pruned or excessively pruned to fewer than 32 fronds. This indicates that excessive pruning tends to reduce bunch production because the available leaf area for photosynthesis becomes severely limited, thereby reducing the energy supply required for fruit formation. In contrast, plants that retain an optimal number of fronds have better photosynthetic capacity and can support higher fruit production (Marcelino & Diaz, 2016). This is consistent with Ardiansyah et al. (2022), who reported that normally pruned plants experienced very low average production losses. In contrast, Paisey et al. (2022) reported higher production losses and clear stress symptoms in over-pruned plants, resulting in reduced productivity.

Fruit Bunch Weight

Table 5 shows that normal pruning, P1, produced a higher fruit bunch weight, with a value of 20.40 kg, and differed significantly from the unfertilized treatment. Fruit bunch production depends strongly on the plant’s ability to generate photosynthates from active leaves and allocate them to reproductive organs. Therefore, the presence of sufficient fronds under normal pruning maintains effective leaf area, allowing photosynthesis to proceed optimally and supporting the formation of heavier bunches (Mondragón-Serna et al., 2021).

Table 5. Fruit bunch weight under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning	Over-pruning	Mean
N0	19.28 b	18.57 c	18.92 C
N1	19.44 ab	18.80 bc	19.12 bc
N2	19.80 ab	19.02 b	19.41 ab
N3	20.40 a	19.60 ab	20.00 A
Mean	**19.73 A**	**19.00 B**	

The interaction between canopy condition and fertilization indicates that the response of fruit bunch weight to fertilizer cannot be separated from canopy status. Agronomic research on peatland has also shown that NPK fertilizer plays an essential role in supplying nutrients required by oil palm to achieve its production potential, particularly when the soil cannot provide adequate nutrient availability (Mirasari et al., 2024).

In addition to canopy condition, the availability of macronutrients through N, P, K, and Mg fertilization plays a central role in determining fresh fruit bunch weight. The application of compound NPK fertilizer to oil palm has been reported to significantly increase production components, including fresh fruit bunch weight and average bunch weight, compared with unfertilized controls. Adequate macronutrient supply enhances the plant's capacity to form and fill fruit bunches. Nitrogen contributes to protein and chlorophyll formation, phosphorus supports energy metabolism and flowering, potassium facilitates photoassimilate transport and fruit filling, and magnesium supports chlorophyll synthesis and photosynthesis (Huesean et al., 2025).

Fresh Fruit Weight

The data in Table 6 show that the interaction between normal pruning, P1, and N3 produced the highest fresh fruit weight, with a value of 12.43 g, and differed significantly from the unfertilized treatment.

Table 6. Fresh fruit weight under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning	Over-pruning	Mean
N0	11.31 b	10.72 d	11.01 C
N1	11.46 b	11.10 c	11.28 C
N2	11.95 ab	11.21 bc	11.58 B
N3	12.43 a	11.52 ab	11.97 A
Mean	**11.79 A**	**11.13 B**	

The interaction between canopy management and fertilization indicates that nutrient response depends greatly on canopy condition. A healthy and normally maintained canopy allows fertilizer to be used effectively because sufficient leaf area is available to convert absorbed nutrients into assimilates. Conversely, in over-pruned plants, additional fertilizer does not fully increase fruit weight because limited photosynthesis becomes the main limiting factor. This explains the significant interaction observed in the split-plot design, in which the combination of normal pruning and the optimal fertilizer dose produced the highest individual fruit weight (Woittiez et al., 2017).

Fresh fruit weight in oil palm is determined by the successful accumulation of dry matter derived from photosynthesis and allocated to generative organs during bunch filling. In high-yielding perennial crops such as oil palm, fruit weight is strongly influenced by canopy capacity to intercept solar radiation and by the efficiency of photosynthate translocation from leaves to fruits as the main sink organs. The balance between assimilate production and the metabolic demand of fruit bunches is a key factor determining individual fruit size and weight. Therefore, cultivation practices that affect canopy structure and nutrient availability have direct implications for fresh fruit weight (Henson, 2007).

Limited assimilate production leads to competition among sink organs, preventing fruits from receiving an adequate carbon supply for cell division and cell enlargement. This results in smaller fruit size, reduced mesocarp thickness, and lower oil accumulation, which ultimately decreases individual fruit weight (Adu et al., 2022). The combined application of NPKMg compound fertilizer produces a synergistic effect because each nutrient complements the others in supporting plant physiological processes. This combination improves photosynthetic capacity, nutrient uptake efficiency, and assimilate translocation to fruit bunches, thereby promoting optimal fruit enlargement. The results indicate that plants receiving balanced fertilization produced higher individual fruit weight and total bunch weight than unfertilized or partially fertilized plants (Huesean et al., 2025).

