Nucleus Journal
Jurnal Sains dan Teknologi
Website: https://ejournal.undar.or.id/index.php/Nucleus
e-ISSN: 2964-4100
p-ISSN: 2964-4097

Turning Waste into Value: Biodecomposition of Oil Palm Trunk Biomass for Sustainable Compost Fertilizer Production

[1*] Nina Veronika, [2]Sri Wahyuni, [3]Nur Asma Deli, [4]Hayatul Khairul Rahmat, [5]Barokat Mamah
[1,2,3] Department of Palm Oil Processing Technology, Politeknik Kampar, Bangkinang, Indonesia
[4] Department of Environmental Sciences, Graduate School, Universitas Negeri Padang, Padang, Indonesia
[5] Department of Mathematics and Computer Science, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[1] nina@poltek-kampar.ac.id, [2] u_nie@poltek-kampar.ac.id, [3] nurasmadeli@poltek-kampar.ac.id,
[4] hayatul.rahmat@student.unp.ac.id, barokat.mamah@gmail.com

Article Info

Article history:

Received 8 March 2026
Revised 1 April 2026
Accepted 26 April 2026

Keyword:

Oil Palm Trunk Waste
Composting
Biodecomposition
Organic Fertilizer
Biomass Utilization

ABSTRACT

The rapid expansion of the oil palm industry has generated a substantial volume of lignocellulosic biomass waste, particularly oil palm trunk (OPT) residues from replanting activities. While previous studies have extensively explored the composting of oil palm by-products such as empty fruit bunches and fronds, limited attention has been given to the biodecomposition of OPT, especially in relation to compost maturity and nutrient stabilization. This study addresses this gap by evaluating the feasibility of converting OPT biomass into organic compost through an aerobic biodecomposition process using microbial activation. An experimental approach was employed using chopped OPT biomass combined with organic additives and a microbial activator under controlled composting conditions. Key physicochemical parameters, including moisture content, organic carbon, C/N ratio, pH, and macronutrient content ($N + P_2O_5 + K_2O$), were monitored to assess compost quality and maturity. The results showed that moisture content ranged from 9.47% to 26.5%, organic carbon from 46.3% to 52.1%, C/N ratio from 20.2 to 21.9, pH from 7.58 to 8.00, and total macronutrients from 7.03% to 8.74%. The observed reduction in C/N ratio and stabilization of pH indicate progressive biodegradation of lignocellulosic components and the formation of mature compost. Variations among treatments suggest that differences in substrate composition and microbial activity significantly influence decomposition efficiency and nutrient mineralization. Overall, the compost products met all tested quality parameters based on SNI 7763:2024 for solid organic fertilizers. This study highlights the potential of OPT biomass as an underutilized resource for sustainable compost production and contributes to the development of circular biomass management strategies in oil palm plantations.

DOI: https://doi.org/10.32492/nucleus.v5i1.5101

Corresponding Author:
Nina Veronika
Kampar Polytechnic, Bangkinang, Indonesia
Address: Jl. Tengku Muhammad KM.2, Batu Belah, Bangkinang District, Kampar Regency, Riau 28463
Email: nina@poltek-kampar.ac.id

I. INTRODUCTION

The rapid expansion of the oil palm industry has played a crucial role in meeting the global demand for vegetable oil and supporting economic development in many tropical countries, particularly in Indonesia and Malaysia [1], [2], [3]. Oil palm plantations cover millions of hectares and contribute significantly to agricultural productivity, export revenues, and rural livelihoods. However, alongside its economic benefits, the industry also generates substantial amounts of biomass waste throughout the production cycle, including empty fruit bunches, palm fronds, palm kernel shells, and oil palm trunks. Among these, oil palm trunk waste generated from replanting activities represents one of the largest but least utilized biomass resources in oil palm plantations.

Oil palm trees generally have a productive lifespan of approximately 25–30 years. After this period, plantations undergo replanting programs to maintain productivity, resulting in the removal of old palm trees. This process generates a large volume of oil palm trunk biomass that is often left in the field or disposed of through burning. Such practices can lead to several environmental issues, including greenhouse gas emissions, soil degradation, and inefficient use of organic resources. Therefore, effective management and utilization of oil palm trunk waste are essential for improving the sustainability of the oil palm industry [4], [5].

Oil palm trunk biomass contains significant amounts of lignocellulosic materials, including cellulose, hemicellulose, and lignin. These components provide a rich source of organic matter that can potentially be converted into valuable agricultural inputs such as organic fertilizers or compost. Composting is a biological decomposition process in which microorganisms break down complex organic materials into stable humus-like substances that are beneficial for soil fertility [6], [7], [8]. Through composting, agricultural residues can be transformed from waste materials into valuable resources that contribute to nutrient cycling and sustainable soil management.

The application of compost derived from agricultural biomass has been widely recognized for its positive impacts on soil health and crop productivity. Organic compost improves soil structure, enhances water retention capacity, increases microbial activity, and supplies essential nutrients for plant growth [9], [10]. In contrast to synthetic fertilizers, which may cause soil acidification and environmental contamination when used excessively, organic fertilizers provide a more environmentally friendly approach to maintaining soil fertility. Therefore, the conversion of oil palm trunk waste into compost can provide a sustainable alternative to chemical fertilizers while simultaneously addressing the issue of agricultural waste management.

In recent years, the concept of circular economy has gained increasing attention in agricultural and environmental management. Circular economy principles emphasize resource efficiency, waste reduction, and the reuse of materials within production systems. In the context of oil palm plantations, the valorization of biomass waste through composting aligns with these principles by transforming plantation residues into useful agricultural products. This approach not only reduces environmental impacts but also supports sustainable agricultural practices by returning nutrients to the soil.

Despite the significant potential of oil palm trunk biomass for compost production, several challenges remain in the biodecomposition process. One of the main limitations is the high lignin content in oil palm trunks, which slows down microbial degradation and prolongs the composting process. Lignin is a complex aromatic polymer that is resistant to microbial breakdown, making lignocellulosic biomass more difficult to decompose compared to other organic materials. As a result, effective composting of oil palm trunk waste often requires the use of microbial decomposers or compost activators to accelerate the biodegradation process.

