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The Potential Benefits of Palm Oil Waste-Derived Compost in Embracing the Circular Economy

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Abstract: The environmental impact of peat extraction in plant nurseries requires urgent attention due to climate change and habitat destruction. Substituting peat moss with compost derived from palm oil waste in oil palm nurseries presents a viable solution. However, the challenges in its implementation must be considered. This research focuses on optimizing composting conditions for palm oil waste and examines the impact of the compost on soil quality, nutrient availability, and seedling growth. Measurements such as the culling rate, plant height, leaf length, and chlorophyll content were taken to assess seedling growth in nurseries. The compost was also tested as a soil amendment for 5-year-old palm trees, with foliar analysis conducted to evaluate the nutrient assimilation. The results show that optimized compost significantly enhanced the seedling growth by 20–50%, evidenced by the increased plant height, longer leaf length, and higher chlorophyll content. Additionally, the foliar analysis demonstrated an improvement of 5–15% in the nutrient assimilation in the 5-year-old palm trees. This research highlights the potential of optimizing oil palm waste composting for sustainable planting media in nurseries, mitigating environmental impacts and promoting productivity in oil palm plantations. Adopting this circular economy model can address waste management challenges while ensuring a resilient and sustainable approach in the palm oil industry.

Keywords: empty fruit bunch; POME; decanter cake; growth performance

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1. Introduction

Nursery cultivation is a globally recognized intensive production system that aims to produce high-quality seedlings while efficiently managing resources. One crucial factor influencing the success of nursery cultivation is the choice of growing media. In the 1950s, peat began to be used as a growing medium for containerized crops in the US [1–3]. Peat is highly favored for its beneficial physical properties, including its high porosity, water holding capacity (WHC), slow degradation rate, and low bulk density. It also possesses favorable chemical properties, such as a high cation exchange capacity (CEC) [4–6]. Over the past half-century, peat has been widely employed as a substrate in horticulture. However, peat extraction contributes to carbon emissions, habitat destruction, and the loss of biodiversity [6,7].

Growing environmental and ecological concerns surrounding peat usage have led researchers, practitioners, and growers to explore alternative substrates such as biochar, compost, and other materials. Studies suggest that compost made from the algae *Rugulopteryx okamurae* shows promise as a growing medium for tomato nurseries [8]. However, compost derived from empty fruit bunches (EFB) and palm oil mill effluent (POME) is less effective than peat for potting oil palm seedlings [9].

The use of compost as a substrate or substrate component can be limited by specific physicochemical or physical factors. These limitations [10–12] include unsuitable physical properties [13], its variable quality and composition [14], and the inherent content of the compost itself. Palm oil mill wastes, such as empty fruit bunches (EFB), palm oil mill effluent (POME), and decanter cakes, are renewable feedstocks for composting and are among the most abundantly available byproducts in palm oil-producing countries like Malaysia and Indonesia. Exploring and optimizing the quality of compost derived from palm oil mill waste is crucial for promoting a circular economy and meeting the demand for alternative nursery potting or growing media.

Palm oil, derived from oil palm fruit, is widely used in the food industry, cosmetics, biofuels, and consumer products due to its exceptional cooking properties, extended shelf life, and high energy content [15,16]. However, the growing demand for crude palm oil (CPO) has led to an increasing volume of waste generated by palm oil mills. Specifically, palm oil mills with a 30 tons/h capacity generate substantial solid waste, totaling 16,090.09 kg/h, equivalent to 53.63% of the fresh fruit bunches [17–20]. This waste comprises empty fruit bunches (26.97%), fibers (17.67%), and shells (6.46%). Additionally, these mills generate 18,113.15 kg per hour of liquid waste, made up of mud (18.38%) and water (42.05%). The disposal of palm oil mill waste has been a critical environmental issue; there is limited research exploring the practical and sustainable transformation or disposal of this waste.

When considering compost derived from palm oil mill waste as a growing media in nurseries, several factors must be evaluated, including the nutrient content, pH levels, water holding capacity, and drainage properties of the compost. Additionally, considerations such as its disease and pest management, environmental sustainability, and cost-effectiveness compared to peat should be considered. By carefully assessing these factors, nursery operators can make an informed decision about utilizing oil palm waste-derived compost as a sustainable alternative to peat in the nursery production chain.

The aim of the present study specifically focuses on optimizing composting conditions for palm oil waste-derived compost and determining its effectiveness in various growth stages, including in the prenursery (1–3 months seedling), the main nursery (4–12 months seedlings), and 5-year-old young mature palms. This experiment does not include a comparison with a peat treatment, as peat stands as a well-established potting medium. Instead, the aim of this study is to demonstrate the viability of utilizing compost derived from oil palm waste as a potting or growing medium in the plant nursery chain. This study pioneers an approach by not only transforming palm oil mill waste into compost but also by rigorously evaluating its suitability for reuse in oil palm nurseries and plantations, contributing to a circular economy model in the palm oil industry, and assessing the long-term benefits and sustainability of this practice.

2. Materials and Methods

The methodology employed in this research study encompasses three distinct stages, each focusing on the optimization and application of compost derived from oil palm waste materials. The methodology is outlined below.

2.1. Optimization of Oil Palm Waste Composting Conditions

The primary objective of this stage was to transform oil palm waste into high-quality compost through the optimization of the composting conditions. The materials utilized included empty fruit bunches (EFB), decanter cake, and palm oil mill effluent (POME). These materials were treated to enhance their suitability for the composting. The EFB waste underwent chipping to the size 3 cm × 3 cm using an EFB cutter Brand YKL/Diamatix. This was to facilitate airflow and microbial activity, promoting efficient decomposition. The decanter cake, with its organic content, was employed to enrich the compost. Prior to its incorporation, the POME underwent a moisture reduction to 40% using a dewatering machine to control the moisture levels during the composting.

