



Valorization of Water Hyacinth and Banana Pseudostem through Co-Composting with Goat Manure: Effects of Biomass Ratio on Macronutrient Quality

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ABSTRACT: Water hyacinth and banana pseudostem are abundant aquatic and agricultural biomasses with contrasting physicochemical properties that may provide complementary nutrient and carbon sources during composting. However, the effects of progressively substituting lignocellulosic banana pseudostem with nutrient-rich water hyacinth under a constant manure input remain insufficiently understood. This study evaluated how different water hyacinth–banana pseudostem ratios influence the nutrient composition and C/N characteristics of compost. Four 6-kg feedstock formulations were investigated: X1 (4 kg banana pseudostem + 1 kg water hyacinth + 1 kg goat manure), X2 (3 + 2 + 1 kg), X3 (2 + 3 + 1 kg), and X4 (1 + 4 + 1 kg), using five independent 90-L composting units per formulation ($n = 20$). The mixtures were composted for 30 days and turned every two days. Total N, P, and K, organic C, and C/N ratio were determined at the end of composting. Feedstock formulation significantly affected total P ($F(3,16) = 6.583$, $p = 0.004$, $\eta^2 = 0.552$), with the highest concentration observed in X2 ($0.794 \pm 0.167\%$). Total N and K were numerically highest in X3, although differences among formulations were not statistically significant ($p = 0.091$ and $p = 0.095$, respectively). Organic C ($p = 0.816$) and C/N ratio ($p = 0.256$) also showed no significant differences, with mean C/N ratios ranging from 11.04 to 12.87. In contrast, aggregate $N + P_2O_5 + K_2O$ differed significantly among formulations ($F(3,16) = 10.255$, $p < 0.001$, $\eta^2 = 0.658$), with X2, X3, and X4 exceeding X1 but not differing significantly from one another. These findings reveal a threshold-type rather than monotonic nutrient response, indicating that increasing water hyacinth beyond the X2 proportion did not produce proportional improvements in aggregate nutrient content. Co-composting water hyacinth, banana pseudostem, and goat manure therefore provides a promising nutrient-recovery strategy for managing invasive aquatic biomass and agricultural residues, although maturity assessment, contaminant screening, and soil–plant validation are required before field-scale application.

KEYWORDS: Circular bioeconomy; environmental health; phosphorus dynamics; resource recovery; organic amendment

1. Introduction

Organic-waste accumulation represents a growing environmental challenge because inadequate management contributes to sanitation problems, greenhouse-gas emissions, odor generation, and the loss of potentially recoverable carbon and nutrients. Composting provides a practical pathway for converting biodegradable residues into stabilized organic amendments while reducing dependence on disposal. However, composting performance is strongly influenced by feedstock composition, moisture, aeration, temperature, pH, and carbon-to-nitrogen (C/N) balance. These factors regulate organic-matter decomposition, nutrient transformation, and the generation or loss of NH_3 , N_2O , CH_4 , and CO_2 , thereby linking compost-process management directly to nutrient recovery and environmental performance [1–3]. A central challenge is therefore to identify feedstock combinations that promote nutrient conservation and satisfactory compost quality while simultaneously providing a productive management pathway for problematic organic residues.

Water hyacinth (*Pontederia crassipes*, synonym *Eichhornia crassipes*) is a rapidly proliferating aquatic macrophyte that can obstruct waterways, alter aquatic ecosystem functioning, and generate substantial biomass-management burdens. Nevertheless, its ability to accumulate nutrients from the water column also creates opportunities for resource recovery. Recent studies have demonstrated the potential of water hyacinth for composting, soil amendment, and thermochemical conversion, showing that harvested biomass can be transformed from an aquatic nuisance into a potentially valuable agricultural resource [4–9]. However, its high moisture content and physicochemical characteristics can complicate composting when it is used as a dominant or sole substrate. Its successful valorization therefore depends on appropriate co-substrate selection, process management, and verification of the agronomic quality and environmental safety of the final product [4–9].

Banana pseudostem provides a potentially complementary feedstock. Large quantities of pseudostem biomass remain after banana harvesting, creating an additional agricultural-residue management challenge. This material contains substantial cellulose, hemicellulose, lignin, moisture, and mineral constituents and can therefore provide structural material and carbon during composting. However, its lignocellulosic composition may restrict decomposition when used alone or in excessive proportions. Recent circular-bioeconomy studies have identified banana pseudostem as a versatile biomass for value-added biological products and agricultural applications, supporting its utilization rather than disposal [10, 11]. Combining fibrous, carbonaceous banana pseudostem with wetter and comparatively nutrient-rich water hyacinth may consequently create a more balanced composting substrate than either biomass used individually.

