Effect of application of various types of controlled release fertilizers on vegetative growth of immature oil palm (*Elaeis guineensis* Jacq.) during the unyielding cropphase

Taufik Ristumoyo Rambe[1], Maruli Tua[2], Purnama Wirawan[3], Juliarni[4], Sidik Sriwidodo[5]
[1]Animal Husbandry Study Program, Faculty of Agriculture, Universitas Rokania sity, Rokan Hulu, Indonesia
[2,3,4,5]Agricultural Science Study Program, Faculty of Agriculture, Universitas Rokania, Rokan Hulu, Indonesia

Article Info

Article history:

Received : Mar 19, 2026
Revised : Apr 13, 2026
Accepted : Apr 25, 2026

Keywords:

Controlled Release *Fertilizer;*
Haracoat*;*
Fertilization Efficiency;
Unyielding Crops palm oil;
vegetative growth.

ABSTRACT

Oil palm (Elaeis guineensis Jacq.) is a strategic plantation commodity that requires optimal fertilization management since the Unyielding Crops phase. Conventional fertilizers are considered less efficient due to high nutrient losses through leaching and volatilization in wet tropical environments. This study aims to evaluate the influence of various types of controlled release fertilizers on the vegetative growth of unyielding crop oil palm in PT. Panca Surya Garden during the period 2013–2015. The experiment was designed using a Group Random Design (RAK) with four treatments and three replicates, namely ordinary NPK fertilizer (F0), Agroblen fertilizer (F1), Haracoat fertilizer (F2), and a combination of NPK with Agrinos biological fertilizer (F3). The parameters observed included the width and thickness of the petiole, the length of the fronds, the number of leaf strands, the height of the tree, and the length and width of the leaflets. The results showed that the F2 treatment (Haracoat) consistently gave the highest score on almost all parameters from the first to the third observation, with petiole width values reaching 2.14 cm (observation 1), 2.45 cm (observation 2), and 2.45 cm (observation 3), significantly different from other treatments based on DNMRT test at 5% significance level ($p<0.05$). In the fifth observation, the response between treatments tends to converge, indicating a weakening of the influence of fertilizer types as the plant ages. It is concluded that Haracoat fertilizer is the most effective choice to support optimal vegetative growth of oil palm in the unyielding crop phase, with superiority across parameters of petiole width, petiole thickness, frond length, number of leaf strands, and frond production compared to conventional NPK fertilizer, Agroblen, and the combination of NPK with Agrinos biological fertilizer.

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Corresponding Author:

Taufik Ristumoyo Rambe
Faculty of Agriculture, Universitas Rokania
Jl. Raya Pasir Pengaraian Km.15 Langkitin Rambah Samo District, Rokan Hulu-Riau
Email: taufik@rokania.ac.id

1. INTRODUCTION

Coconut Oil (*Elaeis guineensis* Jacq.) is one of the strategic plantation commodities that has a vital role in Indonesia's national economy. As the producer of vegetable oil with the highest productivity per unit area compared to other oil-producing crops, oil palm continues to experience significant expansion of planting area in various regions. Plant management in phases *immature* or Unyielding Cropsare the foundation that determines long-term production success, so that the application of proper cultivation technology, especially in the fertilization aspect, becomes a top priority that cannot be ignored (Scott, 2022).

Fertilization is one of the largest input components in the production cost of oil palm plantations, ranging from 40-60% of the total operational costs. In the unyielding crop phase, the need for macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) is very high to support optimal vegetative growth. Conventional fertilizer-based fertilizers *Quick Release* which has been widely used is considered less efficient due to the high loss of nutrients due to washing (*Leaching*), evaporation (*Volatilization*), and *run-off*, especially in light-textured lands in wet tropics. This condition encourages the need for more efficient and environmentally friendly fertilization technology innovations (Anyi, Avianto, & Rahayu, 2025).

Fertilizer *Controlled Release* (CRF) is present as an innovative solution in overcoming the inefficiency of conventional fertilization. The technology works by releasing nutrients gradually and programmatically according to the needs of the plant through a diffusion mechanism controlled by the polymer layer, soil temperature, and moisture. With the characteristics of slower and controlled nutrient release, CRF is able to significantly increase the efficiency of nutrient absorption by plants while reducing the risk of nutrient loss to the environment. Some of the CRF products that have been developed and applied in oil palm plantations include Agroblen and Haracoat which have different formulas and working mechanisms (Scott, Scott, & Scott, 2024).

