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Research Article

Synergistic enriched compost with biochar and fly ash for improving Ultisols in tropical acid soils

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Abstract

Ultisols are characterized by low pH, low alkaline saturation, low cation exchange capacity, and high levels of soluble Al and Fe. Compost is usually applied to increase soil fertility, but its effect is only temporary in tropical conditions because organic matter decomposes quickly. Biochar and fly ash-enriched compost have been proposed as a synergistic approach to improve the chemical properties of Ultisols. This study evaluated the effect of compost enriched with biochar and fly ash on soil chemical dynamics over 16 months in pineapple plantations in Lampung, using a randomized block design with three treatments: compost enriched at the initial stage, compost alone as a control, and compost enriched at the end of composting. The results showed that biochar and fly ash increased soil pH during the initial phase by supplying alkaline cations. Fluctuations occurred during the intermediate stage due to the decomposition of organic matter and nitrogen transformation: organic C and total N increase, influenced by microbial activity and environmental conditions. Phosphorus followed a mineralization-immobilization-remobilization pattern, with late-stage enrichment producing P. Potassium, calcium, and magnesium initially increased but later decreased, likely due to leaching. Early-stage enrichment provided a more stable release of alkaline cations. Fe, Mn, Cu, and Zn show fluctuations in the enriched treatment. The application of biochar and fly ash-enriched compost synergistically with early-stage enrichment effectively enhances the chemical properties of Ultisol.

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Introduction

Ultisols are among the most widely distributed soil orders in Indonesia, particularly across Sumatra, Kalimantan, Sulawesi, and Papua (Pratamaningsih et al., 2024; Sianipar et al., 2025). These soils develop from parent materials that have undergone intensive weathering under humid tropical conditions (Pratamaningsih et al., 2024). Ultisols are characterized by strongly acidic soil reactions, low base saturation, low cation exchange capacity (CEC), and high concentrations of soluble Al and Fe. Such conditions severely limit the availability of essential macronutrients, particularly N, P, K, Ca, and Mg

(Purwanto et al., 2020; Pratamaningsih et al., 2024). In the agricultural sector, Ultisols are generally considered unproductive in the absence of appropriate amelioration, thereby constituting a major constraint to agricultural land development outside Java (Purwanto et al., 2020). From a land degradation perspective, the extensive distribution of Ultisols poses a major challenge for sustainable land management and long-term soil productivity in tropical regions.

Various strategies have been employed to improve the physical, chemical, and biological properties of Ultisols (Endriani et al., 2025). Compost is widely used in Indonesia as a source of organic matter due to its availability and its ability to improve soil structure, enhance microbial activity, and supply nutrients. However, under hot, humid tropical conditions, compost decomposes rapidly, yielding short-lived benefits (Fajarindo et al., 2024). The relatively labile carbon fraction of compost also limits the sustainability of soil fertility improvements (Grigatti et al., 2024). Therefore, enriching compost with additional soil conditioners is necessary to enhance its effectiveness in ameliorating acidic soils. This condition underscores the importance of developing integrated soil amendment strategies that improve soil quality more persistently.

Biochar has emerged as one of the most extensively studied soil amendments in Indonesia. Given the abundance of locally available feedstocks, such as wood waste, rice husks, palm kernel shells, and other agricultural residues, biochar can be produced cost-effectively and sustainably (Barus, 2016; Oktavia et al., 2023; Saputra et al., 2024). In general, biochar has been shown to ameliorate soil acidity, enhance water-holding capacity, provide favorable habitats for soil microorganisms, and contribute stable carbon to the soil (Antonangelo et al., 2025; Enebe et al., 2025; Zhu et al., 2025). In Ultisols and other acidic soils in Indonesia, biochar has been demonstrated to reduce Al saturation and improve fertilizer use efficiency (Pratamaningsih et al., 2024; Sianipar et al., 2025). Due to its relatively stable nature, biochar is considered suitable for supporting long-term rehabilitation of degraded acidic soils (Antonangelo et al., 2025; Zhu et al., 2025).

Fly ash, particularly that derived from biomass or coal combustion in Indonesian industries and power plants, is rich in Ca, Mg, K, and Si (Hermawan et al., 2014; Asof et al., 2022; Aziz et al., 2025). Its alkaline properties make it effective in increasing soil pH and alleviating Al toxicity in acidic soils. The application of fly ash as a soil conditioner also aligns with efforts to reduce industrial waste and promote sustainable agricultural practices. In Indonesian Ultisols, fly ash has considerable potential to enhance P availability, which is typically strongly fixed by Fe and Al compounds (Aziz et al., 2025). The addition of fly ash formulation in the form of granules with tapioca and molasses binders increased the biomass of sorghum plants from 2,723 kg ha^{-1} to 8,486 kg ha^{-1} (Agusta et al., 2021). Nevertheless, the effectiveness of fly ash depends on soil characteristics and its interaction with organic amendments. The combined application of compost enriched with biochar and fly ash has considerable potential for rehabilitating acidic soils in Indonesia (Hermawan et al., 2014; Aziz et al., 2025). Compost supplies organic matter and beneficial microorganisms, biochar contributes stable carbon and improves soil structure, and fly ash increases soil pH while supplying base cations (Hermawan et al., 2014; Asof et al., 2022; Aziz et al., 2025). The synergistic interaction among these components can enhance soil aggregate stability, increase cation exchange capacity, reduce soil acidity and Al saturation, improve the availability of P, K, Ca, and Mg, enrich soil carbon stocks over the long term, and stimulate soil microbial activity. In addition, biochar has been reported to effectively mitigate greenhouse gas emissions, particularly N_2O and CH_4, through mechanisms such as enhanced nitrogen immobilization, improved soil aeration, and alterations in denitrifying microbial communities (Zhang et al., 2022; Enebe et al., 2025). Therefore, an integrated soil management strategy combining compost, biochar, and fly ash offers substantial potential not only for rehabilitating marginal soils in Indonesia, especially highly acidic Ultisols. However, quantitative field-based studies evaluating the combined effects of these amendments on soil chemical properties under tropical Ultisol conditions remain limited.

