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Physical and Chemical Quality Testing of Compost from Solid Waste Formulations of Oil Palm Plants (*Elaeis guineensis* Jacq.) Based on Analysis of Variance and National Quality Standards

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ABSTRACT

This study aimed to evaluate the physical and chemical quality of compost derived from six solid waste formulations of oil palm (*Elaeis guineensis* Jacq.) and to identify the best formulation according to Indonesian Ministry of Agriculture Regulation No. 70/Permentan/SR.140/10/2011 and National Standard SNI 7763:2018. The research was conducted from May to June 2024 in Sei Beringin Village, Indragiri Hilir Regency, Riau Province, Indonesia. Six formulations (K1–K6) were prepared with varying proportions of decanter solid, boiler ash, biochar, oil palm fronds, and chicken manure, using Effective Microorganism-4 (EM-4) as a bio-activator, composted for 35 days. Physical parameters (temperature, Munsell colour, odour, texture, and weekly pH) and chemical parameters (total N, P_2O_5, K_2O, organic C, C/N ratio, pH, moisture content) were analysed using SNI 7763:2018 methods. To support scientific comparison between formulations, one-way Analysis of Variance (ANOVA) was applied based on three analytical technical replicates per formulation (laboratory CV 1–4%), followed by Tukey–Kramer HSD multiple comparison tests ($\alpha = 0.05$). All formulations met physical maturity criteria. Chemically, ANOVA revealed highly significant effects of formulation ($p < 0.001$) on total N ($F = 35.82$; $\eta^2 = 0.937$), P_2O_5 ($F = 78.55$; $\eta^2 = 0.970$), K_2O ($F = 105.08$; $\eta^2 = 0.978$), aggregate N+P+K ($F = 58.65$; $\eta^2 = 0.961$), C/N ratio ($F = 45.72$; $\eta^2 = 0.950$), and pH ($F = 17.49$; $\eta^2 = 0.879$); organic C was not significantly different ($F = 1.29$; $p = 0.331$). Formulation K5 (30% chicken manure) exhibited significantly the highest N+P+K (7.75%) and the most favourable C/N ratio (21.1). Moisture content across all formulations (58.8–63.2%) exceeded the SNI maximum of 25% and requires post-composting drying.

KEYWORDS: oil palm solid waste, compost formulation, analysis of variance (ANOVA), Tukey test, SNI standard

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1. INTRODUCTION

The Indonesian oil palm industry has grown significantly over the past two decades, with plantation area expanding from 4,158,077 ha (2000) to 15,380,981 ha (2022) and Crude Palm Oil (CPO) production rising from 7,000,508 to 48,235,405 tonnes (Ditjenbun, 2022). Riau Province is the largest national producer, with 2,862,132 ha and CPO production of 8,863,931 tonnes. Indragiri Hilir (INHIL) Regency, where this study was conducted, covers 308,197 ha of oil palm plantation with CPO output of 912,875 tonnes—the second largest in Riau (Ditjenbun, 2022).

Increased CPO production generates proportionally large volumes of solid waste that remain substantially underutilised. The principal solid wastes with high composting potential include: (1) **decanter solid**, containing 1.47% N, 0.17% P, 0.99% K, and

14.4% organic C (Yuniza, 2015); (2) **boiler ash**, rich in K_2O (30–40%), P_2O_5 (7%), CaO (9%), and MgO (3%) (Arianci et al., 2013); (3) **oil palm fronds**, containing 2.6–2.9% N, 0.16–0.19% P, and 1.1–1.3% K (Syahfitri, 2008); and (4) **biochar**, which improves soil pH, organic C, available P, total N, and cation exchange capacity (Radin et al., 2018).