Biodecomposition technology plays an important role in improving the efficiency of composting processes. Various microorganisms, including bacteria, fungi, and actinomycetes, are capable of producing enzymes that degrade cellulose, hemicellulose, and lignin. The use of microbial inoculants can significantly enhance the rate of organic matter decomposition and improve the quality of the resulting compost [11], [12], [13], [14], [15]. By optimizing microbial activity, the composting process can be accelerated, and nutrient availability in the final product can be improved.

Furthermore, compost derived from oil palm biomass has the potential to support sustainable agriculture by reducing dependency on chemical fertilizers and improving soil quality. The integration of organic waste recycling into plantation management systems also contributes to environmental conservation by reducing waste accumulation and minimizing pollution. In addition, the use of organic compost can improve soil organic carbon levels, which is an important factor in mitigating climate change through carbon sequestration in agricultural soils.

Although several studies have explored the utilization of oil palm residues such as empty fruit bunches and palm fronds for compost production, research focusing specifically on oil palm trunk waste remains relatively limited [16], [17], [18], [19]. Existing studies have primarily emphasized general composting performance or nutrient content, with limited investigation into the biodecomposition dynamics of lignocellulosic materials and their relationship to compost maturity indicators. In particular, there is a lack of systematic analysis examining how variations in substrate composition and microbial activity influence key physicochemical parameters such as C/N ratio, organic carbon transformation, pH stabilization, and nutrient mineralization during the composting of oil palm trunk biomass. This gap restricts a comprehensive understanding of the mechanisms governing compost maturity and limits the optimization of composting strategies for this specific biomass resource.

Therefore, this study aims to examine the potential utilization of oil palm trunk waste as compost fertilizer through biodecomposition processes. The novelty of this study lies in its focus on oil palm trunk biomass as an underutilized lignocellulosic resource, combined with a systematic evaluation of compost maturity based on physicochemical parameters and their linkage to biodecomposition mechanisms. By converting plantation biomass waste into valuable organic fertilizer, this research contributes to sustainable waste management and supports environmentally friendly agricultural practices. The findings of this study are expected to provide scientific insights into the optimization of composting processes and promote the adoption of circular resource management in oil palm plantation systems.

II. Research Methods

A. Research Design

This study employed an experimental approach using a completely randomized design (CRD) to evaluate the biodecomposition of oil palm trunk (OPT) biomass into compost. Five composting treatments were established based on different substrate compositions and the use of microbial activators. Each treatment was conducted in triplicate, resulting in a total of 15 experimental units. The treatments were defined as follows:

1. Compost 1 (C1): OPT + cattle manure (1:1, w/w) + EM4
2. Compost 2 (C2): OPT + cattle manure (2:1, w/w) + EM4
3. Compost 3 (C3): OPT only + EM4
4. Compost 4 (C4): OPT + cattle manure (1:2, w/w) + EM4
5. Compost 5 (C5): OPT + cattle manure (1:1, w/w) without activator (control)

This experimental setup was designed to assess the effects of substrate composition and microbial activation on compost maturity and nutrient characteristics.

B. Materials and Composting Procedure

The primary material used in this study was oil palm trunk waste obtained from plantation replanting activities in Indonesia. Oil palm trunk biomass contains high lignocellulosic components that require microbial degradation to accelerate decomposition [20], [21]. Prior to composting, the trunks were chopped into smaller pieces to increase surface area and facilitate microbial activity.

An organic microbial activator such as Effective Microorganisms (EM) was added to enhance the biodecomposition process. The composting process followed an aerobic method, which is widely used in organic waste management due to its efficiency and environmental safety [20]. The mixture of oil palm trunk biomass and microbial activator was arranged in composting piles with a moisture content maintained at approximately 50–60%, which is considered optimal for microbial growth [22]. The compost piles were periodically turned to ensure adequate aeration and uniform decomposition. The composting process was conducted for approximately 30–60 days until the compost reached maturity.

C. Data Collection

Data were collected periodically throughout the composting process to monitor physical and chemical changes in the compost material. The parameters observed included:

1. Temperature, measured daily to monitor microbial activity and identify composting phases such as mesophilic and thermophilic stages [23].
2. Moisture content, maintained between 50–60% to support optimal microbial metabolism [24].
3. pH, measured using a digital pH meter to determine acidity levels during the composting process.
4. C/N ratio, analyzed as an important indicator of compost maturity and stability.
5. Nutrient content (N, P, K), analyzed in the final compost to evaluate fertilizer quality and its suitability for agricultural application [25].

D. Data Analysis

The collected data were analyzed using descriptive statistical methods to evaluate trends and variations among treatments. The results were presented in the form of tables and graphs to illustrate the biodecomposition process and compost quality. Comparative analysis was conducted to assess the influence of treatment variations on key composting parameters [24].

III. RESULTS AND DISCUSSION

The composting process is a bioconversion activity in which organic materials are transformed into more stable compounds through the activity of microorganisms. During this process, part of the energy generated from decomposition is utilized for microbial cell growth, while the remaining energy is released as heat. The success of composting is largely determined by the characteristics of the raw materials, particularly the carbon-to-nitrogen (C/N) ratio, moisture content, pH, aeration, and temperature during the process [26]. Optimal micro-environmental conditions, such as moisture levels of 50–60%, thermophilic temperatures ranging from 50–65°C, and periodic turning of the compost pile, play an important role in maintaining microbial activity and accelerating the decomposition process [27].

Composting of oil palm trunks is carried out to accelerate the degradation of lignocellulosic compounds present in oil palm trunk biomass through the assistance of decomposer microorganisms. The main stages of this process include raw material preparation, chopping, mixing with supplementary materials, fermentation, and compost quality analysis. Finely chopped oil palm trunks facilitate the mixing process and increase the surface area available for microbial activity. The addition of animal manure serves as a nitrogen source and enriches nutrients required for microbial growth [28].

