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Optimizing co-composting ratios of cocoa pod husk and poultry manure for cocoa organo-mineral fertilizer formulation in the West African cocoa belt

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Cocoa is a valuable global commodity but its management results in residues such as cocoa pod husk, leaves and placenta which are under-utilised as a resource. This study sought to address this by evaluating the impacts of different mixing ratios of cocoa pod husk (CPH), placenta (PL) and locally sourced poultry manure (PM) on compost quality and which mixing ratio will enhance compost NPK stoichiometry required for cocoa organo-mineral (OMF) fertiliser formulations. Quality of compost within OMF can influence nutrient release and potentially improve soil health in cocoa farms. The composting study considered 8 treatments consisting of different combinations of PM, and CPH at ratios of 1:1, 2:1, 1:2 and 1:3, with and without addition of PL. Treatments with PL recorded the highest (32 %) organic carbon at the end of the composting period. Highest available N (5919 mg kg⁻¹) was observed in treatments with PL and the lowest (1146 mg kg⁻¹) was observed in treatments without PL. Treatments without PL recorded the highest available P (3843 mg kg⁻¹) and treatments with PL yielded the lowest (2167 mg kg⁻¹). Highest (16922 mg kg⁻¹) available K was observed in treatments with PL and the lowest (12263 mg kg⁻¹) observed in treatments without PL. Addition of PL to CPH and PM causes an increase in organic carbon, available N, available K but reduces available P. Compost PM+CPH (2:1) and PM+CPH (1:2) have NPK stoichiometry which aligns with nutrient requirements of young cocoa (<7 years old) and matured cocoa (≥8 years), respectively. This study demonstrates the use of circular economy to improve resource efficiency in cocoa farms. For future studies, it is important to ascertain agronomic effectiveness of the compost PM+CPH (2:1) and PM+CPH (1:2) ratios on the young and matured cocoa trees, respectively.

KEYWORDS

cocoa NPK requirement, cocoa placenta, cocoa pod husk, compost, poultry manure

1 Introduction

The West African cocoa belt contributes approximately 70% of the world's cocoa production (FAOSTATS, 2024). The average cocoa bean yield of the West African cocoa belt is estimated at 300–600 kg ha⁻¹ (Asante et al., 2021), less than 25% of the yield potential of 1891–3,245 kg ha⁻¹ (Ahenkorah et al., 1987; 2000 kg ha⁻¹; Appiah et al., 2000; 3245 kg ha⁻¹; Aneani and Ofori-Frimpong, 2013; 1891 kg ha⁻¹). Soil fertility depletion in the West African cocoa belt is the major factor contributing to the high cocoa yield gap (Appiah et al., 2000; Aneani et al., 2012; Danso-Abbeam and Baiyegunhi, 2017). Soil-specific problems accounting for the high yield gap in the West African cocoa belt are attributed to the fact that the majority of the cocoa-growing regions are characterized by Acrisols, Ferrosols, Luvisols, Oxisols, and Ultisols. These soils are low in cation exchange capacity (< 24 cmol + kg⁻¹), pH (<5), and organic carbon (OC) (< 1.5%) (Asiamah, 2008; Jayne et al., 2015; Food and Agriculture Organization of the United Nations, 2015; Bationo et al., 2018), with a high level of kaolinites/silicate minerals and Fe and Al sesquioxide, leading to a high potential for P fixation.

In the moist evergreen and semi-deciduous zones of Ghana where cocoa production is dominant, elevated rainfall regime and the high temperature catalyze leaching of basic cations and rapid decomposition of soil organic matter (SOM). This results in the above soil nutrient constraints rendering the soil less responsive to mineral fertilizer application. Although some studies have demonstrated the potential for cocoa mineral fertilization to improve cocoa yield (Ahenkorah et al., 1987; Appiah et al., 2000; Aneani and Ofori-Frimpong, 2013), farmers hardly adopt the mineral fertilizer due to scarcity and inaccessibility within the cocoa-growing communities. To counterbalance the low fertility-driven productivity challenges coupled with challenges for access to mineral fertilizers, an alternative solution for such constraints is necessary. The application of organic fertilizers supplemented with a reduced quantity of mineral fertilizers, termed as organo-mineral fertilizer (OMF), an integrated soil fertility management strategy, could be a sustainable solution for the cocoa cropping systems. This will improve soil physical, chemical, and biological properties (Nigussie et al., 2015; Alvarenga et al., 2017; Coleman et al., 2017). The decomposition of the organic component of the OMF will result in carboxylic functional groups having negative charges (Xiao et al., 2013; Wang et al., 2016). These charges (–) have the potential to neutralize the kaolinite/silicate mineral surface charges (+) and chelate Fe³⁺ and Al³⁺ sesquioxide. This will increase soil pH, which will enhance nutrient availability, especially P, for cocoa plant uptake, while the mineral fertilizer portion of OMF will help meet immediate nutrient needs.

Exploring readily available organic residues within cocoa-growing communities is key for the OMF cocoa nutrition strategy. A tonne of cocoa bean production generates ten (10) tonnes of cocoa pod husk (CPH) (Khanahmadi et al., 2015), which are commonly discarded as waste. Previous studies have demonstrated the potential for cocoa pod husks to improve crop agronomy and soil properties (Moyin-Jesu, 2007; Agele and Agbona, 2008; Ofori-Frimpong et al., 2010; Sosu, 2014; Fidelis and Rajashekhar, 2017; Munongo et al., 2017). However, information on organic residue amendment in Ghanaian cocoa systems has mainly been limited

to the use of poultry manure (PM) and the ash from burnt CPH (Opoku-Ameyaw et al., 2010) until recently, biochar-compost from CPH (Anokye et al., 2024). The potential use of CPH for OMF for cocoa production is underexplored. Exploring CPH as a potential organic residue for the OMF formulation is key for sustainable cocoa production.

For sustainable cocoa production, mature cocoa plants (≥ 8 years) require more P, followed by K and N (P > K > N). Cocoa pod husk contains 1.5–1.7% N, 0.2–0.8% P, and 2.0–3.7% K (Kayode et al., 2015; Fidelis and Rajashekhar, 2017; Nartey et al., 2017; Essel et al., 2021), whereas poultry manure contains 2.1–2.7% N, 1.8–2.1% P, and 1.2–1.6% K (Kayode et al., 2015; Fidelis and Rajashekhar, 2017; Dogbatse et al., 2020; George et al., 2021). This suggests that CPH and PM NPK stoichiometry (relative quantity) is K > N > P and N > P > K, respectively. Since CPH and PM each have NPK stoichiometry, which does not conform with cocoa NPK needs, it is important to combine them for applications. The combination of these two organic residues that are readily available in Ghanaian cocoa farms/communities could be a valuable source of NPK and organic C for sustainable management of the cocoa production in Ghana. However, the co-application of these residues in raw form will result in slow release of nutrients and nutrient asynchrony as well as disease spread on the cocoa farms.