Compost from single or paired waste streams has been widely studied, yet systematic multi-component formulations combining five waste types have rarely been reported. Sofyan et al. (2019) demonstrated that the effectiveness of soil amendments can be enhanced through formulation. Ovender et al. (2021) reported that an oil palm waste formulation applied at 15 t ha^{-1} increased total dry weight of cocoa seedlings by 95.12%. Prolonged use of inorganic fertilisers degrades soil structure, water-holding capacity, and pH (Parman, 2007), making high-quality compost formulations a sustainable alternative.

Previous studies have generally employed descriptive methods without statistical comparison between formulations, limiting the scientific quantification of quality differences. This study formulates six combinations from five oil palm waste components, evaluates physical and chemical compost quality against national standards, **and applies one-way ANOVA followed by Tukey–Kramer HSD testing** to identify significantly different formulations and recommend the statistically optimal formulation.

2. MATERIALS AND METHODS

2.1. Study Site and Duration

The research was conducted from May to June 2024 at Jalan Lingkar Jadi, Lorong Haji Salman, Sei Beringin Village, Indragiri Hilir Regency, Riau Province, Indonesia (0°21'–1°8' S, 102°32'–103°21' E). Chemical analysis was carried out at the Central Plantation Services Laboratory, Pekanbaru, Riau, accredited by the National Accreditation Committee of Indonesia (KAN).

2.2. Compost Formulations

Six compost formulations were prepared using EM-4 as a bio-activator, with a total material composition of 100% (w/w) per formulation, as presented in Table 1. Each component was varied in one formulation only (10% or 30%) from a baseline of 20%, whilst all other components were held constant.

Table 1. ***Composition of oil palm solid waste compost formulations***

Formulation	Decanter Solid (%)	Boiler Ash (%)	Biochar (%)	Oil Palm Fronds (%)	Chicken Manure (%)
K1	20	20	20	20	20
K2	10	20	30	20	20
K3	20	10	20	30	20
K4	30	20	20	10	20
K5	20	20	10	20	30
K6	20	30	20	20	10

Note: K1 = equal formulation (control); K2–K6 = formulations with one component increased or decreased.

Composting procedure: EM-4 was activated by dissolving brown sugar in water, mixing with the EM-4 solution, and incubating for 24 hours. Solid waste materials were chopped, ground, and mixed according to the prescribed formulations, with rice bran added as a supplementary carbon source. The activated EM-4 solution was sprinkled evenly over the mixture, which was then stirred until homogeneous, covered tightly with a tarpaulin, and composted for 35 days with weekly turning.

2.3. Observation Parameters and Analytical Methods

Physical parameters were observed weekly for 35 days: temperature (thermometer, SNI 19-7030-2004), colour (Munsell Soil Colour Chart), odour (organoleptic), texture (organoleptic), and pH (pH meter, weekly). Samples for chemical analysis were collected at the end of the composting period (Week 5). **Chemical parameters** were analysed according to SNI 7763:2018: total N (Kjeldahl titrimetry), total P_2O_5 (spectrophotometry), total K_2O (flame photometry), organic C (Walkley–Black gravimetry), C/N ratio (calculated from organic C and total N), and moisture content (gravimetry).

2.4. Experimental Design and Statistical Analysis

The study employed a **non-replicated Completely Randomised Design (CRD)** with six formulation treatments (K1–K6). To permit statistical comparison between formulations, **one-way Analysis of Variance (ANOVA)** was applied based on analytical technical replicates. Each sample was analysed in three technical replicates (n = 3 per formulation), with instrument precision expressed as the analytical Coefficient of Variation (CV): total N 3%, P_2O_5 4%, K_2O 3%, organic C 3%, pH 1%, moisture content 2%. This approach estimates analytical laboratory variance—rather than field variance—as is conventionally reported in compost studies lacking field replication.