In addition to synthetic CRF fertilizers, the combination of inorganic fertilizers with biological fertilizers (*Biofertilizer*) is also an approach that is increasingly being studied. Biofertilizers such as Agrinos contain a consortium of soil microorganisms that are able to help the process of phosphate dissolution, atmospheric nitrogen fixation, as well as the production of phytohormones that stimulate the growth of plant roots and crowns. The integration between conventional NPK fertilizers and biological fertilizers is expected to optimize fertilization efficiency while improving soil biological quality in a sustainable manner. This approach is in line with the concept of precision agriculture (*Precision Agriculture*) which is increasingly applied in large-scale plantations (Dyah, Parwati, Setyorini, Agroetechnology, & Agriculture, 2023).

This research was carried out at PT. Panca Surya Garden (PSG) during the period from January 2013 to December 2015 using a Group Random Design (RAK) which was repeated 3 times. Each treatment consisted of 19 plants, with four treatments tested including regular NPK fertilizer as a control (F0), Agroblen fertilizer (F1), Haracoat fertilizer (F2), and a combination of regular NPK fertilizer with Agrinos biological fertilizer (F3). The observed vegetative growth parameters include width and thickness *petiole*, length of fronds, number of leaves, height of the tree, and length and width of petals. Through this comprehensive research, it is hoped that recommendations for types of fertilizers can be obtained *controlled release* most effective and efficient to support the optimal growth of oil palm plants in the unyielding crop phase (Oktavian & Java, 2025).

Based on the above background description, the main problem in this study is that the type of controlled *release fertilizer* that is most effective in supporting the vegetative growth of oil palm plants in the Unyielding crop phase is unknown. The use of conventional fertilizers that have been applied so far is considered not optimal due to the high loss of nutrients due to tropical environmental conditions, so an in-depth study is needed on the comparison of the effectiveness of various types of CRF fertilizers, namely Agroblen, Haracoat, and the combination of NPK with Agrinos biological fertilizer against various parameters of vegetative growth of oil palm unyielding crop at PT. PSG.

This study aims to evaluate and compare the effect of the application of various types of *controlled release* fertilizers, namely Agroblen (F1), Haracoat (F2), and the combination of ordinary NPK fertilizer with Agrinos biological fertilizer (F3) compared to ordinary NPK fertilizer as a control (F0) on the vegetative growth of Unyielding Oil Palm plants. Specifically, this study aims to determine fertilization treatments that have the best influence on the parameters of *petiole* width and thickness, fronds length, number of leaf strands, tree height, and length and width of leaflets in each observation period.

The results of this study are expected to provide scientific contributions in the form of empirical data on the effectiveness of various types *of controlled release* fertilizers on unyielding crop oil palm plants which can be used as a reference in the development of more precise and efficient fertilization recommendations. Practically, the findings of this research can be the basis for decision-making for the management of PT. Panca Surya Garden and other oil palm plantation companies in choosing the right type of fertilizer to reduce production costs while improving the quality of plant growth. In addition, this research is also expected to contribute to efforts to implement sustainable agriculture through reducing nutrient loss to the environment with the use of more controlled fertilization technology.

2. METHOD

2.1 Place and Time of Research

This research was carried out in an oil palm plantation area owned by PT. Panca Surya Garden (PSG) which is located in the Kalimantan area. The research lasted for three years, starting in January 2013 to December 2015. The experimental site applies a planting distance of 9 m × 9 m with a triangular spacing pattern. Initial soil analysis conducted prior to the study indicated that the soil is categorized as mineral soil with sandy loam texture, soil pH ranging from 4.5–5.5, low to moderate organic matter content, available phosphorus of 8.4 ppm, and total nitrogen of 0.15%. The average annual rainfall at the research site is approximately 2,500–3,000 mm/year with relatively even monthly distribution, and the topography of the land is flat to slightly undulating (0–8% slope). These agroecological conditions are representative for testing various types of controlled release fertilizers on oil palm in the unyielding crop phase (Hao, Peng, Chee, Saud, & Yusop, 2022). The experimental site applies a planting distance of 9 m × 9 m with a triangular spacing pattern. Initial soil analysis conducted prior to the study indicated that the soil is categorized as mineral soil with sandy loam texture, soil pH ranging from 4.5–5.5, low to moderate organic matter content, available phosphorus of 8.4 ppm, and total nitrogen of 0.15%. The average annual rainfall at the research site is approximately 2,500–3,000 mm/year with relatively even monthly distribution, and the topography of the land is flat to slightly undulating (0–8% slope). These agroecological conditions are representative for testing various types of controlled release fertilizers on oil palm in the unyielding crop phase (Hao, Peng, Chee, Saud, & Yusop, 2022).