The relative proportion of these two biomasses is particularly important because changes in feedstock composition may alter nutrient availability and retention rather than simply producing proportional changes in the final compost composition. In the present formulation, goat manure provides a nutrient- and microorganism-rich co-substrate. Maintaining the manure input at the same mass across treatments allows the relative proportions of water hyacinth and banana pseudostem to serve as the principal experimental contrast. This distinction is especially relevant to nitrogen because ammonification, nitrification, denitrification, microbial assimilation, and gaseous losses occur simultaneously during composting. Previous metagenomic, process-based, and meta-analytical studies have demonstrated that nitrogen retention depends on substrate composition, microbial pathways, pH, temperature, moisture,

aeration, and process management [12–15]. Consequently, increasing the proportion of a nominally nutrient-rich substrate cannot be assumed to produce a linear increase in final compost nutrient concentration.

Evaluation of compost quality also requires appropriate interpretation of nutrient measurements. Laboratory analyses commonly quantify total N, elemental P, and elemental K, whereas fertilizer-quality assessments may express phosphorus and potassium as P_2O_5 and K_2O equivalents. Maintaining this distinction is essential to avoid incorrect interpretation of nutrient concentrations. Furthermore, endpoint macronutrient concentrations alone cannot establish complete compost maturity or agronomic suitability. C/N ratio, mineral nitrogen forms, germination indices, respiration activity, microbial indicators, and other stability parameters can provide complementary evidence of compost maturity and quality [16–20]. Feedstock formulation should therefore be evaluated not only in terms of individual nutrient concentrations but also in relation to carbon characteristics and the overall fertilizer-oriented nutrient composition.

Despite increasing interest in water-hyacinth valorization and biomass co-composting, the effect of progressively substituting banana pseudostem with water hyacinth while maintaining a constant manure input remains insufficiently understood. Previous co-composting studies have frequently modified several feedstock components simultaneously, making it difficult to distinguish the specific influence of the plant-biomass ratio from the contribution of animal manure. Consequently, it remains unclear whether progressively increasing water hyacinth produces a proportional improvement in final nutrient composition or whether nutrient recovery reaches a threshold or favorable formulation range. Resolving this relationship is important for designing compost mixtures that simultaneously valorize invasive aquatic biomass and agricultural residues without assuming that greater incorporation of nutrient-rich biomass necessarily produces superior compost.

The novelty of this study lies in the systematic substitution of two contrasting plant biomasses within a constant composting matrix. Goat manure was maintained at a fixed mass, while banana pseudostem was progressively replaced by water hyacinth from a pseudostem-dominant ratio of 4:1 to a water-hyacinth-dominant ratio of 1:4, with two intermediate formulations. This experimental design enables the specific formulation effect of the two plant biomasses to be evaluated while minimizing variation associated with manure input and allows determination of whether nutrient responses follow a monotonic or threshold-type pattern.

Accordingly, this study aimed to determine how progressive substitution of banana pseudostem with water hyacinth under a constant goat-manure input influences the nutrient and carbon characteristics of the resulting compost, based on total N, total P, total K, organic C, final C/N ratio, and aggregate $N + P_2O_5 + K_2O$, and thereby identify a favorable formulation range for the valorization of aquatic and agricultural biomass residues.

2. Materials and Methods

2.1. Experimental Design and Feedstock Formulation.

A single-factor experiment was conducted using four compost formulations that differed only in the relative proportions of banana pseudostem (BP) and water hyacinth (WH), while the mass of goat manure was maintained at 1 kg in all treatments. Each composting unit contained an initial feedstock mass of 6 kg, comprising 5 kg of plant biomass and 1 kg of goat manure.

The four formulations were X1 (4 kg BP + 1 kg WH + 1 kg goat manure), X2 (3 kg BP + 2 kg WH + 1 kg goat manure), X3 (2 kg BP + 3 kg WH + 1 kg goat manure), and X4 (1 kg BP + 4 kg WH + 1 kg goat manure). Five independent batches were prepared for each formulation, resulting in 20 composting drums. Each drum was treated as an independent biological experimental unit. The progressive substitution series, ranging from a BP-dominant mixture (4:1) to a WH-dominant mixture (1:4), was designed to evaluate whether changes in compost characteristics followed a progressive response or exhibited a threshold-type pattern. The composition of each formulation is presented in Table 1.

Table 1. Compost Feedstock Formulations.

Formulation	Banana pseudostem (kg)	Water hyacinth (kg)	Goat manure (kg)	BP:WH ratio
X1	4	1	1	4:1
X2	3	2	1	3:2
X3	2	3	1	2:3
X4	1	4	1	1:4

BP = banana pseudostem; WH = water hyacinth. Goat manure was fixed at 1 kg in every treatment, so the intended treatment contrast was the progressive substitution of BP by WH.

Water hyacinth, banana pseudostem, and goat manure were sourced locally from Bengkulu City, Indonesia. The individual feedstocks were not chemically characterized before composting; consequently, baseline moisture content, pH, organic C, C/N ratio, and N, P, and K concentrations were unavailable. This limitation prevented direct quantification of nutrient mass balances and restricted attribution of differences in final compost composition to the initial chemical characteristics of individual feedstocks. Nevertheless, maintaining the same total feedstock mass and goat-manure input across treatments provided a consistent experimental basis for evaluating the effect of progressive BP substitution by WH. The overall experimental procedure, from feedstock preparation and formulation through composting, final sampling, laboratory analysis, and statistical evaluation, is illustrated in Figure 1.

