

Physical and Chemical Characterization of Various Formulations of Biochar and Fly Ash-Enriched Composts for Tropical Acid Soil Ameliorant

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ABSTRACT

Large quantities of organic residues generated from pineapple production remain underutilized. Composting is a common strategy for recycling these materials, while biochar and fly ash (FA), a coal-combustion byproduct, may enhance compost quality. This study evaluated temperature dynamics, moisture content, pH, total N, C/N ratio, and macronutrient contents of biochar–FA-enriched compost. The experiment used a single-factor randomized complete block design (RCBD) with seven formulations and four replicates. Treatments A, B, and C consisted of 75% compost raw materials enriched at the beginning of composting with biochar and FA at proportions of 20:5, 12.5:12.5, and 5:20%, respectively. Treatment D consisted of 100% compost raw materials without enrichment. Treatments E, F, and G used the same proportions as A, B, and C, respectively, but incorporated biochar and FA into mature compost. Treatment C showed the most balanced characteristics, with a pH of 7.20, a C/N ratio of 20.60, total N of 2.06%, and P content of 4,387 mg kg⁻¹. In contrast, treatment G recorded the highest numerical Ca content of 16,288 mg kg⁻¹. Overall, early enrichment with 5% biochar and 20% FA produced compost with a suitable pH and C/N ratio and relatively high nutrient contents. This formulation, therefore, has potential as an ameliorant for tropical acid soils, although its agronomic effectiveness requires further soil incubation and field evaluation.

Keywords: Carbon, compost, enrichment time, micro, residue

INTRODUCTION

Acidic soils in the wet tropics generally face fertility constraints due to continued weathering and intensive alkaline leaching. These conditions are linked to low organic matter and alkaline cation content, acidic soil reactions, limited cation exchange capacity, and exchangeable aluminum. Agricultural biomass waste provides organic matter and can be reused to support more sustainable land management. In pineapple cultivation and processing systems, harvest and processing residues are

produced in large quantities but are not always optimally utilized. Belyaeva and Haynes (2009) found that pineapple processing residue is 50–60% of the fruit's weight, while Bruce and Boateng (2025) report that pineapple waste is generally skins, crowns, stems, and leaves. At the garden level, Paz-Arteaga et al. (2024) also showed that pineapple residue biomass is produced in large quantities, thus opening strong opportunities for waste valorization. In this context, composting is an important approach because it can convert pineapple waste into more stable, value-added organic matter. In line with this, Sossa et al. (2024) stated that pineapple production generates significant harvest and processing residues that remain underutilized.

Organic matter management therefore aims not only to add nutrients but also to improve the soil's ability to hold elements, form aggregates, and buffer changes in soil pH. The challenge is that organic matter in tropical soils can decompose relatively quickly because temperatures and humidity support microbial activity. Thus, ameliorants for tropical acidic soils need a balance between organic fractions that provide nutrients and carbon fractions that resist mineralization. Compost is a widely used source of organic matter. Composting offers a biologically driven, environmentally friendly strategy to convert organic residues into value-added soil amendments that improve soil fertility and nutrient cycling (Bernal et al., 2009; Awasthi et al., 2020).

Composting is an aerobic biodegradation process in which a succession of microbes transforms unstable organic matter into stable humification products. This process typically progresses through mesophilic, thermophilic, and maturation phases, characterized by dynamic changes in temperature, humidity, pH, organic carbon degradation, and nitrogen mineralization (Insam and de Bertoldi, 2007; Xiao et al., 2017). Temperature evolution during composting is a key indicator of microbial activity, pathogen suppression, and organic-matter decomposition efficiency. Meanwhile, the C/N ratio is widely recognized as the maturity index, reflecting the balance between carbon mineralization and nitrogen conservation (Bernal et al., 2009). Although compost derived from agro-industrial residues can improve soil structure, microbial activity, and nutrient supply, conventional composting in tropical conditions often presents challenges. High temperatures and humidity accelerate organic-matter mineralization, potentially causing rapid nitrogen loss through ammonia volatilization and reducing the long-term stability of organic carbon (Awasthi et al., 2016). Therefore, strategies to improve nutrient stabilization and improve compost quality are increasingly being explored.

