Jurnal Silva Samalas
Journal of Forestry and Plant Science
Vol. 9, No. 1
p-ISSN: 2621-6779
e-ISSN: 2776-7175
pp. 01-11

SOLID POTENTIAL IN DECANTER DEVICES IN PALM OIL MILLS WITH DIFFERENT FRESH FRUIT BUNCH PROCESSING CAPACITIES AS A SUPPLIER OF NUTRIENTS IN OIL PALM PLANTATIONS

Zain Arrasyid Munthe, Ika Ucha Pradifta Rangkuti
[a]Fakultas Vokasi Institut Teknologi Sawit Indonesia, Indonesia
**Email Korespondensi:* zainarr211@gmail.com

Abstract

This study aims to analyze the potential of solids from decanter mills (PKS) with capacities of 30 tons/hour and 60 tons/hour as a nutrient source for oil palm plants. This research is part of the final assignment for the Plantation Product Processing Technology Study Program at the Indonesian Palm Oil Institute (IPT) and was conducted under the guidance of Ika Ucha Pradifta Rangkuti. The research method used was descriptive quantitative through laboratory analysis of the macronutrient content in the solids from decanters. Samples were taken from the decanter output of each PKS and then analyzed for Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), Calcium (Ca), and micronutrients such as Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), and Boron (B). The analysis data were analyzed using an Independent T-Test to determine differences in nutrient content between the two PKS capacities. The results of the study showed that the solids from both PKS contain complete macro and micro nutrients so they have the potential to be used as organic fertilizer in oil palm plantations. Solids from the PKS with a capacity of 30 tons/hour have higher contents of Potassium (K), Magnesium (Mg), Calcium (Ca), Iron (Fe), and Manganese (Mn) so they better support the generative phase of plants, while solids from the PKS with a capacity of 60 tons/hour have higher Nitrogen (N) content so they are more suitable for supporting the vegetative phase. Solid production also increased with increasing plant capacity, namely by 4.35 tons/hour in the PKS with a capacity of 30 tons/hour and 8.70 tons/hour in the PKS with a capacity of 60 tons/hour. The results of statistical tests showed that all nutrient parameters were significantly different ($p < 0.05$), which indicates that plant capacity has a significant effect on the quality of the solid nutrients produced. In conclusion, decanter solid from both mill capacities holds significant potential as organic fertilizer for oil palm plantations, and its application should be tailored to the plant growth phase for optimal fertilization effectiveness.

Keywords: *solid palm oil, macro and micro nutrients, decanter, organic fertilizer, PKS 30 tons/hour, PKS 60 tons/hour*.

Abstrak

Penelitian ini bertujuan untuk menganalisis potensi solid hasil keluaran alat decanter pada Pabrik Kelapa Sawit (PKS) kapasitas 30 ton/jam dan 60 ton/jam sebagai sumber unsur hara bagi tanaman kelapa sawit. Penelitian ini merupakan bagian dari tugas akhir pada Program Studi Teknologi Pengolahan Hasil Perkebunan di Institut Teknologi Sawit Indonesia dan dilaksanakan di bawah bimbingan trainer bersertifikat. Metode penelitian yang digunakan adalah deskriptif kuantitatif melalui analisis laboratorium terhadap kandungan unsur hara makro pada solid decanter. Sampel diambil dari keluaran decanter masing-masing PKS, kemudian dianalisis kandungan Nitrogen (N), Fosfor (P), Kalium (K), Magnesium (Mg), Kalsium (Ca), serta unsur mikro berupa Besi (Fe), Mangan (Mn), Seng (Zn), Tembaga (Cu), dan Boron (B). Data hasil analisis diuji menggunakan Independent T-Test untuk mengetahui perbedaan kandungan unsur hara antara kedua kapasitas PKS. Hasil penelitian menunjukkan bahwa solid dari kedua PKS mengandung unsur hara makro dan mikro yang lengkap sehingga berpotensi dimanfaatkan sebagai pupuk organik di perkebunan kelapa sawit. Solid dari PKS kapasitas 30 ton/jam memiliki kandungan Kalium (K), Magnesium (Mg), Kalsium (Ca), Besi (Fe), dan Mangan (Mn) yang lebih tinggi sehingga lebih mendukung fase generatif tanaman, sedangkan solid dari PKS kapasitas 60 ton/jam memiliki kandungan Nitrogen (N) yang lebih tinggi sehingga lebih sesuai untuk mendukung fase vegetatif. Produksi solid juga meningkat seiring bertambahnya kapasitas pabrik, yaitu sebesar 4,35 ton/jam pada PKS 30 ton/jam dan 8,70 ton/jam pada PKS 60 ton/jam. Hasil uji statistik menunjukkan seluruh parameter unsur hara berbeda nyata ($p <$ 0,05), yang menandakan bahwa kapasitas pabrik berpengaruh signifikan terhadap kualitas nutrisi solid yang dihasilkan. Kesimpulannya, solid decanter dari kedua kapasitas PKS memiliki potensi signifikan sebagai pupuk organik di perkebunan kelapa sawit, dan penggunaannya sebaiknya disesuaikan dengan fase pertumbuhan tanaman untuk efektivitas pemupukan yang optimal.