The composting process typically lasts for 30–60 days until the compost reaches maturity, which is indicated by stabilized temperature, a near-neutral pH (6.5–7.5), and a C/N ratio of ≤20. Laboratory analysis of oil palm trunk compost includes parameters such as moisture content, pH, temperature, C/N ratio, organic carbon content, and the concentration of macronutrients (N, P, and K). This evaluation aims to ensure that the quality of the produced compost meets the Solid Organic Fertilizer Quality Standards according to SNI No. 7763: 2024 [29], as presented in **Table 1.**

Table 1. Quality Standards for Solid Organic Fertilizer According to Indonesian National Standard (SNI 7763:2024)

No	Parameter	Unit	Quality Standard
1	Foreign materials (glass fragments, plastic, gravel, and/ or meta)	%	Max. 2
2	Moisture content	%	8 – 25
3	Organic Carbon (C-organic)	%	Min. 15
4	C/N Ratio	–	Max. 25
5	pH	–	4 – 9
6	Heavy metals		
	Mercury (Hg)	mg/kg	Max. 1
	Lead (Pb)	mg/kg	Max. 50
	Cadmium (Cd)	mg/kg	Max. 2
	Arsenic (As)	mg/kg	Max. 10
	Chromium (Cr)	mg/kg	Max. 180
	Nickel (Ni)	mg/kg	Max. 50
7	Macronutrients ($N + P_2O_5 + K_2O$)	%	Min. 2
8	Micronutrients		
	Total Fe	ppm	Max. 15,000
	Available Fe	ppm	Max. 1,000
	Total Zn	ppm	Max. 5,000
9	Particle size (2 – 4.75 mm)*	%	Min. 60
10	Particle hardness*	–	50 – 90
11	Bulk density*	g/ml	0.7 – 0.9
12	Microbial contamination		
	Escherichia coli	MPN/g	$<10^2$
	Salmonella spp.	MPN/g	$<10^2$

However, in this study, the analysis was limited to several parameters, including moisture content, organic carbon (C-organic), C/N ratio, pH, and macronutrient content ($N + P_2O_5 + K_2O$). The results of the compost fertilizer analysis are described as follows.

First, moisture content. Moisture content is an important parameter in the composting process because it directly influences microbial activity, pile temperature, and the rate of organic matter decomposition. Water functions as a medium for biochemical reactions that enable microorganisms to break down organic materials into simpler compounds [30]. Excessive moisture can inhibit oxygen diffusion and create anaerobic conditions, while insufficient moisture can slow down microbial activity and the decomposition process [31]. Therefore, maintaining an optimal moisture level is essential for producing high-quality compost. Figure 1 presents the results of the moisture content analysis for each compost fertilizer sample.

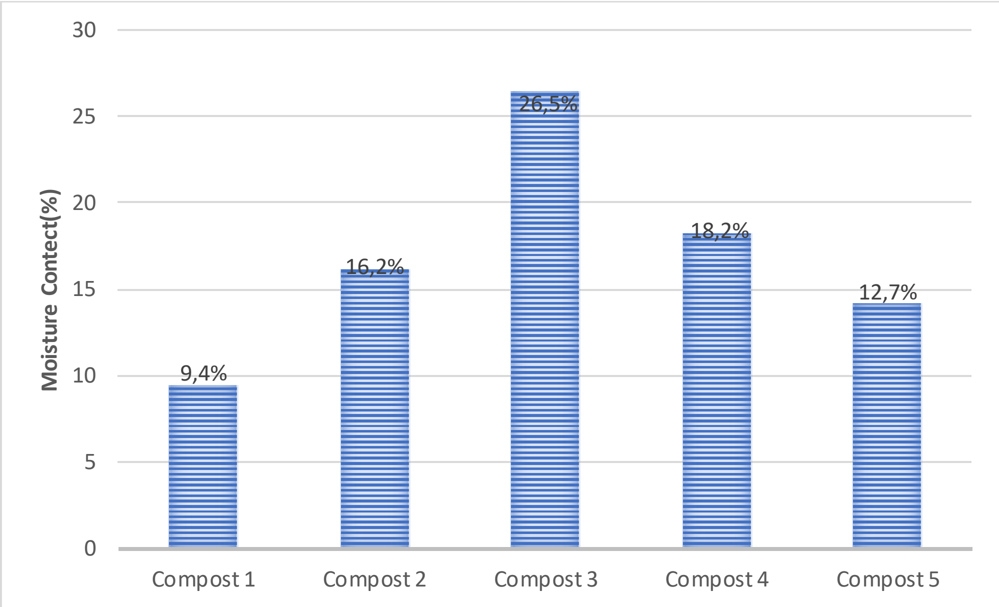

Figure 1. The Results of The Moisture Content Analysis

Based on the analysis results presented in Figure 1, the moisture content of oil palm trunk compost showed considerable variation among samples, ranging from 9.47% to 26.5%. According to SNI No. 7763: 2024 concerning solid organic fertilizer, the quality standard for organic fertilizer requires moisture content to be within the range of 8–25%. Based on this standard, Compost 1 (9.47%), Compost 2 (16.2%), Compost 4 (18.2%), and Compost 5 (12.7%) meet the required quality criteria, whereas Compost 3 (26.5%) exceeds the recommended limit.

The higher moisture content observed in Compost 3 may be attributed to excessively fine particle size or insufficient aeration, causing the compost pile to retain more water. This finding is consistent with Hau et al. [32], who reported that oil palm biomass with finer particles tends to have greater water retention capacity compared to coarser materials. In contrast, lower moisture content values indicate a more effective drying process or reduced microbial activity due to the depletion of easily degradable organic materials.

According to Mahapatra et al. [33], a decrease in moisture content is an indicator of compost maturity because it reflects increased biological stability and reduced decomposition activity. Moisture levels within the range of 8–25% also facilitate packaging and distribution processes while reducing the risk of quality degradation during storage [31].

Overall, these results indicate that most oil palm trunk compost samples meet the required quality standards. However, better control of moisture levels and more regular turning of compost piles are necessary to ensure that all samples remain within the ideal range of 8–25% according to SNI standards. Optimal moisture levels help maintain microbial activity, prevent the formation of toxic compounds, and produce compost fertilizer that is more stable and easier to apply in oil palm replanting areas.

Second, organic carbon (C-organic). The analysis of organic carbon content is one of the main parameters used to evaluate compost quality because carbon levels reflect the stability of organic materials resulting from the decomposition process. A high C-organic content indicates that the compost still contains a large amount of undecomposed organic matter, whereas lower values suggest that decomposition has progressed effectively, making nutrients more readily available for plant uptake [34]. Figure 2 presents the results of the C-organic analysis for each compost fertilizer sample.