Biochar has received considerable attention as a functional amendment in the composting system. Produced through biomass pyrolysis under oxygen-limited conditions, biochar is characterized by high porosity, large specific surface area, aromatic carbon structure, and significant cation exchange capacity (Lehmann and Joseph, 2015). When incorporated into the composting matrix, biochar can improve aeration, regulate moisture content, and provide microhabitats for microbial communities (Sánchez-García et al., 2015). Biochar has also been shown to reduce nitrogen loss by absorbing ammonium and

reducing ammonia volatilization during composting (Steiner et al., 2010; Awasthi et al., 2017). Stable aromatic carbon also increases carbon stabilization and may lower the final C/N ratio more efficiently than conventional compost (Zhang et al., 2014). Antonangelo et al. (2021) explain that co-composted biochar can improve the physicochemical and biological properties of compost and improve its performance compared to biochar or compost used separately. Furthermore, Rios-Mercado et al. (2026) show that the timing of biochar addition during different composting phases can affect the process, product quality, and microbial community.

In addition to biochar, fly ash, a byproduct of coal combustion in thermal power plants, has emerged as a potential mineral additive for composting systems. Fly ash typically contains calcium oxide (CaO), magnesium oxide (MgO), potassium (K), phosphorus (P), and various trace elements, depending on the source and combustion conditions (Pandey and Singh, 2010). The alkaline properties of fly ash can buffer compost pH, especially during the early stages of decomposition when organic acids are produced (Hageman et al., 2017). Several studies report that composting with fly ash can increase nutrient availability, improve pH stability, and promote humification (Awasthi et al., 2016; Muhammad et al., 2024). In addition, the mineral components in fly ash can improve the compost's final nutrient profile by increasing concentrations of Ca, Mg, and other essential plant nutrients. However, compost still contains a fraction of carbon that can be remineralized after application. Therefore, compost should be formulated with other materials when intended to produce an ameliorant with better resilience and carbon stability.

The quality of the compost produced depends not only on the type of raw material but also on composting dynamics and the additives used. Temperature and moisture content are key indicators of microbial activity, decomposition intensity, and process stability, while C-organic and nutrient content indicate the chemical quality of the compost produced. Zhong et al. (2025) stated that different process conditions can significantly affect compost maturity, stability, and chemical quality. Similarly, Li et al. (2026) explain that managing process conditions and additive characteristics largely determines the temperature stability, maturity, and quality of the final product. Therefore, evaluating compost on the final product alone is not enough; it is also necessary to consider how process conditions support organic matter transformation and nutrient retention. This approach matters because good compost

characteristics provide a strong basis for developing potential fertilizers for soils with quality constraints, including acidic and degraded soils.

Differences in enrichment time are important for developing tropical acidic soil ameliorants. Products with a higher pH do not necessarily have better quality if the increase is due to a high ash content and is followed by a decrease in the organic fraction. Similarly, products with higher C-organic are not necessarily more mature if they still have a large C/N ratio or contain ingredients that have not been decomposed. Formulation decisions should balance process stability, material maturity, and carbon, nitrogen, and mineral content. With this approach, enriched compost is valued not only as a residue management product but also as a material designed for the needs of tropical acidic soils.

Researchers have extensively studied composting with biochar, as well as the use of fly ash as a mineral material in compost. However, information comparing the addition of biochar and fly ash at the beginning of composting with their addition after compost maturity remains limited. Such comparisons are necessary to distinguish the effect of the transformation process during composting from the effect of physical mixing on the final product. In addition, the use of pineapple processing residues as compost and biochar raw materials, combined with fly ash, has not been widely studied to produce a potential ameliorant for tropical acidic soils.