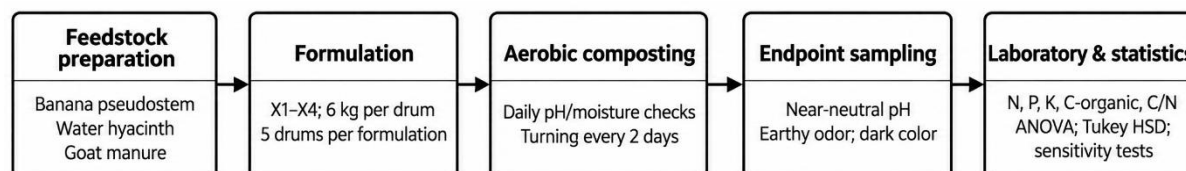


Figure 1. Experimental Workflow for Compost Preparation, Processing, and Analysis.

2.2. Composting procedure and endpoint determination.

For each experimental unit, the assigned feedstocks were weighed separately, thoroughly mixed to obtain a reasonably homogeneous substrate, and transferred to an individual 90-L composting drum. All formulations were composted aerobically for 30 days under the same operational conditions. The composting material was turned every two days to improve aeration, redistribute the decomposing biomass, and minimize localized accumulation of heat. Moisture conditions were monitored daily by direct observation. No additional water was required during the composting period because the inherent moisture of the water hyacinth maintained adequate moisture conditions for decomposition. Because continuous quantitative measurements of temperature and moisture were unavailable, these parameters were considered operational process conditions rather than experimental response variables.

At the end of the 30-day composting period, each drum was evaluated using the operational endpoint observations adopted in the study, including pH approaching neutrality,

development of an earthy odor, and a dark-brown to black appearance. These characteristics were used only as supporting indicators of the final composting condition and were not considered sufficient evidence of complete compost maturity. The final C/N ratio provided an additional physicochemical indicator; however, comprehensive maturity assessment generally requires complementary measurements such as electrical conductivity, germination index, respiration stability, mineral nitrogen forms, and microbiological safety. At day 30, the material in each drum was homogenized separately, after which a representative sample was collected from each experimental unit for laboratory analysis at the Faculty of Agriculture Laboratory, Universitas Bengkulu, Indonesia. Samples from different drums were analyzed independently and were not pooled.

2.3. Determination of Total N, Total P, Total K, Organic C, and C/N Ratio.

Laboratory analyses were performed separately for each composting unit to determine total N, total P, total K, and organic C. Organic-matrix mineralization for nutrient analysis was conducted using H₂SO₄-based wet digestion according to the laboratory operating procedure. Total N was determined using the Kjeldahl method. Briefly, organic nitrogen was converted to ammonium during acidic digestion, followed by alkalization of the digest, distillation of liberated ammonia, and quantification of nitrogen in the distillate according to the laboratory procedure. Organic C was determined using the Walkley–Black wet oxidation method. The final C/N ratio was subsequently calculated on a mass basis using the paired organic C and total N values obtained from each independent experimental unit. Total N and organic C were expressed as percentages.

Total P was determined from the wet-digestion extract using spectrophotometry. Following color development according to the laboratory procedure, absorbance was measured and the P concentration was determined against laboratory standards or an appropriate calibration curve. The results were reported as elemental total P (%). Total K was determined from the corresponding digest using flame photometry. The sample solution was introduced into the flame, and the potassium emission response was quantified against K standards within the instrument working range. The results were reported as elemental total K (%). This analytical distinction was maintained throughout the study because spectrophotometric and flame-photometric measurements represented elemental P and K, whereas P₂O₅ and K₂O were subsequently calculated as fertilizer-reporting equivalents rather than directly measured chemical species.

2.4. Oxide-Equivalent Conversion and Fertilizer-Quality Benchmark.

For interpretation on a fertilizer-reporting basis, elemental P and K concentrations were converted stoichiometrically to their corresponding oxide equivalents. Total P was converted to P₂O₅ using a conversion factor of 2.291, while total K was converted to K₂O using a factor of 1.205. Nitrogen remained expressed as total N. An aggregate macronutrient value (N + P₂O₅ + K₂O) was calculated separately for each experimental unit before treatment means and standard deviations were determined. Performing the conversion and aggregation at the individual-drum level preserved within-treatment variability and ensured that subsequent statistical analyses reflected the five independent biological replicates.

The calculated N + P₂O₅ + K₂O values were compared descriptively with the macronutrient reporting framework of Indonesian SNI 7763:2024 for solid organic fertilizer

and the relevant national regulatory framework for organic-fertilizer registration [21, 22]. This comparison was used solely as a scientific benchmark and should not be interpreted as evidence of regulatory certification or full product compliance. The present study evaluated only selected nutrient and carbon characteristics and did not perform the complete suite of physicochemical, biological, and safety analyses required for formal certification. Accordingly, all comparisons with regulatory standards were restricted to the measured or calculated macronutrient parameters.