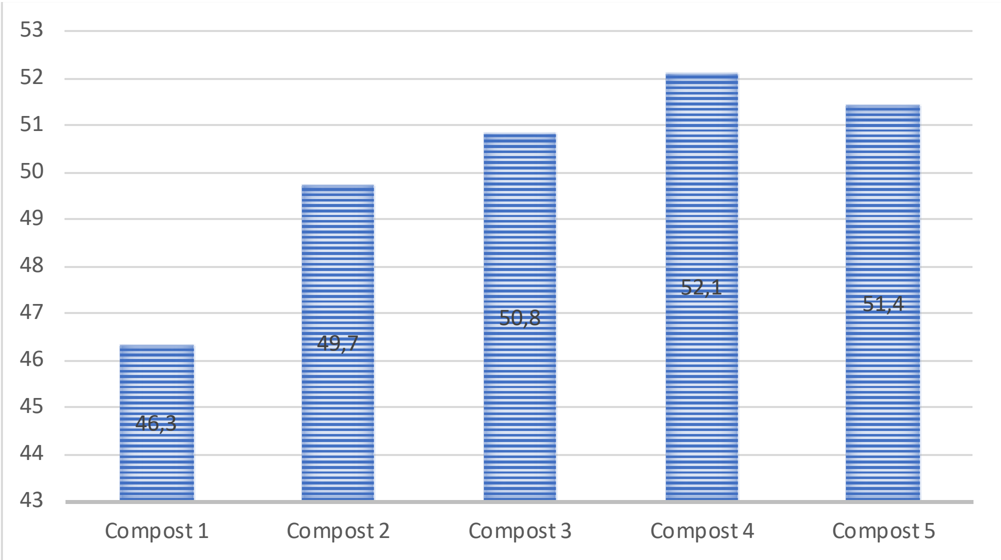

Figure 2. The Results of The C-Organic Analysis

Based on the analysis results presented in Figure 2, the organic carbon (C-organic) content of oil palm trunk compost ranged from 46.3% to 52.1%. The highest value was observed in Compost 4, reaching 52.1%. This variation is likely influenced by differences in the proportion of additional materials such as animal manure, which affects the availability of carbon and nitrogen during the decomposition process.

The relatively high C-organic content in the compost samples indicates that the decomposition process of organic materials is still actively occurring, supported by intensive microbial activity, possibly due to a relatively high initial C/N ratio. In contrast, compost samples with lower C-organic content suggest that the composting process has approached the maturity phase, where complex organic compounds such as lignin and cellulose have been degraded into simpler substances [35].

According to SNI No. 7763: 2024, the minimum standard for organic carbon content in solid organic fertilizer is 15%. Therefore, all oil palm trunk compost samples in this study meet the required quality standards. The relatively high C-organic values also indicate that the compost has the potential to improve soil structure, enhance cation exchange capacity, and increase water retention, which are essential for oil palm replanting areas [36]. These results suggest that the produced oil palm trunk compost is suitable for use as an organic fertilizer, particularly for improving soil fertility during the immature oil palm growth stage.

Third, the C/N ratio. The carbon-to-nitrogen (C/N) ratio is one of the main indicators used to determine compost maturity and quality. During the composting process, carbon serves as an energy source for microorganisms, while nitrogen is required for cellular protein synthesis. The balance between these two elements greatly influences the rate of organic matter decomposition and the stability of the resulting compost [37], [38], [39], [40]. An ideal C/N ratio indicates that the degradation of organic materials has proceeded optimally and that the compost is ready for field application. Figure 3 presents the results of the C/N ratio analysis for each compost fertilizer sample.

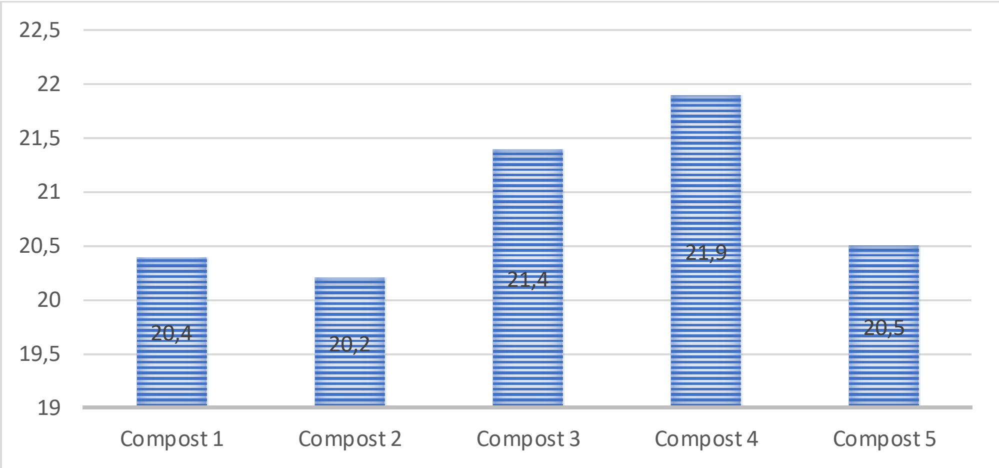

Figure 3. The results of The C/N Ratio Analysis

Based on the analysis results presented in Figure 3, the C/N ratio of oil palm trunk compost ranged from 20.2 to 21.9. The highest value was recorded in Compost 4 (21.9), while the lowest value was observed in Compost 2 (20.2). The variation among samples indicates differences in the decomposition rate of organic materials, which may be influenced by the composition of additional materials, particularly animal manure that serves as a source of nitrogen and basic minerals. All samples exhibited C/N ratios within the ideal range of ≤25 according to SNI No. 7763: 2024, indicating that the composting process had progressed optimally and produced biologically mature compost.