Therefore, research on the synergistic application of compost enriched with biochar and fly ash to improve Ultisols in tropical acidic soils is both relevant and timely. This approach is expected to provide an ecologically based solution that supports the development of sustainable agricultural systems on tropical acidic soils. This study aimed to evaluate the effects of compost enriched with biochar and fly ash on selected soil chemical properties of Ultisols as a basis for sustainable land management in tropical agricultural systems.

Materials and Methods

This research was conducted from February 2024 to June 2025 in the research and development area of a pineapple plantation in Lampung, with coordinates -4°80'82.36" S 105°17'75.83" E, with an altitude of ± 45 m above sea level. The study area has a humid tropical climate with annual rainfall ranging from 2,200 to 2,500 mm and an average temperature of 26-28 °C. The soils at the study site were classified as Ultisols according to the USDA Soil Taxonomy, with typical characteristics including an acidic pH (<5.5), low alkaline saturation, a low to medium cation exchange capacity (CEC), and a relatively high exchangeable Al content. These characteristics represent the conditions of tropical acidic soils that are commonly found in Indonesia. The materials used in this study were compost, biochar, and fly ash, all sourced from an integrated production system at a pineapple plantation in Lampung. The soil amendment used in this study consisted of compost, fly ash, and biochar.

Compost was produced from pineapple pulp waste, a by-product of the pineapple processing industry, mixed with mature cow manure from local farms around the research area. Composting was carried out aerobically using a windrow system for ±8-10 weeks, with daily reversals to maintain aeration and decomposition homogeneity. The initial material ratio was adjusted to achieve a C/N ratio of about 25-30, and the moisture content was maintained at 55-65%. Compost is considered ripe based on temperature stability, dark brown color, crumbly texture, and a C/N ratio <20. The chemical characteristics of compost include a neutral–slightly alkaline pH, a high organic C content, and macronutrients (N, P, K, Ca, and Mg) that improve soil fertility in acidic soils.

Biochar was produced from pineapple pulp waste through a slow pyrolysis process at a temperature of 400-500 °C under limited oxygen conditions for 3-4 hours. After cooling, the biochar was crushed and sifted to <2 mm before application. The resulting biochar has a high alkaline pH, stable carbon content, and ash fractions containing alkaline cations, so it has the potential to increase cation exchange capacity and neutralize soil acidity.

The fly ash used is a by-product of burning medium-high-grade coal (bituminous coal) from a pineapple plantation in Lampung internal power plant. The characteristics of fly ash, dominated by SiO_2 (±69.7%) and relatively low Ca content (±4.8%), indicate F-type fly ash according to ASTM C618 criteria. These characteristics exhibit pozzolanic properties, with the potential to increase soil pH by supplying alkaline cations and reacting with Al^{3+} ions in acidic soils.

A quantitative approach was used, employing factorial experiments in a random block design, to evaluate the effects of compost enriched with biochar and fly ash on the improvement of the chemical properties of Ultisols. Each treatment was replicated four times, with each replication consisting of 10 pineapple plants, for a total of 120 experimental units. Observational data were analyzed using a variety of methods. After the variety analysis, the differences between the averages were assessed using the Least Significant Difference (LSD) post hoc test at $\alpha = 0.05$. The statistical analysis and visualization were carried out using RStudio (RStudio Inc., Boston, USA) in 2025.

Soil sampling was carried out at 3, 6, 9, 11, and 16 months after planting (MAP). Laboratory analysis was carried out at the research and development laboratory of a pineapple plantation in Lampung. It included the measurement of pH (potentiometry method (1:2.5), organic C (Walkley and Black), N (Kjeldahl), P (Bray-1), K, Ca, Mg (Ammonium Acetate Extraction 1N pH 7 – AAS), Fe, Mn, Cu, Zn (DTPA Extraction – AAS).