The above drawbacks highlight the need to valorize the residues by way of co-composting before formulating cocoa OMF. Co-composting studies that involved CPH and PM contained a third feedstock other than CPH and PM alone (Fidelis and Rajashekhar, 2017; Munongo et al., 2017; Dogbatse et al., 2020; Anokye et al., 2024). Another CPH composting study used mineral NPK as an “activator” (Amponsah-Doku, 2020). To the best of our knowledge, only a single study investigated co-composting between CPH and PM only, but with one mixing ratio (3:1) (Kayode et al., 2015). Even Essel et al. (2021) and Nartey et al. (2017), who explored CPH-cattle manure (1:3) and CPH-dewatered fecal sludge (1:1) co-composting only, respectively, also considered one ratio treatment for the respective co-compost feedstocks. This does not give an indication of the optimal compost mixing ratio between CPH and “animal manure” in general, let alone PM for cocoa nutrient needs. It is therefore clear from the literature that there is a knowledge gap, as no established optimal compost mixing ratio exists between CPH and PM. This hinders scientific decision and implementation for sustainable cocoa cropping. On the contrary, research on using OMF for combinable crops such as cereals and forage maize has been reported by Deeks et al. (2013), Pawlett et al. (2015), Antille et al. (2017), and Burak and Sakrabani (2023) as an intervention that does not compromise crop yield when compared to mineral fertilizers. Lessons and approaches from using OMF in combinable cropping systems can be adopted for cocoa. To the best knowledge of the authors, OMF use in cocoa is novel, and this manuscript addresses the compost quality aspect of it.

Cocoa placenta (PL) is another cocoa residue generated on the cocoa field after pod cracking and bean removal. The PL contains sugar compounds and nutrients and has been explored for the formulation of livestock feed and beverages (Goude et al., 2019; Fabrice et al., 2023). Although the placenta could catalyze composting, its potential as a source of sugar in enhancing composting is yet to be

studied. There is the need to explore various composting mixing ratios between poultry manure and cocoa pod husk with and without cocoa placenta. This will help to establish optimal co-composting decisions and implementation toward OMF formulation in cocoa cropping systems. To address the compost agronomic quality and the gaps of optimal co-composting ratio between CPH and PM as well as PL potential in composting, this study aimed to: (i) assess the impacts of CPH and PM ratios (with/without PL) on compost agronomic quality and (ii) identify optimal mixing ratios for cocoa NPK needs for OMF formulation. We hypothesized that different mixing ratios of PM and CPH co-compost enhanced with/without PL will: (i) improve compost agronomic quality and (ii) help to identify the optimal compost NPK stoichiometry required for cocoa OMF formulation in the West African cocoa belt.

2 Materials and methods

2.1 Feedstock preparation and composting experimental design

The CPH was milled, while fresh PL was shredded or chopped into pieces to increase surface area for microbial activity and decomposition. Poultry manure (PM) and CPH were co-composted in a shed/composting structure at Council of Scientific and Industrial Research (CSIR)—Soil Research Institute, Kumasi, Ghana. Composting under a shed structure was necessary to protect compost from rain to regulate moisture as well as prevent nutrient losses through run-off and leaching. The PM and CPH were weighed for co-composting according to the ratios (v/v) in [Table 1](#). The criteria and reason for choosing the various mixing ratios were different NPK stoichiometry of CPH and PM compared to cocoa NPK demands. Furthermore, it was not possible to predict the optimal mixing ratio until after composting. Fresh cocoa placenta (CP) was added to the four mixing ratios, while another four mixing ratios were without the addition of cocoa placenta ([Table 1](#)). The quantity of PL added was a quarter of the total volume of poultry manure and cocoa pod husk treatment mixtures (ratios). The quarter volume of PL was chosen because the PL generated on the cocoa field is less (approximately a quarter of CPH). The PL was

added as a catalyst providing sugar for microbes to proliferate and mineralize locked nutrients in the feedstock mixture. Overall, 8 treatment mixtures were formulated and replicated 3 times in a completely randomized design (CRD) in windrows/heaps, giving a total of 24 piles/windrows.

The compost piles were moistened with water to approximately 50% moisture content according to [Estevez-Schwarz et al. \(2011\)](#). The composting piles were turned every 7 days to provide moisture adjustment, aeration, and homogenization, giving a total of 12 turnings for a 90-day composting period. Daily temperature readings were taken by inserting a soil/compost thermometer on top and sides of each pile. Moisture content was monitored using a moisture probe (SEM2260).

2.2 Data collection and laboratory analysis

The raw PM, CPH, and PL were air-dried and milled (0.5 mm) to homogenize the samples for chemical characterization. A total of five samples were taken from five different points: the top, middle, lower, bottom, and base of each compost pile, at time zero (0), 30, 60, and 90 days. At each sampling period, samples from each sampling position were combined, thoroughly mixed, and subsampled (500 g) for laboratory analysis. Both the feedstocks and compost samples were analyzed for electrical conductivity (EC), pH, OC, total N, P, K, Ca, and Mg. For the compost, additional analysis was carried out for available N, P, K, and mineralizable (oxidizable) C. pH and electrical conductivity were measured using pH and EC meters, respectively, in a 1:5 compost–water slurry. The C/N ratio was calculated from total carbon and nitrogen contents determined using the [Kjeldahl \(1983\)](#) and [Walkley and Black \(1934\)](#) procedures, respectively. Nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) N were extracted by 1 M KCl in a 1:5 fresh compost-to-extractant ratio, while available P was extracted using Olsen P extractant (0.5 M NaHCO_3) in a 1:20 dry compost-to-extractant ratio. Available K was extracted with a 0.01 M CaCl_2 and 0.002 M DTPA (diethylenetriaminepentaacetic acid) extracting solution at a ratio of 1:20 and analyzed using an inductively coupled plasma-optical emission spectrometer (ICP-AES). Total element concentrations (P, K, Ca, and Mg) were determined by digesting 1 g of compost samples in a microwave digestion system (MARS 6). This was followed with the addition of 8 mL of nitric acid and 2 mL of ultrapure water. The digests were then analyzed using ICP-AES (Avio 560 max). Mineralizable C was determined using the procedure described by [Weil et al. \(2003\)](#).