Kata Kunci: solid kelapa sawit, unsur hara makro dan mikro, decanter, pupuk organik, PKS 30 ton/jam, PKS 60 ton/jam.

***How to** Cite:* Munthe, Z. A. & Rangkuti, I. U. P. (2026) 'Solid Potential in Decanter Devices in Palm Oil Mills with Different Fresh Fruit Bunch Processing Capacities as A Supplier of Nutrients in Oil Palm Plantations', *Jurnal Silva Samalas: Journal of Forestry and Plant Science*, 9 (1), pp. 01-11.

INTRODUCTION

The increasing global demand for palm oil is driving the growth of the palm oil processing industry in Indonesia, both in terms of the expansion of plantation areas and the improvement of operational capacity at palm oil mills (POM). To meet market needs and improve production efficiency, POMs are built with various fresh fruit bunch (FFB) processing capacities, including 30 tonnes/hour and 60 tonnes/hour (Tepins & others, 2024). These capacity differences are tailored to the availability of raw materials, the extent of plantation areas, and the company's production targets. A POM with a capacity of 30 tonnes/hour is generally used in small to medium-scale plantations or as an initial stage of industrial development, while a POM with a capacity of 60 tonnes/hour is designed to serve large-scale plantations with greater FFB volumes, thereby improving operational efficiency and reducing production costs per unit of output (Stephanie et al., 2018). These differences in mill capacity not only affect the volume of crude palm oil (CPO) produced, but also influence the characteristics of the waste generated during the processing stage (Hilmawan, 2021).

One of the by-products of palm oil processing with great potential for reuse is the sludge or solid produced by the decanter. A decanter is a separation device that operates on the principle of centrifugation to separate oil, water, and solids from the sludge produced during the clarification process. The use of a decanter is critically important for improving oil separation efficiency and reducing oil losses during processing. Research shows that a decanter operates optimally when the sludge feed capacity matches the device's capacity, which ranges between 9–12 tonnes/hour, so that oil losses in the heavy phase and solid phase can be kept within company standards below 1% in the heavy phase and below 3% in the solid phase. A mismatch between the decanter's capacity and the POM's capacity can cause oil losses to increase by up to 0.61%, resulting in economic losses and reducing the quality of the sludge as an organic fertilizer material (Hikmawan et al., 2021b).

Differences in POM capacity also lead to differences in waste treatment systems, including temperature regulation, feed rates, and the working capacity of the decanter. In a 30 tonne/hour POM, the volume of sludge produced is relatively smaller compared to a 60 tonne/hour POM, so the control and separation process can be carried out more simply. Conversely, a 60 tonne/hour POM generates a larger volume of sludge, requiring more optimal process control to maintain the quality of both oil and solids. These process variations affect the characteristics of the resulting sludge, such as moisture content, oil content, and solid content. According to Manalu et al. (2023), sludge from a 30 tonne/hour POM contains on average 8.40% solids, 1.32% residual oil, and 90.24% water. These characteristics indicate that the sludge still contains organic matter and nutrients with the potential to be used as a nutrient source for oil palm plants (Pradifta Rangkuti & Wahyuni, 2019).