2.5. Statistical Analysis.

The experiment consisted of five independent composting drums for each of the four formulations ($n = 5$ biological replicates per treatment; $N = 20$ experimental units). Data are presented as mean $\pm$ standard deviation (SD). Before inferential analysis, homogeneity of variance was evaluated using Levene's test, while the normality of model residuals was assessed using the Shapiro–Wilk test.

Differences among formulations in total N, total P, total K, organic C, C/N ratio, and aggregate $N + P_2O_5 + K_2O$ were evaluated using one-way analysis of variance (ANOVA), with formulation as the independent factor and the individual composting drum as the experimental unit. Statistical significance was established at $\alpha = 0.05$. When the omnibus ANOVA indicated a significant treatment effect, pairwise comparisons were conducted using Tukey's honestly significant difference (HSD) test. Effect size was quantified using eta-squared (η^2) to complement significance testing and indicate the proportion of variation attributable to feedstock formulation.

Because the residuals for total P deviated from normality, the Kruskal–Wallis test was additionally performed as a nonparametric sensitivity analysis to assess the robustness of the ANOVA result. The same nonparametric analysis was applied to the remaining response variables for consistency. Statistical interpretation therefore considered the direction and magnitude of treatment effects, p-values, effect sizes, and agreement between parametric and nonparametric analyses. All conclusions were restricted to the four feedstock formulations and experimental conditions evaluated in this study.

3. Results and Discussion

3.1. Macronutrient Concentrations Across Formulations.

Progressive substitution of banana pseudostem with water hyacinth produced distinct nutrient-response patterns among the four compost formulations, as summarized in Table 2. Total P increased from $0.516 \pm 0.084\%$ in X1 to its highest concentration of $0.794 \pm 0.167\%$ in X2, before decreasing to $0.680 \pm 0.063\%$ in X3 and $0.706 \pm 0.046\%$ in X4. In contrast, total N and total K reached their highest mean concentrations in X3, at $1.812 \pm 0.173\%$ and $0.980 \pm 0.085\%$, respectively. Because the conversion of elemental P and K to P_2O_5 and K_2O equivalents is linear, oxide-equivalent reporting altered the numerical magnitude but not the relative ranking of the treatments. The aggregate $N + P_2O_5 + K_2O$ concentration was lowest in X1 ($3.851 \pm 0.293\%$) and highest in X3 ($4.551 \pm 0.259\%$), while X2 and X4 produced similarly high values.

Table 2. Macronutrient Concentrations And Oxide-Equivalent Fertilizer Values Across Compost Formulations.

Formulation	Total P (%)	P ₂ O ₅ equiv. (%)	Total K (%)	K ₂ O equiv. (%)	Total N (%)	N+P ₂ O ₅ +K ₂ O (%)
X1	0.516±0.084 ^a	1.182±0.192 ^a	0.880±0.045 ^a	1.060±0.055 ^a	1.608±0.092 ^a	3.851±0.293 ^a
X2	0.794±0.167 ^b	1.819±0.382 ^b	0.880±0.095 ^a	1.060±0.115 ^a	1.608±0.193 ^a	4.487±0.124 ^b
X3	0.680±0.063 ^{ab}	1.558±0.145 ^{ab}	0.980±0.085 ^a	1.181±0.103 ^a	1.812±0.173 ^a	4.551±0.259 ^b
X4	0.706±0.046 ^b	1.617±0.104 ^b	0.952±0.047 ^a	1.147±0.057 ^a	1.756±0.094 ^a	4.521±0.227 ^b

Note: Values are mean ± SD (n=5). Within a column, means sharing the same superscript letter are not significantly different at $\alpha=0.05$ (Tukey HSD following a significant omnibus ANOVA; where ANOVA was not significant, all treatments share the same letter). equiv. = oxide equivalent. P₂O₅ = 2.291 × total P and K₂O = 1.205 × total K. N+P₂O₅+K₂O was calculated for each independent drum before treatment means and SDs were summarized.

The results in Table 2 demonstrate that the nutrient response to feedstock substitution was not monotonic. Total P was particularly sensitive to formulation and reached its maximum in X2 rather than in the WH-dominant X3 or X4 treatments. Thus, the results do not support a simple assumption that progressively increasing water hyacinth necessarily increases compost nutrient concentration. Instead, replacing part of the strongly BP-dominated matrix in X1 with additional WH in X2 produced the largest increase in P, whereas further substitution generated no proportional improvement. Previous studies on water-hyacinth composting and vermicomposting similarly indicate that final nutrient composition depends on interactions among substrate composition, decomposition processes, and composting conditions rather than on the proportion of aquatic biomass alone [4, 6, 7, 23]. Within the formulations evaluated here, X2 should therefore be interpreted as the most P-enriched treatment rather than as a universally optimal formulation. The comparative macronutrient profiles of the four formulations are further illustrated in Figure 2. The figure highlights the pronounced increase in P from X1 to X2 and the comparatively smaller variation in N and K across treatments.

