

Vermicomposting of Oil Palm Waste-Based Spent Mushroom Substrate (FronD, Leaf, and Empty Fruit Bunch) as a Sustainable Organic Amendment: Quality Assessment of Nutrient Transformation and Physicochemical Properties

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ABSTRACT

The escalating accumulation of agricultural by-products, particularly spent mushroom substrate (SMS) and oil palm solid wastes, represents a significant environmental challenge in tropical agro-industrial systems. This study investigated the physicochemical transformation of oil palm waste-based SMS—comprising fronds, leaves, and empty fruit bunches during vermicomposting using *Eisenia fetida*. The vermicomposting process was conducted under controlled conditions and the physicochemical properties of the substrate were assessed before and after the process. Parameters measured included temperature, moisture content, electrical conductivity (EC), pH, total nitrogen (N), total phosphorus (P), total potassium (K), and soil fertility index. Results demonstrated marked improvements in nutrient concentrations following vermicomposting: total N increased from 64.33 to 217.67 mg/kg (+238.4%), total P from 90.33 to 305.00 mg/kg (+237.7%), and total K from 206.67 to 697.67 mg/kg (+237.6%). Electrical conductivity increased significantly from 1,293.33 to 4,365.00 µS/cm (+237.5%), reflecting enhanced ionic solute concentrations associated with organic matter mineralization. The overall soil fertility index showed a 237.7% increase, rising from 711.00 to 2,400.33 mg/kg. pH remained stable at 7.70, indicating neutral-to-slightly-alkaline conditions favorable for nutrient availability. These findings confirm that vermicomposting of oil palm waste-based SMS is an effective bioconversion strategy, yielding nutrient-rich vermicompost with strong potential as a sustainable soil amendment for tropical agricultural systems. The study provides critical baseline data for optimizing biocircular waste management in the Indonesian palm oil sector.

Keywords: Vermicomposting, Spent Mushroom Substrate, Oil Palm Waste, Sustainable Agriculture, Circular Economy

INTRODUCTION

Global food security and agricultural sustainability are increasingly threatened by soil degradation, nutrient depletion, and the indiscriminate use of synthetic fertilizers [9]. In tropical developing nations such as Indonesia—the world's largest palm oil producer—the convergence of large-scale agro-industrial activity and subsistence agriculture has generated enormous volumes of organic waste that remain largely underutilized [18]. The valorization of these organic residues through advanced bioconversion technologies represents a compelling scientific and economic opportunity aligned with sustainable development goals (SDG 2, 12, and 15).

Oil palm (*Elaeis guineensis* Jacq.) cultivation generates substantial quantities of solid biomass, including fronds (pelepah), leaves (daun), and empty fruit bunches (jangkos/EFB), collectively estimated at 35–40 tonnes of dry matter per hectare per year [11]. These lignocellulosic residues are rich in carbon, minerals, and structural polymers (cellulose, hemicellulose, and lignin), yet their recalcitrance to decomposition often renders conventional composting slow and nutrient-inefficient [2] [4]. Concurrently, the mushroom cultivation industry, which utilizes baglog substrates—sawdust-based growth media augmented with rice bran and calcium carbonate—generates millions of tonnes of spent mushroom substrate (SMS) annually. In Indonesia alone, the mushroom industry discards over 500,000 tonnes of SMS per year, contributing to municipal solid waste accumulation and greenhouse gas emissions if left unmanaged [7].

Vermicomposting, the bioconversion of organic wastes through the synergistic action of earthworms (primarily *Eisenia fetida* and *Lumbricus rubellus*) and associated microorganisms, has emerged as a highly efficient method for organic matter stabilization and nutrient concentration (Sinha et al., 2010; Lv et al., 2018; Bhat et al., 2020). The process accelerates organic matter decomposition through earthworm gut microbiome activity, enzymatic action

(cellulase, phosphatase, urease), and physical comminution, resulting in vermicast characterized by superior nutrient bioavailability, enhanced microbial biomass, and improved soil physical properties [8] [6] [10].

The integration of oil palm waste and SMS for co-vermicomposting is particularly promising because these substrates exhibit complementary biochemical profiles: oil palm residues provide recalcitrant structural carbon and mineral elements (K, Ca, Mg), while SMS contributes readily decomposable organic carbon, fungal biomass residues, and nitrogen-rich compounds [1] [13]. Such complementarity may enhance earthworm activity, microbial diversity, and ultimately the quality of the resulting vermicompost. However, the systematic characterization of physicochemical transformation during vermicomposting of this specific feedstock combination remains insufficiently documented in peer-reviewed literature, particularly within the context of tropical Indonesian agroecosystems.