2.3 Statistical analysis

Data for chemical properties of feedstocks were analyzed using analysis of variance (ANOVA) after testing for homogeneity of variance assumptions. A post-hoc analysis using the least significant difference (LSD) was used to separate the means of measured feedstock properties. For compost analysis, a repeated measure model approach was used to analyze the effects of compost treatments on measured parameters between and within

TABLE 1 Poultry manure (PM) and cocoa pod husk (CPH) co-composting ratios.

Treatments	Feed stocks	Ratios (v/v)
1	PM + CPH	1:1
2	PM + CPH	2:1
3	PM + CPH	1:2
4	PM + CPH	1:3
Cocoa placenta (PL) addition		
5	PM + CPH + PL	(1:1): $\frac{1}{4}$
6	PM + CPH + PL	(2:1): $\frac{1}{4}$
7	PM + CPH + PL	(1:2): $\frac{1}{4}$
8	PM + CPH + PL	(1:3): $\frac{1}{4}$

PM, Poultry manure; CPH, Cocoa pod husk; PL, Cocoa placenta.

measurement days. Compost treatments and measurement days were treated as fixed-effects factors, and replications were treated as random factors. Parameter margins of treatments between measurement days were analyzed with pairwise comparison, while parameter margins within measurement days were based on multiple comparisons. The analysis was carried out using the Statistical Package for the Social Sciences at a < 5% probability level ($p < 0.05$). Figure 1 summarizes the compost methodological steps.

3 Results

3.1 Dynamics of compost agronomic quality indicators

3.1.1 Dynamics of carbon-to-nitrogen ratio, nitrate, and ammonium N

3.1.1.1 C: N ratio

Carbon-to-nitrogen ratio (C: N) of compost mixing ratios significantly ($p < 0.05$) varied between and within measurement periods (Figure 2a). The C: N ratio for all treatments except T6 and T2 increased at day 30 but declined after day 30 till day 90 ($p < 0.05$). Generally, T2 and T8 yielded the highest (20.7–26.3) and the lowest (8.3–16.8) C: N, respectively. At the end of the composting period (day 90), C: N recorded among treatments followed the order: $T8 > T4 > T7 > T3 > T5 = T1 > T6 > T2$. Operations “>,” “<,” and “=” indicate statistically higher significance, lower significance, and non-significance, respectively.

3.1.1.2 Nitrate N

Compost treatments significantly impacted nitrate N ($p < 0.05$) between and within sampling periods (Figure 2b). Nitrate N for all treatments consecutively increased ($p < 0.05$) throughout the measurement periods except for treatments T8 and T4, whose nitrate N only improved at day 90. The highest nitrate N (488–5,919 mg kg⁻¹) was observed in T6, and the lowest (278–1,146 mg kg⁻¹) was observed in T4. Within day 30, nitrate N was

statistically similar in all treatments except for T8 and T4, whose values were significantly lower than in other treatments. Nitrate N within the day 60 sampling varied ($p < 0.05$) as: $T6 > T2 > T5 = T7 = T1 = T3 > T8 = T4$. At the end of the composting period (day 90), nitrate N differed ($p < 0.05$) as follows: $T6 > T2 > T5 > T1 > T7 > T3 > T8 = T4$.

3.1.1.3 Ammonium N

The ammonium N of compost mixing ratios significantly ($p < 0.05$) varied between and within sampling periods (Figure 2c). Ammonium N increased ($p < 0.05$) between the day 0 and 30 measurement periods for all treatments. Between days 30 and 60, ammonium N decreased ($p < 0.05$) in T8, T4, and T3 treatments, unlike other treatments. Instead, in the other treatments, the ammonium values between the two periods were statistically similar except in the T5 treatment, where the value increased. Between the day 60 and 90 measurement periods, the ammonium values for all treatments greatly declined ($p < 0.05$). Within day 30, ammonium N in T6 and T2 was statistically similar ($p > 0.05$) but higher ($p < 0.05$) than other treatments. Ammonium N within the day 60 measuring period followed the order: $T5 = T6 = T2 > T7 = T1 > T3 = T8 = T4$. Ammonium N observed at the end of the composting period was comparable among all the treatments apart from the T6 treatment.

3.1.2 Changes in plant-available P and K

Plant-available P measured from compost mixing ratios statistically differed ($p < 0.05$) between and within sampling periods (Figure 3a). Available P for all treatments increased between the day 0 and 30 measurements, decreased between the day 30 and 60 measurements, and increased between the day 60 and 90 measurements. However, for treatments T2 and T1, the available P increased between the day 30 and 60 measurements. Treatment T2 recorded the highest available P (258–3,843 mg kg⁻¹), and T4 yielded the lowest (115–2,167 mg kg⁻¹). Generally, within all sampling periods, available P among the treatments was in the order ($p < 0.05$): $T2 > T6 > T1 > T3 > T5 > T4 > T7 > T8$.

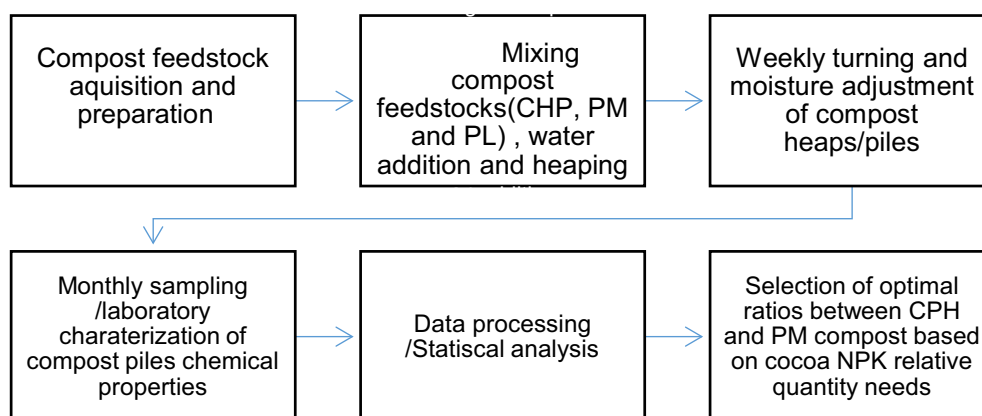


FIGURE 1
Flowchart for methodological steps in composting.