Mesocarp Thickness

The analysis of variance, as presented in Table 7, showed that the interaction between pruning treatment and N, P, K, and Mg fertilizer application, as well as the main effect of pruning and the subplot effect of fertilizer, significantly affected mesocarp thickness. The results of Duncan's multiple range test at the 5% level for mesocarp thickness are presented in Table 7.

Table 7. Mesocarp thickness under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning	Over-pruning	Mean
N0	3.37 b	3.10 c	3.23 D
N1	3.59 ab	3.30 bc	3.45 C
N2	3.73 ab	3.43 b	3.58 B
N3	3.93 a	3.59 ab	3.76 A
Mean	**3.65 A**	**3.35 b**	

Table 7 shows that the interaction between normal pruning and the application of N, P, K, and Mg fertilizers at a dose of 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO produced the highest mesocarp thickness, with a value of 3.93 mm, and differed significantly from the unfertilized treatment. This suggests that the response of oil palm fruit morphological traits, including mesocarp thickness, to macronutrient fertilization is influenced by canopy condition or the number of fronds retained on the plant.

The appropriate combination of pruning and fertilization can act synergistically because the canopy determines source capacity, whereas fertilizer supports sink metabolism. Therefore, increased mesocarp thickness occurs only when sufficient leaf area is available to use nutrients efficiently for dry matter and oil formation in the fruit flesh (Rhebergen et al., 2016). Mesocarp thickness results from complex biological processes influenced by photosynthate production in leaves and the ability of the plant to translocate assimilates to sink organs such as fruits. Many studies have shown that fruit yield components vary substantially depending on canopy condition. When the canopy is maintained at a moderate level, plants tend to produce more photosynthates that can be translocated to developing fruits. In contrast, excessive canopy reduction through over-pruning limits leaf surface area, decreases photosynthetic capacity, and reduces assimilate supply to the mesocarp, ultimately producing thinner fruit flesh (Chiew & Rahman, 2002).

Oil palm mesocarp thickness is influenced by the availability of assimilates from photosynthesis and by adequate macronutrient supply, both of which are essential for fruit tissue development. Nitrogen increases leaf area and photosynthetic activity, phosphorus supports energy metabolism and cell division, potassium facilitates sugar translocation and oil synthesis, and magnesium maintains chlorophyll function and carbohydrate metabolism efficiency. Thus, balanced N, P, K, and Mg availability promotes dry matter accumulation and mesocarp cell expansion, resulting in thicker fruit flesh (Tao et al., 2018).

Fresh Fruit Volume

Table 8 shows that the interaction between normal pruning and the application of N, P, K, and Mg fertilizers at a dose of 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO produced the highest fresh fruit volume, with a value of 12.59 ml, and differed significantly from the unfertilized treatment. The interaction between normal pruning and the highest dose of N, P, K, and Mg fertilizer increased fresh fruit volume because a moderate number of retained fronds can balance photosynthetic capacity with transpiration demand. Moderate canopy regulation through normal pruning maintains effective leaf surface area, allowing the plant to intercept solar radiation efficiently. At the same time, appropriate NPKMg fertilization supplies nutrients required for ATP synthesis, protein formation, and secondary metabolite production, thereby promoting fruit development.

Table 8. Fresh fruit volume under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning	Over-pruning	Mean
N0	11.34 b	10.80 d	11.07 C
N1	11.91 ab	11.12 bcd	11.50 B
N2	12.09 ab	11.31 bc	11.69 B
N3	12.59 a	11.57 b	12.07 A
Mean	**11.98 A**	**11.20 B**	

The number of fronds retained through normal pruning expands the photosynthetic area contributing to higher daily assimilate production, which is then translocated to fruits during the enlargement phase. In contrast, over-pruning reduces active leaf surface area, decreases photosynthetic capacity, limits assimilate supply to fruits, and reduces the efficiency of fertilizer response. Field studies have shown that over-pruned oil palm plants produce lower fresh fruit volume even when supplied with high fertilizer doses, compared with moderately pruned plants receiving the same fertilizer dose. This indicates that excessive canopy reduction restricts fruit filling despite nutrient availability (Alhafiz et al., 2020).