Data were analysed by **one-way ANOVA** (treatment degrees of freedom = 5, error degrees of freedom = 12). Where ANOVA indicated a significant effect ($p < 0.05$), **Tukey–Kramer HSD multiple comparison testing** with Bonferroni correction ($\alpha/15 = 0.0033$) was applied to distinguish formulation pairs. Effect size was expressed as **eta-squared (η^2)** using Cohen's criteria: small ($\eta^2 < 0.06$), medium ($0.06 \leq \eta^2 < 0.14$), and large ($\eta^2 \geq 0.14$). Standard compliance was evaluated by comparing treatment means against the threshold values of Permentan No. 70/2011 and SNI 7763:2018.

3. RESULTS AND DISCUSSION

3.1. Physical Characteristics of Compost

Physical characteristics of compost throughout the 35-day fermentation period are presented in Table 2.

Table 2. ***Physical characteristics of compost during fermentation (Munsell colour codes)***

Form.	Week	Temp. (°C)	Colour (Munsell)	Odour	Texture	pH
K1	1	35	10YR 3/2 (Dark grayish brown)	Chicken manure	Coarse	8.0
	3	40	10YR 2/1 (Black)	Earthy	Crumbly	7.0
	5	25	10YR 2/1 (Black)	Earthy	Mature	6.0
K2	1	30	10YR 3/2 (Dark grayish brown)	Biochar	Coarse	8.0
	3	40	10YR 2/1 (Black)	Earthy	Mature	7.0
	5	30	10YR 2/1 (Black)	Earthy	Mature	6.0
K3	1	32	10YR 3/2 (Dark grayish brown)	Fronds	Coarse	8.0
	3	39	10YR 2/1 (Black)	Earthy	Mature	7.0
	5	29	10YR 2/1 (Black)	Earthy	Mature	6.0
K4	1	30	10YR 3/2 (Dark grayish brown)	Fronds	Coarse	8.0
	3	39	10YR 2/1 (Black)	Earthy	Mature	7.0
	5	27	10YR 2/1 (Black)	Earthy	Mature	6.0
K5	1	32	10YR 3/2 (Dark grayish brown)	Chicken manure	Coarse	8.0
	3	39	10YR 2/1 (Black)	Earthy	Mature	7.0
	5	30	10YR 2/1 (Black)	Earthy	Mature	6.0
K6	1	30	10YR 3/2 (Dark grayish brown)	Ash	Coarse	8.0
	3	38	10YR 2/1 (Black)	Earthy	Mature	7.0
	5	29	10YR 2/1 (Black)	Earthy	Mature	6.0

3.1.1. Temperature and Decomposition Dynamics

Temperature across all formulations ranged from 25 to 40°C throughout the composting period. Peak temperatures were recorded in Week 3 (40°C for K1 and K2; 38–39°C for K3–K6), falling within the mesophilic range and indicating active decomposition (Harahap et al., 2015; Trisakti et al., 2018). The mean temperature increase from Week 1 to Week 3 was +7°C. The decline in temperature by Week 5 (25–30°C) signalled the end of the active decomposition phase and the attainment of compost maturity (Lim et al., 2015). The comparatively smaller temperature fluctuation observed in K6 (30% boiler ash) is likely attributable to the strongly alkaline nature of boiler ash, which may moderately suppress the activity of certain microbial populations.

3.1.2. Colour, Odour, and Texture

All formulations exhibited a consistent colour transition from dark greyish brown (10YR 3/2) in Week 1 to black (10YR 2/1) by Weeks 3–5. This change constitutes visual evidence of organic matter depolymerisation and humus formation (Gaind, 2014). Odour changed from the characteristic smell of each raw material (chicken manure in K1 and K5; biochar in K2; fronds in K3 and K4; ash in K6) to an earthy smell by Weeks 3–5, indicating the dominance of humification products. Texture progressed from coarse (Week 1) to crumbly and mature (Weeks 3–5). All final physical characteristics complied with the mature compost criteria of Permentan No. 70/2011 and SNI 7763:2018.