Results and Discussion

Changes in soil pH during the observation period showed a dynamic pattern influenced by the combined effects of soil change characteristics and soil biogeochemical processes (Table 1). At 3 MAP, the soil pH was highest across all treatments, ranging from 4.97 to 5.18. This increase in pH value can be attributed to the alkaline properties of fly ash, which contains alkaline metal oxides and carbonates such as CaO, MgO, K, and Na. These compounds react with hydrogen ions (H^+) in soil, thereby reducing soil acidity and rapidly increasing soil pH after application (Idwar et al., 2025). This calcification effect is consistent with the chemical properties of fly ash, which neutralizes H^+ ions by forming water and releasing alkaline cations.

The increase in soil pH during the early phase is influenced not only by fly ash but also by biochar addition. This shows that biochar is alkaline, mainly when produced from mineral-rich raw materials and at high pyrolysis temperatures. The results of a study by Singh et al. (2022) indicated that biochar can release alkaline cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+), as well as carbonates and oxides, thereby increasing soil pH, especially in acidic soils.

Table 1. Soil pH after treatment for 16 months of observation.

Treatment	**pH**				
	3 MAP	**6 MAP**	**9 MAP**	**11 MAP**	**16 MAP**
A	5.01	4.49	4.83	4.34	4.49
B	4.97	4.51	4.83	4.37	4.51
C	5.18	4.46	4.77	4.22	4.46

Note: not significant at p = 0.05 among the treatments. MAP = Months After planting.

The combined application of fly ash and biochar in the early stages of composting increases soil pH at 3 MAP. Soil pH degradation occurred for all treatments at 6 and 11 MAP. This suggests that the decomposition of organic matter is consistent with the production of a variety of organic acids, including humic acid, fulvic acid, and low-molecular-weight organic acids. These compounds release H^+ ions into the soil solution, thereby lowering soil pH (Shi et al., 2019). In addition, nitrogen transformation through nitrification contributes to soil acidification by oxidizing ammonium (NH_4^+) to nitrate (NO_3^-), with nitrifying microorganisms releasing H^+ as a by-product, thereby accelerating soil acidification (Shi et al., 2019).

Nitrogen transformation through nitrification contributes to soil acidification by oxidizing ammonium (NH_4^+) to nitrate (NO_3^-) and releasing H^+ ions as a by-product of nitrifying microorganisms, thereby accelerating soil acidification (Shi et al., 2019). This mechanism explains the consistent pattern of pH decline observed during the intermediate phase of the study.

A temporary increase in soil pH occurred at 9 MAP. This increase phenomenon can be attributed to the capacity of biochar and humic fractions to absorb and retain alkaline cations on their surfaces, then release them gradually over time. Biochar is known to have a relatively high CEC, which facilitates the desorption of alkaline cations and thereby increases soil pH during subsequent phases (Shi et al., 2019). In addition, the increased stability of decomposed organic matter during the intermediate phase can reduce the production of organic acids, thereby allowing the soil pH to rise again.

The soil pH value showed a slight increase relative to 16 months after planting, although it did not reach the levels observed in the early phases. These improvements indicate that soil conditions are approaching a stable state, in which the effects of remediation, organic matter decomposition, and soil chemical processes begin to stabilize. These findings indicate that the buffer capacity of biochar applied at a relatively low level (e.g., 5%) is likely insufficient to sustain long-term pH increases, and that some soluble alkaline cations may have been lost through leaching, especially in tropical conditions with high rainfall. These results are in line with meta-analytical findings that the effects of increasing biochar pH are highly dependent on the nature of the initial soil, biochar characteristics, and application rates, and tend to decline over time (Tusar et al., 2023). Overall, the soil pH dynamics observed in this study illustrate the interactions among the chemical properties of soil amendments (biochar and fly ash), organic matter decomposition, and nitrogen transformation. Mechanistically, the initial repair pattern, followed by decline during the intermediate phase, and subsequent stabilization in the final phase, are consistent with biogeochemical processes in tropical soils rich in active organic matter and characterized by intensive alkaline cation cycles.

Soil organic C concentrations showed that temporal patterns were relatively stable during the observation period (Figure 1), except at 11 MAP when noticeable improvement was observed in all treatments. The organic C value has increased by a factor of 3 compared to the base value. Because these spikes occurred consistently across treatments, it suggests the influence of systemic factors beyond the direct effects of compost-biochar-fly ash applications. These findings indicate that the resulting pattern is consistent with previous research that states that soil moisture dynamics and hydrological conditions can stimulate the release of dissolved organic carbon (DOC) from soil organic matter, especially in soils that experience fluctuations in moisture content due to rainfall or irrigation (Chen, 2023; Wang et al., 2023). Biochar has adsorption and desorption capacities for dissolved organic carbon, which depend on its porosity, surface area, and pyrolysis maturity (Feng et al., 2021; Azeem et al., 2023).

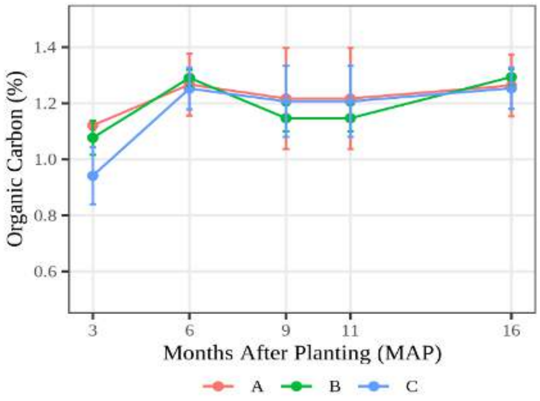


Figure 1. Organic C content in soil during 16 months of observation. Error bars indicate the standard deviation of each treatment.