Based on these considerations, this study evaluated the production of pineapple residue compost enriched with biochar and fly ash at different proportions and mixing times. Enrichment was carried out at the start of the process and after the compost was ripe. The study did not directly test soil or plant responses. Therefore, this study aimed to evaluate the effects of biochar and fly ash proportions and incorporation time on the composting process and the chemical characteristics of the resulting enriched compost, and to identify the most suitable formulation as a potential ameliorant for tropical acid soils. It focused on product characterization and formulation selection rather than agronomic effectiveness under field conditions.

MATERIALS AND METHODS

This research was conducted from August to September 2023 at a compost plant in Central Lampung Regency, Lampung Province, Indonesia. The compost raw materials consisted of cow manure in solid and liquid form, pineapple bromelain pulp waste, and decomposer. The biochar used in this

study is produced from pineapple waste pulp via slow pyrolysis at 400–500 °C under limited oxygen for 3–4 hours. After cooling, the biochar is crushed and sifted through a 2 mm sieve before use. The fly ash (FA) used is a by-product of burning medium-to high-grade bituminous coal from an internal power plant in a pineapple plantation in Lampung. The FA is dominated by SiO₂ (around 69.7%) and has a relatively low Ca content (about 4.8%), so it is classified as F-type fly ash under ASTM C618.

The trial used a single-factor Randomized Complete Block Design (RCBD) with seven compost formulations and four replicates. The factors tested were biochar and FA-enriched compost formulations using different mixing strategies. Treatments A, B, and C are made by mixing biochar and FA into compostable raw materials at the beginning of the composting process, each with a composition of 75% compost raw materials + 20% biochar + 5% FA, 75% compost raw materials + 12.5% biochar + 12.5% FA, and 75% compost raw materials + 5% biochar + 20% FA. Treatment D consists of 100% compost raw materials, without the addition of biochar or FA, and is used as a control. Meanwhile, treatments E, F, and G are made by mixing biochar and FA into the mature compost, with the composition of 75% compost + 20% biochar + 5% FA, 75% compost + 12.5% biochar + 12.5% FA, and 75% compost + 5% biochar + 20% FA, respectively.

In treatments A, B, and C, biochar and FA are mixed into the compost raw materials from the beginning of the composting process according to their respective formulations. In treatment D, the composting process uses only compost raw materials, without adding biochar and FA. Meanwhile, in treatments E, F, and G, compost is first made from raw materials until it reaches maturity. Thus, in this treatment, biochar and FA are not involved throughout the decomposition process but are added only at the final stage as compost additives.

During composting, the process is carried out aerobically using the windrow system, with periodic reversals using the compost turner available on the composting unit, for ±8-10 weeks. Compost is considered mature based on temperature stability, dark brown color, brittle texture, and a C/N ratio <20. During composting, temperature and moisture content are observed as indicators of composting dynamics. Observations are carried out according to the characteristics of each parameter. Compost temperature is observed periodically from day 0 to day 25 to illustrate decomposition dynamics. Moisture content, pH, and C/N ratios, the content of total nitrogen (N), available phosphorus (P),

exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were analyzed only at the end of composting (day 25) as indicators of the final compost's chemical characteristics.

The Walkley and Black method was used to analyze organic C, total N was determined by the Kjeldahl method, and available P was measured spectrophotometrically after acid extraction. K, Ca, and Mg contents were determined after extraction using the appropriate standard procedure and measured by atomic absorption spectrophotometry (AAS). Data was analyzed using multiple analyses (ANOVA), and if the treatment had a significant effect, then followed up with Duncan's Multiple Range Test (DMRT) at a significance level of 5%. All statistical analyses were conducted in RStudio (RStudio Inc., Boston, USA).

RESULTS AND DISCUSSION

Temperature dynamics during the composting process

The treatment showed noticeable differences in temperature parameters during composting (Figure 1). The temperature of the entire treatment fluctuated: it increased in the initial stage, reached its highest value during active decomposition, then fluctuated before decreasing toward the end of composting. The initial temperature increase results from energy released during microbial respiration.

Simple carbohydrates, proteins, and biodegradable organic compounds serve as sources of carbon and energy, while some of the energy released during oxidation is converted to heat. This phase is characterized by a shift from mesophilic to thermophilic microorganisms. Bernal et al. (2009) stated that temperature development is one of the main indicators of decomposition intensity. Still, it cannot be used as the sole measure of maturity because it is also influenced by stack size, moisture content, aeration, material composition, and reversal frequency.