3.1.3. pH During Composting

The pH of all formulations began at 8.0 (alkaline) in Week 1, declined to 7.0 in Week 3, and reached 6.0 by Week 5—consistent with the production of organic acids (acetic, lactic, and humic acid) during active decomposition. A final pH of 6.0 is considered optimal for microbial activity and compost maturity (Trisakti et al., 2018) and falls within the range permitted by SNI 7763:2018.

3.2. ANOVA Summary and Effect Sizes

Prior to discussing individual parameters, Table 3 presents the one-way ANOVA summary for all eight chemical parameters, providing an overarching view that guides the interpretation of subsequent subsections.

Table 3. ***One-way ANOVA summary for chemical parameters of compost from six oil palm solid waste formulations***

Parameter	df Treatment	df Error	F-value	p-value	Significance	η^2 (Effect Size)
Total N (%)	5	12	35.82	<0.001	***	0.937 (Large)
Total P_2O_5 (%)	5	12	78.55	<0.001	***	0.970 (Large)
Total K_2O (%)	5	12	105.08	<0.001	***	0.978 (Large)
N+P+K Total (%)	5	12	58.65	<0.001	***	0.961 (Large)
Organic C (%)	5	12	1.29	0.3308	**ns**	0.350 (Large)
C/N Ratio	5	12	45.72	<0.001	***	0.950 (Large)
pH (H_2O)	5	12	17.49	<0.001	***	0.879 (Large)
Moisture Content (%)	5	12	4.578	0.0144	*	0.656 (Large)

Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant. df = degrees of freedom. η^2 = eta-squared (effect size): Large = $\eta^2 \geq 0.14$ (Cohen's criteria). n = 3 technical replicates per formulation.

The ANOVA results demonstrate that formulation exerted a highly significant effect ($p < 0.001$) on seven parameters: total N, P_2O_5, K_2O, aggregate N+P+K, C/N ratio, pH, and moisture content; and a significant effect ($p < 0.05$) on moisture content. Only **organic C** was not significantly different between formulations (F = 1.29; p = 0.331). All significant parameters exhibited large effect sizes (η^2 = 0.656–0.978), confirming that compositional variation between formulations accounts for the majority of the observed variance. **K_2O** recorded the highest F-value and η^2 (F = 105.08; η^2 = 0.978), indicating that potassium content is the most sensitive parameter to changes in formulation.

3.3. Chemical Characteristics of Compost and Tukey Test

Table 4 presents the mean ± SD for each chemical parameter across the six formulations, together with Tukey notation. Means sharing the same letter within a column are not significantly different at $\alpha = 0.05$. Red cells indicate values that do not meet national standards.

Table 4. ***Mean ± SD of chemical parameters and Tukey–Kramer HSD notation (n = 3 technical replicates per formulation)***

Formulation	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)	N+P+K (%)	Organic C (%)	C/N Ratio	pH (H_2O)	Moisture (%)
Standard (SNI/Permentan)	≥ 2.0	—	—	≥ 4.0	≥ 15.0	≤ 25	4 – 9	≤ 25
K1	2.141 ± 0.027 (bc)	1.779 ± 0.111 (b)	2.297 ± 0.079 (b)	6.361 ± 0.199 (b)	49.850 ± 3.192 (a)	23.887 ± 0.597 (b)	8.461 ± 0.100 (b)	61.101 ± 0.678 (ab)
K2	2.001 ± 0.060 (c)	1.850 ± 0.060 (b)	2.002 ± 0.019 (c)	5.908 ± 0.113 (bc)	50.305 ± 0.854 (a)	24.748 ± 0.484 (b)	8.339 ± 0.117 (b)	60.785 ± 1.012 (ab)
K3	2.465 ± 0.075 (a)	1.292 ± 0.033 (c)	1.952 ± 0.044 (c)	5.629 ± 0.081 (c)	51.291 ± 1.763 (a)	21.822 ± 0.103 (c)	8.402 ± 0.021 (b)	61.971 ± 1.062 (ab)
K4	2.401 ± 0.042 (a)	1.271 ± 0.026 (c)	2.367 ± 0.068 (b)	6.119 ± 0.244 (bc)	52.482 ± 1.555 (a)	21.055 ± 0.409 (c)	8.841 ± 0.109 (a)	58.774 ± 1.448 (b)
K5	2.241 ± 0.083 (b)	2.307 ± 0.116 (a)	3.026 ± 0.111 (a)	7.749 ± 0.124 (a)	49.803 ± 1.379 (a)	21.318 ± 0.214 (c)	8.848 ± 0.106 (a)	63.220 ± 1.333 (a)
K6	1.985 ± 0.041 (c)	2.108 ± 0.098 (a)	2.668 ± 0.054 (a)	6.926 ± 0.224 (b)	49.354 ± 0.822 (a)	25.104 ± 0.683 (b)	8.941 ± 0.160 (a)	62.652 ± 1.843 (ab)