Under certain conditions, biochar can release a fraction of its surface-bound soluble carbon, especially when derived from raw materials with high lignocellulose content. The desorption process can result in a surge in soil organic carbon in response to changes in environmental conditions, including pH, humidity, and ionic strength.

Fly ash, as a source of inorganic minerals, can also affect soil organic carbon dynamics by altering soil pH and CEC. The results indicated that an increase in soil pH resulting from fly ash application can enhance the solubility of specific humate fractions, thereby altering dissolved organic carbon concentrations (Xu et al., 2019). In addition, the interaction between the basic minerals in fly ash and the functional groups of biochar or composted organic matter can alter the stability of organo-mineral associations, thereby promoting the release of carbon into soil solutions.

The increase in organic C at 11 MAP is most likely a combined result of (i) dissolved carbon release caused by changes in soil moisture, (ii) carbon desorption from biochar surfaces, and (iii) changes in soil chemical conditions resulting from fly ash-biochar interactions that affect the mobility of organic fractions. A similar phenomenon has been reported in studies of carbon dynamics in tropical soils altered by organic mineral inputs, where dissolved carbon peaks often occur in response to specific environmental events rather than solely as a consequence of individual treatments (Bekchanova et al., 2024).

The total N content of the soil showed a relatively stable temporal pattern during the observation period (Figure 2), but increased sharply at

9 MAP, reaching values of 1.63-1.79%. This value represents a tenfold increase compared to 3, 6, and 16 MAP. A total increase in N was consistently observed across all treatments; these results likely reflect process- or environment-driven factors affecting the entire experimental system rather than the specific effects of biochar or fly ash applications. This pattern can be explained by the dynamic nature of the nitrogen cycle, which is highly sensitive to hydrological conditions and soil microbial activity in open field systems. One of the main mechanisms contributing to an increase in total N is ammonification, the microbial conversion of organic nitrogen to the mineral form ammonium (NH_4^+). Soil microbial activity tends to increase when biodegradable organic substrates are available and environmental conditions, such as temperature and humidity, are within the optimal range. Variations in soil moisture, especially wet-dry cycles, can significantly stimulate microbial activity and accelerate the mineralization of organic nitrogen.

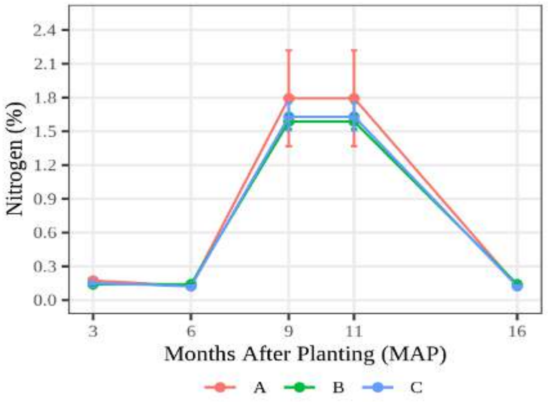


Figure 2. Total N content in soil during 16 months of observation. Error bars indicate the standard deviation of each treatment.

Soil re-wetting after a dry period results in a rapid increase in mineralization and in measured nitrogen release in the form of NH_4^+ and NO_3^- into soil solutions, especially in open-field soils that experience moisture fluctuations, referred to as the Birch effect. The results showed that the application of biochar and charcoal as amendments to maize plants that occurred during the wet-dry cycle can increase nitrogen mineralization through increased microbial respiration and enzymatic activity, thereby accelerating the decomposition of organic matter and increasing the availability of total N over a period of time (Wan et al., 2025).

Biochar has a complex role in soil nitrogen dynamics. Critical reviews have shown that biochar can modulate the nitrogen cycle, with effects that depend on the characteristics of the raw material, pyrolysis temperature, and field conditions. The phenomenon explains that biochar can retain mineral nitrogen (NH_4^+ and NO_3^-) and reduce nitrogen loss through leaching or evaporation, thereby increasing soil nitrogen availability in some cases. At the same time, in other situations, it does not show significant long-term effects in field conditions. However, since biochar generally contains a low concentration of intrinsic nitrogen, its main contribution lies in nitrogen retention and transformation rather than serving as a direct nitrogen source (Ahmad et al., 2021).

In addition, the effects of biochar on soil microbes have been extensively examined in relation to nitrogen dynamics in soils. Biochar applications have been shown to increase soil microbial biomass and total N concentration, as well as the diversity of microbial communities involved in mineralization and nitrogen transformation. The results suggest that adding biochar can increase total N while altering the composition and function of microbial communities involved in the nitrogen cycle, including nitrification and microbial assimilation (Hu et al., 2023).