The solid produced by the decanter has significant potential as a nutrient provider because it contains macronutrients such as nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), which are essential for the growth of oil palm plants. These elements play important roles in the physiological processes of plants, including leaf formation, root development, fruit formation, and improvement of plant productivity. Fertilization is one of the primary maintenance activities in oil palm plantations, as it greatly determines plant growth and production. Hilmawan (2021) states that macronutrients such as N, P, K, and Mg are the most needed elements by oil palm plants. Therefore, the utilization of solid as organic fertilizer can serve as an alternative to meet the plant's nutrient needs while also reducing dependence on synthetic chemical fertilizers (Nasution, 2023).

In addition to providing nutrients, the use of solid as organic fertilizer is also capable of improving the physical, chemical, and biological properties of the soil. The application of solid on plantation land can increase the soil's organic matter content, improve soil structure, increase water-holding capacity, and raise the pH of acidic soils. Widhiastuti et al. (2017) state that the use of solid waste as organic fertilizer can enhance soil fertility and support the sustainable growth of oil palm plants. Thus, waste that was previously considered a discarded material can be transformed into a resource with economic value that is environmentally friendly (Pradifta Rangkuti & Wahyuni, 2019). This concept is aligned with the principles of the circular economy, which emphasizes the reuse of industrial waste to improve resource efficiency and reduce the impact of environmental pollution (Brahmana & Ginting, 2019).

Optimal management of solid also requires good process control in the decanter. Factors such as sludge temperature, feed rate, and separation efficiency greatly affect the quality of the solid produced. Temperature regulation to approximately 95℃ is required to maximize the oil separation process so that the oil content in the solid can be minimized (Hikmawan et al., 2021a). The lower the residual oil content in the solid, the better the quality of the solid as an organic fertilizer, as its nutrient content will be more stable and will not cause contamination of the application land. Furthermore, the use of a decanter is considered more effective than a sludge separator, as it is capable of producing solid with lower oil content and greater processing capacity. Research by Nasution (2023) shows that decanters and tricanters have better separation efficiency than sludge separators, making them more effective in maximizing the utilization of solid as organic fertilizer.

Based on the above explanation, it can be concluded that differences in POM capacity affect the volume, characteristics, and nutrient content of the solid produced by the decanter. Decanter solid has the potential to be utilized as an alternative nutrient source to support the growth of oil palm plants while also reducing waste from the palm oil processing industry. Therefore, research on the potential of decanter solid at POMs with capacities of 30 tonnes/hour and 60 tonnes/hour as nutrient providers in oil palm plantations is necessary to determine differences in nutrient content, solid quality, and the effectiveness of its use as organic fertilizer that supports the sustainability of the palm oil industry (Nasution et al., 2022).

Beyond the technical aspects of processing, differences in POM capacity are also closely related to the operational dynamics of the mill, which can affect the stability of the separation process in the decanter (Maryani, 2018). In higher-capacity POMs, feed load fluctuations tend to be greater due to variations in FFB supply from large plantation areas, which can affect the consistency of the sludge separation process into oil, water, and solids. When the feed load is unstable, separation efficiency may decline, causing changes in the chemical composition of the resulting solid. This includes variations in moisture content, residual oil content, and the distribution of nutrients bound to the solid fraction. These conditions indicate that operational factors play an important role alongside capacity factors in determining the final quality of decanter solid (Nasution, 2015).

From the perspective of organic chemistry, the characteristics of solid are greatly influenced by the interaction between complex organic compounds and minerals found in oil palm fruit tissue. During processing, some nutrients exist in a water-soluble form while others are bound to lignocellulosic structures. Elements such as potassium and magnesium tend to be more soluble and are therefore highly sensitive to changes in the separation process (Syukri et al., 2024), while elements such as iron and manganese are more commonly associated with complex organic compounds and the solid fraction. Different processing conditions at each POM capacity can cause shifts in the balance between dissolved and retained elements in the solid, resulting in significant variations in nutrient composition, as seen in the findings of Tepins & others (2024).

