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RESEARCH ARTICLE

ASSESSMENT OF THE EFFECTS OF COCOA POD HUSK AND CATTLE MANURE ON OLD COCOA PLANTATION SOIL CHEMISTRY UNDER TROPICAL LOWLAND AGROCLIMATIC CONDITIONS IN PAPUA NEW GUINEA

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ABSTRACT

This study examined the effects of two organic matter sources of high carbon and low nitrogen (cocoa pod husk) or high nitrogen and low carbon (cattle manure) contents on the chemistry of a volcanic soil under cocoa production in Papua New Guinea (PNG). A field study with eight treatments: no amendment (control), cocoa pod husk (CPH), cattle manure (CM), NPK, CPH+CM, CPH+NPK, CM+NPK, and CPH+CM+NPK. All treatments were replicated five times in five blocks, each with a treatment of five trees, and were set up in a randomized complete block design. The treatments were applied in a split manner, initially and after two and a half months. Soil samples for measurement of parameters and nutrients was done within the depth of 50 cm of the soil at the end of the fifth month, and four out of the five replicates were used. The treatment averages for all parameters were obtained by averaging the four replicates (n=4) and statistically analyzed. To compare the treatment means, significant differences ($p<0.05$) were determined by two-way ANOVA. If an interaction between the treatments and profile depth was found, one-way ANOVA with all combinations was performed using Tukey's HSD (honest significant difference) and pairwise comparisons. The results obtained showed that CPH and CM addition alone or in combination under cocoa improved all the soil physical and chemical properties. Soil organic matter, organic carbon, organic carbon stock, and macronutrients were more strongly influenced by carbon (CPH) than by nitrogen (CM). On the other hand, soil water-holding capacity, moisture, pH, electrical conductivity, and most micronutrients were improved by the nitrogen. These organic matter sources are relatively inexpensive and readily available in PNG, and the results have implications for the sustainable management of soil fertility under cocoa production, aiming to enhance cocoa yields for smallholder farmers.

KEYWORDS

Cocoa, cattle manure, cocoa pod hush, organic matter, soil fertility, PNG

1. INTRODUCTION

In Papua New Guinea (PNG), cocoa is the third most important agricultural crop, after oil palm and coffee, and generates approximately 14 percent of the country's agricultural export revenue. More than 80 percent of the production is by smallholder farmers and is the primary source of income for more than two million people who grow the crop, primarily in the lowlands of PNG. Despite the importance of the crop to national agricultural export revenue generation and the livelihood of rural people, the production of the crop continues to face several problems due to pests and diseases, decline in soil fertility, aging cocoa plantations, and a loss of interest due to a lack of government incentives and extension services (Singh et al., 2019). These factors have led farmers to abandon cocoa farming, significantly affecting the socio-economic status of smallholder farmers. Stakeholders have implemented measures to mitigate the impacts. In most farms, farmers have been trained to use integrated pest and disease management and introduce new hybrid varieties that are high-yielding and tolerant to local conditions. At the same time, farmers have been encouraged to replant aging cocoa plantations and reinvest due the increased availability of information on how to improve production (Singh et al., 2019).

In the recent past, shortage of people interested in growing cocoa as a result of aging or the younger generation shifting their interest elsewhere has also become a problem, not to mention the rise in cost of chemical fertilizers affecting affordability by smallholder farmers and availability becoming more of an inherent concern because of the remoteness of most farms, coupled with the impacts of climate change (Michael, 2019; 2020). Due to those above, a rise in the need for sustainable production has emerged to address some of the issues and help boost the interests of smallholder cocoa farmers (Michael, 2022). One of the standout topics of discussion to sustain cocoa production is the use of low-cost inputs to help farmers generate more income sustainably, particularly to address the inherent loss of soil fertility and the affordability and availability issues with chemical fertilizers (Peter and Michael, 2023). It is the use of organic matter of plant and animal origin, either from the agriculture sector itself, other industries such as logging or from any other environmental settings as pointed out in various studies (e.g., Michael, 2014; 2019a; b; 2020a; b; c; d; e; f; g; h).