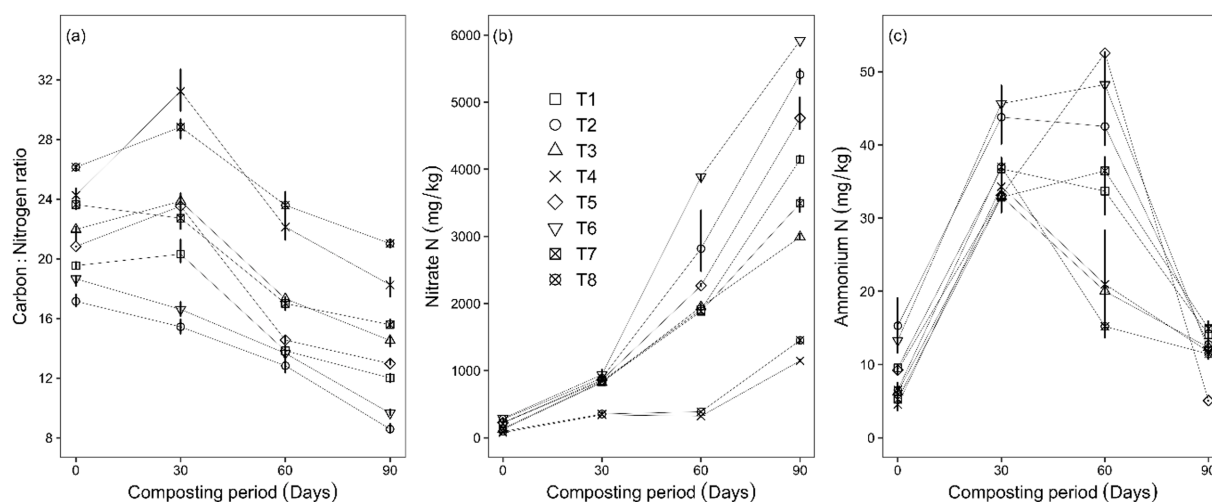


FIGURE 2

Carbon-Nitrogen ratio (a), nitrate (b) and ammonium (c) nitrogen changes as affected by different compost mixing ratio between cocoa pod husk (CPH) and Poultry manure (PM) with or without cocoa placenta (PL). T1=PM+CPH (1:1), T2= PM+CPH (2:1), T3=PM+CPH (1:2), T4 = PM+CPH (1:3), T5=PM+CPH (1:1) +PL, T6 = PM+CPH(2:1)+PL, T7 =PM+CPH (1:2)+PL & T8=PM+CPH (1:3) +PL. Numbers in the bracket are mixing ratios between PM and CPH. Error bars are LSD ($p < 0.05$).

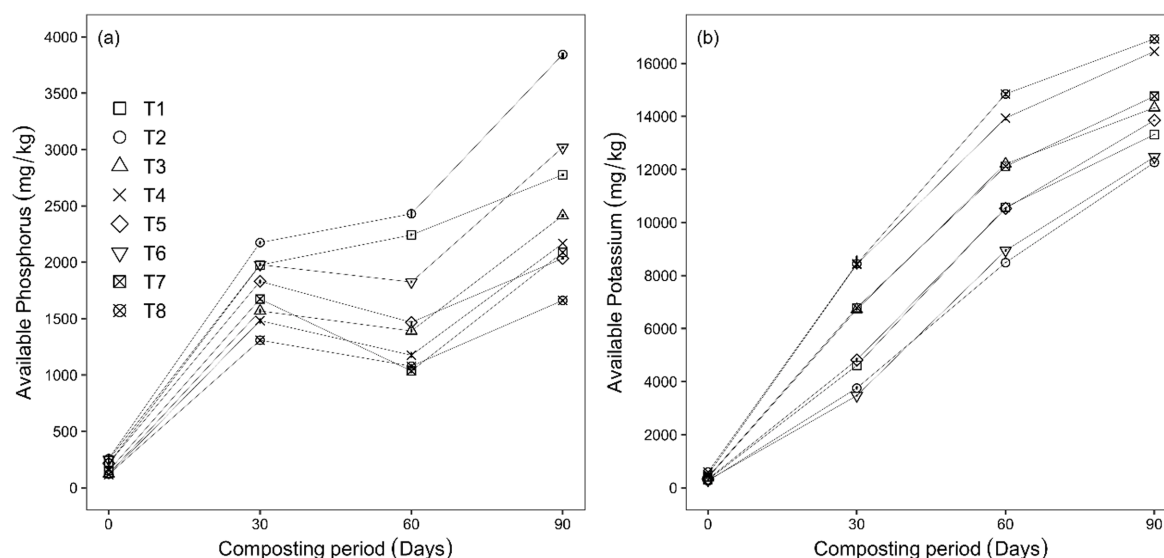


FIGURE 3

Compost available Phosphorus (a) and Potassium (b) dynamics during composting period as influenced by different mixing ratios of cocoa pod husk (CPH) and poultry manure (PM) with or without cocoa placenta (PL). T1=PM+CPH (1:1), T2 = PM+CPH (2:1), T3 = PM+CPH (1:2), T4 = PM+CPH (1:3), T5 = PM+CPH (1:1)+PL, T6 = PM+CPH(2:1)+PL, T7 = PM+CPH (1:2)+PL & T8 = PM+CPH (1:3)+PL. Numbers in the bracket are mixing ratios between PM and CPH. Error bars are LSD ($p < 0.05$).

Compost treatments influenced ($p < 0.05$) available K concentration, both between and within sampling periods (Figure 3b). Available K for all treatments increased exponentially between measurement periods throughout the study. The highest (592–16,922 mg kg⁻¹) available K and the lowest (255–12,263 mg kg⁻¹) available K were observed in T8 and T2, respectively. Generally, within all measurement periods, available K among the treatments was in the order ($p < 0.05$): T8 > T4 > T7 > T3 > T5 > T1 > T6 > T2.

3.2 Cocoa pod husk, poultry manure, and cocoa placenta co-compost NPK stoichiometry

Total NPK stoichiometry for T6 and T2 was in the order: N > K > P (Figure 4a). Total NPK for the other treatments was in the order: K > N > P. In terms of available NPK (Figure 4b), the order was K > N > P for all the treatments.