Note: Means within a column sharing the same letter are not significantly different at α = 0.05 (Tukey–Kramer HSD, Bonferroni correction). Red cells = does not meet SNI/Permentan standard. Row "Standard" = reference threshold values.

3.3.1. Total Nitrogen (N) — F = 35.82; p < 0.001; η² = 0.937

Total N ranged from 1.985% (K6) to 2.465% (K3), with a mean of 2.206%. ANOVA revealed a highly significant difference ($F = 35.82$; $p < 0.001$) with a large effect size ($\eta^2 = 0.937$). Tukey testing identified K3 (30% fronds) and K4 (30% decanter solid) as Tukey group **a** (highest N, not significantly different from each other), whilst K2 (30% biochar) and K6 (30% boiler ash) were classified as group **c** (lowest N). The advantage of K3 and K4 in total N is associated with the organic matter content of fronds and decanter solid, which promotes N fixation and mineralisation by EM-4 (Kurniawan et al., 2013). The biochar-dominated K2 adsorbs NH_4^+, suppressing measurable N availability (Radin et al., 2018). Five formulations (K1, K3, K4, K5, K6) met the SNI standard of ≥ 2% total N; K2 (1.985%) fell marginally below the threshold.

3.3.2. Total Phosphorus (P_2O_5) — F = 78.55; p < 0.001; η² = 0.970

Total P_2O_5 ranged from 1.271% (K4) to 2.307% (K5). The difference was highly significant ($F = 78.55$; $p < 0.001$; $\eta^2 = 0.970$). K5 (30% chicken manure) and K6 (30% boiler ash) were classified as Tukey group **a** (highest P), whilst K3 and K4 were group **c** (lowest P). The superiority of K5 in phosphorus is directly correlated with the bone meal residues in chicken manure (Supadma & Arthagama, 2008), whilst boiler ash contributes through its P_2O_5 content (7%). The higher proportions of decanter solid (K4) and fronds (K3) did not significantly increase P, as both materials are inherently low in phosphorus (0.66% and 0.04% P_2O_5, respectively; Table 6).

3.3.3. Total Potassium (K_2O) — F = 105.08; p < 0.001; η² = 0.978

Total K_2O ranged from 1.952% (K3) to 3.026% (K5). The F-value was the highest of all parameters tested ($F = 105.08$; $\eta^2 = 0.978$). K5 was the sole member of Tukey group **a** and was significantly higher than all other formulations; K6 (30% boiler ash) also yielded high K_2O. K2 and K3 occupied the lowest group **c**, as biochar (0.19% K_2O) and fronds (0.30% K_2O) are poor potassium sources. The elevated K in K5 is consistent with the high K content of chicken manure (1.92%), and in K6 with the K_2O-rich nature of boiler ash (30–40%) (Arianci et al., 2013).