In PNG, numerous organic matter sources are available; however, utilizing them sustainably remains a challenge due to a lack of technology and awareness regarding their use as bioresources, which promotes the circular economy. Based on the findings of some of recent studies [e.g.,

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Michael, 2020a; b; c) on the use of organic matter to manage problem soils, reviewed the importance of organic matter uses in the production of root and tuber crops, e.g., sweet potato, and based on that, conducted a trial using leucaena chops (Topas et al., 2024). The results showed that the addition of the chops not only maintained soil fertility and general soil health but also increased yield compared to the results from the unamended soil. Similar to that, studied the nutrient dynamics under unmanaged rubber, cocoa and oil palm plantations under lowland agroclimatic conditions and pointed out that the general soil health and nutrient availability status of the soils under these perennial crops were sustained by the fallen organic matter from the trees compared to the adjacent grassland dominated by cogon grass (*Imperata cylindrica*)(Joel and Michael, 2022).

The practice of use of organic matter in agricultural farms is widely covered in the literature pointing out its importance in managing soil parameters that affect soil nutrient status, health and productivity, establishment of microbial ecology and management of problem soils [e.g., Michael, 2020g; h]. Based on wider studies on the use of organic matter, we have extended the work to broaden the understanding of the potential use of organic matter addition in agriculture under perennial crop production by adding cocoa pod husk (CPH) and cattle manure (CM) (Joel and Michael, 2022). The CPH is almost available on smallholder farms, free of charge. Similarly, the cattle industry in PNG has expanded, resulting in a significant increase in manure production due to the rise in cattle herd size. The availability of both the CPH and CM in large quantities in the farms and their disposal have become an environmental concern (pollution as solid waste and odor), and there is a broader consensus on how to manage them sustainably (van Vliet and Giller, 2017; Caspi et al., 2018; Kome et al., 2018; Balentić et al., 2018; Anogara et al., 2024).

This study was conducted to investigate the importance of utilizing CHP and CM in cocoa production as a bioresource, promoting the concept of a circular economy, which is crucial for smallholder farmers and the overall environment.

2. MATERIALS AND METHODS

2.1 Description of the study site

The study was conducted in an old cocoa plantation at the PNG UNRE in the Gazelle District, ENBP, PNG, located at 324.16 meters above sea level, has an annual temperature of 27.6 °C, and receives 357 mm of precipitation. The province's warmest month is June; the coldest is August; the wettest is March; and September is the driest month. The farm is approximately 30 years old, with hybrid cocoa trees and has never been replanted, the trees are of the same age and is on an Andisol (volcanic soil). The selected soil parameters of the study site are listed in Tables 3.1 and 3.2, respectively.

Table 1: Selected soil parameters of the study site.

Soil parameters	Compositions	
Soil organic matter (%)	3.64	
Soil organic carbon (%)	1.65	
Soil organic carbon stock (t ha^{-1})	150.24	
Water holding capacity (%)	35.21	
Moisture (%)	11.52	
pH	5.56	
Electrical conductivity (dS cm^{-1})	0.12	
Bulk density (g cm^{-3} soil)	1.27	
Total porosity (%)	32.12	

The nutrient contents of the original soil sampled before the study are given as Soil*(Table 3.2) and particle composition was 88.3% sand, 10.2% clay and <1% silt, a sandy loam soil.

Table 2: The treatment combinations and their nutrient contents.

Nutrients (mg kg^{-1})	Treatments (Organic matter composition, CPH:CM is 2:1)							
	Soil*	NPK	CPH	CM	CPH+CM	NPK+CPH	NPK+CM	NPK+CPH+CM
N	1.5	12	10	5	15	22	17	27
P	270	5	2,100	1,050	3,050	2,105	1,055	3,155
K	9.0	9	125	63	188	134	72	197
S	250	–	950	475	1,425	950	475	1,425
Mg	840	–	2,000	1,000	3,000	2,000	1,000	3,000
Ca	2400	–	9,150	4,575	13,725	9,150	4,575	13,725
Zn	40	–	70	35	105	70	35	105
Mn	7.0	–	60	30	90	60	30	90
Fe	8400	–	175	88	263	175	88	263
Cu	5.0	–	3.01	5.11	8.12	3.01	5.11	8.12
Mo	0.9	–	2.01	3.12	5.03	2.01	3.12	5.03

The mineral composition of the NPK used is 5:2:4. The soil nutrient contents of the soil sampled prior to setting the study are denoted by Soil*.