The increase in total N at 9 MAP is most likely the result of an interaction between environmental conditions, such as fluctuations in humidity and precipitation, and increased soil microbial activity, which promotes the mineralization of organic nitrogen into detectable mineral forms. This change in conditions occurs because a temporary accumulation of soil mineral nitrogen is reflected as a sharp increase in measured total N.

Overall, the observed total N pattern suggests that variations in local environmental conditions and soil microbial activity may play a dominant role in regulating soil nitrogen dynamics in open field systems. In contrast, the specific effects of biochar and fly ash serve as modifiers of soil physicochemical conditions and nitrogen retention rather than as a direct source of nitrogen. These findings are consistent with previous research showing that fluctuations in rainfall and humidity govern soil nitrogen dynamics through complex interactions among biological processes, soil physicochemical properties, and environmental factors (Ahmad et al., 2021; Hu et al., 2023).

The soil phosphorus (P) concentration showed clear temporal fluctuations during the observation period (Figure 3), reflecting the complexity of P transformation in the soil composting system. Microbial activity, soil mineral properties, and interactions with soil amendment applications can explain the phenomenon. During the initial phase, a sharp increase in P concentration was observed from 3 to 6 MAP in all treatments, reaching 33.96 ppm (A), 33.92 ppm (B), and 38.34 ppm (C). These improvements indicate the intensive mineralization of organic phosphorus compounds (organo-P) into dissolved inorganic phosphates, a process driven mainly by microbial phosphatase activity during the early stages of organic matter decomposition. The findings are consistent with previous reports showing that organic P mineralization is the primary source of P available in soil systems that receive fresh organic inputs. In addition to organic P mineralization, the increase in soil P during the initial phase is likely due to the release of phosphates from inorganic materials such as fly ash. Fly ash contains a relatively soluble fraction of P and can modify soil pH, thereby increasing P solubility and reducing initial fixation by Fe and Al minerals (Glaser and Lehr, 2019).

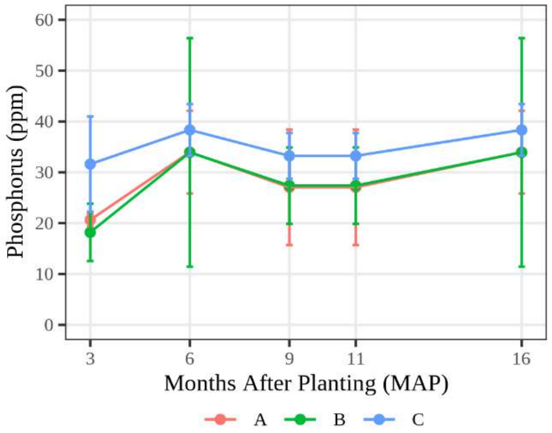


Figure 3. Total phosphorus content in the soil during 16 months of observation. Note: Error bars indicate the standard deviation of each treatment.

A decrease in soil P concentration at 9 MAP indicates the emergence of phosphorus immobilization by microbial biomass and phosphate precipitation as Fe-P and Al-P complexes. In acidic soil conditions, inorganic phosphates readily react with Fe and Al oxides and hydroxides, leading to fixation in a less soluble form and a reduction in dissolved P concentration. Previous research has shown that the change from mineralization to immobilization is a common feature of P dynamics in soil systems rich in active organic matter (Zhang et al., 2025).

Soil P concentrations dropped sharply to near zero across all treatments at 11 MAP. The results showed that peak phosphorus immobilization by soil microorganisms was accompanied by extensive phosphate precipitation into highly insoluble forms of Fe-P and Al-P. Previous research has reported that during the microbial period of maximum biomass growth, phosphorus can become highly absorbed in microbial cells and soil mineral fractions, making it almost undetectable as P available to plants (Silva et al., 2023).

The soil P concentration at 16 MAP increased again towards a relatively high range (33-38 ppm), indicating phosphorus remobilization. This remobilization is likely to occur due to microbial biomass lysis, reduced immobilization activity, and phosphorus desorption from Fe/Al complexes, facilitated by the presence of humified organic matter and biochar. Biochar is known to reduce P fixation through mechanisms such as increasing local soil pH, anion competition, and the formation of weaker organo-mineral associations, thereby inducing phosphate release back into soil solutions (Fan et al., 2025). Treatment C consistently showed the highest soil P concentration at each observation time, suggesting that adding fly ash and biochar at late stages of the composting process was more effective at suppressing P fixation than early-stage mixing (treatment A) or the control (treatment B). These findings are consistent with previous reports suggesting that the application of biochar and minerals as amendments can improve the stability of available P in acidic soils by inhibiting the formation of Fe-P and Al-P complexes and increasing phosphorus recycling during compost maturation (Yevdokimov et al., 2016).

The results of the study, from an agronomic perspective, showed that compost formulations enriched with fly ash and biochar have considerable potential to increase phosphorus availability in acidic soils and to provide a more stable P supply during compost maturation. The changes in P concentrations observed between 11 and 16 MAP reflect a typical mineralization-immobilization-remobilization cycle in soil organic systems. These findings indicate that biochar- and fly ash-enriched compost is consistent with phosphorus dynamics reported for various organic matter management and mineral remediation strategies.