The differences among samples reflect variations in the decomposition rate of organic matter influenced by the proportion of supplementary materials such as animal manure. Animal manure provides nitrogen and active microorganisms that accelerate the decomposition process. Relatively high C/N values suggest that some lignocellulosic materials remain incompletely decomposed, particularly from oil palm trunk fractions that are rich in lignin and hemicellulose. This finding is consistent with the study of Xie et al. [41], which reported that higher C/N values at the later stages of composting indicate the presence of lignin components that are resistant to microbial degradation. Conversely, lower C/N values indicate that the decomposition process has progressed further, resulting in compost that is more stable, mature, and nutrient-rich. These results are consistent with the findings of Yu et al. [42], who reported that a decrease in the C/N ratio reflects an increased level of humification and greater stability of organic materials due to efficient microbial degradation of complex carbon compounds. Therefore, all oil palm trunk compost samples produced in this study meet the quality standards for organic fertilizer and can be categorized as chemically and biologically mature compost. This condition indicates that oil palm trunk compost is suitable for use as an organic fertilizer and has the potential to improve soil structure and enhance nutrient availability in oil palm replanting areas [43].

Fourth, potential of hydrogen (pH). The pH value is an important indicator in determining the maturity and stability of compost fertilizer. During the composting process, pH changes occur as a result of microbial activity that decomposes organic materials, producing organic acids in the early stages and alkaline compounds such as ammonia in the later stages [35]. Excessively low pH levels can inhibit the activity of decomposer microorganisms, while excessively high pH values may lead to nitrogen loss through ammonia volatilization. Therefore, pH measurement is an essential parameter to ensure that the compost produced is stable and safe for application in agricultural soils. Figure 4 presents the pH analysis results for each compost fertilizer sample.

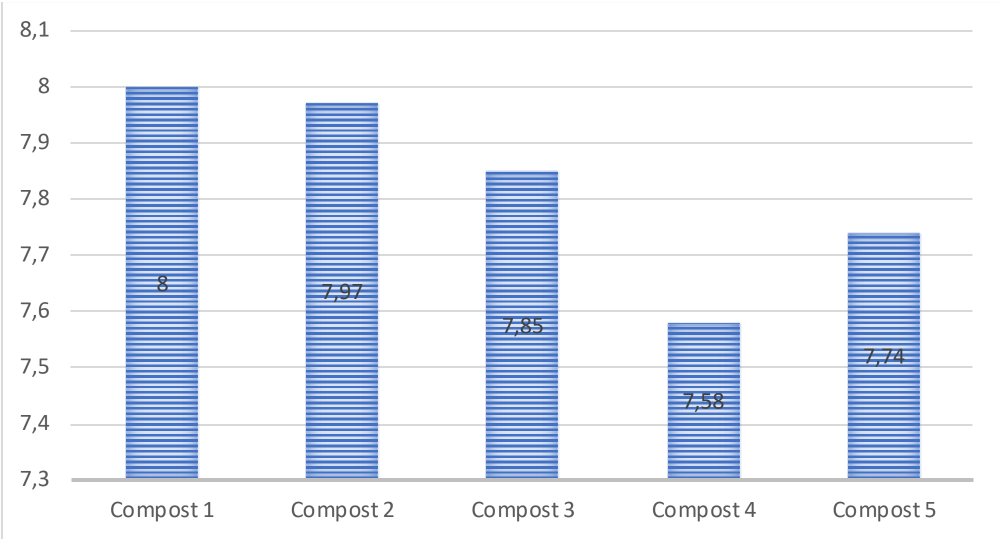

Figure 4. pH Analysis

Based on the analysis results presented in Figure 4, the pH values of oil palm trunk compost ranged from 7.58 to 8.00. The highest value was observed in Compost 1 with a pH of 8.00, while the lowest value was recorded in Compost 4 with a pH of 7.58. According to SNI No. 7763: 2024, solid organic fertilizers meet quality standards when the pH value ranges between 4 and 9. Therefore, all oil palm trunk compost samples in this study comply with the quality standards established by the government. The slightly alkaline pH values (around 8.00) indicate that the decomposition process has reached an advanced stage, in which organic acids formed during the initial phase have been degraded and replaced by alkaline compounds such as ammonia and carbonates [44]. A stable pH value suggests that the compost has reached a good level of maturity and is ready for application. According to Guo et al. [30], mature compost generally exhibits neutral to slightly alkaline pH due to the formation of humic and fulvic compounds during the humification process. Excessively high pH values (>9) may lead to nitrogen loss through ammonia volatilization, whereas pH values below 6 tend to inhibit the decomposition of organic materials. Therefore, the pH conditions observed in this study indicate that the composting process of oil palm trunk biomass proceeded in a balanced manner, producing compost that is biologically and chemically mature.

Thus, the results indicate that oil palm trunk compost meets the required quality standards and is suitable for application in agricultural land, particularly for improving soil chemical properties during oil palm replanting phases. The slightly alkaline pH is also beneficial for neutralizing soil acidity in Ultisols, which commonly dominate oil palm plantation areas in Indonesia [45].

Fifth, macronutrients (N + P_2O_5 + K_2O). The content of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) is a key indicator in assessing the agronomic value of compost fertilizer. These nutrients play essential roles in plant growth: nitrogen supports vegetative tissue formation, phosphorus contributes to root and flower development, and potassium enhances plant resistance to both biotic and abiotic stresses[46], [47]. In the context of organic fertilizers, sufficient NPK content reflects an optimal decomposition process and effective microbial activity during composting. Figure 5 presents the results of the total NPK analysis for each compost fertilizer sample.