Before setting the experiment, the chosen site was thoroughly weeded, and fallen leaves, dead pods, and any other source of organic matter around the plants chosen to receive the treatments, including the guard rows, were removed. At the same time, a selected number of primary roots were identified and gently dug outward from the bases of the trees to determine where most of the feeder roots were concentrated. This

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exercise showed that most feeder roots were concentrated at 40–60 cm from the base of the trees. Therefore, the treatments were applied 50 cm from the base of plants, forming a circle.

2.2 Preparation of organic matter and application

The organic matter sources, CPH and CM, were sourced from the PNG University of Natural Resources and Environment Agriculture Farm. The CPH was chopped and blended into smaller pieces before using. The CPH and CM were partially decomposed into several buckets for 2 months, removed, sun-dried for a few days, and packed. To assist the application, shallow circular trenches of 20–30 cm were dug around each tree 50 cm away from the bases, forming a circular ring. Application was made in a split, 900 g initially and 450 g after 2.5 months, in the trenches. The NPK was applied at 150 kg N/ha/year in a similar manner, and when a combined application was made, half of the amounts (450 g for organic matter sources and 75 kg NPK) were considered.

2.3 Experimental design

There were five experimental blocks of 640 m^2 (25.3 m x 25.3 m) containing eight treatment plots. Each plot was 16 m^2 (4 m x 4 m) within a block area of 128 m^2 and contained four trees an experimental plot, 20 trees a treatment, and a total of 160 trees within the experimental site. Each treatment plot was separated by two guard rows of cocoa trees, serving as a buffer between the treatments. All treatments within a block were arranged in a completely randomized block design and replicated five times (n = 5).

2.4 Production management

Manual weeding was done to ensure there was no weed growing within the treatment application circle. Fallen cocoa leaves or any plant matter, such as dead branches, were removed, and the area around the treatments was kept clean. No chemicals were used for any purpose in the study either. Basic sanitation practices, such as removing infected and wilted flowers, cherelles, pods, and beans, were carefully carried out to ensure the plots were free of pests and pathogenic organisms.

2.5 Soil sampling

Soil samples were taken along the circular trenches where organic matter was applied at the end of the five months and processed for laboratory assessments of the changes in soil chemistry. Soil samples collected under the four threes of a treatment in a block were composited, packed into pre-labelled, sealable plastic bags, and kept separately as replicates. Under laboratory conditions, these soil samples were placed on a canvas, spread thinly, and air-dried for 2 days under laboratory conditions. A total of 500 g was sub-sampled from the composite air-dried samples, packed into several paper bags, and sent to the laboratory for measurement of the soil parameters and instrumental analysis of the soil nutrients.

2.6 Laboratory analysis and measurements

Important soil physical and chemical properties that determine and influence soil fertility, mineral nutrient availability, plant biomass production, and yield were measured and analyzed using laboratory analytical equipment and the standard equations. Total nitrogen was analyzed by the Kjeldahl method (Buchi K436 speed digester and Buchi K-350 Kjeldahl distillation unit). A sample of one-gram (< 2 mm) air-dried soil was digested using 15 ml of concentrated sulfuric acid at 300 – 400˚C (H_2SO_4 reduces nitrogen as ammonium sulphate $(NH_4)_2SO_4$). The sample solution was distilled using 60% sodium hydroxide (NaOH), where ammonium (NH_4^+) was converted to ammonia (NH_3) gas, which was collected using 25 ml of 2% boric acid with 3 drops of mixed indicator. It was then back titrated using 0.01 M HCl. The available nitrogen (NO_3^-N) was determined by the transition of the salicylic acid method using UV after extracting with 0.027 M $Ca(OH)_2$.

The available phosphorous was determined by Olsen method using a spectrophotometer (UV1800, Shimadzu Corporation, Japan) using 0.5 M sodium bicarbonate ($NaHCO_3$) after adjusting the pH to 8.5 with NaOH. Extraction was for 30 minutes using a 200-rpm shaker at a soil-to-extraction solution ratio of 1:20 (w/v).