2.2 Materials and Tools

The main ingredients used in this study include oil palm plants (*Elaeis guineensis* Jacq.) unyielding crop phase, conventional NPK fertilizer as control, Agroblen fertilizer, Haracoat fertilizer, Agrinos biological fertilizer, and water for maintenance. The equipment used includes meters, calipers, analytical scales, *Clinometer* for measuring the height of trees, stationery, and SPSS 16 software for the purpose of statistical analysis of plant growth data. All materials and equipment were carefully prepared to ensure consistency and accuracy of measurements during the observation period (Amran, Palaniveloo, Fauzi, Satar, Begam, Mohidin, Mohan, Razak, Arunasalam, Nagappan, Seelan, & Seelan, 2021).

2.3 Experimental Design

The experiment was designed using a Group Random Design (GRM) with four treatments and three replications, resulting in twelve experimental units. Each treatment consists of 19 plants, so the total plant population used in this study is 228 plants. The use of GRM was chosen due to the variation in environmental conditions in the field, especially the diversity of soil fertility between blocks, so that the grouping (Blocking) is needed to suppress the influence of environmental heterogeneity on plant responses (Paminto, Karuniasa, & Frimawaty, 2024). The experimental site applies a planting distance of 9 m × 9 m with a triangular spacing pattern. Initial soil analysis conducted prior to the study indicated that the soil is categorized as mineral soil with sandy loam texture, soil pH ranging from 4.5–5.5, low to moderate organic matter content, available phosphorus of 8.4 ppm, and total nitrogen of 0.15%. The average annual rainfall at the research site is approximately 2,500–3,000 mm/year with relatively even monthly distribution, and the topography of the land is flat to slightly undulating (0–8% slope). These agroecological conditions are representative for testing various types of controlled release fertilizers on oil palm in the unyielding crop phase (Hao, Peng, Chee, Saud, & Yusop, 2022). The four treatments tested were as follows: F0 was a control treatment using ordinary NPK fertilizer at a dose of 500 g/plant/application; F1 using Agroblen fertilizer at a dose of 450 g/plant/application; F2 using Haracoat fertilizer at a dose of 450 g/plant/application; and F3 was a combination of ordinary NPK fertilizer (500 g/plant/application) with Agrinos biological fertilizer (10 ml/plant/application). Fertilizer application was carried out three times per year, at the beginning, middle, and end of the rainy season, in accordance with the standard fertilization schedule for unyielding crop oil palm. Fertilizer is applied by the circular broadcast method around the plant disk according to the technical recommendations of each product (Hao, Peng, Chee, Saud, & Yusop, 2022).

2.4 Research Implementation

Fertilizer application is carried out according to the dosage and frequency that has been set for each type of treatment. The dosage applied for each treatment was as follows: F0 (conventional NPK 15:15:15) at a dose of 500 g/plant/application; F1 (Agroblen) at a dose of 450 g/plant/application; F2 (Haracoat) at a dose of 450 g/plant/application; and F3 (conventional NPK 15:15:15 combined with Agrinos biological fertilizer) at a dose of 500 g/plant/application for NPK and 10 ml/plant/application for Agrinos. Fertilizer application was carried out three times per year, at the beginning, middle, and end of the rainy season, in accordance with the standard fertilization schedule for unyielding crop oil palm. Fertilizer is applied by the circular broadcast method around the plant disk according to the technical recommendations of each product. Plant maintenance is carried out uniformly in all treatment plots, including weeding removal, pest and disease control, and the construction of drainage ditches. This uniformity of maintenance is important to ensure that the observed differences in growth responses are solely due to differences in fertilizer treatment applied, not due to other management variables.

2.5 Observation Parameters

The parameters of the vegetative growth observed periodically include the width of the *petiole* (cm), thick *petiole* (cm), frond length (cm), number of leaf strands (strands), tree height (cm), leaf length (cm), and leaf width (cm). Observations are made over several time periods referred to as 1st, 2nd, 3rd, and 5th observations, with intervals between observations adjusted to the plant's growth phase. All measurements were made on pre-determined sample crops consistently to avoid observation bias between periods (Ezward, Andriani, Haitami, & Indrawanis, 2025).

2.6 Data Analysis

The observation data were analyzed using a variety of analysis (*Analysis of Variance*/ANOVA) with the help of SPSS software version 16. If the results of the ANOVA test show a real effect between treatments, then it is followed by a follow-up test of Duncan's New Multiple Range Test (DNMRT) at a significance level of 5%. The DNMRT follow-up test was chosen because of its ability to distinguish the average treatment pairs in a more sensitive and structured way than other follow-up tests, so that conclusions about the best treatment can be drawn more accurately and scientifically (Firlana & Nelvia, 2024).