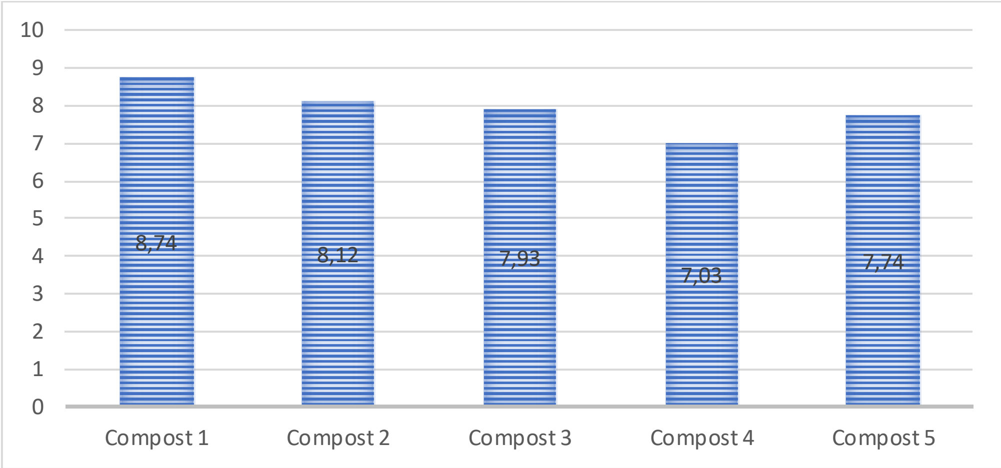

Figure 5. The Results of The Total NPK analysis

Based on the analysis results presented in Figure 5, the total NPK content in oil palm trunk compost ranged from 7.03% to 8.74%. The highest value was observed in Compost 1 with a total NPK content of 8.74%, while the lowest value was recorded in Compost 4 at 7.03%. According to SNI No. 7763: 2024, the quality standard for solid organic fertilizers requires a minimum total nutrient content of N + P_2O_5 + K_2O of 2%. Therefore, all oil palm trunk compost samples produced in this study meet the required quality standards for organic compost fertilizers.

The variation in NPK content among the samples indicates differences in nutrient availability resulting from variations in the proportion of additional organic materials and the maturity level of the compost. The relatively high NPK value observed in Compost 1 suggests that the decomposition process resulted in optimal nutrient mineralization, where nitrogen, phosphorus, and potassium were converted from complex organic forms into more plant-available forms [48]. In contrast, the slightly lower value in Compost 4 may be attributed to the presence of residual lignocellulosic components that have not been fully degraded, or to nitrogen losses through volatilization during the thermophilic phase of the composting process [49]

These findings are consistent with the study of Loh et al. [50], which reported that composting oil palm biomass with animal manure can significantly increase total NPK content beyond 2%, due to the additional nitrogen supplied by livestock manure and enhanced microbial nitrification activity. Overall, the total NPK content observed in all oil palm trunk compost samples indicates that the resulting product possesses good agronomic value and complies with organic fertilizer standards. The adequate macronutrient content has the potential to improve soil fertility, enhance soil chemical properties, and support sustainable oil palm replanting programs.

IV. Conclusion

This study confirms that oil palm trunk waste can be effectively transformed into high-quality organic compost through a biodecomposition process. The resulting compost showed C-organic content of 46.3–52.1%, a C/N ratio of 20.2–21.9, pH values of 7.58–8.00, and total macronutrient content (N + P_2O_5 + K_2O) of 7.03–8.74%, all of which meet the quality standards for solid organic fertilizers according to SNI No. 7763: 2024. These results indicate that the compost produced is mature, nutritionally adequate, and suitable for improving soil fertility, particularly in oil palm replanting areas.

Future research is recommended to evaluate the long-term agronomic performance of oil palm trunk compost under field conditions, including its effects on crop productivity, soil microbial activity, and soil carbon sequestration. Further studies could also explore optimization of composting techniques and microbial inoculants to enhance nutrient availability and accelerate the biodecomposition process.

V. References

[1] H. Herdiansyah and K. I. Majesty, "Conflict Mitigation Strategies for Sustainable Agriculture in Palm Oil Expansion," *International Journal of Sustainable Development and Planning*, vol. 19, no. 5, pp. 1893–1902, 2024, doi: 10.18280/ijsdp.190527.

[2] W. Erwiningsih, "Analyzing Drivers and Mitigation of Deforestation for Oil Palm Expansion in Indonesia, 2000-2020," *International Journal of Sustainable Development and Planning*, vol. 18, no. 11, pp. 3657–3664, 2023, doi: 10.18280/ijsdp.181132.

[3] B. Azhar *et al.*, "Mitigating the risks of indirect land use change (ILUC) related deforestation from industrial palm oil expansion by sharing land access with displaced crop and cattle farmers," *Land use policy*, vol. 107, 2021, doi: 10.1016/j.landusepol.2021.105498.

[4] F.-O. Tapia-Silva and J. García-Hernández, "Assessing the relationship between river water pollution and the LULC composition of a basin in the Isthmus of Tehuantepec in Oaxaca, Mexico," *Environ. Monit. Assess.*, vol. 196, no. 11, 2024, doi: 10.1007/s10661-024-13147-3.

[5] M. V Noordwijk, "Sustainable Palm Oil: Dissecting a Global Debate," in *IOP Conference Series: Earth and Environmental Science*, S. Sudarsono, A. Junaedi, M. Fuad, E. Mulyana, I. M. Trisawa, Bursatriannyo, and E. Kristiyaningsih, Eds., Institute of Physics Publishing helen.craven@iop.org, 2020. doi: 10.1088/1755-1315/418/1/012002.

[6] A. W. Satria *et al.*, "Valorization of palm oil fronds waste for biochar-slow-release fertilizer," in *AIP Conference Proceedings*, E. Humaidi, D. P. Widiyani, D. Berliana, W. R. Hartari, D. D. Putri, and R. Rahim, Eds., American Institute of Physics, 2026. doi: 10.1063/5.0307564.

[7] Y. Siddiqui, S. Meon, R. I. Mohd, M. Rahmani, and A. Ali, "Efficient conversion of empty fruit bunch of oil palm into fertilizer enriched compost," *Asian Journal of Microbiology, Biotechnology and Environmental Sciences*, vol. 11, no. 2, pp. 247–252, 2009, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-75749099765&partnerID=40&md5=affc79876815941858ca3270f2f71cb3

[8] B. Purwanto and W. Shalihy, "Effect of NPK Fertilizer and Trichoderma harzianum-Enriched Oil Palm Empty Fruit Bunch Compost on the Growth of Oil Palm Seedlings," *Agro Bali*, vol. 8, no. 2, pp. 407–421, 2025, doi: 10.37637/ab.v8i2.2356.

[9] M. W. A. Musrab, A. H. A. Yazid, and N. M. Mokhtar, "Conversion of Oil Palm Empty Fruit Bunch Fiber Waste into Green Liquid Organic Fertilizer," *Journal of Advanced Research in Applied Mechanics*, vol. 125, no. 1, pp. 161–173, 2025, doi: 10.37934/aram.125.1.161173.