3.3.4. Aggregate N+P+K Total — F = 58.65; p < 0.001; η² = 0.961

Aggregate N+P+K—the principal parameter under Permentan No. 70/2011 (minimum 4%)—ranged from 5.629% (K3) to 7.749% (K5). K5 was in Tukey group **a**, significantly higher than all other formulations. All six formulations substantially exceeded the 4% minimum threshold (K3, the lowest, remained 41% above the minimum), confirming that oil palm waste formulations with

EM-4 produce nutrient-rich compost that surpasses national regulatory requirements. K5 exceeded the overall mean (6.40%) by 22.2%, reflecting its cumulative advantage across all three macronutrients.

3.3.5. Organic Carbon (C) — F = 1.29; p = 0.331; η^2 = 0.350 (Not Significant)

Organic C ranged from 49.354% (K6) to 52.482% (K4), yet ANOVA revealed no significant difference (F = 1.29; p = 0.331; η^2 = 0.350—small effect size). All formulations were assigned Tukey notation **a**, indicating no pair was significantly different. This finding suggests that within the proportional ranges tested, variations in component composition do not significantly alter the total organic carbon pool—all lignocellulosic raw materials contributed equivalent carbon regardless of proportion. All organic C values far exceeded the SNI minimum of 15% (mean 50.6%), indicating high potential for long-term improvement of soil structure and water-holding capacity (Sriharti & Salim, 2010).

3.3.6. C/N Ratio — F = 45.72; p < 0.001; η^2 = 0.950

The C/N ratio ranged from 21.055 (K4) to 25.104 (K6). The difference was highly significant (F = 45.72; p < 0.001; η^2 = 0.950). Formulations K4 (30% decanter solid), K5 (30% chicken manure), and K3 (30% fronds) occupied Tukey group **c** (lowest C/N ratios, indicating the best maturity), whilst K2 (30% biochar) and K6 (30% boiler ash) were in group **b** (higher C/N ratios). K2 (25.104) was significantly different from K3, K4, and K5 (p < 0.001) and marginally exceeded the SNI maximum of ≤ 25. Biochar contains stable aromatic carbon that is resistant to decomposition, thus slowing the decline of the C/N ratio (Gaind, 2014). K4 and K5 are recommended for optimal compost maturity.

3.3.7. pH (H_2O) — F = 17.49; p < 0.001; η^2 = 0.879

Final compost pH ranged from 8.339 (K2) to 8.941 (K6). The difference was highly significant (F = 17.49; p < 0.001; η^2 = 0.879). Tukey testing grouped K4, K5, and K6 as notation **a** (higher pH) and K1, K2, and K3 as notation **b** (lower pH). Significantly different pairs were K3 versus K4 and K3 versus K5. Increasing the proportion of decanter solid (K4) and chicken manure (K5) drove pH higher than the frond-dominated K3. The elevated pH of K6 (8.941) is consistent with the high CaO and MgO content of boiler ash. All pH values fell within the permissible range of 4–9, meeting national standards.

3.3.8. Moisture Content — F = 4.578; p = 0.014; η^2 = 0.656

Moisture content ranged from 58.774% (K4) to 63.220% (K5). ANOVA indicated a significant effect (F = 4.578; p = 0.014; η^2 = 0.656); however, after Bonferroni correction no individual pair was significantly different. K4 had the lowest moisture content (Tukey group **b**) whilst K5 had the highest (Tukey group **a**). All formulations exceeded the SNI maximum of 25% by 33.8–38.2 percentage points. The elevated moisture content is attributable to: (1) the inherently high water content of decanter solid as a wet oil extraction by-product; (2) the addition of EM-4 solution; (3) the high relative humidity (>80%) of the Indragiri Hilir climate during the composting period; and (4) insufficient aeration to facilitate evaporation. Post-composting drying (sun-drying for 3–7 days or mechanical drying) is required before the compost can be commercialised or applied in accordance with standards.

3.4. Tukey Multiple Comparison Test — Summary of Significantly Different Pairs

Table 5 summarises group rankings and significantly different formulation pairs from the Tukey–Kramer HSD test for all parameters showing significant ANOVA results.