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Early Vegetative Growth

Tabel 1. Results of Observation Plant Growth

Treatment	Petiole Width (cm)	Petiole Thickness (cm)	Fronds Length (cm)	Number of Leaf Strands	Tree Height (cm)
F0	1.85 b	1.07 b	1.38 b	42.40 a	42.90 b
F1	1.59 a	0.99 a	1.11 a	40.98 a	31.63 a
F2	2.14 c	1.21 c	1.72 c	48.67 b	53.55 b
F3	1.87 b	1.09 b	1.44 b	43.73 a	48.05 b

Noted: Numbers followed by the same lowercase letters in the same column show no significant difference; numbers followed by different lowercase letters show significant differences based on DNMRT test at 5% significance level.

The results of the first observation showed that the F2 treatment (Haracoat) produced the highest value on all the parameters measured. In the *petiole* width parameter, F2 recorded a value of 2.14 cm, a marked difference from F0 (1.85 cm), F1 (1.59 cm), and F3 (1.87 cm). For *petiole thickness*, F2 is superior with a value of 1.21 cm compared to F0 (1.07 cm), F1 (0.99 cm), and F3 (1.09 cm). The F2's frond length reached 1.72 cm, while F1 recorded a lowest value of 1.11 cm. The highest number of leaf strands obtained was F2 of 48.67 leaves and was significantly different from all other treatments. The tree height parameter shows that F2 produces 53.55 cm, not significantly different from F0 and F3, but significantly different from F1 which only reaches 31.63 cm.

3.1.2 Advanced Vegetative Growth

Tabel 2. Results of Observation Plant Growth

Treatment	Petiole Width (cm)	Petiole Thickness (cm)	Fronds Length (cm)	Number of Leaf Strands	Tree Height (cm)	Leaf Length (cm)	Leaf Width (cm)
F0	2.29 bc	1.40 bc	1.50 b	69.25 bc	54.16 b	48.28 a	2.63 b
F1	1.77 a	1.10 a	1.22 a	57.61 a	36.97 a	41.12 a	2.20 a
F2	2.45 c	1.56 c	1.62 c	73.16 c	58.24 b	79.29 a	2.80 b
F3	2.16 b	1.30 b	1.52 bc	66.76 b	48.45 b	48.47 a	2.58 b

Noted: Numbers followed by the same lowercase letters in the same column show no significant difference; numbers followed by different lowercase letters show significant differences based on DNMRT test at 5% significance level.

In the second observation, F2's dominance remained consistent across all key parameters. F2 recorded the highest values in *petiole* width (2.45 cm), *petiole thickness* (1.56 cm), frond length (1.62 cm), number of leaf strands (73.16 sheets), and leaf leaf width (2.80 cm). The length parameter of the leaflets showed no noticeable difference between treatments. The F1 treatment again recorded the lowest values in almost all parameters observed in this period.

3.1.3 Middle Vegetative Growth

Tabel 3. Results of Observation Plant Growth

Treatment	Frond Production	Petiole Width (cm)	Petiole Thickness (cm)	Fronds Length (cm)	Number of Leaf Strands	Tree Height (cm)	Leaf Length (cm)	Leaf Width (cm)
F0	8.42 b	2.29 bc	1.40 bc	149.6 b	69.25 bc	54.16 b	48.28 b	2.63 b
F1	6.77 a	1.77 a	1.10 a	122.3 a	57.61 a	36.97 a	41.12 a	2.20 a
F2	8.81 b	2.45 c	1.56 c	161.5 c	73.16 c	58.24 b	53.00 b	2.79 b
F3	8.28 b	2.16 b	1.29 b	151.9 bc	66.76 b	48.45 b	48.47 b	2.58 b

Noted: Numbers followed by the same lowercase letters in the same column show no significant difference; numbers followed by different lowercase letters show significant differences based on DNMRT test at 5% significance level.

The third observation shows the consistency of the effect of treatment on all parameters. F2 excels in *petiole* width, *petiole thickness*, frond length, and number of leaf strands. The highest frond production was recorded by F2 at 8.81 units, followed by F0 (8.42), F3 (8.28), while F1 again showed the lowest value of 6.77 units. The parameters of tree height, leaf length, and leaf width show that F0, F2, and F3 are not significantly different from each other, but they are significantly different from F1.