The compost piles were established at a consistent size of 0.7 m × 6 m × 3 m on flat ground to ensure uniform environmental conditions. Four composting treatment ratios, denoted as CPT 1, CPT 2, CPT 3, and CPT 4, were explored. These ratios varied the proportions of the EFB, decanter cake, and POME, as shown in Table 1.

Table 1. Compost feedstock ratios.

Waste	CPT 1	CPT 2	CPT 3	CPT 4
Empty fruit bunch (EFB)	30%	30%	30%	30%
Dry decanter cake (40% Moisture)	40%	30%	40%	20%
POME	30%	40%	30%	50%
Turning stockpile	Biweekly	Biweekly	No turn	Biweekly
Replication	3	3	3	3

During the 75-day composting period, turning practices differed among the treatments. CPTs 1, 2, and 4 involved biweekly turning using an excavator to promote aeration and decomposition. CPT 3 remained undisturbed to allow natural decomposition. Temperature and moisture measurements were taken biweekly from randomized points within the compost piles, typically at distances of 0.4 m from the ground surface, to monitor changes. It is noted that each treatment involved three replications for the compost stockpiles.

The table below references the specified ratios of the four composting treatments and turning practices.

2.2. Compost Usability in Oil Palm Pre-Nursery Stage (0–3 Months Seed Planting)

This stage focused on evaluating the usability of the compost in the pre-nursery stage of oil palm growth. Oil palm seeds of the IOI hybrid variety were planted in Hyplug trays using two different planting media: topsoil and compost (CPT 3). A total of 2000 oil palm seeds were planted in the topsoil, while another 2000 seeds were planted in the compost (CPT 3). Only the CPT 3 compost was subjected to testing, as it represented a good compost that was a dark, crumbly, and well-decomposed soil amendment with an earthy scent, neutral pH, and rich nutrient content; it was potentially free from pathogens and weed contaminants, achieved through the application of elevated temperatures during the composting. Rain tape irrigation was employed for consistent moisture supply scheduled to deliver water once a day, with each irrigation session lasting approximately 10–15 min, providing an estimated water volume of 0.3–0.5 L per Hyplug tray pot. A 70% shading netting was provided for optimal light conditions.

During the initial two months of this stage, controlled release fertilizer (SK Cote, 19-10-13+2.5MgO+TE) was applied at 5 g per planting hole, followed by a third-month cessation to encourage natural nutrient uptake and decrease reliance on external fertilizers. As part of a standard pre-nursery practice, proactive pest and disease management was upheld throughout the entire three months, involving rotational chemical sprays—Antracol (50 gm) + Cyper (60 mL), Dithane (50 gm) + Destroy (30 mL), Thiram (50 gm) + Becker (20 gm), and Daconil (50 gm) + Destroy (30 mL)—on a weekly basis in a four-week cycle, effectively safeguarding the oil palm seedlings and promoting their healthy growth. Furthermore, manual weed removal sustained an environment conducive to the seedling development.

At the 3-month mark, the growth parameters of the seedlings, including the leaf appearance, length, number of leaves, and root characteristics, were recorded across three replications. Additionally, a culling rate assessment during the pre-nursery stage was conducted to evaluate seedling viability. The culling rate assessment involved replicating the experiment with 2000 seedlings using topsoil and 2000 seedlings using CPT 3, both as the planting media.

2.3. Compost Usability in Oil Palm Main Nursery Stage (4–12 Months Seedling Planting)

In this stage, 3-month-old seedlings from pre-nursery Hyplug trays were transplanted into the main nursery 15′ × 18′ black polybags, and a rain tape irrigation system was set up for an efficient watering of 1.5 L of water per day. In order to establish an environment conducive to minimizing the risk of disease transmission, optimize sunlight exposure (which proves especially beneficial when the seedlings reach 12 months old and leaf opening becomes crucial), and facilitate efficient maintenance work for the plantation workers, the oil palm seedlings were meticulously arranged with a 3-feet spacing.

During the transplanting process, a controlled-release fertilizer named SK Cote (19-10-13+2.5MgO+TE) was applied at 75 g per polybag, furnishing vital nutrients to support the initial seedling growth. Subsequently, Compound 55 (15/15/6/4) was administered at 20 g per polybag monthly, ensuring a continuous nutrient supply for sustained development in the main nursery. An encompassing pest and disease management program was instituted, involving rotational chemical combinations for control, including Antracol (50 gm) with Cyper (60 mL), Dithane (50 gm) with Destroy (30 mL), Thiram (50 gm) with Becker (20 gm), and Daconil (50 gm) with Destrol (30 mL), applied weekly to prevent resistance. Two weeding methods were utilized to maintain cleanliness and seedling health: interrow spraying with a glufosinate–ammonium-based herbicide and manual weed removal from polybags. These approaches collectively ensured an environment conducive to seedling growth, minimizing the weed competition and optimizing the resource availability while safeguarding against potential negative effects. Parameters were also recorded across three replications, with the leaf appearance, length, seedling height, and root biomass being measured after 12 months.

2.4. Compost Usability in Oil Palm Plantation (5 Years Oil Palm Tree)

This stage aimed to assess the impact of utilizing CPT 3 compost as a soil amendment on mature oil palm trees within a plantation setting. The methodology for this stage is described as follows.