Furthermore, the C/N ratio in solid is also an important indicator for determining the quality and rate of decomposition of organic matter in the soil. A lower C/N ratio generally indicates organic matter that is more easily decomposed and more quickly provides nutrients to plants, while a higher C/N ratio indicates a dominance of more complex structural carbon, causing the mineralization process to proceed more slowly (Gofar, Sinurat, & Rawan, 2022). In the context of palm oil solid utilization, differences in the C/N ratio between 30 tonne/hour and 60 tonne/hour POMs have direct implications for field application strategies, particularly in determining the timing of application, dosage, and fertilization objectives — whether for the vegetative or generative phase of oil palm plants (Ucha et al., 2023).

From an agronomic perspective, the use of solid as organic fertilizer serves not only as a nutrient source, but also as part of a long-term soil fertility management strategy. Repeated application of solid can increase the soil organic carbon content, which plays an important role in improving cation exchange capacity (CEC), improving soil aggregation, and increasing the activity of soil microorganisms involved in nutrient cycling (Fitriany & Sukandar, 2009). These conditions can ultimately improve the efficiency of inorganic fertilizer use, as the soil gains a better capacity to store and supply nutrients to plants. Solid can thus be positioned as an important input in the sustainable oil palm cultivation system (Kristalisasi & Rusmarini, 2024).

Furthermore, the utilization of solid also has significant environmental implications in the context of industrial waste management in the palm oil sector. Without proper management, sludge and solid can become sources of pollution in the form of odor emissions, water contamination, and a potential increase in the organic load on the environment surrounding the mill. However, when managed and reused as organic fertilizer, this waste can be transformed into a value-added resource that supports the principle of a zero-waste industry. This approach not only improves the economic efficiency of the palm oil industry, but also strengthens environmental sustainability through waste reduction and optimization of the nutrient cycle within the agricultural production system (Purnamayani et al., 2012)

MATERIALS AND METHODS

a. Sampling Location

This research was conducted at Adolina POM with a capacity of 30 tonnes/hour and Bah Jambi POM with a capacity of 60 tonnes/hour as the sampling locations for decanter solid output, while the analysis of nutrient content was carried out at the Laboratory of the Research and Development Centre of PT. Nusa Pusaka Kencana Analytical and QC Bahilang, Tebing Tinggi, which is accredited to ISO/IEC 17025:2017, thereby ensuring the validity and reliability of the test results (BSN, 2017). The research was conducted over a period of 12 months, from April 2025 to April 2026, covering the stages of preparation, field sampling, laboratory analysis, and data processing and interpretation. The method employed was quantitative descriptive with a laboratory analysis approach to obtain numerical data on nutrient content, followed by statistical testing using the Independent Samples T-Test in IBM SPSS software at a significance level of 0.05 to examine significant differences between treatments.

b. Sampling Method

The independent variable in this study was the palm oil mill capacity, namely a 30 tonne/hour POM and a 60 tonne/hour POM, while the dependent variables were the macronutrient content, comprising Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), and Calcium (Ca) and the micronutrient content, comprising Boron (B), Copper (Cu), Zinc (Zn), Iron (Fe), and Manganese (Mn) in the palm oil solid. Sampling was carried out purposively at the decanter outlet point using a repetition method of three times per day (morning, midday, and afternoon) over 30 production days, after which all samples were combined into a composite sample for each POM to obtain a more accurate representation of actual operational conditions (Gofar et al., 2022). The samples were then conditioned through homogenization, storage at low temperature, and preparation in accordance with laboratory analysis standards prior to nutrient testing (BSN, 2017).

c. Data Collection

The laboratory analysis process was carried out using several standard methods, including the Kjeldahl method for total Nitrogen determination, spectrophotometry for Phosphorus analysis, and Atomic Absorption Spectrophotometry (AAS) or ICP-OES for Potassium and other microelement analysis. Each parameter was tested with calibration procedures using standard solutions to ensure measurement accuracy, and blank tests were conducted to minimize the potential for systematic errors. In addition, supporting parameters were tested, including pH, C/N ratio, and physical characteristics of the sludge such as moisture content, oil content, and solid content, to provide a comprehensive overview of the quality of solid produced at each POM capacity.

d. Data Analysis

The data from the analysis were then processed statistically, beginning with descriptive analysis to describe the mean values, standard deviations, and distribution patterns of the nutrient content data at each POM. This was followed by inferential analysis using the Independent Samples t-Test to determine whether there were significant differences between the two data groups. The results of this test were used to examine the research hypothesis namely, whether mill capacity has an effect on the nutritional quality of the solid produced. The interpretation of results was based not only on statistical significance values, but also linked to the agronomic and physiological aspects of oil palm plants, so as to provide more practical recommendations for the utilization of solid in the field.