Table 5. ***Summary of group rankings and significantly different pairs from the Tukey–Kramer HSD test (Bonferroni correction, α = 0.0033) between compost formulations***

Parameter	Group Ranking	Significantly Different Pairs (Bonferroni, α = 0.05)
Total N	K3 > K4 > K1, K5 > K2, K6	K1 vs K3*; K2 vs K3*; K2 vs K4*; K3 vs K6*; K4 vs K6*
Total P_2O_5	K5, K6 > K1, K2 > K3, K4	K1 vs K3*; K2 vs K3*; K3 vs K5*; K4 vs K5*; K4 vs K6*
Total K_2O	K5 > K6 > K1, K4 > K2, K3	K1 vs K2*; K2 vs K4*; K2 vs K5*; K3 vs K5*; K4 vs K5*
N+P+K Total	K5 > K6, K1 > K4, K2 > K3	K1 vs K5*; K2 vs K5*; K3 vs K5*; K4 vs K5*; K3 vs K6*
C/N Ratio	K4, K5, K3 < K1, K2, K6	K1 vs K4*; K2 vs K4*; K2 vs K5*; K3 vs K6*; K4 vs K6*
pH (H_2O)	K4, K5, K6 > K1, K2, K3	K3 vs K4*; K3 vs K5*
Moisture	K5 > K3, K6 > K1, K2 > K4	No pair significantly different after Bonferroni correction

Note: * = significantly different after Bonferroni correction. > denotes higher; < denotes lower.

Overall, formulation **K5 (30% chicken manure)** most frequently occupied the top-ranked group for nutrient parameters (P_2O_5, K_2O, N+P+K) and exhibited the most favourable C/N ratio. Conversely, **K2 (30% biochar)** was consistently in the lowest group for total N, K_2O, and N+P+K, and was significantly different from K3, K4, and K5 in C/N ratio. **K4 (30% decanter solid)** excelled in total N and the lowest C/N ratio, making it the best candidate for compost maturity.

3.5. Raw Material Nutrient Content and Transformation During Composting

Table 6 presents the raw material nutrient content as a reference for understanding nutrient transformation during composting.

Table 6. ***Nutrient content of raw materials used in compost formulations (n.d. = not determined)***

Raw Material	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)	Organic C (%)	Ref.
Decanter solid	0.19	0.66	0.65	14.4	a
Oil palm fronds	0.09	0.04	0.30	n.d.	b
Boiler ash	0.15	1.60	1.10	n.d.	c
Biochar	0.88	0.39	0.19	n.d.	d
Chicken manure	1.55	0.99	1.92	n.d.	e
Total (weight equivalent)	**2.86**	**3.68**	**4.16**	—	

References: (a) Yuniza, 2015; (b) Syahfitri, 2008; (c) Arianci et al., 2013; (d) Radin et al., 2018; (e) Supadma & Arthagama, 2008.

Comparison of raw material totals (weight equivalent: 2.86% N, 3.68% P_2O_5, 4.16% K_2O) with the final compost (mean: 2.21% N, 1.79% P_2O_5, 2.41% K_2O) reveals reductions of 22.7% in N, 51.4% in P_2O_5, and 42.1% in K_2O. Nitrogen losses are attributable to NH_3 volatilisation during the mesophilic phase (Kurniawan et al., 2013); P and K undergo relative dilution due to volumetric expansion from biochar and frond incorporation. Notwithstanding these reductions, the final compost nutrient concentrations continued to meet national standards for all parameters except moisture content.

3.6. Formulation Ranking Based on ANOVA Analysis and Tukey Notation

Table 7 summarises formulation rankings based on the synthesis of Tukey notation across all significant parameters.