2.4.1. Materials

The central material for this stage was the CPT 3 compost, obtained from the earlier composting optimization stage. The compost was packed in 30 kg bags for their convenient application. Additionally, mature 5-year-old oil palm trees within the plantation served as the subjects of this investigation.

2.4.2. Treatment

The treatment process involved the application of 120 kg of CPT 3 compost per palm tree. One plantation block area of 8 hectares of oil palm trees was included in this treatment and a control block area of 1 hectare did not involve the application of 120 kg of the CPT 3. Four bags, each containing 30 kg of compost, were spread around the base of each tree. Care was taken to ensure an even distribution by starting the application at a distance of 1 m from the tree trunk. The compost was applied directly around the root zone to maximize its interaction with the soil and root system.

2.4.3. Continuation of Fertilization Program

Throughout this stage, the manuring program followed the established plantation fertilization program. A total of four rounds of fertilizer application took place in a year, specifically, one round of 2 kg of Compound 55 (15/15/6/4) and three rounds of 2 kg of compound 45 (12/12/17/2).

2.4.4. Foliar Analysis

Foliar analysis was conducted as a pre-application and post-application assessment to understand the nutrient composition of the leaves before and after the compost application. Prior to applying the compost, three leaf samples were collected from a representative sample of palms across the plantation. These leaves were analyzed to establish a baseline nutrient profile. One year after the compost application, a second round of leaf sampling was performed; three leaf samples were collected from both the treatment block and the control block, and the nutrient composition of the leaves was determined once again.

2.4.5. Data Collection and Analysis

The key data collected during this stage included the nutrient concentrations in the leaves before and after the compost application. The nutrient values were compared to assess any changes resulting from the incorporation of the CPT 3 compost.

2.4.6. Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics version 29.0 Universiti Putra Malaysia Sarawak Edition to determine the significance of any observed differences in the growth performance of the oil palm seedlings planted in the different potting media.

2.4.7. Interpretation of Results

The results of the foliar analysis were interpreted to determine the effectiveness of incorporating the CPT 3 compost as a soil amendment for mature oil palm trees. Any changes in the nutrient concentrations, especially in essential elements for plant growth, were evaluated to assess the benefits of the compost application on tree health and productivity.

3. Results

3.1. Compost Characteristics and Temperature–Moisture Dynamics

3.1.1. Temperature and Moisture

The temperature dynamics of the composting process were investigated across the various compost stockpiles, namely CPT 1, CPT 2, CPT 3, and CPT 4, with the intention of comprehending the decomposition and breakdown of organic materials (refer to Figure 1). CPT 1, CPT 2, and CPT 3 consistently maintained elevated temperatures (45–55 °C) for nearly 70 days throughout the composting duration. This pattern signified the proficient decomposition of organic matter and robust microbial activity. In contrast, CPT 4 displayed a distinct pattern, wherein a rapid temperature increase to 45–51 °C occurred only after 50 days of composting, persisting for 30 days. This suggests a slower composting process. The moisture content across the compost piles was approximately 22%, indicating a notably low level. This reduced moisture content could likely be attributed to the warm weather conditions and the absence of covering for the compost piles to prevent water evaporation.

3.1.2. CPT 1

The CPT 1 compost showcased a pH value of 7.34 and a balanced carbon-to-nitrogen (CN) ratio of 9.5:1, indicating a favorable compost quality. Notably, the CPT 1 displayed a remarkable cation exchange capacity (CEC) of 49.13%, enhancing its nutrient retention potential. The electrical conductivity (EC) of the compost was 2.55 $\pm$ 0.04 dS/m. Furthermore, this compost type exhibited elevated nutrient levels, including phosphate (P) at 7114 ppm, potassium (K) at 9596 ppm, and calcium (Ca) at 25,672 ppm, all contributing to its nutritional richness.

3.1.3. CPT 2

The compost from the CPT 2 exhibited a slightly acidic pH of 6.75, along with a higher CN ratio (10.5:1), an EC of 2.22 $\pm$ 0.02 dS/m, and a CEC of 33.59%. Moderate nutrient levels were observed, including phosphorus (P) at 5918 ppm and potassium (K) at 7484 ppm. Additionally, the CPT 2 displayed a substantial calcium content (Ca) of 45,749 ppm, indicating its potential for supporting plants' physiological processes.

3.1.4. CPT 3

The CPT 3 compost exhibited a slightly acidic pH (6.86), an EC of 2.90 $\pm$ 0.07 dS/m, and a lower CN ratio (6.1:1). With a CEC of 32.38%, it showcased its nutrient retention capacity. Notably, the CPT 3 exhibited moderate phosphorus (P) levels of 5899 ppm and an ample potassium (K) content of 7884 ppm. However, it had relatively lower calcium (Ca) content at 23,700 ppm, potentially affecting the calcium availability to plants.