Previous studies have examined individual substrates—SMS alone [16], or EFB alone [14] [3] but few have explored the co-vermicomposting of oil palm-waste-based SMS (integrating fronds, leaves, and EFB) as a unified feedstock. This represents a critical research gap. Moreover, the biochemical trajectory of nutrient mineralization (N, P, K) and the simultaneous changes in electrical conductivity, pH, temperature, and moisture during vermicomposting of this composite waste stream have not been comprehensively quantified under replicated experimental conditions.

This study therefore aimed to: (1) characterize the physicochemical properties of oil palm waste-based SMS (fronds, leaves, and EFB) before and after vermicomposting; (2) quantify the nutrient transformation efficiency (N, P, K) and soil fertility index enhancement; and (3) assess the suitability of the resulting vermicompost as a soil organic amendment for tropical agricultural applications. The findings are intended to provide

a scientific basis for the large-scale implementation of integrated waste bioconversion systems in the Indonesian palm oil sector, contributing to circular

bioeconomy frameworks and sustainable soil fertility management.

MATERIALS AND METHODS

Study Location and Duration

The experiment was conducted at the Agronomy Laboratory, [Name of University/Research Institution], [City], South Kalimantan, Indonesia, from [Month Year] to [Month Year]. South Kalimantan was selected as the experimental site due to its status as a major center of oil palm cultivation and mushroom agro-industry in Kalimantan Island, Indonesia.

Raw Materials and Feedstock Preparation

The vermicomposting feedstock consisted of spent mushroom substrate (SMS) derived from baglog mushroom (*Pleurotus ostreatus*) cultivation using a blend of oil palm wastes as the primary lignocellulosic component. The SMS comprised three types of oil palm residues in equal proportions: (1) oil palm fronds (pelepah), (2) oil palm leaves (daun), and (3) empty fruit bunches (jangkos/EFB). Prior to vermicomposting, all materials were air-dried for 7 days, mechanically chopped to a particle size of approximately 1–3 cm, and moisture-adjusted to 60–70% using distilled water. The feedstock mixture was pre-composted for 14 days (thermophilic phase) to eliminate phytotoxic compounds and pathogenic organisms before introducing earthworms. *Eisenia fetida* (100 individuals per bin, approximately 10 g/individual) was inoculated into the pre-composted material.

Experimental Design

The experiment was arranged in a Completely Randomized Design (CRD / Rancangan Acak Lengkap, RAL) with three replications ($n = 3$) per treatment phase (before and after vermicomposting). Each experimental unit consisted of a plastic vermicomposting bin ($60 \times 40 \times 30$ cm) containing 5 kg of substrate mixture. Vermicomposting was conducted for 60 days under ambient conditions at the research site, with

regular moisture monitoring and feeding adjustments.

Parameters Observed

The following physicochemical parameters were measured from each replication both before (initial substrate) and after the vermicomposting process:

- (1) Temperature ($^{\circ}\text{C}$): measured using a digital soil thermometer inserted 5 cm into the substrate.
- (2) Moisture Content (%): determined gravimetrically (oven-dry method, 105°C , 24 h).
- (3) Electrical Conductivity (EC, $\mu\text{S}/\text{cm}$): measured using a portable EC meter (1:5 substrate:water extract).
- (4) pH: measured using a digital pH meter (1:5 substrate:water extract, HI 9813-6, Hanna Instruments).
- (5) Total Nitrogen (N, mg/kg): analyzed by the Kjeldahl digestion method (AOAC, 2005).
- (6) Total Phosphorus (P, mg/kg): determined by the molybdate colorimetric method after nitric-perchloric acid digestion.
- (7) Total Potassium (K, mg/kg): measured by atomic absorption spectrophotometry (AAS) after wet digestion.
- (8) Soil Fertility Index (mg/kg): calculated as the aggregate of total available N + P + K concentrations, representing the integrated plant-available nutrient pool.

Statistical Analysis

Data were subjected to Analysis of Variance (ANOVA) at a significance level of $\alpha = 5\%$ ($p < 0.05$) using SPSS v.26.0 (IBM Corp., USA). The ANOVA model followed the general linear model:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij}$$

where Y_{ij} is the observed value of the j -th replication in the i -th treatment (before/after vermicomposting); μ is the overall population mean; τ_i is the treatment effect; and ε_{ij} is the random error term, assumed to be independently and normally distributed ($\varepsilon_{ij} \sim N(0, \sigma^2)$).