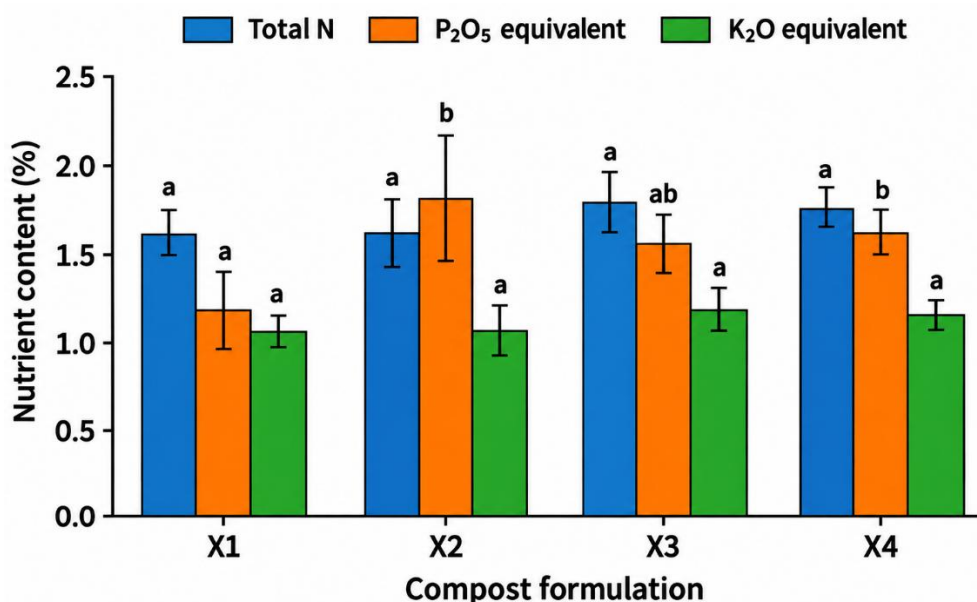


Figure 2. Macronutrient Profile of the Four Compost Formulations. Note: Different Lowercase Letters Above Bars Indicate Tukey HSD Groupings At $\alpha=0.05$ For Each Nutrient; Identical Letters Indicate No Statistically Significant Pairwise Separation.

A plausible explanation for the observed P pattern is the balance among degradability, moisture, and physical structure created by combining the two plant residues. Water hyacinth can provide relatively labile biomass and mineral nutrients, whereas banana pseudostem contributes lignocellulosic carbon and structural material. Under strong pseudostem

dominance, slower lignocellulosic decomposition may constrain nutrient release, whereas high WH incorporation may increase moisture and reduce pore continuity if aeration is insufficient. These conditions could affect microbial mineralization, immobilization, and P retention within the solid compost. However, because moisture dynamics, oxygen availability, microbial communities, and P fractions were not directly quantified, these mechanisms should be regarded as plausible explanations rather than demonstrated causal pathways [16, 18–20].

Total N did not differ significantly among formulations, although X3 produced the highest numerical mean and the effect size was moderate ($\eta^2 = 0.325$). Nitrogen is particularly dynamic during composting because ammonification, nitrification, denitrification, microbial assimilation, and gaseous losses may occur simultaneously. Previous metagenomic, process-based, and meta-analytical studies have demonstrated that final N retention depends strongly on microbial pathways and composting conditions and that substantial N losses may occur during organic-waste composting [12, 14, 15, 24]. The constant addition of 1 kg of goat manure to all treatments may also have established a common N-rich baseline, thereby reducing the treatment contrast attributable specifically to the BP:WH ratio. Consequently, the higher N concentration in X3 should be regarded as a numerical formulation signal rather than definitive evidence of superior N retention.

Process interventions can further modify N conservation without changing the primary feedstock ratio. Biochar, zeolite, wood vinegar, modified sorbents, and microbial inocula have been reported to influence ammonia retention, microbial N transformations, and gaseous N losses during composting [13, 25–29]. The present study did not quantify NH_3 , N_2O , NH_4^+ , NO_3^- , or microbial functional genes; therefore, the mechanisms responsible for the numerical differences in N among formulations could not be resolved.

Total K also varied within a relatively narrow range, from 0.880% to 0.980%, with X3 producing the highest numerical concentration. Unlike organic N, much of the K in plant biomass occurs in soluble ionic forms, and its final concentration may reflect both release during tissue decomposition and losses through leaching. Previous nutrient-recovery studies have shown that N, P, and K can exhibit different retention and release patterns during biomass processing [24]. The limited variation observed in the present study suggests that changing the BP:WH ratio alone was insufficient to generate strong separation in K concentrations.