Available potassium concentrations showed apparent temporal variation between treatment and observation time, highlighting the complexity of the processes of release, retention, and loss of K in soil-compost systems enriched with biochar and fly ash (Figure 4). In the initial sampling (3 MAP), treatment C, which included the addition of 5% biochar and 20% fly ash at the final stage of the composting process, showed the highest available K (13.02 cmol kg^{-1}). This value is substantially higher than that of other treatments, indicating rapid release of K from the soluble fractions of fly ash and biochar. Adekiya et al. (2022) reported that biochar and fly ash generally contain potassium in a water-soluble, exchangeable form, leading to a significant increase in available K immediately after application.

The increase in available K observed in treatment C is temporary. A sharp decrease in K concentration to 1.30 cmol·kg^{-1} at 16 MAP indicates that the K released during the initial phase does not persist in the soil system. This decline is consistent with studies showing that potassium derived from biochar is primarily released during the initial stages after application and then decreases over time due to washing, adsorption to the soil-dense phase, or transformation into a less agronomically available K fraction (Xiu et al., 2025). Other studies have also stated that biochar can rapidly increase K availability and long-term K retention capacity, which is strongly influenced by soil texture, cation exchange capacity, and rainfall or irrigation intensity (Fachini et al., 2022).

Treatment A, which involved the initial mixing of fly ash and biochar, showed fluctuations in available K, with a decrease at 6 MAP followed by an increase at 9 MAP. This pattern shows the combined effects of the rapid release of dissolved K from fly ash during the initial phase and the gradual release of physically or chemically bound K from the compost and biochar matrices. Previous research has reported that some potassium in biochar and organic matter can be adsorbed within pores or associated with surface functional groups, resulting in slower release during organic matter decomposition and in response to changes in the soil environment (Doulgeris et al., 2023).

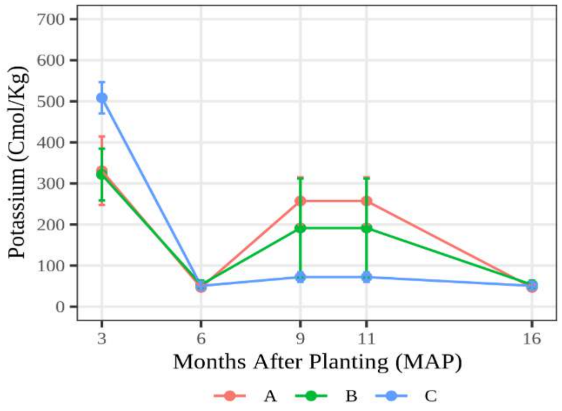
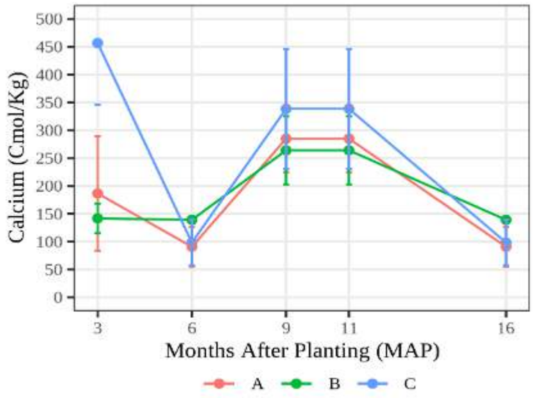


Figure 4. Total potassium content in the soil during 16 months of observation. Error bars indicate the standard deviation of each treatment.

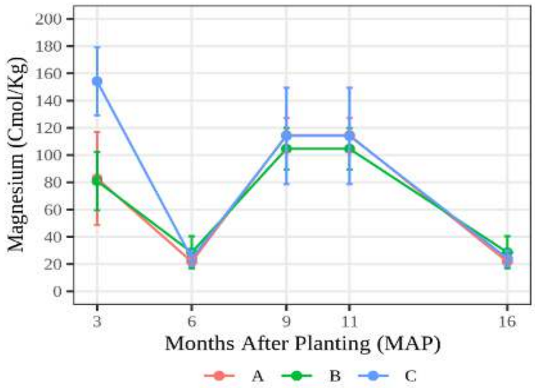
Overall, all three treatments showed a reduction in available K of more than 80% from the baseline to the end of the observation period. This substantial decrease suggests that potassium loss is the dominant process in the system, most likely driven by highly mobile K^+ ion leasing, especially under open-field conditions. Potassium is known not to form stable organic compounds. This phenomenon can be explained by research results showing that K did not undergo strong biological immobilization, unlike nitrogen or phosphorus, making it highly susceptible to leaching outside the root zone through permeable water (Elbana et al., 2025). The partial K content can be adsorbed onto the biochar surface or trapped in the secondary mineral phase, further reducing the amount of K available to the plants.

From an agronomic perspective, this study showed that applying biochar and fly ash effectively increases available K during the initial phase; this effect is temporary and requires additional management strategies to maintain long-term potassium availability. A significant decrease in available K during treatment C suggests that late-stage application promotes rapid but less effective K release during K retention, whereas early mixing (treatment A) results in a more gradual release pattern. The results of this study are consistent with the concept that biochar primarily functions as an available source of potassium rather than as a long-term K buffer, unless applied in soils with high cation exchange capacity or integrated with repeated fertilization strategies (Elbana et al., 2025; Xiu et al., 2025).