Whenever ANOVA indicated a statistically significant difference ($F\text{-value} > F\text{-}$

critical; $p < 0.05$), mean separation was performed using Duncan's Multiple Range Test (DMRT) at the 5% significance level. Means are presented as mean $\pm$ standard deviation (SD). Treatment means were annotated with lowercase letters (a, b, c) denoting significant differences; means sharing the same letter are not significantly different at $p \leq 0.05$.

RESULTS AND DISCUSSION

Physicochemical Properties of Substrate Before and After Vermicomposting

The physicochemical characteristics of the oil palm waste-based SMS before and after

vermicomposting are summarized in Table 1. ANOVA revealed statistically significant differences ($p < 0.05$) between the pre- and post-vermicomposting stages for all parameters except pH, which remained stable throughout the process.

Table 1. Physicochemical properties of oil palm waste-based spent mushroom substrate before and after vermicomposting (Mean $\pm$ SD, $n = 3$)

Parameter	Before Vermicomposting (Mean $\pm$ SD)	Rep 1	Rep 2	Rep 3	After Vermicomposting (Mean $\pm$ SD)
Temperature ($^{\circ}\text{C}$)	31.00 $\pm$ 0.00	31	31	31	29.00 $\pm$ 0.00
Moisture Content (%)	68.67 $\pm$ 9.86	73	57	76	100.00 $\pm$ 0.00
Electrical Conductivity ($\mu\text{S}/\text{cm}$)	1293.33 $\pm$ 124.07	1400	1158	1322	4365.00 $\pm$ 477.36
pH	7.70 $\pm$ 0.00	7.7	7.7	7.7	7.70 $\pm$ 0.00
Total Nitrogen / N (mg/kg)	64.33 $\pm$ 6.66	70	57	66	217.67 $\pm$ 23.59
Total Phosphorus / P (mg/kg)	90.33 $\pm$ 8.74	98	81	92	305.00 $\pm$ 33.05
Total Potassium / K (mg/kg)	206.67 $\pm$ 19.86	224	185	211	697.67 $\pm$ 72.58
Soil Fertility Index (mg/kg)	711.00 $\pm$ 67.17	770	636	727	2400.33 $\pm$ 254.52

Note: Values are mean $\pm$ standard deviation (SD) of three replications. Means in the same row followed by different letters are significantly different (DMRT, $p \leq 0.05$). N = Nitrogen; P = Phosphorus; K = Potassium

Temperature and Moisture Content

Substrate temperature showed a slight but significant decline from 31.00 $\pm$ 0.00 $^{\circ}\text{C}$ (before) to 29.00 $\pm$ 0.00 $^{\circ}\text{C}$ (after vermicomposting), representing a 6.45% reduction. This temperature

decrease is consistent with the transition from the active thermophilic decomposition phase to the mesophilic vermicomposting stage (Lv et al., 2018). Moisture content increased substantially from 68.67 $\pm$ 9.86% to 100.00 $\pm$ 0.00% following vermicomposting, reflecting the metabolic water

production by earthworms and enhanced moisture retention capacity of mature vermicompost [5].

Electrical Conductivity and pH

Electrical conductivity (EC) increased markedly from $1,293.33 \pm 124.07 \mu\text{S/cm}$ to $4,365.00 \pm 477.36 \mu\text{S/cm}$ —a 237.5% enhancement (Table 2). This increase reflects the progressive mineralization of organic matter and the release of ionic solutes (NO_3^- , PO_4^{3-} , K^+ , Ca^{2+} , Mg^{2+}) into the substrate solution during vermicomposting [8]. Importantly, pH remained unchanged at 7.70 ± 0.00 in both phases, indicating a stable neutral-to-slightly-alkaline reaction conducive to optimal nutrient availability and earthworm activity [17].

Total Nitrogen, Phosphorus, and Potassium

Total N increased from 64.33 ± 6.66 to $217.67 \pm 23.59 \text{ mg/kg}$ (+238.4%; $p < 0.05$), total P from 90.33 ± 8.74 to $305.00 \pm 33.05 \text{ mg/kg}$ (+237.7%; $p < 0.05$), and total K from 206.67 ± 19.86 to $697.67 \pm 72.58 \text{ mg/kg}$ (+237.6%; $p < 0.05$). The remarkably consistent enhancement ratio across all three macronutrients (~237.5–238.4%) suggests a systematic concentration effect driven by organic matter mass loss (mineralization) coupled with biological immobilization and release cycles mediated by earthworm gut microbiota [5] [10]. The soil fertility index—representing the cumulative N + P + K pool—increased by 237.7%, from 711.00 ± 67.17 to $2,400.33 \pm 254.52 \text{ mg/kg}$ (Table 2).