3.2. Statistical Effects of Feedstock Ratio.

The statistical effects of feedstock formulation on individual nutrients, aggregate macronutrient concentration, organic C, and C/N ratio are summarized in Table 3. Formulation significantly affected total P ($F(3,16) = 6.583$, $p = 0.004$, $\eta^2 = 0.552$), indicating that approximately 55% of the observed variation in total P was associated with differences among the tested formulations. Tukey HSD showed that X2 contained significantly more P than X1 ($p = 0.003$), while X4 also exceeded X1 ($p = 0.041$). X3 did not differ significantly from either X1 or the higher-WH formulations. Although the total-P residuals deviated from normality (Shapiro–Wilk $p = 0.009$), the Kruskal–Wallis sensitivity analysis also identified a significant formulation effect ($H = 10.265$, $p = 0.016$), supporting the robustness of the conclusion. As shown in Table 3, neither total N nor total K reached statistical significance at $\alpha = 0.05$. Total K ranged from 0.880% to 0.980% ($F(3,16) = 2.512$, $p = 0.095$, $\eta^2 = 0.320$), while total N ranged from 1.608% to 1.812% ($F(3,16) = 2.565$, $p = 0.091$, $\eta^2 = 0.325$). The corresponding Kruskal–Wallis tests produced consistent conclusions for K ($p = 0.085$) and N ($p = 0.087$). Although both variables

showed moderate effect sizes and X3 produced the highest numerical means, the absence of statistically significant omnibus effects means that these patterns should be interpreted as trends rather than confirmed treatment differences.

Table 3. Omnibus Tests, Nonparametric Sensitivity Analyses, and Effect Sizes for Compost-Quality Responses.

Parameter	F(3,16)	ANOVA p	η^2	Kruskal–Wallis p
Total P / P_2O_5	6.583	0.004	0.552	0.016
Total K / K_2O	2.512	0.095	0.320	0.085
Total N	2.565	0.091	0.325	0.087
N + P_2O_5 + K_2O	10.255	<0.001	0.658	0.011
Organic C	0.312	0.816	0.055	0.690
C/N ratio	1.487	0.256	0.218	0.258

The aggregate fertilizer-reporting metric, N + P_2O_5 + K_2O , exhibited the strongest formulation effect ($F(3,16) = 10.255$, $p < 0.001$, $\eta^2 = 0.658$), with the Kruskal–Wallis analysis providing a concordant result ($p = 0.011$). Tukey HSD indicated that X2, X3, and X4 each had significantly higher aggregate macronutrient concentrations than X1 ($p = 0.003$, $p = 0.001$, and $p = 0.002$, respectively), whereas no significant differences occurred among X2, X3, and X4. Thus, the principal improvement occurred when the formulation shifted from the strongly BP-dominated X1 mixture to formulations containing at least 2 kg WH within the 6-kg composting matrix. Further substitution of BP with WH did not produce a proportional increase in aggregate macronutrient concentration. Pasted text

This threshold-type response and its relationship with the 2% SNI 7763:2024 macronutrient benchmark are illustrated in Figure 3. The figure shows that all four formulations exceeded the benchmark, while X2–X4 formed the statistically higher group relative to X1.

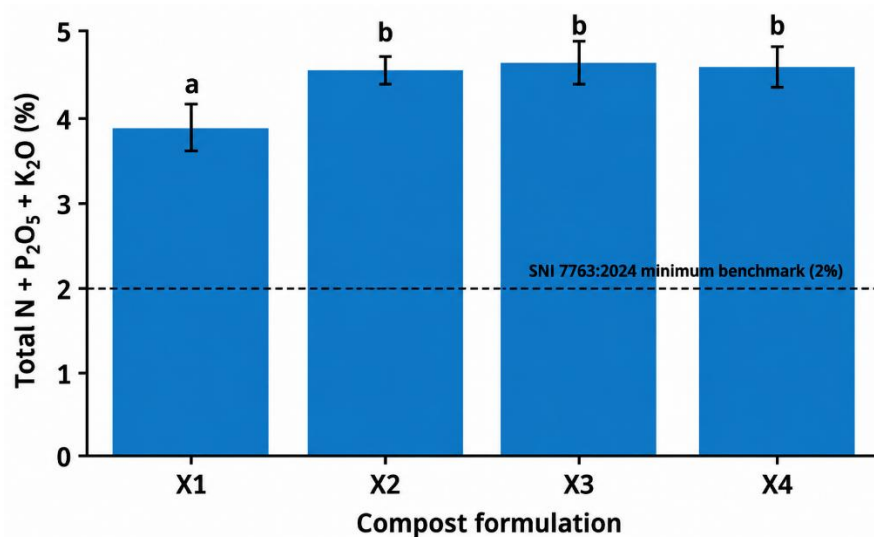


Figure 3. Total Macronutrients Expressed As Total N + P_2O_5 + K_2O . Note : Different Letters Indicate Tukey HSD Groups; The Dashed Line Indicates The 2% SNI 7763:2024 Minimum Macronutrient Benchmark.