Figure 1. Temperature dynamics during composting of pineapple residues enriched with different proportions of biochar and fly ash. Vertical bars represent [standard deviation/standard error]. Different letters at the same observation time indicate significant differences according to DMRT at $p < 0.05$.

At the start of the observation, the material temperature was still relatively low, and there were no significant differences between treatments. The temperature then increased to a peak around day 7, with highs of 76°C in A and B, 73°C in C, and 68°C in D. These differences suggest that the proportions of biochar and fly ash in treatments A and B created initial conditions that favored organic-matter decomposition. Biochar can reduce the mixture's density and create additional air chambers, while fly ash can alter the material's pH and ionic environment. However, the effect of the two

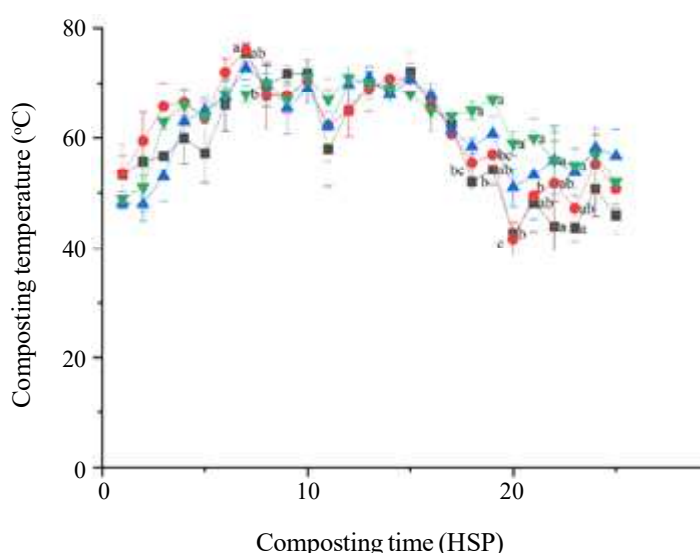


Figure 1. Temperature dynamics during composting of pineapple residues enriched with different proportions of biochar and fly ash. Vertical bars represent [standard deviation/standard error]. Different letters at the same observation time indicate significant differences according to DMRT at $p < 0.05$.
 ■ : A, ● : B, ▲ : C, ▼ : D.

ingredients is not always linear with dosage because increasing mineral fractions can reduce the proportion of organic substrates available to microorganisms. Sánchez-García et al. (2015) used up to 3% biochar on a dry-weight basis in the composting of a mixture of poultry manure and straw for 19 weeks. The addition accelerated organic-matter degradation and mineral nitrogen formation but did not cause a large change in gas emissions compared to controls. The results suggest that low-dose biochar can improve the physical condition of composting without requiring the highest temperature throughout the process.

After the peak phase, the temperature of the whole treatment fluctuates. These fluctuations may relate to pile reversal, moisture redistribution, oxygen entry, and the re-availability of substrates previously in the pile's interior or bottom. An increase shortly after reversal does not necessarily indicate a return to the initial phase but may reflect the recovery of microbial respiration as aeration conditions improve. Entering the final part of the observation at 23 HSP, the treatment D (compost only) tended to maintain a higher temperature than some formulations enriched with biochar and fly ash. Biochar and fly ash enrichment accelerated the temperature drop during the final phase, indicating reduced thermal decomposition intensity. The C/N ratio, moisture content, pH, and chemical character of the final product further confirm the maturity interpretation. The pattern suggests that compost alone still retains relatively greater decomposition activity in the late phases, while mixtures with biochar and fly ash approach low thermal conditions more quickly. Belyaeva and Haynes (2009) reported that green waste composting without fly ash reached about 50 °C for 6 days, whereas mixtures with 25% and 50% fly ash only reached about 36–38 °C. This means that the peak temperature in the fly ash mixture is about 12–14 °C lower than the control. At 75 and 100% proportions, there is almost no self-heating. The findings show that adding too large an ash fraction can limit heat production by reducing active organic matter.