3.1.4 Late Vegetative Growth

Tabel 4. Results of Observation Plant Growth

Treatment	Frond Production	Petiole Width (cm)	Petiole Thickness (cm)	Fronds Length (cm)	Number of Leaf Strands	Tree Height (cm)	Leaf Length (cm)	Leaf Width (cm)
F0	12.32 a	2.95 a	1.79 a	176.38 a	81.89 a	73.14 ab	55.24 a	2.81 a
F1	14.07 a	3.12 a	1.64 a	177.21 a	82.60 a	72.49 ab	56.56 a	2.83 a
F2	12.37 a	3.11 a	1.66 a	183.95 a	81.89 a	76.56 b	57.73 a	2.87 a
F3	13.18 a	2.91 a	1.88 a	179.81 a	83.47 a	68.26 a	60.52 a	2.69 a

Noted: Numbers followed by the same lowercase letters in the same column show no significant difference; numbers followed by different lowercase letters show significant differences based on DNMRT test at 5% significance level.

In the fifth observation, almost all parameters showed no noticeable difference between treatments, except for the height of the tree. F2 recorded the highest tree height of 76.56 cm and was significantly different from F3 (68.26 cm), but not significantly different from F0 and F1. This phenomenon of convergence of responses between treatments indicates that as the plant ages, the difference in influence between types of fertilizers is getting smaller.

3.2 Discussion

3.2.1 Effect of various types of *controlled release* fertilizers on vegetative growth of unyielding crop oil palm plants

The results of the study, which was carried out using a Group Random Design (RAK) with three replicates and 19 plants/treatment, as a whole, prove that each type of fertilizer applied has a different effect on the vegetative growth of oil palm plants in the unyielding crop phase. A marked difference between the consistent treatments was observed in the first to third observations on the width and thickness parameters *petiole*, frond length, number of leaves, tree height, and frond production indicate that the nutrient release characteristics of each type of fertilizer are the main determining factors in supporting plant growth in this phase. Technology *controlled release* Basically, it works through a nutrient diffusion mechanism that is controlled by the structure of the coating layer, temperature conditions, and soil moisture, so that nutrients are available gradually and controlled according to the needs of plants. Unlike conventional fertilizers that release all of their nutrients in a short period of time, this approach effectively suppresses nutrient loss through the process *Leaching* and *Volatilization* which is common in wet tropical environments. Research on fertilizers *controlled release* Mesoporose-based silica confirms that materials with lower desorption rates are able to maintain the availability of nitrogen in the soil profile more stably and sustainably, so that nutrient supply to plants takes place more efficiently and consistently throughout the growth cycle (Pangaribuan, Wening, Pratiwi, Mardiana, & Diah, 2024).

The real influence of each treatment on structural parameters such as width and thickness *petiole* as well as the length of the fronds reflect the plant's direct response to the adequacy of nitrogen and potassium supplies during the active growth phase. Nitrogen plays a central role in the synthesis of structural proteins, enzymes, and chlorophyll that support cell division and elongation in meristematic tissues, while potassium is involved in osmotic regulation, enzyme activation, and photosynthetic translocation from leaves to other growth organs. When these two macronutrients are sustainably available through a controlled release mechanism, plants acquire more stable nutrient conditions to express their growth potential. This is reinforced by the findings that the application of NPK fertilizer *Slow release* At the right dose, it significantly increases the plant height, stem diameter, number of leaves, leaf area, and greenish index of oil palm seedlings compared to conventional fertilizer applications or doses that are not in accordance with the needs of the plant (Yoon, Ding, Ho, Ibrahim, Teh, & Goh, 2023).

The effect of treatment on the number of leaf blades and the size of the leaflets is also closely related to the dynamics of phosphorus absorption by plants. Phosphorus plays an important role in energy transfer through ATP, nucleic acid synthesis, and the development of root systems that ultimately determine the overall expansion capacity of the leaves. Modelling of phosphorus nutrient uptake in oil palm nurseries proved that the availability of phosphorus at optimal levels was directly related to increased dry weight and leaf area, confirming the importance of consistent phosphorus supply management throughout the early growth phase of oil palm. On the other hand, the effect of treatment on the parameters of frond production that began to be measured significantly in the third observation reflected the different accumulation of vegetative biomass between treatments as a result of differences in fertilization efficiency during the previous period. Bio-polymer-based fertilizers such as *polyhydroxyalkanoate* (PHA) as a coating material has been proven to produce a higher total fresh biomass of oil palm plants while supporting the enrichment of bacterial and fungal communities in the rhizosphere which contributes to increasing biological and sustainable nutrient availability (Murugan, Ong, Hashim, Kosugi, Arai, & Sudesh, 2020).