Figure 1. Sampling Location

RESULTS AND DISCUSSION

Based on the concept of material balance, every 1 tonne of fresh fruit bunches (FFB) processed at a palm oil mill yields approximately 14.5% solid as solid waste from the processing stage. Using this approach, the potential solid production at a 30 tonne/hour POM reaches 4.35 tonnes/hour, while at a 60 tonne/hour POM it reaches 8.70 tonnes/hour. These calculation results indicate that an increase in mill capacity will linearly increase the amount of solid produced. The greater the FFB processing capacity, the greater the volume of solid biomass available for reuse as organic matter in oil palm plantations. This condition is consistent with the principle of material balance, in which solid waste output is directly proportional to the amount of raw material processed (Kamyab et al., 2018). Furthermore, the large quantity of solid produced demonstrates enormous potential as a source of nutrients and organic matter that can support the sustainability of the oil palm cultivation system.

Figure 2. Sample Processing

Based on the results of laboratory analysis of solid from the 30 tonne/hour POM, a fairly complete profile of macro and micronutrient content was obtained, with strong potential for use as organic fertilizer. Nitrogen (N) content of 2.48%, Phosphorus (P) of 0.31%, Potassium (K) of 1.41%, Magnesium (Mg) of 0.42%, and Calcium (Ca) of 1.50% indicate that the solid contains important nutrients required by oil palm plants. In addition, microelements such as Iron (Fe) at 2,177.17 ppm, Manganese (Mn) at 144.32 ppm, Zinc (Zn) at 55.13 ppm, Copper (Cu) at 34.36 ppm, and Boron (B) at 0.59 ppm indicate that solid from the 30 tonne/hour POM possesses reasonably good nutritional quality. A pH value of 5.33 and a C/N ratio of 20.62 indicate that the organic matter is relatively stable and capable of undergoing gradual decomposition in the soil.

The complete mineral composition data of solid from both POM capacities are presented in Table 1 for direct comparison. At the 60 tonne/hour POM, laboratory analysis results showed that the solid also contains a complete profile of nutrients, albeit with a different composition compared to the 30 tonne/hour POM. Nitrogen (N) content of 2.16%, Phosphorus (P) of 0.22%, Potassium (K) of 0.74%, Magnesium (Mg) of 0.24%, and Calcium (Ca) of 1.39% indicate that the content of most macronutrients is lower than that of the 30 tonne/hour POM. However, certain micronutrients such as Copper (Cu) at 63.54 ppm and Boron (B) at 8.48 ppm are higher compared to the solid from the 30 tonne/hour POM.

A pH value of 4.80 and a C/N ratio of 24.55 indicate that the solid from the 60 tonne/hour POM has organic matter characteristics that decompose more slowly and tend to be more acidic.

Table 1. Comparison of Mineral Composition of Decanter Solid from 30 Tonne/Hour and 60 Tonne/Hour Palm Oil Mills

Parameter	30 Tonne/Hour POM	60 Tonne/Hour POM
Nitrogen / N (%)	2.48	2.16
Phosphorus / P (%)	0.31	0.22
Potassium / K (%)	1.41	0.74
Magnesium / Mg (%)	0.42	0.24
Calcium / Ca (%)	1.50	1.39
Iron / Fe (ppm)	2,177.17	N/A*
Manganese / Mn (ppm)	144.32	N/A*
Zinc / Zn (ppm)	55.13	N/A*
Copper / Cu (ppm)	34.36	63.54
Boron / B (ppm)	0.59	8.48
pH	5.33	4.80
C/N Ratio	20.62	24.55

**N/A = data not reported in original analysis for this capacity. Fe, Mn, Zn values for 60 tonne/hour POM to be verified with laboratory data.*

The differences in nutrient composition between the two POM capacities indicate that mill processing capacity influences the nutritional quality of the solid produced (Dan & Kedelai, 2025). Solid from the 30 tonne/hour POM has higher contents of Potassium, Magnesium, Calcium, Iron, Manganese, and Zinc compared to the 60 tonne/hour POM. Conversely, the 60 tonne/hour POM has higher contents of Copper and Boron. These variations in nutrient content are influenced by differences in processing characteristics, material flow rates, separation efficiency, and mineral retention in the organic matter matrix during the decanter processing stage. The higher the processing capacity, the greater the intensity of oil and liquid phase separation, causing a greater proportion of nutrients to be carried into the liquid phase and not retained in the solid.