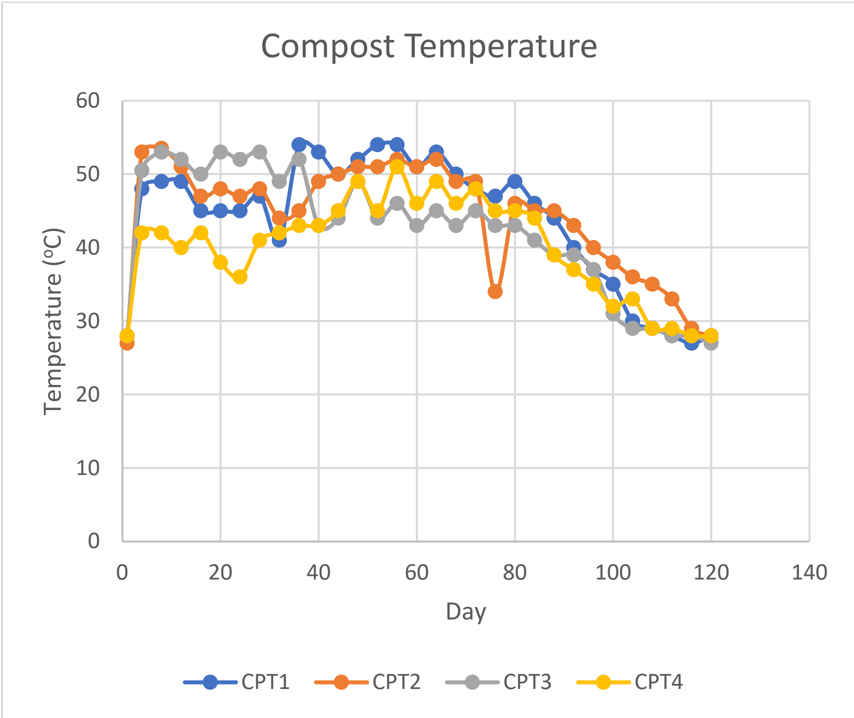

Figure 1. Compost temperature throughout 120 days of composting.

3.1.5. CPT 4

The compost from the CPT 4 had the lowest pH (5.79), suggesting a need for pH adjustment before its application. Its CN ratio was 7.8:1, and it exhibited a CEC of 32.35%. The EC was 2.36 ± 0.05 dS/m. Moderate nutrient levels were found, including phosphorus (P) at 5508 ppm and potassium (K) at 5757 ppm. Furthermore, the CPT 4 displayed an elevated calcium (Ca) content of 23,762 ppm.

3.1.6. Compost Appearance and Texture

All the compost piles (CPT 1, CPT 2, CPT 3, and CPT 4) shared similar attributes in terms of appearance and texture, characterized by a dark gray–brown color, crumbly texture, and moisture content of approximately 20%. This texture facilitated the ease of handling, packing, and transportation.

3.2. Seedling Performance at Pre-Nursery Stage (0–3 Months Seed Planting)

3.2.1. Leaf Appearance, Leaf Length, and Number of Leaves

The compost-amended seedlings (CPT 3) displayed darker green leaves, indicating their robust health and nutrient uptake (Figure 2). In contrast, the topsoil-planted seedlings had lighter green leaves, suggesting a relatively lower nutrient content.

Based on the collected data, significant differences were observed in the growth parameters of the seedlings planted using the compost (CPT 3) compared to those planted using the topsoil. The average leaf length of the compost-amended seedlings was measured at 27 cm, whereas the topsoil-planted seedlings exhibited an average leaf length of 18 cm. This highlights a clear advantage for the compost-amended group, indicating their superior growth in terms of leaf length.

Furthermore, when considering the number of leaves, the compost-amended seedlings (CPT 3) displayed an average of four leaves, whereas the topsoil-planted seedlings averaged three leaves. This disparity in leaf production underscores the enhanced growth and development of the compost-amended seedlings, reflecting their overall better performance.

Figure 2. Compost-amended seedlings (CPT 3) displayed darker and longer green leaves.

3.2.2. Root Appearance and Root Biomass

The compost-amended seedlings (CPT 3) showcased well-developed root systems with distinct primary and secondary roots (Figure 3), reflecting their health and vigorous growth. Their vibrant color indicated an efficient nutrient uptake. These seedlings had a greater number of thicker and longer roots compared to the topsoil-planted seedlings. The latter displayed paler, thinner, and shorter roots, suggesting their relatively slower development and nutrient uptake.

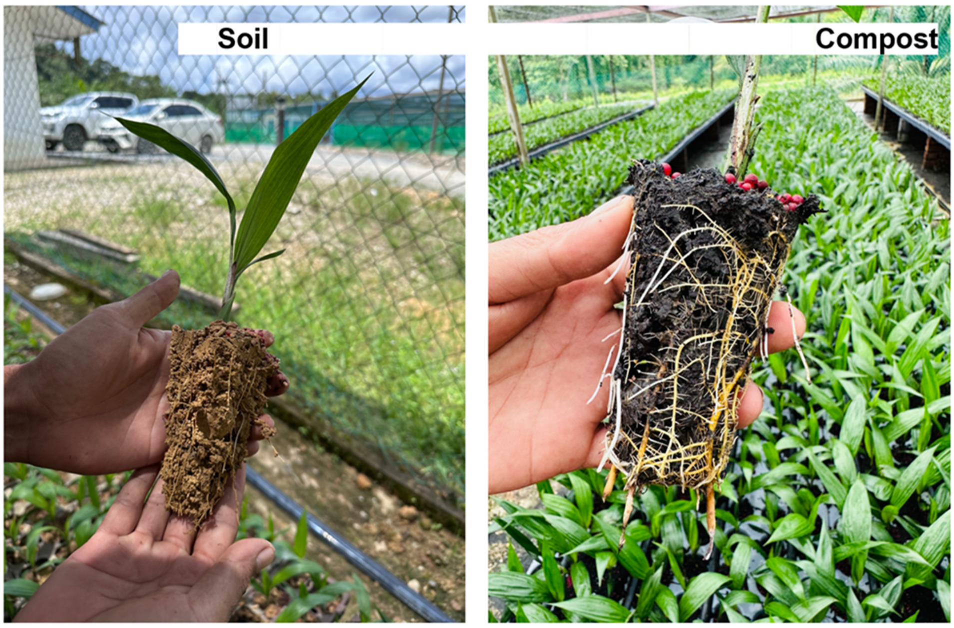

Figure 3. Compost-amended seedlings (CPT 3) had more established root system.