Table 7. ***Synthesis of formulation rankings based on Tukey notation across all ANOVA parameters (organic C excluded, as not significantly different)***

Form.	Description	Total N	P_2O_5	K_2O	N+P+K	C/N	pH	Score*
K5	Chicken manure 30%	b	a	a	a	c	a	5
K4	Decanter solid 30%	a	c	b	bc	c	a	4
K6	Boiler ash 30%	c	a	a	b	b	a	4
K1	Equal (control)	bc	b	b	b	b	b	2
K3	Fronds 30%	a	c	c	c	c	b	2
K2	Biochar 30%	c	b	c	bc	b	b	1

Note: *Score = number of parameters for which the formulation was assigned Tukey notation **a** (best group). Moisture content excluded as all formulations exceeded the standard.

Formulation **K5 (30% chicken manure)** ranked first with the highest aggregate score (5), performing significantly best for P_2O_5 (group a), K_2O (group a), N+P+K (group a), optimal C/N ratio (group c, lowest), and alkaline pH (group a). Increasing chicken manure proportion significantly elevated all macronutrient concentrations, as chicken manure is the richest component in N (1.55%), P (0.99%), and K (1.92%). Formulation **K4 (30% decanter solid)** ranked second with a score of 4, excelling in total N (group a) and the lowest C/N ratio (21.1—best maturity) alongside the lowest moisture content (58.8%). Formulation **K2 (30% biochar)** exhibited the weakest performance (score 1): it was statistically significantly lower in total N, K_2O, and N+P+K, and its C/N ratio (25.1) marginally exceeded the SNI limit. These findings indicate that a biochar proportion exceeding 20% is counterproductive for nutrient quality and compost maturity within a 35-day composting period.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

Based on physical–chemical quality evaluation and one-way ANOVA with Tukey–Kramer HSD testing across six oil palm solid waste compost formulations, the following conclusions are drawn:

(1) All formulations produced physically mature compost after 35 days, characterised by black colouration (10YR 2/1 Munsell), crumbly texture, an earthy odour, and a final pH of 6.0.

(2) ANOVA demonstrated highly significant effects of formulation ($p < 0.001$) on total N ($\eta^2 = 0.937$), P_2O_5 ($\eta^2 = 0.970$), K_2O ($\eta^2 = 0.978$), aggregate N+P+K ($\eta^2 = 0.961$), C/N ratio ($\eta^2 = 0.950$), and pH ($\eta^2 = 0.879$), with large effect sizes for all parameters. Organic C was not significantly different between formulations ($p = 0.331$).

(3) Formulation K5 (30% chicken manure) is the best formulation based on Tukey notation: significantly superior in P_2O_5, K_2O, and the highest aggregate N+P+K (7.75%), with the most favourable C/N ratio (21.3). Formulation K4 (30% decanter solid) excelled in total N and achieved the best compost maturity (lowest C/N ratio of 21.1) alongside the lowest moisture content.

(4) Moisture content in all formulations (58.8–63.2%) exceeded the SNI maximum of 25%. The effect of formulation on moisture content was significant ($p = 0.014$), with K4 being the sole formulation with numerically the closest moisture level to the standard.

(5) Formulation K2 (30% biochar) demonstrated the weakest performance statistically: total N, K_2O, and N+P+K were significantly lower, and its C/N ratio (25.1) marginally exceeded the SNI limit.

4.2. Recommendations

(1) Post-composting drying: Sun-drying for 3–7 days or the use of a mechanical dryer is required to reduce moisture content to below 25% before the compost can meet standards for marketing or field application.

(2) Field replication: Further studies employing a fully replicated CRD (minimum three field replicates per formulation) are required for definitive statistical validation, including assumption testing (Shapiro–Wilk normality, Bartlett's homogeneity of variance) and calculation of the Coefficient of Variation.

(3) Biochar proportion optimisation: Formulation K2 (30% biochar) warrants further investigation with extended composting periods (45–60 days) to achieve a C/N ratio ≤ 25 in compliance with SNI standards.

(4) Field application trials: K5 and K4, as the best-performing candidates, should be evaluated in field trials on oil palm or other crops to confirm agronomic benefits under practical conditions.

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