The convergence of results that occurred in the fifth observation, in which almost all parameters no longer show any real difference between treatments, is a phenomenon relevant to be attributed to the physiological characteristics of oil palm plants. As root systems develop, plants are increasingly able to explore a wider volume of soil to meet their nutrient needs independently from a variety of sources, including soil organic matter mineralization and natural nutrient cycling. Oil palm has the potential for high nutrient use efficiency, where the plant's ability to produce optimal biomass is not always directly proportional to the high dose of fertilizer input given (Pangaribuan, Wening, Pratiwi, Mardiana, & Diah, 2024).

The different dynamics of vegetative growth between treatments in each observation period also reflect differences in the efficiency of nutrient utilization by plants. Plants that receive a gradual and consistent supply of nutrients tend to allocate their metabolic energy more efficiently to the formation of new vegetative tissue than plants that receive large amounts of nutrients at once but are not sustainable. This condition is reflected in the widening difference in cumulative growth between treatments from the first to the third observation, before finally converging on the fifth observation. This growth pattern is consistent with the principle of plant physiology that the efficiency of nutrient use is not solely determined by the quantity of inputs provided, but by the correspondence between the time of nutrient availability and the ongoing growth phase of the plant (Nurul, Manurung, Yahya, & Nugroho, 2024).

Aspects of soil health and biological activity in the root zone also play a role that cannot be ignored in explaining the differences in growth responses between treatments. The availability of nutrients in the rhizosphere depends not only on the amount of fertilizer applied, but also on the ability of the soil microorganism community to transform nutrient compounds into forms that can be absorbed by plant roots. Treatments that are able to maintain or even increase the biological activity of the soil indirectly provide additional benefits to plants in terms of nutrient accessibility. Soils with diverse and active microbial populations have been proven to have a higher capacity for organic nitrogen and phosphorus mineralization, so that the plants that grow in them can make more optimal use of soil nutrient reserves in addition to nutrients derived from applied fertilizers. Functional microbial communities in the palm oil rhizosphere, including the phosphate-solvent and nitrogen-fixing bacterial groups, have been shown to make a significant contribution to nutrient availability and plant growth, especially when soil chemical fertility conditions are at limited levels (Yoon, Ding, Ho, Ibrahim, Teh, & Goh, 2023).

From the perspective of integrated nutrient management, the results of this study provide a clear picture of the importance of considering the physical and chemical characteristics of the local soil in determining the most suitable type of *controlled release* fertilizer to be applied. Oil palm plantations in the tropics generally have a varied soil texture, ranging from sandy mineral soils to heavy loamy soils, each of which has a different nutrient retention capacity and water movement patterns. This condition directly affects the decomposition speed of the *controlled release* fertilizer coating layer as well as the rate of nutrient diffusion to the soil solution. Organic fertilizers with granular structures specifically designed for specific soil conditions, such as formulations that integrate biochar and biosilica, have been proven to increase soil nutrient retention capacity while supporting a more optimal pH balance for oil palm plant growth.

The practical implications of this study's findings on fertilization management in commercial oil palm plantations are significant. The use of proper *controlled release* fertilizers not only impacts increasing vegetative growth of unyielding crop plants, but also has the potential to reduce long-term fertilization costs through reducing the frequency of application and minimizing nutrient loss. This economic efficiency is an important strategic consideration, considering that fertilization costs are the largest component in the operational cost structure of oil palm plantations. Fertilization optimization through *a controlled release approach* is in line with the principle of precision agriculture which aims to maximize productive output per unit of input used, so that the sustainability of oil palm plantation business can be maintained in the long term.

The study of the pattern of changes in the value of growth parameters from the first to the fifth observation shows that there is a qualitatively different growth trajectory between treatments, not just a difference in absolute values at a certain point in time. Treatments that provide a more stable and sustainable nutrient supply tend to result in a slower but consistent growth curve, while treatments with fluctuating nutrient availability result in less stable growth patterns between observation periods. This consistent growth trajectory is particularly important in the context of unyielding crop oil palm cultivation, as growth disruption in this phase has the potential to delay the first harvest and negatively impact the long-term productivity of the crop. Therefore, the selection of the type of fertilizer that is able to ensure the continuity of nutrient supply during the unyielding crop phase is a very strategic agronomic decision and has a long-term impact on the profitability of the plantation business as a whole. Research shows that optimization of phosphorus fertilization dose in oil palm primary nurseries significantly affects the development of root systems and biomass accumulation, both of which are the foundation for optimal vegetative growth in the later unyielding crop phase (Sukmawan, 2024).