3.2.3. Culling Rate

In the pre-nursery stage, the topsoil-planted seedlings exhibited a culling rate of 4.4%, while compost-amended seedlings (CPT 3) had a slightly higher culling rate of 6.09%.

However, the culling rate for both the topsoil and compost was below the maximum acceptable rate of 15%, suggesting the potential suitability of palm oil waste-derived compost as a potting medium.

3.3. Seedling Performance at Main Nursery Stage

The performance of the seedlings at the main nursery stage was evaluated when the CPT 3 compost was used as the planting medium, and a comparison was made against traditional soil-based planting. The growth parameters, including growth rate and leaf length, were analyzed to assess the impact of the planting medium on the seedling development.

3.3.1. Growth Rate

The seedlings planted using the CPT 3 compost demonstrated a significantly improved growth rate (Table 2) compared to those planted in the soil. The growth in the height of the CPT 3-amended seedlings was observed to be 20% higher than that of the soil-planted seedlings. This notable difference suggests that the compost-enriched medium provides essential nutrients and conditions that promote faster and healthier growth during the main nursery stage.

Table 2. Growth performance of oil palm seedlings under different potting media.

Planting Media	Seedling Height (mm) After 12 Months	Stem Girth (mm) After 12 Months	Root Biomass (g) After 12 Months
Soil	1455.56 ± 8.172^{b}	31.92 ± 0.743^{b}	24.94 ± 0.439^{b}
Compost CPT 3	1748.00 ± 9.852^{a}	44.34 ± 2.210^{a}	33.52 ± 0.507^{a}

Means with the same superscript letter in the column were not significantly different at $p \leq 0.05$ using Mann–Whitney U test.

3.3.2. Leaf Length

The leaf length of the seedlings was measured as an indicator of their overall vigor and health. The seedlings grown in the CPT 3 compost medium exhibited consistently longer leaves compared to those planted in the soil (Table 3). On average, the CPT 3-amended seedlings had leaves that were 20–40% longer than their soil-planted counterparts. This indicates that the compost medium not only supports increased growth but also contributes to enhanced leaf development, potentially leading to better photosynthetic efficiency and overall plant vitality.

Table 3. Oil palm seedlings leaf width and number under different potting media.

Planting Media	Leaf Width (mm) After 9 Months	Leaf Number After 9 Months
Soil	21.40 ± 5.502^{b}	13.20 ± 1.135^{a}
Compost CPT 3	28.60 ± 6.535^{a}	13.80 ± 0.789^{a}

Means with the same superscript letter in the column were not significantly different at $p \leq 0.05$ using the Mann–Whitney U test.

3.3.3. Root Development

Root development is crucial for establishing strong and resilient plants. The seedlings grown in the CPT 3 compost showed a remarkable root system development, with roots that were denser, longer, and more extensively branched compared to those grown in the soil. This enhanced root development is indicative of their improved nutrient and water uptake capabilities, contributing to the robustness of the seedlings.

3.3.4. Overall Health and Vigor

A visual assessment of the seedlings' overall health and vigor further reinforced the advantages of using the CPT 3 compost as a planting medium. The CPT 3-amended seedlings displayed a more vibrant and lush appearance, characterized by dark green leaves and a more pronounced and healthy stem. In contrast, the soil-planted seedlings exhibited a slightly paler appearance with a comparatively less vigorous growth.

The data obtained from this stage of the study reaffirm the positive impact of the CPT 3 compost as a potting medium during the main nursery stage. The increased growth rate, enhanced leaf length, improved root development, and overall health of the seedlings suggest that utilizing the CPT 3 compost can contribute to the successful cultivation and development of robust plants in the main nursery phase.

3.4. Year 5 Oil Palm Tree Performance

In the fifth year of their growth, the performance of the oil palm trees was assessed based on a foliar analysis to evaluate the impact of supplementing with the CPT 3 compost on the nutrient content in the palm fronds. The study aimed to determine whether the annual supplementation of 120 kg of the CPT 3 compost per palm influenced the nutrient composition of the palm fronds compared to the palms without the supplementation.

3.4.1. Nutrient Content in Palm Fronds

The palm fronds from the trees supplemented with the CPT 3 compost exhibited notable differences in their nutrient content compared to those without the supplementation. The analysis revealed that the palms receiving the compost supplementation demonstrated a higher increment in their nitrogen and phosphorous content within the palm fronds. Specifically, the nitrogen content increased by 13.57%, and the phosphorus content increased by 6.72%. In contrast, the palms without the compost supplementation showed a comparatively lower increment in the nitrogen content, at 3.43%, and phosphorus content, at 2.24%. Both groups of palms showed an increment in the boron content, with an increase of approximately 17.8–17.92%. This increment in the boron content was observed irrespective of the compost supplementation.

3.4.2. Potassium and Magnesium Content

Interestingly, all the palms, regardless of whether they received the compost supplementation, exhibited a reduction in their potassium and magnesium content as they matured into five-year-old palms.