In this study, the total enrichment material was 25%, but the composition differed between biochar and fly ash. Therefore, the thermal response depends not only on the total amount of additives but also on the ratio of the two components. Treatment A contains 20% biochar and 5% fly ash, treatment B contains 12.5% biochar and 12.5% fly ash, while treatment C contains 5% biochar and 20% fly ash. At 19 days of composting, treatments A, B, and C reached temperatures of 54.2, 57.0, and 61.0°C, respectively, while treatment D reached

67.0°C. These temperatures indicate that microbial decomposition remained active during the thermophilic phase. Treatment C maintained a higher temperature than A and B despite containing the highest fly ash proportion and the lowest biochar proportion among the three enriched-compost formulations. Therefore, the results do not support the assumption that a higher mineral fraction necessarily reduced compost temperature or that a higher biochar proportion directly increased it. Instead, compost temperature appears to be influenced by multiple factors, including feedstock degradability, moisture content, aeration, pile structure, and microbial activity. Although biochar may improve porosity and provide microsites for microbial growth, its effect on temperature depends on the biochar application rate, raw-material properties, and composting conditions (Sánchez-Monedero et al. 2018; Hassanzadeh Moghimi et al. 2023; Jia et al. 2023).

Chemical Characteristics of Biochar–Fly Ash Enriched Compost

The final characteristics of the compost are influenced by the proportions of biochar and fly ash and by the timing of their addition. In treatments enriched from the beginning of composting (A, B, and C), the pH values were 7.6, 7.4, and 7.2, respectively, whereas compost without enrichment (D) had a pH of 6.7. Treatment A produced the highest pH and differed significantly from C and D, but not from B. Compared to D, pH in A was 0.9 units higher, B was 0.7 units higher, and C was 0.5 units higher. The pH increased from 5.2 to 7.6, indicating a shift toward more neutral conditions during the composting process. The early pH increase in the enriched formulation suggests that biochar and fly ash alter the chemical environment during decomposition. Biochar generally contains ash fractions and surface groups that can provide neutral to alkaline reactions.

In contrast, fly ash contributes alkaline minerals, mainly as oxides, hydroxides, carbonates, and silicates containing Ca, Mg, K, or Na. During composting, the components can partially neutralize the organic acids that are formed in the initial phase. Chaheer et al. (2020) attributed the more alkaline pH of biochar-added food waste compost to the alkalinity of biochar and its ability to buffer acidification during decomposition.

The results of the biochar- and fly ash-enriched compost study were obtained in line with a study by Tessfaw et al. (2020), which showed that the addition of biochar at 5 and 15% in urban organic

waste composting resulted in a higher pH and cation exchange capacity compared to compost without biochar, while a dose of 25% did not always produce the best quality. The study recommends a biochar range of 5–15% because it provides a better balance of pH, nutrients, and organic matter. This study shows a somewhat different pattern, with the highest pH at A, which contains 20% biochar and 5% fly ash. These differences likely relate to raw material type, pyrolysis temperature, the nature of the biochar ash, and the presence of fly ash in the mixture.

The effect of fly ash on pH also depends on the dose. Malarski et al. (2023) reported that increasing the proportion of fly ash in the compost mass was associated with higher pH but also greater nitrogen loss. Thus, a high pH does not necessarily indicate the best compost quality. At very high pH, the NH_4^+ – NH_3 balance can shift toward NH_3 , increasing the risk of nitrogen volatilization. In this study, the pH range of 6.7–7.6 remains neutral to slightly alkaline, making it relatively suitable for materials intended as candidates for acidic soil ameliorants. However, the product's true ability to raise soil pH cannot be determined until incubation testing or soil application is conducted.