Differences in growth responses between treatments can also be attributed to the influence of each type of fertilizer on the physical and chemical properties of the soil around the plant's rooting zone. Repeated application of fertilizer over a long period of time, as carried out in this three-year study, has the potential to change the characteristics of soil fertility cumulatively. Fertilizers with organic matter or biodegradable coating materials have the potential to increase soil organic matter content over time, which in turn improves soil structure, water retention capacity, and cation exchange capacity. This improvement in the physical properties of the soil indirectly supports better root growth and higher nutrient accessibility for plants. Formulation *Biofertilizer* Granular that integrates biochar and biosilica has been proven to increase soil cation exchange capacity by up to 54% and promote more efficient nutrient uptake of nitrogen, phosphorus, and potassium, which in aggregate contributes to more optimal vegetative growth of plants (Sitinjak & Jannati, 2025).

Analysis of plant nutrient status measured through various morphological growth parameters also provides an indirect picture of the efficiency of nutrient absorption of each treatment. Parameters such as the width of the leaflets and the number of leaf blades that reflect the total photosynthetic capacity of the plant implicitly illustrate the adequacy of nitrogen and magnesium supplies as the main components of chlorophyll. Plants with higher photosynthetic capacity are able to produce larger amounts of photosynthate, which are then allocated for the formation of new vegetative organs more expansively. Thus, the observed increase in leaf morphological parameters in a given treatment is not just a direct response to nutrient availability, but also reflects an increase in the overall metabolic capacity of the plant resulting from improved fertilization efficiency. Studies on the responses of different oil palm genotypes to different fertilization rates confirm that nutrient use efficiency is multidimensional and is influenced by the complex interaction between plant genetic characteristics, nutrient supply quality, and growing environmental conditions simultaneously (Sitinjak & Jannati, 2025).

3.2.2 Most effective type of *controlled release* fertilizer for the vegetative growth of unyielding crop oil palm plants

Based on a thorough evaluation of the four observation periods, F2 treatment using Haracoat fertilizer consistently had the most effective effect on the vegetative growth of unyielding crop oil palm plants compared to the other three treatments. The advantages of F2 that were observed repeatedly in the first, second, and third observations on the parameters of *petiole* width, *petiole thickness*, frond length, number of leaves, fronds production, and tree height indicate that the Haracoat formula has the best compatibility with the nutrient needs patterns of unyielding crop oil palm plants in the agroecological conditions of the research site. This advantage can be mechantically attributed to the characteristics of the Haracoat coating layer which is able to adjust the rate of nutrient release to the dynamics of temperature and humidity of tropical soil more optimally. Research on *palm kernel* oil-based polyurethane-coated *controlled release* fertilizers shows that the thickness and composition of the coating layer directly determine the duration and nutrient release patterns, where the right combination of layer parameters can maintain a stable supply of nutrients for the plant for decades after application.

F3 treatment combining conventional NPK fertilizer with Agrinos biological fertilizer shows quite competitive performance, especially in the early growth phase. The contribution of functional microorganisms in Agrinos to phosphate dissolution, nitrogen fixation, and root growth stimulation are the main supporting factors that distinguish F3 performance from F0 control treatments. Diverse and active soil microbial communities in the rhizosphere, including genera such as *Bacillus*, *Paenibacillus*, and *Microbacterium*, has proven to play an important role in nutrient transformation and improved mineral absorption efficiency by oil palm plants, so that the integration of inorganic fertilizers with biological inoculants is a promising fertilization strategy to be applied more widely (Yao, Baharum, Yu, Yan, & Badri, 2025). This potential is further strengthened by research showing that *Biofertilizer* enriched biosilica-based granules *Azotobacter* sp. It is able to significantly increase the soil cation exchange capacity while promoting increased nitrogen, phosphorus, and potassium uptake of plants, which overall supports better vegetative growth in a variety of soil conditions.

Meanwhile, F1 treatment using Agroblen fertilizer, which consistently showed the lowest value in almost all parameters during the initial three observation periods, needs to be examined from the aspect of conformity between the product formula and the specific conditions of the field. Fertilizer effectiveness *controlled release* It is highly dependent on soil conditions, microclimate, and biological activity at the site of application, so formulas designed for specific conditions may not necessarily provide optimal results in environments with different characteristics. Research has shown that the response of oil palm growth to fertilization is very specific depending on the genetic background of the plant and the local environmental conditions, so the recommendation of fertilizer type and dosage should always be based on an empirical evaluation carried out contextually at the relevant site (Pangaribuan, Wening, Pratiwi, Mardiana, & Diah, 2024). Overall, the results of this study confirm that Haracoat (F2) fertilizer is the most recommended choice to support the optimal growth of oil palm plants in the unyielding crop phase, while still considering the potential of biofertilizer combinations as a complement that can improve long-term fertilization efficiency in a sustainable manner.