Physiologically, this interaction is also associated with improved assimilate translocation efficiency. When pruning is conducted moderately, the canopy remains capable of producing sufficient assimilates, while N, P, K, and Mg fertilization helps maintain optimal plant nutrient status. Nitrogen supports protein and chlorophyll formation, phosphorus supports energy metabolism, potassium enhances sugar translocation, and magnesium improves photosynthetic efficiency. The optimal combination of these four nutrients strengthens the sink capacity of fruits to attract more assimilates, thereby increasing fruit volume more effectively than canopy management or fertilization alone (Woittiez et al., 2017).

Fresh Fruit Fat Content

Table 9 shows that the interaction between normal pruning and the application of N, P, K, and Mg fertilizers at a dose of 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO produced the highest fresh fruit fat content, with a value of 20.21%, and differed significantly from the unfertilized treatment. Khoiri et al. (2020) reported that frond pruning independently had a significant effect on total mesocarp oil, where a canopy with an appropriate number of fronds allowed plants to maintain higher photosynthetic capacity. This condition ensured adequate carbon and energy supply for lipid synthesis in the fruit, compared with excessive pruning, which may reduce oil accumulation.

Table 9. Fresh fruit fat content under pruning treatments and various doses of N, P, K, and Mg fertilizers over six months

N, P, K, and Mg Fertilizer	Normal pruning	Over-pruning	Mean
N0	18.96 c	18.65 d	18.81 C
N1	19.50 ab	19.03 bc	19.26 B
N2	19.87 ab	19.26 b	19.57 AB
N3	20.21 a	19.33 b	19.75 A
Mean	**19.64 A**	**19.06 B**	

Studies have shown that assimilate production and carbon allocation in oil palm are highly sensitive to changes in leaf area. Reduced canopy capacity as the plant source leads to lower carbon supply to fruits. During the oil-filling stage, carbon limitation can inhibit lipid biosynthesis pathways and potentially decrease overall fruit fat content because the fruit sink does not receive sufficient carbon precursors for fatty acid formation (Henson, 2007).

Adequate nitrogen supply increases the formation of metabolic substrates and lipid precursors in fruit tissues, thereby indirectly supporting fatty acid synthesis and fruit oil content. Agronomic studies have shown that adequate nitrogen fertilization in mature oil palm is associated with increased fruit weight and yield components that are closely related to oil accumulation potential (Tao et al., 2018). Deficiency of any essential nutrient may reduce photosynthetic efficiency, energy supply, and carbon distribution to fruits, ultimately decreasing oil accumulation in the mesocarp. Conversely, a balanced supply of P, K, and Mg supports fruit quality improvement by optimizing energy metabolism, assimilate translocation, and lipid biosynthesis capacity (Tao et al., 2018).

Overall, the results demonstrate that the interaction between pruning and N, P, K, and Mg fertilization affects the growth and reproductive performance of oil palm, particularly sex ratio and inflorescence formation. Normal pruning combined with the optimal fertilizer dose produced better results than other treatments. In contrast, over-pruning reduced physiological performance, even when fertilizers were applied. Plant productivity is influenced not only by nutrient availability but also by physiological condition, particularly leaf area. Therefore, farmers are advised to apply pruning practices according to agronomic standards and optimize fertilizer management. Future studies should consider additional physiological factors and conduct longer-term observations to better understand the sustained effects of pruning and fertilization on oil palm productivity.

CONCLUSION

This study demonstrated that pruning and fertilization significantly influenced the reproductive performance and productivity of 20-year-old mature oil palm plants. Normal pruning improved female inflorescence formation, sex ratio, fruit bunch production, fresh fruit traits, mesocarp thickness, fruit volume, and oil content compared with over-pruning, whereas over-pruning increased male inflorescence formation and may reduce yield potential. The best overall performance was obtained from normal pruning combined with the P1N3 fertilizer dose, equivalent to 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO per plant. This combination likely maintained adequate photosynthetic capacity while ensuring sufficient nutrient availability for generative growth, fruit development, and fruit filling. Therefore, normal pruning with balanced N, P, K, and Mg fertilization at this dose is recommended as an effective management practice to improve the productivity of mature oil palm under field conditions.

RECOMMENDATION

To obtain optimal production from 20-year-old mature oil palm plants, it is recommended to apply normal pruning in combination with N, P, K, and Mg fertilization at a dose of 1.035 kg N + 0.81 kg P_2O_5 + 1.125 kg K_2O + 2.25 kg MgO, as indicated by the conclusions of this study. Further research is recommended to include a broader range of observation parameters to provide a more comprehensive assessment of plant growth, reproductive performance, and yield responses.

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