Among the palms supplemented with the CPT 3 compost, the reduction in the potassium and magnesium content was more significant. The potassium content was reduced by 38.10%, and the magnesium content was reduced by 41.38%. In comparison, the palms without the compost supplementation experienced a reduction of 6.94% in the potassium content and 28% in the magnesium content.

4. Discussion

The comprehensive results obtained from the composting process, pre-nursery stage, main nursery stage, and performance of the oil palm trees provide a holistic understanding of the potential benefits and challenges associated with the use of the CPT 3 compost in oil palm cultivation.

The temperature and moisture profiles observed during the composting process provide insights into the effectiveness of the different composting methods (CPTs). The sustained high temperatures in the CPT 1, CPT 2, and CPT 3 indicate efficient decomposition and microbial activity, leading to the breakdown of organic materials into stable compost. The attainment of temperatures ranging from 45 °C to 55 °C during the composting plays a crucial role in ensuring the production of top-quality compost. A primary aim of composting is to decrease detrimental microorganisms to levels that ensure the protection of public well-being and the ecosystem [20]. This objective is commonly considered accomplished when the end product shows no indications of pathogens [21]. Of special note are enteric organisms, encompassing bacteria, viruses, protozoa, and helminths, which prompt specific apprehensions [22] due to their potential to endanger human health and the environment. In contrast to enteric sources, fungi are not encompassed in the regulations set by the USEPA [21].

Numerous biological processes come into play during composting, collectively contributing to the reduction in pathogens. These include the competition between native microorganisms and pathogens, antagonistic interactions, the specific fungi and actinomycetes producing antibiotics, natural die-off in the composting environment, the generation of toxic byproducts like gaseous ammonia, nutrient depletion, and thermal destruction [23–26]. Among these mechanisms, elevated temperatures are consistently regarded as the most reliable method for sanitizing compost [27]. These temperatures not only offer dependability but also present a practical factor for facility operators to monitor and manage, often being stipulated by regulatory bodies as an effective means of pathogen elimination [25].

The EPA's 40 CFR Part 503 [28] classifies biosolids into two categories based on the extent of the pathogen reduction achieved within the solids: Class A and Class B. To qualify as Class A, the Part 503 Rule mandates that the composting process sustains a temperature of at least 55 °C for a minimum of three days, effectively eradicating pathogens. For Class B, these regulations outline that a substantial pathogen reduction can be accomplished through composting by maintaining a minimum operating temperature of 40 °C for five days, with temperatures exceeding 55 °C for at least four hours within this period, particularly for Class B finished products. Importantly, all our compost batches, including the CPT 1, CPT 2, CPT 3, and CPT 4, satisfy the thermal destruction requirements stipulated by these regulations.

It is worth noting that incorporating EFB within the composting process yields evident advantages. In the context of aerated static pile composting (CPT 3), EFB serve as a valuable bulking agent, enhancing airflow and promoting composting without requiring manual turning. However, it is crucial to recognize that periodically turning the compost, especially when the temperature exceeds 60 °C, can expedite the overall process while also ensuring that beneficial microbes are not eliminated. Moreover, the absence of turning can result in localized high temperatures and anaerobic production within the pile. This, in turn, encourages the generation of CH_4 and the loss of nutrients [29].

The nutrient content in different CPTs reflects their potential as organic fertilizers. CPT 1 displayed a balanced nutrient profile with a higher CEC and greater levels of total potassium and total phosphorus, indicating its suitability for nutrient supplementation. CPT 2 exhibited a slightly acidic pH and higher carbon-to-nitrogen ratio, which could influence its nutrient release and microbial activity. CPT 3's lower pH and nitrogen-rich composition align well with plant nutrient requirements. CPT 4, with its lower pH (5.79) and balanced nutrient ratios, presents a viable option for specific soil conditions.

The pre-nursery stage revealed valuable insights into the seedling growth and survival when using the CPT 3 compost as a planting medium. The seedlings planted using the CPT 3 compost exhibited a superior leaf appearance, longer leaf lengths, and a higher number of leaves compared to those planted using the topsoil. The notable nitrogen content within the CPT 3 compost could be a contributing factor to this observation. Nitrogen, a vital growth element, plays a pivotal role in stimulating lush, leafy growth. As a fundamental component of proteins, it is integral to the makeup of every living cell. Consequently, this element holds greater responsibility for enhancing plant growth than any other nutrient [30,31]. Within plants, nitrogen undergoes conversion into amino acids, the fundamental building blocks of proteins. Given that enzymes are proteins, nitrogen is essential for catalyzing enzymatic reactions within plants. Furthermore, as an essential part of the chlorophyll molecule, nitrogen directly participates in the process of photosynthesis. It aids in the production and utilization of carbohydrates by the plant and even forms a crucial part of plant DNA.

The development of greener and longer leaves in seedlings is the result of a combination of vital factors. Adequate nutrient availability, particularly nitrogen, contributes to lush growth by serving as a building block for chlorophyll, the pigment responsible for photosynthesis. Efficient photosynthesis, facilitated by proper light exposure, further promotes energy production and leaf expansion. Alongside this, appropriate water supply ensures cell turgidity, supporting overall leaf structure and function. Optimal temperature and air circulation play crucial roles in maintaining ideal growth conditions, while a well-developed root system aids in nutrient and water uptake. Additionally, the quality of the growing medium, genetics, and careful pest and disease management all contribute to fostering robust seedling growth with vibrant, healthy leaves. These factors collectively create an environment conducive to producing seedlings with thriving, green foliage, setting the stage for successful plant development. This suggests that the CPT 3 compost provides favorable conditions for seedling growth and nutrient uptake, potentially due to its enriched nutrient content and improved soil structure. However, the slightly higher culling rate observed in the CPT 3 group emphasizes the importance of precise moisture management to avoid waterlogging.