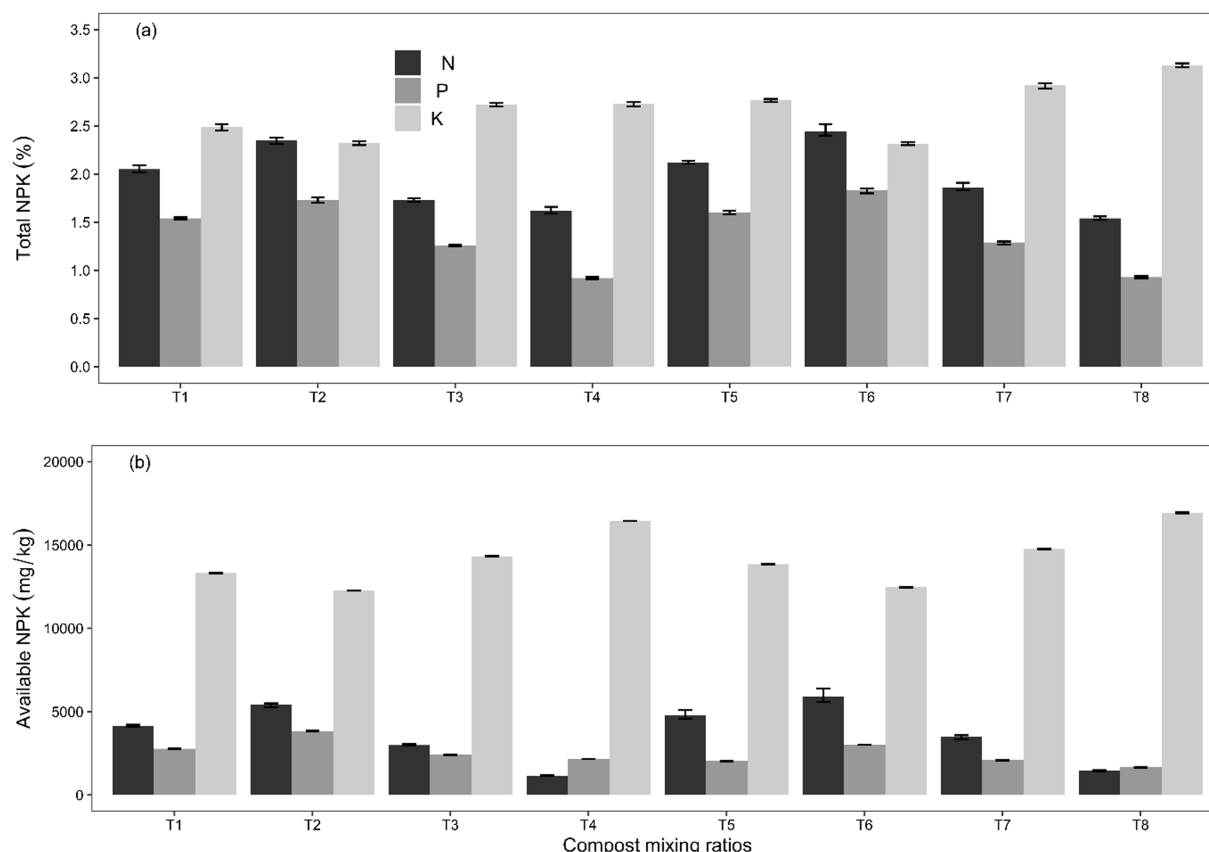


FIGURE 4

Matured compost (day 90) total (a) and available (b) NPK stoichiometry as affected by different cocoa pod husk (CPH) and poultry manure (PM) mixing ratios plus cocoa placenta (PL). T1 = PM+CPH (1:1), T2 = PM+CPH (2:1), T3 = PM+CPH (1:2), T4 = PM+CPH (1:3), T5 = PM+CPH (1:1)+PL, T6 = PM+CPH (2:1)+PL, T7 = PM+CPH (1:2) +PL & T8 = PM+CPH (1:3) +PL. Numbers in the bracket are mixing ratios between PM and CPH. Error bars are LSD ($p < 0.05$).

4 Discussion

4.1 Poultry manure and cocoa pod husk co-compost enhanced with or without cocoa placenta improved compost agronomic quality

4.1.1 Compost temperature

Temperature (38–48 °C) of all compost treatments within the first 2 days showed the initial mesophilic phase (< 50 °C) of the composting process (Supplementary Figure S1). This implied that sugars, amino acids, and proteins were degraded by mesophilic bacteria and fungi quickly increasing the temperature of the compost piles (Keener et al., 2000). Maximum temperatures of 58.5–61.5 °C for all compost treatments between days 3 and 9 corresponded to the thermophilic (50–70 °C) phase. This phase is where maximum degradation of the OM occurred as thermophilic microorganisms degraded fats, cellulose, hemicellulose, and some lignin (Bernal et al., 2009). The declined temperatures (< 50 °C) of all compost piles after 10 days of the composting process, suggested final mesophilic phase, decreased biodegradation due to a reduction in labile organic substrates. Compost piles were recolonized by mesophilic microorganisms, which degraded the remaining sugars, cellulose, and hemicellulose.

The observed similarity in temperatures of all compost piles and the ambient temperature between days 80 and 90 depicted a maturation phase of composting. Little or no degradation occurred beyond the maturation phase due to the depletion of sugars, cellulose, and hemicellulose. This observation is consistent with the studies by Nartey et al. (2017), who observed initial mesophilic, thermophilic, final mesophilic, and maturation temperatures of cocoa pod husk and fecal sludge co-composting study within the first 2 days, 3–6 days, 7–80 days, and 80–90 days, respectively.

Higher temperatures in cocoa placenta-treated compost piles than in their counterpart compost piles without cocoa placenta within the first 35 days underscored the fact that cocoa placenta contained more labile C (sugars: 15%) (Supplementary Table S1), which triggered higher biodegradation with the associated temperature. In the same context, higher temperatures in increasing ratios of poultry manure treatments within the first 35 days depict more biodegradable substrates in poultry manure compared to cocoa pod husks. Conversely, higher temperatures in treatments without cocoa placenta than in their respective piles with cocoa placenta from day 36 until day 80 could be because some biodegradable substrates (sugars) that were protected by complex compounds were now accessible for microbial degradation. Similar observations were made of higher temperatures in compost piles with higher mixing ratios of poultry manure relative to cocoa pod husk from day 36 until day 80. An optimal temperature

of 52–60 °C is conducive for composting (Miller, 1992). Temperatures above 55 °C are required to kill pathogenic microorganisms, but temperatures above 63 °C affect microbial activity as microbial activity declines rapidly when the optimum temperature for thermophilic microorganisms is surpassed (Bernal et al., 1998). In this study, the maximum temperature of 58.5–61.5 °C was within the optimal range for composting (56–63 °C) (Bernal et al., 2009). Thus, the maximum temperature of all compost treatments was above 55 °C, required to kill pathogens, but below 63 °C, favorable for microbial activity (Bernal et al., 2009), making them suitable for agronomic use. The maximum temperature of the current study was higher than that reported by Essel et al. (2021), 33 °C: cocoa pod husk and cattle manure co-composting; Amponsah-Doku (2020), 30 °C: cocoa pod husk and NPK co-composting; Praveena et al. (2018), 56.9 °C: cocoa pod husk and cow dung slurry co-composting; and Nartey et al. (2017), 46.5 °C: cocoa pod husk and fecal sludge co-composting. This may be because the cocoa pod husk used in the current study was milled into powder, giving it a larger surface area for more microbial decomposition with the corresponding temperature, unlike those used in the previously mentioned studies, which only underwent shredding.