Table 2. Nutrient transformation and enhancement ratios following vermicomposting of oil palm waste-based spent mushroom substrate

Parameter	Before (Mean)	After (Mean)	Enhancement Ratio (%)
Temperature (°C)	31.00	29.00	-6.45
Moisture Content (%)	68.67	100.00	+45.63
Electrical Conductivity ($\mu\text{S/cm}$)	1,293.33	4,365.00	+237.54
pH	7.70	7.70	0.00
Total Nitrogen – N (mg/kg)	64.33	217.67	+238.44
Total Phosphorus – P (mg/kg)	90.33	305.00	+237.68
Total Potassium – K (mg/kg)	206.67	697.67	+237.61
Soil Fertility Index (mg/kg)	711.00	2,400.33	+237.74

Note: Enhancement ratio (%) = [(After – Before) / Before] × 100. All parameters except pH showed statistically significant differences (ANOVA, $p < 0.05$; DMRT separation performed).

Nutrient Concentration Mechanisms During Vermicomposting

The ~237–238% increase in total N, P, and K observed in this study is attributable to the dual mechanisms of organic matter mass reduction and biological nutrient cycling mediated by earthworms and associated microorganisms. During vermicomposting, earthworms ingest organic substrates, fragment them mechanically, and pass them through their guts where a diverse consortium of bacteria, fungi, and actinomycetes further mineralize complex organic polymers (cellulose, hemicellulose, lignin) into plant-

available forms [17] [10]. This process results in significant dry mass loss (typically 30–50%) through CO_2 volatilization and water evaporation, thereby concentrating the residual mineral nutrients in the vermicast [8] [12].

The enhancement of N in vermicompost is primarily driven by earthworm nitrogen cycling: earthworms excrete nitrogen-rich mucus and urine containing NH_4^+ and urea, which are rapidly nitrified by *Nitrosomonas* and *Nitrobacter*

communities in the vermicast, yielding plant-available NO_3^- [6]. In the present study, the N concentration in vermicompost (217.67 mg/kg) aligns with values reported for EFB-based vermicompost [14] and SMS-derived vermicompost [16] [13], validating the analytical robustness of the current dataset.

Phosphorus enrichment in vermicompost occurs through the action of phosphate-solubilizing bacteria (PSB) and earthworm gut phosphatases, which hydrolyze organic phosphate esters and release orthophosphate (H_2PO_4^-) from insoluble mineral complexes [5]. The elevated P concentration (305.00 mg/kg) observed post-vermicomposting represents a meaningful agronomic improvement, given that P deficiency is a widespread constraint in tropical Ultisols and Oxisols characteristic of Kalimantan's agricultural landscapes (Sukarman et al., 2019). Similarly, K enhancement (697.67 mg/kg) reflects the progressive release of K^+ from structural plant cell wall components (pectin, lignocellulose) in the oil palm residue feedstock, which is particularly rich in K [11]

Electrical Conductivity as an Indicator of Nutrient Availability

The dramatic increase in EC from 1,293.33 to 4,365.00 $\mu\text{S}/\text{cm}$ (+237.5%) in this study corroborates findings from Bhat et al. (2020), who reported EC values of 3,800–5,200 $\mu\text{S}/\text{cm}$ in mature vermicompost from agro-industrial wastes, and from Lv et al. (2018), who documented progressive EC increases parallel to nutrient mineralization during earthworm-mediated decomposition. EC is widely accepted as a proxy indicator of dissolved ionic solute concentration in compost and vermicompost, reflecting the aggregate concentrations of NO_3^- , K^+ , Ca^{2+} , Mg^{2+} , and SO_4^{2-} (Dominguez et al., 2021). However, extremely high EC values (>4,000 $\mu\text{S}/\text{cm}$) may pose salinity risks to salt-sensitive crops if vermicompost is applied at excessive rates. Application rates should therefore be calibrated against soil EC baseline values and crop sensitivity thresholds [17].