The concentrations of calcium (Ca) and magnesium (Mg) suggest that they are mechanically driven by contrasting temporal dynamics across treatments, reflecting differences in the mechanisms of release, retention, and redistribution of alkaline cations in soil compost systems enriched with fly ash and biochar (Figure 5). At initial sampling (3 MAP), treatment C, which received the addition of fly ash and biochar at the final stage of the composting process, showed a marked spike in available Ca (22.79 cmol kg^{-1}), accompanied by relatively high concentrations of Mg compared to other treatments.



(a)



(b)

Figure 5. Total calcium (a) and magnesium (b) content in the soil during 16 months of observation. Error bars indicate the standard deviation of each treatment.

The increased content of Ca and Mg indicates the rapid release of alkaline cations from fly ash, including CaO, $CaCO_3$, and MgO, which are readily soluble and react quickly after the application of biochar and fly ash-enriched compost. Previous studies have reported that fly ash provides a strong calcification effect and serves as a source of Ca^{2+} and Mg^{2+} available, especially in acidic soils (Pandey and Singh, 2010). However, the initial spike in Ca and Mg observed in treatment C was temporary. The available Ca content decreased sharply to 4.91 cmol kg^{-1}, representing a reduction of approximately 78.5%, while Mg showed a similar downward trend, albeit with a slightly lower magnitude at 16 MAP. The decrease caused by Ca^{2+} and Mg^{2+} released rapidly during the initial phase is particularly susceptible to washing loss, especially in open-field conditions characterized by substantial moisture fluctuations. Calcium and magnesium are relatively mobile alkaline cations; therefore, in the absence of an adequate buffering mechanism, both can be easily transported outside the root zone (Doulgeris et al., 2023).

In contrast, treatment A, which involves the initial mixing of fly ash and biochar, showed more moderate and relatively stable Ca and Mg dynamics over time. The fluctuations in the reduction of Ca (approximately 51.3%) and Mg content were substantially lower than those observed in the C treatment. This suggests that prolonged interactions between alkaline cations, biochar matrices, and organic matter during composting promote more gradual retention and release of Ca and Mg. Biochar is known to have a high surface area, a cation-exchange capacity developed during incubation, and a negatively charged functional group capable of absorbing Ca^{2+} and Mg^{2+}, thereby limiting rapid wash loss and supporting the continued availability of nutrients (Ghiri et al., 2025). Treatment B showed that the dynamics of Ca and Mg were relatively stable during the observation period, with only slight changes compared to treatments A and C. These findings indicate the stability of soil conditions in the absence of substantial external input of alkaline cations, where the natural balance between cation exchange, plant uptake, and leaching mainly regulates variations in Ca and Mg. Under such conditions, the dynamics of Ca and Mg tend to be gradual and are primarily driven by the slow weathering of soil minerals (Munda et al., 2016). Conceptually, the contrasting dynamics of Ca and Mg across treatments reinforce the hypothesis that the timing of fly ash and biochar application is an important factor in determining the sustainability of cation availability. Application at the final stage of the process (C) results in a short-term, apparent increase in Ca and Mg. At the same time, early mixing (A) shows a stronger organo-mineral interaction, leading to a more regular and sustained release of these cations. These findings are consistent with previous reports suggesting that the combined use of biochar and fly ash can serve as a basic cation source and a controlled-release system, depending on the formulation strategy and application timing (Vincekovic et al., 2022).

The implications for pineapple cultivation systems are that the more stable dynamics of Ca and Mg observed at the initial mixing treatment (C) offer potential strategies to sustainably increase soil alkaline saturation, especially in acidic soils lacking alkaline cations. In contrast, a high but temporary increase in Ca and Mg can reduce nutrient utilization efficiency. Therefore, integrating fly ash and biochar into compost at the early stages of composting is recommended to optimize the medium- to long-term availability of Ca and Mg in sustainable farming systems.

The availability of Fe, Mn, Cu, and Zn micronutrient content during the incubation period (3-16 MAP) suggests that there are clear temporal fluctuations and apparent differences between treatments, reflecting the complex interactions between organic matter decomposition, soil pH shifts, and redox conditions, and the role of biochar and fly ash in regulating the transformation and mobility of micronutrients (Table 2). Micronutrients are highly sensitive to changes in the soil chemical environment; therefore, their dynamics tend to be more variable than those of macronutrients (Hailegnaw et al., 2020). During the initial incubation phase (3-6 MAP), Fe and Zn were more available than Mn and Cu across all treatments. This pattern suggests that Fe and Zn are released more quickly than mineral fractions and organic components of compost by-products.

Table 2. Micronutrient content after treatment for 16 months of observation.