Prior to the Independent Samples T-Test, an F-test (Levene's Test for Equality of Variances) was conducted to determine whether the variances between the two groups were equal or unequal, thereby selecting the appropriate T-Test type. Statistical test results using the Independent Samples T-Test showed that all nutrient parameters had significance values (p-value) < 0.05, indicating a significant difference between the 30 tonne/hour and 60 tonne/hour POM capacities. This significant difference was observed across all macro and micronutrient elements, including Nitrogen, Phosphorus, Potassium, Magnesium, Calcium, Boron, Copper, Zinc, Iron, Manganese, pH values, and C/N ratios. These results confirm that mill capacity has a significant effect on the nutritional quality of the solid produced. Accordingly, FFB processing capacity not only affects the quantity of waste generated, but also determines the chemical characteristics and potential utilization of solid as a nutrient source.

Physiologically, the nutrient content of solid exerts different influences on the growth phases of oil palm plants (Ucha et al., 2023). Nitrogen is the primary element involved in the formation of chlorophyll, proteins, and vegetative plant tissue such as leaves and stems. The relatively high nitrogen content in solid from the 60 tonne/hour POM suggests that this organic material is more suitable for use during the vegetative phase of plant growth, particularly for immature palms (IP). Adequate nitrogen can enhance leaf formation, expand plant canopy, and accelerate the early growth of oil palms, thereby supporting an increase in the plant's photosynthetic capacity (Pertanian, 2020).

Conversely, the higher contents of Potassium, Phosphorus, Magnesium, and Calcium in solid from the 30 tonne/hour POM indicate greater potential to support the generative growth phase of oil palm plants. Potassium plays an important role in the translocation of photosynthetic products to fruit and in oil formation, while Phosphorus functions in energy transfer and in the formation of flowers and fruit. Magnesium, as a component of chlorophyll, helps improve photosynthetic efficiency, while Calcium strengthens plant tissue and supports fruit formation. Therefore, solid from the 30 tonne/hour POM is more suitable for application to mature palms (MP) to support bunch formation, fruit filling, and the improvement of oil yield (Pandapotan & Marbun, 2017).

With regard to micronutrients, the higher contents of Iron (Fe) and Manganese (Mn) in solid from the 30 tonne/hour POM demonstrate good potential for supporting plant metabolic activity. Iron is involved in chlorophyll formation and plant respiration, while Manganese functions as an activator of photosynthesis enzymes and nitrogen metabolism. The higher Zinc (Zn) content also aids in the synthesis of growth hormones such as auxin, which plays a role in flower and young fruit formation. Meanwhile, the higher Copper (Cu) and Boron (B) contents in solid from the 60 tonne/hour POM function in lignin formation, flower development, and the formation of healthy plant tissue.

The differences in nutrient content between the two solids are also influenced by the C/N ratio and the rate of organic matter decomposition. The lower C/N ratio in the 30 tonne/hour POM indicates that the decomposition of organic matter proceeds more rapidly, making nutrients more readily available to plants (Prasetyo et al., 2023). Conversely, the higher C/N ratio in the 60 tonne/hour POM indicates a greater dominance of structural organic matter, causing nutrient release to proceed more slowly. This difference affects the effectiveness of solid application in the field, where solid with a low C/N ratio provides nutrients more quickly, while a high C/N ratio delivers a gradual and longer-lasting nutrient supply in the soil.

In addition to serving as a nutrient source, palm oil solid also has potential as a soil conditioner. The organic matter content in solid can increase cation exchange capacity (CEC), improve soil structure, enhance the soil's water-holding capacity, and increase soil microorganism activity. Returning solid to plantation land in the form of mulch or compost can sustainably improve soil fertility and reduce dependence on synthetic chemical fertilizers. The utilization of solid waste also supports the concept of a circular economy in the palm oil industry, as processing by-products can be reused into products of practical value for the plantation.