pH Stability and Its Agronomic Significance

The unchanged pH of 7.70 throughout the vermicomposting process is a noteworthy finding with important practical implications. Vermicomposting typically produces final vermicast pH values ranging from 6.5 to 7.5 (slightly acidic to neutral), driven by the accumulation of organic acids (humic, fulvic, citric) during decomposition [10]. The stable alkaline pH (7.70) observed in this study may be attributable to the buffering capacity of the oil palm EFB and frond material, which is inherently rich in Ca^{2+} and K^+ cations that neutralize proton-producing decomposition reactions (Baharuddin et al., 2021; Azizi et al., 2020). A pH of 7.70 is agronomically favorable for most tropical food crops, including rice, maize, and vegetables, as it promotes the solubility and availability of N, P, Ca, Mg, and Zn while maintaining earthworm habitat suitability (optimum: pH 6.5–7.5)[5].

Comparison with Established Standards and Previous Studies

Compared to the Indonesian National Standard for organic fertilizers (SNI 7763:2018), which stipulates minimum $\text{N} \geq 1\%$, $\text{P}_2\text{O}_5 \geq 0.1\%$, and $\text{K}_2\text{O} \geq 0.2\%$ on a dry weight basis, the vermicompost produced in this study demonstrates N levels of approximately 0.02%, considerably below the SNI threshold. This discrepancy suggests that the current data, expressed in mg/kg of fresh weight, may require conversion to dry weight basis for accurate regulatory comparison. Assuming a dry weight conversion factor and 60-day process duration, the observed N, P, K concentrations are consistent with the early-to-mid vermicomposting stage reported by Dominguez et al. (2021) and Bhat et al. (2020), indicating that extended vermicomposting duration (90–120 days) may yield vermicompost meeting SNI and international certification standards.

Several comparable studies support the transformative potential of the feedstock combination used here. Mohammed et al. (2020) found that EFB-based vermicompost significantly improved soil organic carbon, available P, and

cation exchange capacity in Malaysian tropical soils. Phan and Sabaratnam (2012) demonstrated that SMS-derived vermicompost from oyster mushroom cultivation contained elevated enzyme activities (cellulase, phosphatase) compared to conventional compost. Mazur et al. (2021) confirmed that mixed lignocellulosic SMS vermicompost improved *Spinacia oleracea* growth parameters by 40–65% compared to unamended controls. Collectively, these findings strengthen the validity of the current results and support the agronomic utility of the produced vermicompost.

Soil Physical and Biological Implications

Beyond direct nutrient supply, vermicompost derived from oil palm waste-based SMS is expected to exert beneficial effects on soil physical and biological properties. Application of

vermicompost has been documented to improve soil aggregate stability, reduce bulk density, increase porosity, and enhance water-holding capacity through the incorporation of humic substances and earthworm-produced mucoproteins [6] [10]. Microbiologically, vermicompost introduces diverse communities of plant-growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and phosphate-solubilizing bacteria that colonize the rhizosphere and further enhance nutrient acquisition by plant roots [5] [17]. These synergistic physical-chemical-biological mechanisms collectively underpin the consistent superiority of vermicompost over conventional chemical fertilizers in promoting long-term soil health and crop productivity in tropical agroecosystems.

CONCLUSION

This study demonstrates that vermicomposting of oil palm waste-based spent mushroom substrate—comprising fronds (pelepah), leaves (daun), and empty fruit bunches (jangkos)—using *Eisenia fetida* is an effective bioconversion strategy for transforming agro-industrial waste into nutrient-enriched organic fertilizer. The vermicomposting process resulted in substantial (~237–238%) increases in total N, P, K, electrical conductivity, and the soil fertility index, while maintaining a stable, agronomically favorable pH of 7.70. These findings confirm that the co-vermicomposting of SMS with oil palm lignocellulosic residues represents a promising circular bioeconomy approach for integrated waste management in the Indonesian palm oil and mushroom agro-industries.

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From a practical standpoint, the vermicompost produced offers significant potential as a soil organic amendment for tropical food crop production, with particular relevance for rehabilitating nutrient-depleted and structurally degraded soils in Kalimantan and other palm oil cultivation regions. Future research should focus on: (1) determining optimal earthworm loading rates and feedstock C:N ratios; (2) evaluating the performance of this vermicompost on specific crops (e.g., *Brassica rapa* var. *chinensis*, *Oryza sativa*, *Zea mays*) using pot and field trials; (3) conducting 90–120 day extended vermicomposting trials to achieve regulatory-grade nutrient concentrations; and (4) performing life cycle assessment (LCA) to quantify the environmental and economic benefits of this waste valorization pathway at industrial scale.

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