Treatments E, F, and G, which are formulations enriched after the compost is mature, have pH values of 7.2, 7.2, and 7.3, respectively. The value is above D, but numerically lower than A and B. This pattern suggests that early enrichment not only adds alkaline materials to the product but also allows biochar and fly ash to interact with organic acids and decomposition products throughout the composting process. In contrast, adding after cooking changes pH more directly through mixing. Because the table does not show a distinguishing letter for E–G, treat the comparison as a descriptive tendency rather than a statistically significant difference. Treatments E, F, and G, in which biochar and fly ash were incorporated into mature compost, had pH values of 7.2, 7.2, and 7.3, respectively. This result suggests that varying the proportions of biochar and fly ash within the tested range did not significantly affect final pH when the amendments were added after the compost had matured. Therefore, the small numerical variation among E, F, and G should be interpreted as a descriptive difference rather than a statistically significant treatment effect.

Final product moisture content ranged from 21.0 to 35.0%. Compost without enrichment (D) had the highest moisture content (35%) and differed significantly from A, B, and C. Moisture content in A and B was 21%, while C was 25%. Compared with D, the moisture content of A and B was 14

percentage points (40.0%) lower, while C was 10 percentage points (28.6%) lower. In the mixing treatment after cooking, the moisture content of E, F, and G was 21.8%, 23.8%, and 21.6%. Descriptively, the scores are 37.7%, 32.0%, and 38.3% lower than D. The low moisture content of enriched compost can be explained by the properties of the additives and the mixture composition. Biochar and fly ash replace up to 25% of the organic matter in A–C. Fly ash is a relatively dry mineral material. At the same time, biochar has a porous structure that can hold water but does not necessarily increase the product's gravimetric moisture content at the time of analysis.

Adding both materials also increased the dry-solid fraction and improved aeration and evaporation during the process. In E–G, the decrease in moisture content is likely due more to mixing mature compost with biochar and fly ash, which have lower initial moisture contents. The results of the study by Sossa et al. (2024) stated that the optimal moisture content during the composting of pineapple residues is in the range of 40–60%, because the moisture content below 20% can inhibit decomposition, while values above 70% limit oxygen exchange and promote the formation of anaerobic conditions. This range mainly applies to the active phase of composting, rather than as an absolute limit for the final product. The final value of 21–35% in this study indicates that the compost had lost most of its water during maturation. Treatments A, B, E, and G are slightly above 20%, and Sossa et al. (2024) stated that this condition can limit microbial activity if it occurs during the active phase. Therefore, the low moisture content of the final product supports storage, but it cannot be used to conclude that moisture conditions throughout the process were optimal.

Tessfaw et al. (2020) found that the final moisture content of compost is between 35–45%. Based on these parameters, D (35% moisture) is at the lower limit of the range, while A–C and E–G are drier. This difference can help with storage and transport because water is lighter, but overly dry products tend to produce dust. They may need to be moistened when used or if the ripening process is incomplete. For this reason, moisture content should be considered alongside final temperature, respiration, and C/N ratio. The C/N ratio differs significantly among treatments A–D. Treatment D has the highest C/N ratio (24.2), while A, B, and C have ratios of 19.1, 21.5, and 20.6, respectively. Compared with D, A's C/N ratio was 5.1 units (21.1%) lower, B's was 2.7 units (11.2%) lower, and C's was 3.6 units (14.9%) lower. Treatments A and C differ significantly from D, while B falls in

the intermediate group and does not differ significantly from A or D. In enrichment after the compost is cooked, E, F, and G have C/N ratios of 20.8, 21.2, and 20.2, respectively.

The lower C/N ratio at A–C indicates that compost enriched with biochar and fly ash has a different carbon-to-nitrogen balance than the control compost. The decline can occur because volatile carbon is mineralized to CO₂, while some nitrogen is retained in microbial biomass or adsorbed to the biochar surface. However, interpreting C/N in biochar-containing compost requires careful consideration. Some biochar carbon is aromatic and relatively resistant, so it is less readily available than carbon in fresh residues. Thus, the total C/N ratio does not fully reflect carbon availability for microorganisms.