When the three macronutrients were integrated on a fertilizer-reporting basis, the formulation response became clearer. Aggregate N + P_2O_5 + K_2O increased markedly from X1 to X2 and subsequently plateaued across X2–X4. This pattern is more informative for formulation selection than ranking treatments according to a single nutrient. X2 produced the highest P concentration, whereas X3 yielded the highest mean N, K, and aggregate

macronutrient concentration. However, because X2, X3, and X4 were statistically indistinguishable for the aggregate response, the results support a favorable formulation range rather than a single statistically superior formulation. From a resource-efficiency perspective, X2 may be particularly attractive where WH availability, collection, transport, or handling is limiting because increasing WH beyond 2 kg did not result in a statistically detectable improvement in the aggregate nutrient metric. Pasted text

The distinction between elemental and oxide-equivalent nutrient reporting is important when interpreting these findings. Spectrophotometry and flame photometry quantified elemental P and K, respectively, whereas P_2O_5 and K_2O were calculated as stoichiometric reporting equivalents. Conversion changed the numerical scale but did not alter treatment rankings or statistical conclusions. All formulations exceeded the 2% SNI 7763:2024 macronutrient benchmark after conversion [21]. However, this finding indicates only that the formulations met the calculated macronutrient benchmark; it does not establish complete fertilizer quality or regulatory compliance because maturity, heavy-metal concentrations, microbiological safety, and other certification requirements were not comprehensively evaluated [22].

From an environmental perspective, co-composting also provides a potential pathway for simultaneously managing two problematic biomass streams. Harvesting water hyacinth can support aquatic-system management, while banana cultivation generates substantial quantities of bulky pseudostem residues. Combining these materials provides a relatively low-technology circular approach in which nutrient-rich aquatic biomass and lignocellulosic agricultural residues can be valorized together rather than managed separately [10, 11]. Nevertheless, nutrient concentration alone is insufficient to establish suitability for agricultural application. Water hyacinth can accumulate contaminants from its aquatic environment, and the present study did not quantify heavy metals, potentially toxic elements, or microbiological safety [8]. Appropriate contaminant screening and maturity assessment are therefore required before field application.

3.3. Organic carbon and final C/N ratio.

Final organic C and C/N ratio were evaluated to determine whether progressive substitution of banana pseudostem with water hyacinth altered the carbon status and carbon-to-nitrogen balance of the final compost. As summarized in Table 4, organic C varied only slightly among formulations, ranging from $19.776 \pm 1.561\%$ in X3 to $20.490 \pm 1.635\%$ in X2. No significant formulation effect was detected ($F(3,16) = 0.312$, $p = 0.816$, $\eta^2 = 0.055$), and the Kruskal–Wallis sensitivity analysis produced the same conclusion ($p = 0.690$). Similarly, the final C/N ratio ranged from 11.038 ± 1.800 in X3 to 12.874 ± 1.824 in X2 and did not differ significantly among treatments ($F(3,16) = 1.487$, $p = 0.256$, $\eta^2 = 0.218$; Kruskal–Wallis $p = 0.258$). Levene’s tests supported homogeneity of variance for both organic C ($p = 0.955$) and C/N ratio ($p = 0.623$), while Shapiro–Wilk tests of the residuals showed no significant departure from normality ($p = 0.196$ and $p = 0.360$, respectively). These findings indicate that feedstock formulation had a considerably stronger influence on P and aggregate macronutrient concentration than on final organic C or C/N balance. The relatively narrow ranges presented in Table 4 suggest that the four feedstock formulations converged toward a broadly comparable carbon status after 30 days of composting despite their contrasting initial BP:WH ratios. In particular, increasing WH from 1 to 4 kg did not produce a systematic increase or decrease in

final organic C. The absence of a significant C/N response similarly indicates that progressive replacement of lignocellulosic BP with WH did not substantially alter the final balance between residual organic C and total N under the tested conditions. This contrasts with the significant P and aggregate macronutrient responses and suggests that nutrient enrichment and final C/N balance responded differently to feedstock substitution.

The final mean

Table 4. Final organic C and C/N ratio across compost formulations.

Formulation	Organic C (%)	C/N ratio
X1	19.838 ± 1.381	12.348 ± 1.036
X2	20.490 ± 1.635	12.874 ± 1.824
X3	19.776 ± 1.561	11.038 ± 1.800
X4	20.484 ± 1.703	11.660 ± 0.994

Note: Values are Mean ± SD (N = 5). One-Way ANOVA Detected No Significant Formulation Effect for Organic C (P = 0.816) or C/N Ratio (P = 0.256); Therefore, No Pairwise Treatment Separation was Inferred.

C/N ratios of 11.038–12.874 are consistent with substantial transformation of organic material during composting. However, these values should not be interpreted independently as evidence of complete compost maturity. C/N ratio represents only one dimension of compost stabilization, and similar endpoint values may arise from different decomposition and nutrient-loss pathways. A more comprehensive assessment requires complementary indicators such as electrical conductivity, NH_4^+ and NO_3^- concentrations, germination index, respiration stability, and microbiological quality [16–20]. Consequently, the present C/N results support a broadly comparable final carbon-to-nitrogen balance among formulations but do not establish complete maturity or absence of phytotoxicity.

This distinction is also relevant to the operational endpoint indicators used in the experiment. Near-neutral pH, earthy odor, and dark coloration provided practical evidence of compost transformation, while the final C/N ratio supplied an additional quantitative indicator. Nevertheless, these parameters alone are insufficient to establish complete stabilization, maturity, or agronomic safety. Multi-indicator approaches are preferable because feedstock composition and composting conditions can affect individual physical, chemical, and biological maturity indicators differently [16–20].