4.1.2 Compost pH

The significant increase and decline of pH at days 30 and 90 (Supplementary Figure S2a), respectively, for all compost treatments suggested maximum transformation of protein to amino acids (aminization) and subsequent conversion of the amino acids into ammonium (ammonification) (Bernal et al., 2009) occurred within day 30, unlike day 90. The ammonium being alkaline raised the pH, but as the ammonium was being converted into nitrate (nitrification) at day 90, the pH declined. Similar compost pH dynamics were observed by Nartey et al. (2017), Praveena et al. (2018), Amponsah-Doku (2020), and Essel et al. (2021).

The pH for the compost treatments in the order: T8 > T4 > T5 > T3 > T6 > T1 > T6 > T2 at the end of the composting period (day 90) indicated that cocoa placenta and increasing ratios of cocoa pod husk had a positive relation with the compost pH. This may be linked to higher exchangeable K (0.90–1.37 cmol⁺ kg⁻¹) in the compost treatments, as K is more soluble in organic substrates. A linear regression analysis showed that exchangeable K is ($p < 0.01$) positively ($R^2 = 0.96$) related to the compost pH (Supplementary Table S2).

Compost pH of 8.8–9.7 at day 90 of the composting period for all treatments in this study was higher than a pH of 8.2 (Essel et al., 2021), 7.4–8.3 (Dogbatse et al., 2020), 7.29 (Praveena et al., 2018), and 7.3 (Nartey et al., 2017). This could be because the milled cocoa pod husk used in the current study increased exchangeable K concentration with its resultant positive effect on compost pH compared to the referenced studies where cocoa pod husk was shredded. Nonetheless, the reported final compost pH of this recent investigation was lower than the value of 10.8 reported by Amponsah-Doku (2020) in a cocoa pod husk and NPK co-composting study. This could be because dry cocoa pod husk used in the current study contained less K (2.9%) compared to the fresh cocoa pod husk K (3.5%) used by Amponsah-Doku (2020), as K was easily leached or lost from pod husk when left on the field to dry (Hougni et al., 2021). Optimum compost pH values were expected to be 5.5–8.0 (de Bertoldi et al., 1983; Miller, 1992). However, the compost pH of 8.8–9.7 at day 90 of the composting period for all treatments was higher than the optimum range.

Although the pH was higher than optimum, it is desirable for the West African cocoa-growing soils, characterized by low pH and high Fe³⁺ and Al³⁺ concentrations. Applying alkaline pH compost as a fertilizer could act as liming material for improving the soil pH and chelating the Fe³⁺ and Al³⁺, which, in turn, enhances P availability, as P is most critical for cocoa productivity in West Africa.

4.1.3 Compost EC

The EC values (0.065–0.08 dS/m) recorded by all compost treatments (Supplementary Figure S2b) at maturity (day 90) were below the maximum threshold (< 4 dS/m: Association of Swedish Compost Production, 2001) suitable for agricultural applications. This supposes that the current compost will not cause detrimental effects to plants when applied on the cocoa field. This is because the low salt concentration in compost will not result in high osmotic gradients that will cause movement of water and nutrients from the plant to the soil systems. The EC observed in this study was far lower than 4.96–5.79 dS/m (Amponsah-Doku, 2020), 1.28 dS/m (Praveena et al., 2018), and 2.73 dS/m (Nartey et al., 2017).

4.1.4 Compost OC, mineralizable C, and C: N

The decreased OC in all compost treatments during the composting period (Supplementary Figure S3a) was due to microbial decomposition of the organic substrates, which resulted in C loss in the form of CO₂. The OC decreased with composting time due to greater availability of labile organic substrates for microbes (Benito et al., 2003). This is confirmed in this current experiment, where a regression analysis suggested that compost OC ($p < 0.01$) was negatively related to compost mineralizable C ($R^2 = -0.76$) (Supplementary Figure S5). High OC content in cocoa placenta compost treatments relative to their respective counterpart treatments with no cocoa placenta (Supplementary Figure S3a) was explained by the high OC content (45.22%) in the cocoa placenta feedstock (Supplementary Table S1). Similarly, high OC in compost treatments with increasing ratios of CPH compared to treatments with higher ratios of PM (Supplementary Figure S3a) was because the CPH feedstock contained higher OC (36.54%) than PM (27.87%). The optimal organic matter range for compost at maturity is 40–60% (California Compost Quality Council, 2001). This OM range in OC equivalence is 23–34% OC. In this experiment, all compost treatments at maturity (day 90) recorded 23.57–31.21% OC, which are within the optimal range except for T2. The OC in the current study for all treatments except PM + CPH (2:1) was higher than 22.8% (Dogbatse et al., 2020) and 21.26% (Nartey et al., 2017), where cocoa pod husk was co-composted with PM/*Panicum maximum* and fecal sludge, respectively. This could be linked to lower C: N in cocoa pod husk feedstocks used by Dogbatse et al. (2020) (C: N: 1.38) and Nartey et al. (2017) (C: N: 25) compared to C: N of 30.28 in the cocoa pod husk feedstock of the current study. Nevertheless, the OC is lower than 38.05% reported by Amponsah-Doku (2020) (cocoa pod husk co-composted with NPK) due to the higher C: N (51.8) of the cocoa pod husk used by the investigator compared to 30.28 in the current study.

The mineralizable (oxidizable) C for all treatments ($p < 0.05$) decreased across all sampling periods (Supplementary Figure S3b) due to depletion of easily biodegradable substrates by microbes. The mineralizable C dynamics can be linked to microbial respiration or CO₂ evolution in composting. Microbes rely on mineralizable C for

their energy and activities. As such, a decrease in oxidizable or mineralizable C decreases microbial activities, therefore giving an indication of CO₂ evolution. Nartey et al. (2017) and Amponsah-Doku (2020) observed decreased microbial activity (CO₂ evolution) over time when they co-composted cocoa pod husk with fecal sludge and NPK, respectively.