[10] D. P. Wulandari, E. A. M. Zuhud, and R. Affandi, "Impact of Organic Fertilizer to Improve Oil Palm Productivity and Farmer Well-Being," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2025. doi: 10.1088/1755-1315/1534/1/012010.

[11] D. Agustina, M. I. Purnamasari, L. U. Karmawan, and A. Suwanto, "Effect of Synthetic Fertilizer on Diazotrophic Bacteria in Secondary Forest and Oil Palm Soils in Central Kalimantan," *Hayati*, vol. 32, no. 1, pp. 106–116, 2025, doi: 10.4308/hjb.32.1.106-116.

[12] A. Qur ania, N. Nurhidayati, S. Gunawan, S. I. Tito, E. Rahayu, and A. Basit, "Growth Responses of Oil Palm (Elaeis guineensis Jacq.) Seedlings to EFB-Derived Nanocompost and NPK Fertilizer Combinations in Inceptisol under Main Nursery Conditions," in *BIO Web of Conferences*, H. Latuconsina, Ed., EDP Sciences, 2026. doi: 10.1051/bioconf/202620902003.

[13] Y. L. Chiew and S. Shimada, "Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer – A case study of Malaysia," *Biomass Bioenergy*, vol. 51, pp. 109–124, Apr. 2013, doi: 10.1016/j.biombioe.2013.01.012.

[14] J. Supriatna, M. R. Setiawati, R. Sudirja, and C. Suherman, "Enhancing soil fertility, inorganic fertilizer efficiency, and oil palm productivity through bio-compost application in oxium biodegradable sacks on former mining land-podzols: Insights from a field study in Indonesia," *Journal of the Saudi Society of Agricultural Sciences*, vol. 25, no. 1, 2026, doi: 10.1007/s44447-025-00091-y.

[15] J. Supriatna, M. R. Setiawati, R. Sudirja, and C. Suherman, "Enhancing soil fertility, inorganic fertilizer efficiency, and oil palm productivity through bio-compost application in oxium biodegradable sacks on former mining land-podzols: Insights from a field study in Indonesia," *Journal of the Saudi Society of Agricultural Sciences*, 2024, doi: 10.1016/j.jssas.2024.09.006.

[16] M. A. A. Mohammed, A. Salmiaton, W. A. K. G. Wan Azlina, and M. S. Mohamad Amran, "Gasification of oil palm empty fruit bunches: A characterization and kinetic study," *Bioresour. Technol.*, vol. 110, pp. 628–636, 2012, doi: 10.1016/j.biortech.2012.01.056.

[17] A. Y. Nurul, H. A. Mohd, P. Hadi, M. S. Hamzah, Z. A. R. Rusila, and A. Tomohiro, "Magnetization of low grade iron ore using empty fruit bunch ash," in *Advanced Materials Research*, Department of Manufacturing and Materials Engineering, International Islamic University Malaysia, 53100 Kuala Lumpur, Malaysia, 2013, pp. 141–144. doi: 10.4028/www.scientific.net/AMR.701.141.

[18] B. T. I. Ali *et al.*, "Enhancing biogas production with fungi from oil palm empty fruit bunches: Isolation and innovative application," *Case Studies in Chemical and Environmental Engineering*, vol. 10, 2024, doi: 10.1016/j.cscee.2024.100845.

[19] S. N. F. Zakaria, H. A. Aziz, and M. Y. D. Alazaiza, "Effectiveness of ozonation with zirconium and tin tetrachloride for stabilized anaerobic landfill leachate treatment," *Water Environment Research*, vol. 94, no. 1, 2022, doi: 10.1002/wer.1672.

[20] F. Rosli, C. M. R. Ghazali, M. A. A. B. Abdullah, and K. Hussin, "A review: Characteristics of oil palm trunk (OPT) and quality improvement of palm trunk plywood by resin impregnation," *Bioresources*, vol. 11, no. 2, pp. 5565–5580, 2016, doi: 10.15376/biores.11.2.Rosli.

[21] M. A. Hassan *et al.*, "Sustainable production of polyhydroxyalkanoates from renewable oil-palm biomass," *Biomass Bioenergy*, vol. 50, pp. 1–9, Mar. 2013, doi: 10.1016/j.biombioe.2012.10.014.

[22] B. P. P. Budhijanto, "Sustainable Hydrogen Production from Oil Palm Trunk Biomass in Indonesia: A Techno-Economic Study," *Agraris*, vol. 10, no. 1, pp. 105–119, 2024, doi: 10.18196/agraris.v10i1.152.

[23] A. Walter, I. H. Franke-Whittle, A. O. Wagner, and H. Insam, "Methane yields and methanogenic community changes during co-fermentation of cattle slurry with empty fruit bunches of oil palm," *Bioresour. Technol.*, vol. 175, pp. 619–623, 2015, doi: 10.1016/j.biortech.2014.10.085.

[24] M. P. Bernal, J. A. Alburquerque, and R. Moral, "Composting of animal manures and chemical criteria for compost maturity assessment. A review," *Bioresour. Technol.*, vol. 100, no. 22, pp. 5444–5453, Nov. 2009, doi: 10.1016/j.biortech.2008.11.027.

[25] J. C. Hargreaves, M. S. Adl, and P. R. Warman, "A review of the use of composted municipal solid waste in agriculture," *Agric. Ecosyst. Environ.*, vol. 123, no. 1–3, pp. 1–14, Jan. 2008, doi: 10.1016/j.agee.2007.07.004.

[26] M. Waqas *et al.*, "Composting Processes for Agricultural Waste Management: A Comprehensive Review," *Processes*, vol. 11, no. 3, 2023, doi: 10.3390/pr11030731.

[27] I. Finore *et al.*, "Thermophilic bacteria and their thermozymes in composting processes: A review," *Chemical and Biological Technologies in Agriculture*, vol. 10, no. 1, p. 7, 2023, doi: 10.1186/s40538-023-00381-z.

[28] T. Bhatia and S. S. Sindhu, "Sustainable management of organic agricultural wastes: Contributions in nutrients availability, pollution mitigation and crop production," *Discover Agriculture*, vol. 2, no. 1, p. 130, 2024, doi: 10.1007/s44279-024-00147-7.