3.4. Study Limitations and Implications.

Several limitations should be considered when interpreting the findings. First, although five independent composting drums were used for each formulation, the experiment was conducted at a relatively small scale and under a single set of operational conditions. The results therefore provide evidence for formulation effects within the tested system but should not be generalized directly to larger composting facilities or substantially different environmental and operational conditions.

Second, the individual feedstocks were not characterized before composting. Initial moisture content, pH, organic C, C/N ratio, and N, P, and K concentrations were unavailable for BP, WH, and goat manure. Consequently, nutrient mass balances could not be established, and the observed differences in final compost composition cannot be attributed quantitatively to the initial nutrient contribution of each feedstock. This limitation is particularly important

for interpreting the apparent threshold response because the experiment identifies the effect of formulation but does not fully resolve the underlying nutrient-transformation mechanisms.

Third, continuous temperature and moisture profiles, oxygen conditions, electrical conductivity, NH_4^+ and NO_3^- dynamics, respiration stability, germination index, leachate production, nutrient fractions, and gaseous emissions were not measured. The observed changes in nutrient concentrations therefore cannot be attributed definitively to mineralization, immobilization, volatilization, leaching, or other transformation pathways. Future experiments incorporating time-resolved process measurements would provide a stronger mechanistic explanation for the formulation-dependent responses.

A further limitation concerns compost safety. Water hyacinth can accumulate contaminants from the aquatic environment, yet heavy metals, other potentially toxic elements, and microbiological safety were not evaluated in this study. Because the WH was collected locally in Bengkulu City, nutrient composition alone cannot establish the safety of the resulting compost for agricultural application. Appropriate screening for contaminants and microbiological hazards should therefore precede field use, particularly when the source water may be affected by anthropogenic inputs.

Despite these limitations, the use of five independent composting units per formulation provides a valid basis for treatment-level statistical inference within the experimental conditions. Importantly, the significant P response and the stronger aggregate $\text{N} + \text{P}_2\text{O}_5 + \text{K}_2\text{O}$ response converged on the same practical pattern: reducing extreme BP dominance improved macronutrient concentration, whereas further substitution with WH produced diminishing returns. X2, X3, and X4 were statistically indistinguishable for the aggregate nutrient response, indicating a favorable formulation range rather than a single optimum mixture. This threshold-type behavior represents the principal contribution of the study because it demonstrates that co-composting should be approached as a formulation problem in which nutrient recovery, feedstock availability, material characteristics, process control, and product safety must be considered simultaneously. Larger-scale studies incorporating feedstock characterization, process monitoring, maturity assessment, contaminant screening, and soil–plant validation are required to determine the broader applicability of this formulation strategy [30–32].

4. Conclusions

This study demonstrated that progressive substitution of banana pseudostem with water hyacinth under a constant goat-manure input significantly influenced the macronutrient composition of the resulting compost, but the response was nonlinear. Total P was the most formulation-sensitive individual nutrient and reached its highest concentration in X2 (3 kg banana pseudostem + 2 kg water hyacinth + 1 kg goat manure). X3 (2 + 3 + 1 kg) produced the highest mean total N, total K, and aggregate $\text{N} + \text{P}_2\text{O}_5 + \text{K}_2\text{O}$, although total N and K did not differ significantly among formulations. Most importantly, X2, X3, and X4 all produced significantly higher aggregate macronutrient concentrations than the strongly pseudostem-dominated X1, while no significant differences occurred among these three formulations. The nutrient response therefore exhibited a threshold rather than a monotonic pattern, indicating that increasing water hyacinth beyond the X2 proportion did not provide a statistically detectable additional benefit in aggregate macronutrient concentration. In contrast, final organic C and C/N ratio remained statistically comparable among formulations, with mean C/N ratios ranging from 11.04 to 12.87. Thus, substantial changes in feedstock ratio altered nutrient

composition more strongly than the final carbon-to-nitrogen balance. From a resource-management perspective, these findings demonstrate the potential of co-composting to integrate invasive aquatic biomass and banana residues into a nutrient-recovery pathway, with X2–X3 representing particularly promising formulations for further evaluation. However, the observed nutrient concentrations and relatively low C/N ratios do not establish complete compost maturity, safety, or regulatory compliance. Future validation should therefore incorporate initial feedstock characterization, larger-scale composting, continuous process monitoring, maturity and phytotoxicity indicators, contaminant and microbiological screening, gaseous and leachate losses, and soil–plant trials. Such validation is necessary to determine whether the favorable nutrient profiles observed under controlled conditions translate into safe and effective agronomic performance.

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Author Contribution

A.W.: Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Visualization, Writing – Original Draft, Project Administration. M.G.: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Review & Editing. Y.: Methodology, Data Curation, Validation, Investigation, Writing – Review & Editing. B.U.: Methodology, Resources, Validation, Investigation, Supervision, Writing – Review & Editing. H.S.: Validation, Investigation, Visualization, Interpretation of Results, Writing – Review & Editing. All authors have read and approved the final manuscript

Competing Interest

The authors declare no conflict of interest.

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