Higher mineralizable C in cocoa placenta treatments than their counterparts without cocoa placenta is because cocoa placenta feedstock contains 15.23% sugar (Supplementary Table S1). Higher mineralizable C in compost treatments with high ratios of poultry manure relative to cocoa pod husk indicates that poultry manure may have more easily biodegradable compounds compared to cocoa pod husk. The optimal level for mineralizable C in a finished compost product should be < 30% of the initial mineralizable C before composting (Cooperband et al., 2003). Interestingly, the mineral C for all treatments at the end of the composting (22.20–28.42%) when expressed as a percentage of the initial mineralizable C was < 30%, indicating that the composts were all matured.

The decreased C: N over composting time (Figure 2a) indicated that OC declined with composting time (Supplementary Figure S3a) due to loss by microbial decomposition. The findings in this study support previous studies (Nartey et al., 2017; Dogbatse et al., 2020; Amponsah-Doku, 2020) that recorded decreased C: N at the end of the composting studies.

The high C: N content in PL compost treatments relative to their respective counterpart treatments without PL (Figure 2a) is explained by the high OC content (45.22%) in the PL feedstock (Supplementary Table S1). Similarly, high C: N in compost treatments with increasing ratios of CPH compared to treatments with higher ratios of PM (Figure 4a) is because the CPH feedstock contains higher ($p < 0.001$) OC (36.54%) than PM (27.87%) (Table 1). The C: N recorded at the end of the composting (day 90) ranged from 8.85 to 21.01 for all treatments (Figure 2a) with the lowest and highest being observed in T2 and T8, respectively. Optimal C: N for a mature compost is 10–25 (Association of Swedish Compost Production, 2001; California Compost Quality Council, 2001). Apart from the C: N of treatment T6 (8.58) and T2 (9.65), the C: N (12.01–21.02) of the other treatments was within the optimal range. The C: N ratios of 12.97 and 12.01 of T5 and T1, respectively, are comparable to 12.15 as reported by Nartey et al. (2017), while the values (14.85–21.02) of the other treatments are higher than the values reported by Nartey et al. (2017) but lower than the results of Amponsah-Doku (2020) (18.4–24.5) and Dogbatse et al. (2020). The variation in the C: N between the current research and the referenced studies may be explained by differences in N content of the respective compost: current research (1.6–2.45% N), Nartey et al. (2017) (1.75% N), Amponsah-Doku (2020) (1.6–2.0% N), and Dogbatse et al. (2020) (0.67% N).

4.1.5 Compost nitrate N, ammonium N, available phosphorus, and available potassium

A sharp increase in nitrate N for treatments after 30 days (Figure 2b) of composting may be explained by decreased pH after day 30, favoring nitrification (conversion of ammonium N to nitrate N) (Figure 2c). The increase of ammonium N within day 30 and a decline after day 30 (Figure 2c) is a function of pH, as the compost pH followed a similar dynamic. A similar observation

was made by Nartey et al. (2017), where nitrate N increased with composting time, while ammonium N only peaked at the initial composting stage when they co-composted cocoa pod husk with fecal sludge. Nitrate N (Figure 2b) recorded among treatments at day 90 suggested that: (i) compost treatments with PL had higher nitrate N than their counterpart treatments without PL and (ii) increasing ratios of PM increased nitrate N compared to increasing ratios of CPH. Interestingly, a lot of maggots were observed visually in: (i) compost piles with cocoa placenta compared to their control counterparts and (ii) compost piles with increasing ratios of poultry manure relative to piles with increasing ratios of cocoa pod husk. These maggots are highly proteinaceous (38% protein) (rich in N) (Sari et al., 2024). As such, their biomass might have contributed to the observed nitrate N variation among compost treatments. The optimal NO₃-N/NH₄-N ratio of > 2 (Association of Swedish Compost Production, 2001) or NH₄-N/NO₃-N ratio of < 0.5 or 0.5–3 (California Compost Quality Council, 2001) for mature compost indicates that all the current compost treatments are matured (NO₃-N/NH₄-N: 134–295 or NH₄-N/NO₃-N: 0.002–0.009) agronomically. Nitrate N of 1,130–5,315 mg kg⁻¹ in the current study is higher than 157–697 mg kg⁻¹ and 1,002 mg kg⁻¹ observed by Amponsah-Doku (2020) and Nartey et al. (2017), respectively.

Decreased available P for all treatments between days 30 and 60 and an increase between days 60 and 90 (Figure 3a) can be linked to compost pH dynamics (Supplementary Figure S2a). Available P among the treatments (Figure 3a) at the end of the composting process depicted that: (i) presence of PL decreased compost available P compared to compost piles without PL and (ii) increasing ratios of PM increased compost available P compared to increasing ratios of CPH. This observation is a function of the compost treatments pH, as a regression analysis showed that compost pH had a significant ($p < 0.01$) strong ($R^2 = -0.82$) negative relation with the compost available P (Supplementary Table S3). This observation highlights that under alkaline pH P is “precipitated” by basic cations such as Ca²⁺, K⁺, and Mg²⁺ due to their higher solubility under alkaline pH. This is confirmed in this current study that the most soluble exchangeable basic cation, K⁺, had a strong ($R^2 = -0.88$) ($p < 0.01$) negative relation with available P (Supplementary Figure S4). The observed available P for all compost treatments P (2167–3,843 mg kg⁻¹) in the current study was higher than 219–232 mg kg⁻¹ reported by Dogbatse et al. (2020). The available P is, however, comparable to 3,400 mg kg⁻¹ of Nartey et al. (2017) while lower than 3,320–8,200 mg kg⁻¹ reported by Amponsah-Doku (2020).

An increase in available K (Figure 3b) in treatments during the composting period may be due to visually observed chitinous brownish eggs of insects, as the chitin is rich in K (Karnila et al., 2024). Generally, the recorded available K at the end of the composting period implied that available K in the compost increased with increasing CPH ratios plus PL compared to piles with higher levels of PM. This is because of the higher K content in the cocoa pod husk (2.90%) and cocoa placenta feedstocks (2.30%) compared to K content in the PM feedstock (1.62%) (Supplementary Table S2). Furthermore, the visually observed chitinous brownish insect eggs were more pronounced in the compost piles with higher concentrations of CPH plus PL compared to piles with higher contents of poultry manure.