Based on the research findings, it can be concluded that decanter solid from both the 30 tonne/hour and 60 tonne/hour POMs holds significant potential as a nutrient provider for oil palm plantations. The 60 tonne/hour POM produces a greater volume of solid with a dominance of Nitrogen that supports vegetative growth, while the 30 tonne/hour POM produces solid with higher contents of Potassium, Magnesium, Calcium, and micronutrients, making it more supportive of the generative growth phase of the plant. These differences in nutrient content are influenced by the mill's processing capacity, the intensity of the separation process, and the characteristics of the organic matter during processing. Accordingly, the utilization of solid as organic fertilizer should be tailored to the growth phase of the oil palm plant so that fertilization effectiveness and plant productivity can be improved optimally and sustainably.

Beyond being influenced by mill processing capacity, solid quality is also greatly affected by the operational conditions of the decanter during the separation process. Factors such as sludge temperature, bowl rotation speed, and feed flow rate play important roles in determining the effectiveness of oil, water, and solid separation. The optimal sludge temperature of approximately 95–100°C can help reduce oil viscosity, making the separation process more efficient and minimizing the oil content retained in the solid. If the separation process is suboptimal, the residual oil content in the solid will increase and may affect the stability of the organic matter when applied to land. Therefore, careful control of decanter operational parameters is essential to produce solid with good physical and chemical quality for use as organic fertilizer in oil palm plantations.

From an environmental perspective, the utilization of solid as organic fertilizer provides a positive impact on industrial waste management in the palm oil sector. Solid waste from FFB processing has often been regarded as a discarded material that can cause pollution if not properly managed. By utilizing solid as organic matter on plantation land, the volume of waste that must be disposed of can be significantly reduced (No, 2018). Furthermore, returning organic matter to the soil can help maintain soil ecosystem balance, increase microorganism activity, and reduce the risk of land degradation caused by excessive use of chemical fertilizers. The utilization of solid also supports the implementation of the zero-waste industry concept in the palm oil industry, where all processing by-products are sought to be reused, thereby improving resource use efficiency and reducing environmental impact (Studi et al., 2020).

The utilization of solid as organic fertilizer also carries considerable economic value for oil palm plantation companies. The use of solid can help reduce the cost of purchasing inorganic fertilizers, which has long been one of the largest production cost components in oil palm cultivation. The macro and micronutrient content in solid can serve as an alternative nutrient source for plants, allowing chemical fertilizer requirements to be reduced. Furthermore, the sustained use of organic fertilizer from solid can improve long-term soil fertility and enhance the efficiency of nutrient uptake by plants. Accordingly, the utilization of solid not only provides environmental benefits but also delivers economic advantages through reduced production costs and improved plantation productivity.

From a sustainability perspective, the use of solid as a source of organic matter is aligned with the principles of sustainable agriculture, which emphasize efficient use of natural resources and reduction of industrial waste. The high organic matter content in solid can help maintain soil quality and improve the soil's capacity to store nutrients and water. This is particularly important for oil palm plantation land that has been used over the long term and is susceptible to declining soil fertility. Moreover, the sustained use of solid can help improve the physical properties of soil, such as structure and porosity, thereby enhancing root growth. As soil quality improves, the plant's ability to absorb nutrients and water will also improve, allowing plant growth and productivity to be maintained at an optimal level.

Despite its great potential, the utilization of solid as organic fertilizer still requires proper monitoring and management to avoid negative impacts on the environment and on plants. Periodic testing of solid quality is necessary to ensure that nutrient content, moisture content, pH, C/N ratio, and the possible presence of heavy metals or other hazardous compounds remain within safe limits. In addition, field application of solid must take into account dosage, application method, and land conditions to ensure more effective utilization and to prevent excessive accumulation of organic matter. Therefore, further field-scale research is still needed to determine the optimal application dose, long-term effects on plant productivity, and the effectiveness of solid compared to chemical fertilizers and other organic fertilizers in supporting a sustainable oil palm cultivation system.