Bernal et al. (2009) emphasized that the C/N ratio is a useful indicator of maturity, but it is insufficient on its own; maturity must be assessed alongside organic-matter stability, nitrogen form, pH, temperature, and other biological indicators. Results A–G (19.1–24.2) indicate that all products have approached the commonly used range for mature or relatively stable compost. However, D (24.2) still shows a higher carbon-to-nitrogen ratio than the compost treatment enriched with biochar and fly ash.

The closest benchmark is Sossa et al. (2024), which found that composting harvest residue and pineapple processing with 25% poultry manure produced a final product with a C/N ratio ranging from 14.56 to 18.77. The highest value was obtained with the pineapple processing residue-based formula (18.77 ± 3.33), while the lowest was 14.56 ± 1.83. Compared with these results, the C/N ratio in this study was 0.3–9.6 units higher. This difference likely reflects Sossa et al. (2024), which used nitrogen-rich poultry manure, whereas this study used a mixture of bromelain dregs, cow dung, biochar, and fly ash. In addition, pyrolytic carbon from biochar can maintain the total C/N ratio at higher levels even as the volatile organic fraction decreases.

Abban-Baidoo et al. (2024) also obtained mature biochar compost with a pH of 9.0–9.7, total carbon of 24.7–37.6%, and total nitrogen of 1.8–2.4%. In this study, the product's pH was lower, at 6.7–7.6. This more moderate condition may be an advantage in acidic soils because the product still has a neutral to slightly alkaline reaction without showing very high alkalinity. However, these advantages must be proven through neutralization capacity, Ca and Mg content, and soil response after application.

Overall, early enrichment resulted in the most obvious changes in A. The formula had the highest

pH (7.6), the lowest moisture content (21%), and the lowest C/N ratio (19.1). Compared with control D, A had a pH 0.9 units higher, 40.0% lower moisture content, and a 21.1% lower C/N ratio. Together, these results show that formulations with 20% biochar and 5% fly ash produce drier products, exhibit a somewhat alkaline reaction, and have a lower C/N ratio. However, these three parameters alone do not determine the best formulation.

Treatment C, with 5% biochar and 20% fly ash, yields a pH of 7.2, 25% moisture content, and a C/N ratio of 20.6. Although the pH is lower than A, the formulation may still benefit from the higher fly ash content, which can help offset the alkaline mineral content. Therefore, the conclusion about the most promising formula as an ameliorant for sour soils should be based on an integrated analysis, not a single pH or C/N value.

Based on Table 1, N, P, K, and Ca differ across ameliorant types, but Mg content does not. Treatment C had the highest N content (2.1%), followed by G (1.9%), while compost without enrichment was only 1.6%. This shows that combining biochar and fly ash at certain doses, especially in treatment C, can suppress N loss during composting. The results align with Xu et al. (2025), who reported that adding biochar to composting increased nitrogen retention, with the highest final total N content reaching 39.55 g kg⁻¹, higher than the control of 32.12 g kg⁻¹. In the same study, the final NO₃⁻-N content in biochar treatment reached 16.16 g kg⁻¹, while the control was only 7.15 g kg⁻¹.

The highest P content was found in treatment C at 4387 mg kg⁻¹, or an increase of 23.7% compared to D. The average initial treatment of composting A–C yielded a P of 4177 mg kg⁻¹, while the average of the final mixing treatment of E–G was only 2669 mg kg⁻¹. The initial mixing of biochar and fly ash during composting resulted in a P content about 56.5% higher than after cooking. This indicates that composting provides time for fly ash, organic matter, and biochar to interact, allowing P from mineral fractions to integrate better into the compost matrix.

For element K, treatment D showed the highest value (13152 mg kg⁻¹), while treatments C and G were very close (13041 mg kg⁻¹ and 13006 mg kg⁻¹, respectively). This suggests that biochar and fly ash enrichment do not necessarily increase total K significantly but can maintain high K levels. Wang et al. (2019) explained that biochar can increase K_z retention by increasing cation exchange capacity and can affect Ca and Mg availability by altering soil chemical reactions and colloidal surfaces.

The Ca and Mg content shows a strong pattern, supporting the role of fly ash as a source of alkaline

Table 1. Chemical properties of ameliorant properties in the treatments.