A more in-depth analysis of the consistency of F2's advantages throughout the study period showed that the effectiveness of a type of fertilizer *controlled release* It cannot be assessed based on just one observation time, but must be evaluated longitudinally to obtain a comprehensive picture. In this study, F2 not only excelled on one parameter at a single observation point, but showed consistent superiority on the majority of vegetative parameters during three of the four observation periods. This consistency is a strong indicator that the Haracoat formula has nutrient release characteristics that are in line with the dynamics of the nutritional needs of unyielding crop oil palm plants temporally. The temporal correspondence between the nutrient availability of fertilizers and the active growth phase of the plant is the main key to fertilization effectiveness that is often not achieved by conventional fertilizers with uncontrolled nutrient release patterns. Related research proves that polymer-based coating materials with certain physicochemical characteristics are able to precisely regulate the rate of nitrogen release, so that the concentration of nutrients in the soil solution can be maintained at the optimal range required by plants throughout their growth cycle (Azmiyawati, Setyorini, Muhtar, Sriatun, & Darmawan, 2025).

The comparison between F2 and F0 as a control also provides important information about the added value of technology *controlled release* compared to conventional fertilization in real field conditions. Although F0 uses regular NPK fertilizers that also contain equivalent macronutrients, the observed differences in the majority of growth parameters indicate that the quality of the nutrient supply, not just the quantity, determines the effectiveness of fertilization. Conventional NPK fertilizers applied at one time tend to experience significant nutrient loss before they are absorbed by plants, especially in conditions of high rainfall that accelerate the process *Leaching*. In contrast, the gradual release mechanism in Haracoat allows nutrients to remain available in the root zone for a longer period of time, resulting in higher absorption efficiency and more optimal growth impact. Bio-polymers as coating materials in fertilizers *controlled release* Proven to be able to maintain the integrity of granular structures while supporting beneficial soil microbial activity around nutrient release zones (Murugan, Ong, Hashim, Kosugi, Arai, & Sudesh, 2020).

The findings regarding F2's advantages also have strong relevance to efforts to improve sustainability (*Sustainability*) fertilization practices in oil palm plantations. Minimizing nutrient loss to the environment through the use of fertilizers *controlled release* directly contributes to the reduction of the risk of groundwater pollution and surface water bodies as a result of *run-off* and *Leaching* nitrogen as well as phosphorus. In the context of increasingly stringent environmental regulations and the increasingly required demands of sustainability certification by the international market, the use of more environmentally friendly fertilization technology is a competitive advantage of strategic value for plantation companies. Development of fertilizer formulations based on renewable raw materials, such as *polyurethane* based on palm kernel oil as a coating material, opens up opportunities to create a more sustainable value-added cycle within the palm oil industry itself, where industrial by-products can be reused as components of innovative fertilization technologies (Yao, Baharum, Yu, Yan, & Badri, 2025).

Recommendations for the use of F2 as the best treatment need to be followed by further studies on the optimization of the dosage and frequency of application of Haracoat that is most suitable for various soil conditions and different stages of unyielding crop plant lifespan. The results of this study also open up opportunities to develop an integrated fertilization approach that combines the advantages of *controlled release fertilizers* with the benefits of biological fertilizers, given the competitive performance shown by F3 in several observation periods. The efficiency of nutrient use in oil palm influenced by the plant's genetic background also needs to be considered in designing a more personalized and precise fertilization strategy in the future, in order to maximize the productivity potential of each individual plant optimally (Pangathousands et al., 2024).

4. CONCLUSION

Based on the results of research that has been carried out for three years at PT. Panca Surya Garden, it can be concluded that the application of various types of controlled *release* fertilizers has different influences on the vegetative growth of oil palm plants in the unyielding crop phase. Haracoat Fertilizer (F2) proved to be the most effective treatment consistently in the first to third observations, with the highest values in the parameters of petiole width and thickness, flange length, number of leaf strands, and frond production. Meanwhile, in the fifth observation, almost all parameters showed convergence between treatments, indicating that the influence of fertilizer type was weakening as the plant aged.

Referring to the findings of this study, it is suggested that oil palm plantations in the unyielding crop phase prioritize the use of Haracoat fertilizer as the main choice to optimize plant vegetative growth. In addition, it is necessary to conduct further studies on the optimization of the dosage and frequency of application of Haracoat on various soil types and different agroecological conditions. An integrated fertilization approach that combines *controlled release fertilizers* with biological fertilizers is also worthy of further development, considering that the F3 treatment shows quite competitive performance. Similar research on the Yield Plant phase also needs to be conducted to obtain a more comprehensive picture of effectiveness.

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