Treatment	**Micronutrient content (ppm)**				
	3 MAP	**6 MAP**	**9 MAP**	**11 MAP**	**16 MAP**
			Fe		
A	107.73	132.76	13.22	54.03	132.76
B	104.55	175.63	16.25	62.22	175.63
C	70.92	86.56	13.90	66.13	86.57
			Mn		
A	3.08	1.64	35.28	5.65	1.64
B	2.61	2.67	36.22	6.40	2.67
C	4.33	1.52	39.30	5.04	1.52
			Cu		
A	0.65	0.69	0.94	3.14	0.69
B	0.64	0.78	0.77	2.97	0.78
C	0.81	0.69	0.83	1.80	0.69
			Zn		
A	4.19	5.14	10.18	194.85	5.15
B	3.27	6.08	8.80	196.79	6.08
C	4.72	4.62	10.84	142.67	4.62

Note: not significant at $p = 0.05$ among the treatments, MAP = Months After Planting.

At the same time, Mn and Cu remain more strongly bound in the initial organic complex. Treatment C showed that the initial concentrations of Mn, Cu, and Zn were slightly higher, due to the addition of biochar and fly ash at the final stage of composting (C), which facilitated faster early release of micronutrients before the formation of stable organo-mineral complexes. The results of this study are in line with the research of Hailegnaw et al. (2020), who stated that micronutrients such as Zn and Cu are relatively labile immediately after the application of mineral amendments, before the adsorption and complexation processes increase.

During the transition phase (9 MAP), all micronutrients showed simultaneous increases in availability, with Fe and Mn exhibiting the most pronounced increases. The increased availability of Fe and Mn during this phase reflects changes in micro-redox conditions driven by intense microbial activity associated with the decomposition of organic matter. The reduction of Fe^{3+} and Mn^{4+} into more soluble forms of Fe^{2+} and Mn^{2+} represents the primary mechanism that increases the mobility of these elements (Sitarz-Palczak and Kalembkiewicz, 2012). An increase in Zn and Cu was observed, although at lower levels; these findings indicate that there was the gradual release of organic complexes and the competitive adsorption of micronutrient cations on the biochar surface.

The most prominent increase in micronutrient availability occurred in 11 MAPs, mainly for Zn and Fe, followed by Cu and Mn. Zn availability increased sharply in all treatments, especially in treatments A and B, whereas treatment C showed lower values. This noticeable increase in Zn suggests substantial release, likely driven by continued organic matter degradation, rapid changes in soil pH, and Zn release from the mineral fraction of fly ash. The lower Zn availability under the treatment C highlights the role of biochar in retaining Zn via surface adsorption and the formation of stable Zn-organic complexes. These findings are consistent with previous reports (Sitarz-Palczak and Kalembkiewicz, 2012; Hailegnaw et al., 2020), which suggests that biochar can effectively reduce Zn availability by increasing soil pH and adsorption capacity.

The results of the Fe and Mn studies showed a secondary increase following the decline in the previous phase, confirming that Fe-Mn dynamics are strongly influenced by redox fluctuations and the stability of organic matter (Ma et al., 2025). The increase in Cu is more limited than that of Zn, reflecting its strong affinity for functional groups in organic matter and on biochar surfaces. Copper is recognized as the most tightly bound micronutrient in the humic complex, resulting in relatively lower mobility than Zn and Mn (Hailegnaw et al., 2020; Vila et al., 2021).

During the final incubation phase (16 MAP), the availability of all micronutrients decreases, returning to low to moderate levels. This decrease reflects the re-immobilization of micronutrients through the formation of more stable organic complexes, precipitation of hydroxides and oxides (especially Fe and Mn), and strong adsorption onto the biochar surface. Treatments A and C consistently showed that lower availability of Fe, Mn, Cu, and Zn compared to controls indicated an increase in soil chemical buffer capacity resulting from the combined application of compost, biochar, and fly ash.

Treatment C showed that micronutrient dynamics were most stable during the incubation period, with fewer extreme fluctuations than in treatments A and B. This suggests that adding biochar and fly ash at the final stage of composting is more effective in regulating the availability of Fe, Mn, Cu, and Zn. Such strategies have the potential to minimize the risk of micronutrient toxicity while maintaining their availability to plants, especially in tropical and acidic soils susceptible to micronutrient imbalances (Rivelli and Libutti, 2022).

Conclusion

This study shows that compost enrichment with biochar and fly ash is a practical, synergistic approach to improve the dynamics of chemical properties in acid tropical Ultisols. Fluctuations in pH, macronutrient content, and micronutrient levels over 16 months of observation confirmed that soil responses were temporal and controlled by interactions among alkaline cation supply, organic matter decomposition, and nitrogen transformation.

The dynamics of organic carbon and total N are mainly influenced by microbial activity and environmental conditions. In contrast, phosphorus follows a pattern of mineralization–immobilization–remobilization that reflects the close interconnectedness between biological processes and soil chemistry. Although end-stage enrichment (treatment C) increases phosphorus availability, mixing biochar and fly ash from the early stages of composting (treatment A) results in more stable release of alkaline cations and more controlled fluctuations in micronutrient levels. Overall, early enrichment (treatment A) showed the most significant potential for sustained increases in Ultisol fertility under tropical conditions.

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