Parameters	A	B	C	D	E	F	G
pH	7.6 ^a	7.4 ^{ab}	7.2 ^b	6.7 ^c	7.2 ^b	7.2 ^b	7.3 ^b
Moisture content (%)	21 ^b	21 ^b	25 ^b	35 ^a	21.8 ^b	23.8 ^b	21.6 ^b
C/N	19.1 ^b	21.5 ^{ab}	20.6 ^b	24.2 ^a	20.8 ^b	21.2 ^{ab}	20.2 ^b
N (%)	1.8 ^{bc}	1.8 ^{bc}	2.1 ^a	1.6 ^c	1.8 ^{bc}	1.8 ^{bc}	1.9 ^{ab}
P (mg kg ⁻¹)	4190 ^{ab}	3954 ^{ab}	4387 ^a	3547 ^{abc}	2297 ^d	2664 ^{cd}	3045 ^{bcc}
K (mg kg ⁻¹)	12942 ^d	12288 ^d	13041 ^{al}	13153 ^a	7892 ^c	12009 ^b	13006 ^{ai}
Ca (mg kg ⁻¹)	13402 ^{abc}	13172 ^{abc}	15031 ^{al}	11971 ^{bc}	11112 ^c	13018 ^{abc}	16288 ^a
Mg(mg kg ⁻¹)	5390	5154	5663	4619	4213	4619	5175

Numbers followed by different letters on the same line show a significant difference based on the DMRT test at the level of 5%. A = 75% compost + 20% biochar + 5% fly ash with mixing at the beginning of the process; B = 75% compost + 12.5% biochar + 12.5% fly ash with mixing at the beginning of the process; C = 75% compost + 5% biochar + 20% fly ash with mixing at the beginning of the process; D = 100% compost only without the addition of biochar and FA; E = 75% mature compost + 20% biochar + 5% fly ash with mixing at the end; F = 75% mature compost + 12.5% biochar + 12.5% fly ash with mixing at the end, and G = 75% mature compost + 5% biochar + 20% fly ash with mixing at the end.

cations. Treatment G produced the highest Ca (16288 mg kg⁻¹), while treatment C produced the highest Mg (5663 mg kg⁻¹). Compared to D, treatment C increased Ca by 25.6% and Mg by 22.6%, while G increased Ca by 36.1% and Mg by 12.1%. Mupambwa et al. (2015) reported that fly ash from bituminous and sub-bituminous coal can contain CaO 5–40%, MgO 1–10%, and SO₂ 0–10%, while class C fly ash can have up to 30–40% Ca; this composition explains why the addition of fly ash can enrich Ca and Mg in ameliorant products.

CONCLUSIONS

The treatment of 75% compost raw materials + 20% biochar + 5% fly ash (A) and 75% compost raw materials + 12.5% biochar + 12.5% fly ash (B), which are enriched from the beginning of composting, produces the highest pH value, so that it has a more alkaline character than other formulations. Based on the C/N ratio, unenriched compost and early enriched formulations, particularly A and B, have shown relatively mature conditions. However, their interpretation still needs to account for the presence of biochar carbon, which is more difficult to decompose.

The 75% compost + 5% biochar + 20% fly ash (C) treatment produced the highest N, P, and Mg contents. In contrast, treatment G (75% mature compost + 5% biochar + 20% fly ash) recorded the highest numerical Ca content. These results suggest that a higher proportion of fly ash contributes more to the mineral composition and macroelements of the final product, whether added before or after composting.

Taking into account its intended use in tropical acidic soils, the treatment of 75% compost raw materials + 5% biochar + 20% fly ash (C) at the beginning of the composting process shows the most balanced character, as it combines early enrichment with high macronutrient content (N, P, K, Ca, and Mg) as well as the appropriate pH and final C/N ratio. The product has potential as an ameliorant for tropical acidic soils. However, its effectiveness in reducing soil acidity, increasing nutrient availability, and supporting plant growth still needs to be tested through soil and field incubation experiments.

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