However, this study observed a slightly higher culling rate during the prenursery phase when utilizing the compost as a potting medium (6.09%), in comparison to using the topsoil (4.4%). This divergence could be attributed to the specific inherent characteristics of compost that potentially influence seedling growth. Of notable importance is compost's ability to retain a substantial concentration of soluble or exchangeable salts, evident from its elevated CEC (32.38%). This quality, in turn, might have implications for seedling development.

The presence of excess soluble salts (electrical conductivity, EC5 > 5 dS m^{-1}) within compost as measured, including ions such as Ca^{2+}, K^+, Mg^{2+}, and Na^+, could result in soil water solute concentrations surpassing those found in plant root cells. Consequently, the osmotic potential diminishes, potentially impeding plant water uptake and thereby hindering growth [32]. However, this scenario is likely not applicable to this experiment since the electrical conductivity (EC) of the compost used was measured at 2.90 ± 0.07 dS m^{-1}, which falls within the range indicative of good-quality compost, specifically, less than 3 dS/m. It is worth noting, though, that, because the EC is hovering at the upper edge of this maximum range, it could potentially exert some stress on the seedlings. Despite this, the overall culling rate remains within an acceptable range and is not significantly distant from that of the control group. If this is the case, this emphasizes the importance of careful consideration for the quality of compost, particularly its salt content, when designing potting media. Striking a balance between compost and topsoil within the mixture could mitigate adverse effects arising from heightened salt concentrations. This approach could foster growth while maintaining a culling rate at an acceptable level. Nevertheless, it is worth noting that the culling rate associated with using CPT 3 falls within the acceptable range (less than 15%).

4.1. Main Nursery Stage and Growth Performance

Transitioning to the main nursery stage, oil palm trees planted using the CPT 3 compost demonstrated an enhanced growth performance in terms of their growth rate and leaf length compared to those planted using the soil. This suggests that the CPT 3 compost continued to provide beneficial conditions for the palm growth and nutrient uptake as the trees matured. The improved growth rate aligns with the nutrient enrichment observed in the pre-nursery stage, further emphasizing the potential of the CPT 3 compost as a sustainable planting medium.

Compost stands as a potent reservoir of organic matter and vital nutrients, exerting a pivotal influence on fostering critical growth factors within plants. A compendium of prior research consistently underscores the advantageous effects of compost in augmenting plant growth and developmental processes [33,34]. In agricultural contexts, soils enriched with compost have demonstrated a substantial elevation in plant growth, yield, and nutrient assimilation, outperforming their non-amended counterparts across various crops such as maize and tomatoes. The findings of this study underscore the applicability of oil palm waste compost in stimulating the growth and development of oil palm seedlings, further solidifying compost's role in sustainable agricultural practices.

Compost actively contributes to growth promotion by bolstering soil structure and bolstering water-retention capabilities. Through the infusion of organic matter, compost facilitates soil aggregation, mitigating compaction and fostering improved root penetration. This augmented exploration of roots, as visually represented in Figure 3, facilitates a heightened accessibility to water and nutrients, thus optimizing their uptake by plants. Moreover, compost serves as a reservoir for nutrients, orchestrating a gradual and controlled release during decomposition, thereby guaranteeing a consistent and enduring nutrient provision for plant sustenance.

Overall, compost's contribution to promoting vital growth factors is multifaceted, encompassing improved soil structure, enhanced nutrient availability, and increased water-holding capacity. Incorporating compost into planting regimes offers a sustainable approach to harnessing these benefits and fostering healthy plant growth.

4.2. Year 5 Oil Palm Tree Performance

Assessing foliar composition holds significance due to leaves being recognized as both a repository and a reservoir of nutrients, constituting a substantial segment of the overall vegetative biomass. In the context of a five-year-old Tenera oil palm, the leaves account for approximately 65% of the entire vegetative biomass [35].

Compared to the previous year, the five-year-old palms displayed an increase in the nitrogen (N), phosphorus (P), and boron (B) content in their fronds, especially those supplemented with the CPT 3 compost. The palms treated with the compost amendments exhibited a significant 13.57% growth in their nitrogen content and a more moderate 6.72% increase in the phosphorus. Conversely, the palms without the compost showed minor changes, with their nitrogen and phosphorus levels growing between 2.19% and 2.94%.

These findings deviate from the observations of Siang et al. and Ng et al. [36,37], who noted decreasing nitrogen (N) and phosphorus (P) concentrations as palm trees aged, notably within the trunk. However, our experiments focused on fronds, aligning with the results of Henson and Chang [37]. Their analysis of published nutrient concentration data revealed decreasing concentrations of N and P within the trunk over time. Nevertheless, the concentrations of N, P, and potassium (K) in other palm tissues remained relatively stable. This consistency between our results and the findings of Henson and Chang [37] underscores the significance of considering specific palm tissues and nutrient dynamics when evaluating changes in nutrient concentrations over time.