[29] L. S. Angulo-Mosquera, A. A. Alvarado-Alvarado, M. J. Rivas-Arrieta, C. R. Cattaneo, E. R. Rene, and O. García-Depraect, "Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives," *Science of the Total Environment*, vol. 795, 2021, doi: 10.1016/j.scitotenv.2021.148816.

[30] X. Guo, H. Liu, and S. Wu, "Humic substances developed during organic waste composting: Formation mechanisms, structural properties, and agronomic functions," *Science of The Total Environment*, vol. 662, pp. 501–510, 2019, doi: 10.1016/j.scitotenv.2019.01.137.

[31] M. S. Ayilara, O. S. Olanrewaju, O. O. Babalola, and O. Odeyemi, "Waste Management through Composting: Challenges and Potentials," *Sustainability*, vol. 12, no. 11, 2020, doi: 10.3390/su12114456.

[32] E. B. Vea, J. Bendtsen, K. Richardson, M. Ryberg, and M. Hauschild, "Spatially differentiated marine eutrophication method for absolute environmental sustainability assessments," *Science of the Total Environment*, vol. 843, 2022, doi: 10.1016/j.scitotenv.2022.156873.

[33] S. Mahapatra, Md. H. Ali, and K. Samal, "Assessment of compost maturity-stability indices and recent development of composting bin," *Energy Nexus*, vol. 6, p. 100062, 2022, doi: 10.1016/j.nexus.2022.100062.

[34] D. K. Maheshwari, S. Dheeman, and M. Agarwal, "Decomposition of Organic Materials into High Value Compost for Sustainable Crop Productivity," in *Composting for Sustainable Agriculture*, Springer, 2014, pp. 245–267. doi: 10.1007/978-3-319-08004-8_12.

[35] K. Azim, B. Soudi, S. Boukhari, C. Perissol, S. Roussos, and I. Thami Alami, "Composting parameters and compost quality: A literature review," *Organic Agriculture*, vol. 8, no. 2, pp. 141–158, 2018, doi: 10.1007/s13165-017-0180-z.

[36] D. K. Boafo, B. Kraisornpornson, S. Panphon, B. E. Owusu, and P. N. Amaniampong, "Effect of organic soil amendments on soil quality in oil palm production," *Applied Soil Ecology*, vol. 147, p. 103358, 2020, doi: 10.1016/j.apsoil.2019.09.008.

[37] M. K. Awasthi *et al.*, "Role of biochar amendment in mitigation of nitrogen loss and greenhouse gas emission during sewage sludge composting," *Bioresour. Technol.*, vol. 219, pp. 270–280, Nov. 2016, doi: 10.1016/j.biortech.2016.07.128.

[38] A. K. Awasthi and J. Li, "Assessing resident awareness on e-waste management in Bangalore, India: a preliminary case study," *Environmental Science and Pollution Research*, vol. 25, no. 11, pp. 11163–11172, 2018, doi: 10.1007/s11356-017-1037-4.

[39] A. K. Awasthi, "Informal sector: A complex link to transform solid waste management in a circular economy system," *Waste Management and Research*, vol. 40, no. 11, pp. 1569–1570, 2022, doi: 10.1177/0734242X221131523.

[40] X. Ouyang, E. Kristensen, M. Zimmer, C. Thornber, Z. Yang, and S. Y. Lee, "Response of macrophyte litter decomposition in global blue carbon ecosystems to climate change," *Glob. Chang. Biol.*, vol. 29, no. 13, pp. 3806–3820, 2023, doi: 10.1111/gcb.16693.

[41] Y. Xie *et al.*, "Effects of the C/N ratio on the microbial community and lignocellulose degradation during branch waste composting," *Bioprocess Biosyst. Eng.*, vol. 45, no. 7, pp. 1163–1174, 2022, doi: 10.1007/s00449-022-02732-w.

[42] H. Deng *et al.*, "Bacterial communities on polyethylene microplastics in mangrove ecosystems as a function of exposure sites: Compositions and ecological functions," *J. Environ. Chem. Eng.*, vol. 10, no. 3, 2022, doi: 10.1016/j.jece.2022.107924.

[43] J. Supriatna, M. R. Setiawati, R. Sudirja, C. Suherman, and X. Bonneau, "Composting for a More Sustainable Palm Oil Waste Management: A Systematic Literature Review," *Scientific World Journal*, vol. 2022, 2022, doi: 10.1155/2022/5073059.
[44] D. Neina, "The Role of Soil pH in Plant Nutrition and Soil Remediation," *Appl. Environ. Soil Sci.*, vol. 2019, p. 5794869, 2019, doi: 10.1155/2019/5794869.
[45] T. B. Prasetyo and P. D. Hayati, "Management effects of ultisol on soil physical and chemical properties as well as maize growth in oil palm replanting area," *Asian Journal of Agriculture and Biology*, no. Special Issue, pp. 190–195, 2019.
[46] D. Sinha and P. K. Tandon, "An Overview of Nitrogen, Phosphorus and Potassium: Key Players of Nutrition Process in Plants," in *Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants*, Springer, 2020, pp. 85–117. doi: 10.1007/978-981-15-8636-1_5.
[47] S. Derakhshandara, V. Franzoni, D. Mezzetti, and V. Poggioni, "Machine Learning Decision Support for Macronutrients in Neonatal Parenteral Nutrition," *IEEE Access*, vol. 12, pp. 170001–170010, 2024, doi: 10.1109/ACCESS.2024.3498059.
[48] S. Majee, G. Halder, and T. Mandal, "Formulating nitrogen-phosphorous-potassium enriched organic manure from solid waste," *Process Safety and Environmental Protection*, vol. 132, pp. 160–168, 2019, doi: 10.1016/j.psep.2019.10.013.
[49] Z. Mengqi, A. Shi, M. Ajmal, L. Ye, and M. Awais, "Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting," *Biomass Convers. Biorefin.*, vol. 13, no. 7, pp. 5445–5468, 2023, doi: 10.1007/s13399-021-01438-5.
[50] S. K. Loh, M. E. Lai, and M. Ngatiman, "Vegetative growth enhancement of organic fertilizer from anaerobically-treated palm oil mill effluent supplemented with chicken manure," *Food and Bioproducts Processing*, vol. 117, pp. 95–104, 2019, doi: 10.1016/j.fbp.2019.06.016.