4.2 Optimal cocoa pod husk and poultry manure co-compost mixing ratios identified for cocoa NPK needs and OMF formulation

The $N > K > P$ stoichiometry for T6 and T2 compost mixing ratios implied (Figure 4) that those compost treatments are suitable for young cocoa (≤ 7 years) OMF formulation. That age group of cocoa needs more N than other nutrients for vigorous vegetative growth. The N form applied in the young cocoa fields has been sulfate of ammonia, which has a high potential for soil acidification and P “fixation” in the Ghanaian cocoa systems. Adopting either T6 or T2 for young cocoa OMF formulation will help meet the N needs of the young cocoa while improving soil pH and SOM since the majority of Ghanaian cocoa soils are low in pH and OC. The current compost has a liming property (pH: 8.75) and a higher nitrate concentration compared to ammonium ($\text{NO}_3\text{-N}/\text{NH}_4\text{-N}$: 251–295), which both mitigate soil acidity.

In terms of reproductive (mature) cocoa, compost mixing ratios with $K > N > P$ stoichiometry are somehow preferred since they contain more K than N, although they do not perfectly correspond to reproductive cocoa (≥ 8 years) NPK needs ($P > K > N$). Although T5, T1, T7, T3, T8, and T4 all have $K > N > P$ stoichiometry (Figure 4), the compost mixing ratio with higher P and OC content, as well as high practicability for adoption, needs to be considered the most preferred compost ratio. Treatment 1 (T1) has higher P content, but T4 has higher OC and can be more practical. The higher P from T1 and higher OC from T4 are both needed to boost cocoa yield, but there are more CPH on the cocoa field. Co-composting 1 part of PM with 3 parts of CPH, which is T4, is more practical than T1 because there are more CPH residues in the cocoa farm than PM. Therefore, in terms of balancing P and OC requirements with practicability, treatment T3 (PM: CPH-1:2) is most preferred for the formulation of mature cocoa OMF. This is because it contains more P than T4 and more OC than T1 while being more practicable than T1. T3 is also preferred for OMF over its counterpart T7 with PL addition because the PL additions increased compost pH, which decreased compost available P. Since the compost available P is low compared to available K and N (Figure 4b), and yet P is key for mature cocoa productivity, the compost should be augmented with mineral P forms, triple or single superphosphate, when formulating the OMF. Alternatively, when formulating the OMF, the compost can be supplemented with cocoa “asase wura” (N: P: K: 0:22:18) or “cocoafeed” (N: P: K: 0:30:20) mineral fertilizer, which contains more P than K but without N.

4.3 Co-compost of CPH and PM for cocoa OMF presents potential impacts

Valorizing CPH and PM for efficient cocoa OMF in the Ghanaian cocoa belt and the West African cocoa belt at large presents several impacts. Using the CPH and PM for OMF formulation presents potential in enhancing soil organic C in the cocoa farms. Increasing soil carbon levels or stocks reduces erosion and leaching as well as improves soil health and nutrient

cycling. Using OMF will also help conserve more moisture for plant use during dry spells, enhancing resilience to dry spells or climate change. Moreover, adopting the CPH and PM co-compost for OMF also reveals a liming property (pH: 9.22), which will improve the soil pH. Improvement in the soil pH will reduce Al and Fe solubility, thereby freeing locked-up P in soil for cocoa plant uptake. In addition, adopting the CPH and PM for cocoa OMF will also reduce wasteful losses of C and nutrient compound footprints since the CPH and PM will no longer be discarded as waste. This will reduce negative impacts on climate (SDG ‘13’) and water pollution (SDG ‘6’). Furthermore, using the CPH and PM co-compost for OMF will reduce overreliance or dependence on mineral fertilizers, building farmers’ resilience to mineral fertilizer scarcity. This intervention therefore aligns with climate-smart agriculture, regenerative agriculture, and sustainable intensification in cocoa systems. This will, in turn, improve cocoa productivity, increase the income of farmers, and reduce poverty (SDG ‘1’), as well as increase financial capacities for quality health and wellbeing (SDG ‘3’) and education (SDG ‘4’). The findings could also provide a basis for companies to produce cocoa OMF and sell it to farmers, creating business and employment opportunities resulting in economic growth (SDG ‘8’). Furthermore, the alkaline pH of the CPH and PM co-compost makes it suitable for the South America and Asian cocoa belts (the majority of soils are dominated by low soil pH and higher Al and Fe) just like the West African cocoa belt. A limitation of the study to consider is that the alkaline pH of the compost may conflict with cocoa cultivating areas with neutral or alkaline soil pH. In addition, an adequate supply of PM and preserving fresh PL are required as feedstocks for composting.

5 Conclusion and recommendations

- All compost mixing ratios improved compost agronomic quality.
- Increasing ratios of poultry manure (PM) enhanced compost total N, P, available N, and P.
- Increasing cocoa pod husk ratios increased compost organic C, total and available K, and pH, but the pH of all the compost treatments presents liming potential to mitigate the low pH of cocoa soils in Ghana.
- Cocoa placenta additions in cocoa pod husk and poultry manure co-compost ratios enhanced OC, pH, total NPK, and available N and K but decreased available P in the cocoa pod husk and poultry manure co-compost.
- T8 (PM: CPH: 1:3 + PL) and T2 (PM: CPH: 2:1) recorded the highest and lowest pH, respectively, at the end of the composting.
- T8 and T2 recorded the maximum and lowest OC at the end of the composting period.
- Highest available N was observed in T6 (PM + CPH: 2:1 + PL), and the lowest was observed in T4 (PM: CPH: 1:3).
- T2 recorded the highest available P, and T4 yielded the lowest.
- The highest available K and lowest available K were observed in T8 and T2, respectively.
- Compost mixing ratios T2 (PM: CPH: 2:1) and T3 (PM: CPH: 1:2) NPK stoichiometry align with young cocoa and mature cocoa NPK needs, respectively.

- The compost mixing ratios PM + CPH (2:1) and PM + CPH (1:2) show the potential for young cocoa (7 years and below) and mature cocoa (8 years and above) OMF formulation, respectively.
- This study therefore recommends PM + CPH (2:1) and PM + CPH (1:2) OMF field validation for the mature and young cocoa, respectively, for future studies to ascertain agronomic and economic efficiency as well as environmental friendliness.

Data availability statement

Data supporting this study are openly available from the CORD repository at <https://doi.org/10.57996/cran.ceres-2802>.

Author contributions

BL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. RS: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing. EY: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. NG: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. DS: Supervision, Writing – review & editing. EM-N: Visualization, Writing – review & editing. JM: Project administration, Writing – review & editing. KA: Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. TO: Project administration, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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