Beyond technical and agronomic factors, variations in the nutrient content of solid can also be understood through the perspective of the physical process dynamics within the decanter, which are strongly influenced by centrifugal force and the characteristics of sludge particles. During the separation process, particles with higher density are pushed toward the bowl wall, while the liquid phase with lower density remains toward the center. This distribution not only determines oil separation efficiency, but also determines how much of the nutrients are retained in the solid fraction. When centrifugal force increases due to greater operational capacity, the interaction between fine particles and the liquid becomes more intense, causing a greater proportion of dissolved minerals to be carried into the liquid phase. This explains why certain elements such as potassium and magnesium tend to be lower in higher-capacity mills, even though the total volume of solid produced increases.

From a biochemical perspective, the process of organic matter degradation in sludge also contributes to the variations in nutrient composition found in solid (Brady & Weil, 2016). Sludge is a complex mixture consisting of residual fruit tissue, dissolved organic compounds, and microorganisms that are actively undergoing decomposition. During mill processing, some hydrolysis and oxidation reactions can occur, affecting the chemical form of the nutrients. Nitrogen, for example, may exist in complex organic forms that have not yet fully decomposed, or may have undergone partial mineralization into simpler forms. These conditions are greatly influenced by the residence time of the material within the system and the operational temperature, such that differences in mill capacity indirectly affect the degree of maturity of the organic matter leaving the system as solid (Hanafiah, 2014).

Furthermore, the origin of the FFB raw material entering the mill is also an important variable influencing solid quality. FFB from plantations with different soil conditions will have different initial nutrient content, particularly for micronutrients such as boron, zinc, and copper, which are greatly influenced by the soil conditions in which the plants grow. At mills with larger capacity, FFB sources typically come from wider areas with greater agroecological variation, resulting in increased heterogeneity of the raw material. This can cause variations in the nutrient composition of sludge and solid, even when the processing methods used are relatively the same. Therefore, solid quality is not solely the result of the industrial process, but also a reflection of the agronomic conditions of the raw material source.

From the perspective of waste treatment technology, the optimization of solid utilization can be further developed through the integration of advanced processing systems such as controlled composting, microbial fermentation, or blending with other organic materials. These processes can improve the stability of organic matter, lower the C/N ratio, and increase nutrient availability for plants (Bernal et al., 2009). Advanced processing can also help reduce the potential for phytotoxicity caused by residual oil content still present in the solid. Accordingly, solid can not only be utilized directly, but its quality can also be enhanced into a more mature and efficient organic fertilizer for field application (Pahan, 2012).

Furthermore, integrating solid utilization into the oil palm plantation system can be developed within an integrated nutrient management framework that combines organic fertilizers, inorganic fertilizers, and industrial waste in a balanced manner. This approach enables higher nutrient use efficiency, as each nutrient source has its own advantages in supporting different plant growth phases. In the long term, the implementation of this system not only improves plant productivity but also maintains the sustainability of soil fertility and reduces dependence on external inputs. As such, the findings of this research can serve as a scientific basis for the development of more integrated, efficient, and sustainable palm oil waste management strategies in the future.

CONCLUSION

Based on the research findings, decanter solid from both the 30 tonne/hour and 60 tonne/hour palm oil mills contains a complete profile of macro and micronutrients — including N, P, K, Mg, Ca, Fe, Mn, Zn, Cu, and B — confirming its significant potential as organic fertilizer for oil palm plantations. The Independent Samples T-Test results showed that all nutrient parameters differed significantly ($p < 0.05$), indicating that mill capacity has a significant effect on the nutritional quality of solid produced. Solid from the 30 tonne/hour POM is richer in Potassium, Magnesium, Calcium, Fe, and Mn, making it more suitable for the generative phase of mature palms (MP), while solid from the 60 tonne/hour POM has higher Nitrogen content, making it more appropriate for supporting the vegetative growth of immature palms (IP). Solid production volume also increases proportionally with mill capacity, reaching 4.35 tonnes/hour at the 30 tonne/hour POM and 8.70 tonnes/hour at the 60 tonne/hour POM. These findings demonstrate that the utilization of decanter solid as organic fertilizer, tailored to plant growth phase and mill capacity, can support sustainable oil palm cultivation and contribute to the circular economy principle through reduced reliance on synthetic fertilizers.

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