However, we observed a decline in the potassium (K), magnesium (Mg), and boron (B) content in the fronds one year after the experiment. Siang et al. [36] conducted a comprehensive study spanning 238 months of palm growth and emphasized the pivotal role of potassium (K) as the most critical nutrient, comprising 54% of the total nutrient requirement, followed by nitrogen (N) at 25%. And data from Siang et al. [36] revealed that fruit bunches were responsible for absorbing a substantial portion, ranging from 37% to 54%, of essential nutrients such as N, phosphorus (P), magnesium (Mg), calcium (Ca), and boron (B) in Tenera palms throughout various growth stages. Intriguingly, potassium (K) displayed a lower allocation to fruit bunches, typically ranging between 19% and 36%. This suggests that potassium (K) may predominantly accumulate within the palm trunk and/or fronds. Consistent with prior research [38,39], higher potassium (K) concentrations were found in all the vegetative tissues, especially in the trunk. Given the substantial demand for potassium (K), the observed reduction in the K content in the fronds one year later may signify an insufficient supply.

Siang et al. [36] suggested that the greatest need for nitrogen (N), phosphorus (P), magnesium (Mg), calcium (Ca), and boron (B) occurred around month 209, corresponding to the period of the highest fruit bunch production. In contrast, the peak requirement for potassium (K) was observed at month 88, which followed nursery planting and marked the pinnacle of vegetative growth. Therefore, for young mature palms aged between 4 and 8 years, we can anticipate a surge in potassium (K) demand. A deficiency in potassium (K) can manifest in symptoms such as leaf yellowing, the browning of leaf edges, and the development of "leaf scorch". These symptoms arise from potassium's role in maintaining water balance within plant cells. Sufficient potassium levels are vital for proper water movement and stomatal regulation, which in turn prevent excessive water loss from leaves and subsequent damage. However, these symptoms were not notably present in our experimental plot, suggesting that the potassium (K) supply was not significantly deficient.

The demand for magnesium (Mg) is also substantial. Both potassium (K) and magnesium (Mg) are mobile nutrients in plants, readily transported through the plant's vascular system. These nutrients are essential for vital physiological processes and robust plant growth. Due to their mobility, potassium (K) and magnesium (Mg) swiftly reach actively growing tissues, particularly in young leaves and meristematic regions. When these nutrients are scarce, deficiency symptoms typically emerge first on older, lower leaves because the plant prioritizes supplying them to younger tissues critical for growth and reproduction. As a result, older leaves become more vulnerable to deficiency symptoms.

Magnesium deficiency often manifests as interveinal chlorosis, where the areas between leaf veins turn yellow while the veins themselves remain green. This occurs because magnesium is a central component of the chlorophyll molecule, crucial for photosynthesis. Inadequate magnesium leads to impaired chlorophyll production and photosynthesis, resulting in reduced energy production and growth. However, these symptoms were also not evident in our experimental plots. Thus, magnesium deficiency may not account for the slight reduction in the magnesium levels in the fronds.

Our findings strongly indicate that the CPT 3 compost, which was rich in supplementation, had a positive influence on nutrient uptake, a vital factor in maintaining palm health and productivity. However, it is important to note that assessing the nutrient uptake solely from a leaf nutrient analysis may not provide a comprehensive picture. Nutrients are also present in substantial concentrations in other vegetative tissues like in the rachis, petiole, leaf bases, and trunk.

Nevertheless, based on these results, we can align with previous research suggesting that, to ensure adequate nutrient supplementation, particularly in peat soils, it is advisable to aim for a K to N ratio exceeding three [40]. This entails applying three times more K2O than nitrogen (N) for optimal results.

4.3. Implications for Sustainable Agriculture and Future Directions

Collectively, the results suggest that the CPT 3 compost holds promise as a viable alternative to traditional planting media and synthetic fertilizers in oil palm cultivation. Its positive impact on the nutrient availability, growth performance, and overall plant health aligns with the principles of sustainable agriculture. Utilizing compost not only enriches the soil with organic matter but also promotes nutrient cycling, reduces reliance on chemical fertilizers, and enhances soil structure and water-holding capacity.

While the current study provides valuable insights, further research is needed to explore the long-term effects of the CPT 3 compost supplementation on oil palm growth, nutrient dynamics, and yield. Longitudinal studies that track the trees over multiple growth cycles would provide a more comprehensive understanding of the sustained benefits of compost supplementation. Additionally, investigating the microbial communities in soils amended with the compost could shed light on the mechanisms underlying nutrient release and uptake.

5. Conclusions

In conclusion, this study's integrated findings from the composting, pre-nursery, main nursery, and palm tree performance stages collectively underscore the potential benefits of utilizing the CPT 3 compost in oil palm cultivation. The results demonstrate its capacity to enrich soil nutrient content, enhance seedling and tree growth, and contribute to sustainable agricultural practices. However, the complex interactions between compost composition, nutrient dynamics, and plant requirements highlight the need for tailored nutrient management strategies for optimal results in various growth stages.

The use of a large compost stockpile in this study, aimed at simulating real-life conditions, limited the available space and feedstock, restricting our ability to test a broader range of composting ratios. Expanding future studies to include more ratios could lead to shorter composting times and improved compost quality.The present study provides a comprehensive evaluation of compost derived from palm oil mill waste, demonstrating its potential as a sustainable alternative for the oil palm plantation sector. The results of the plant growth further strengthen this potential, showcasing the effectiveness of the compost in supporting healthy seedling development. Furthermore, the data from this research may provide solid evidence supporting the value of composting palm oil mill waste, demonstrating its effectiveness within a circular economy.

One disadvantage of this study is that the composting process requires additional space, time, and costs, which may impact nursery or plantation operations. From an economic perspective, this could lead to increased operational expenses associated with the composting process. Additionally, not all plantations or nurseries are located near palm oil mills, making the transportation of waste or composted soil challenging. This logistical issue could complicate the implementation of a circular economy.

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