All the other nutrients (K, Mg, Na, Ca, S, Mn, Zn, B, Cu, Fe, and Al) were extracted with a Melich 3 extraction solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0. 001 M EDTA) in 1:10 (soil: extractant ratio) and analyzed using an ICP OES. The data was calculated as per Melich3 18F1 standard as follows:

$$N = ((C - B) \times (Ve \div Ws)) \quad (1)$$

Where N is nutrient, e.g., K, C is concentration, B is blank ((mg element/dm^3), Ve is effective volume used in the extraction calculation (1:20 soil to solution), and Ws is the weight of the sample, respectively.

The data in milli-equivalent (mEq./100 g soil) were converted to milligrams (mg) as follows:

$$mg = [(mEq \times Aw) \div V)] \quad (2)$$

Aw is the atomic weight of an element (e.g., nitrogen) and V is valence, respectively.

Cation exchange capacity (CEC) was estimated based on the sum of the individual base cations (Ca, Mg, K and Na) as follows:

$$CEC = \left(\frac{\text{Sum of bases}}{\text{Base saturation \%}}\right)100 \quad (3)$$

Sum of bases are in meq/100g and are individual exchangeable base cations. Based saturation (%) is from the soil analysis data (e.g., Table 4).

Soil moisture content was determined by oven-drying samples at 105°C for 24 hours, and the final weight was estimated after 2 hours of cooling by subtracting the dry weight from the initial fresh weight. The pH was measured using a standard dilution (1:5 soil: water w/v)) method (e.g., Michael et al., 2015). Electrical conductivity (EC) was measured using a Direct Soil EC meter (Spectrum Technologies Inc., 12360S Industrial Dr. East Plainfeld, IL 60585).

The bulk density (g cm^{-3}) was calculated by oven-drying the cores at 105°C for 48 hours, followed by weighing again (Michael, 2019a; b). The oven dry weights were divided by the core volume and estimated as follows:

$$BD = (Odw \div \pi r^2 h) \quad (4)$$

Where BD is bulk density (g cm^{-3}), Odw is oven dry weight and formula for estimation of the volume of the core.

The soil organic carbon (SOC) content was analyzed using the weight loss-on-ignition method. A five-gram sample was weighed into a crucible and heated in a muffle furnace for 12 hours at 105°C (Wf). The weights were recorded after 2 hours of cooling, further combusted at 375°C for 17 hours (Fw), cooled for 2 hours, and weighed (e.g., Michael et al., 2015; 2016). The SOC content was estimated by multiplying the carbon value by a conversion factor (1.72) and expressed as a percentage:

$$SOC\ (\%) = [((Wf - Fw) \div Wf) \div 1.724)100] \quad (5)$$

The conversion factor was used to convert the soil organic matter content to organic C, assuming there was 58% C in the organic matter.

The size of the C stock in each profile was calculated as the sum of the individual C fractions (%) × BD (g cm^{-3}) × profile depth (SP cm) and expressed as a percentage as per Michael (2020g) as follows:

$$SOC_{stock}\ (\%) = [((SOC/100) \times BD \times SP)] \quad (6)$$

Where SOC was determined using Eqn. 4 and the conversion factor obtained by 100 ÷58.

The soil organic matter (SOM) contents were estimated using the SOC content and the conversion factor as follows:

$$SOM\ (\%) = [(SOC) \times Cf)] \quad (7)$$

The water holding capacity (WHC) was estimated by soaking soil samples in water (100% WHC) and draining them through filter paper overnight [e.g., Michael, 2020a; b; c; d). These were weighed for the wet weight (W_w), dried in an oven at 105˚C for 24 hours, and reweighed to obtain the oven-dry weight (OD_w). The WHC was estimated as follows:

$$WHC\ (\%) = [((W_w - OD_w) \div OD_w)\ 100] \quad (8)$$

The total porosity was determined (Landon, 1991) as follows:

$$P = [(1 - \left(\frac{BD}{d}\right)100] \quad (9)$$

Where P is total porosity (%), BD was defined and d is particle density of 2.65 g cm^{-3}.

The weight of the SOM to a given depth and area was estimated as follows:

$$SOM\ (tons) = [(SOC \times BD \times SP \times ha)\ 1.72] \quad (10)$$

Where SOC is in %, BD is in g cm^{-3}, SP is in m and ha is hectare (10 000 m^2).

2.7 Statistical analysis

Data from four replicates were used for analysis and data from the fifth replicate were kept as security against loss and mishandling. The treatment averages of all the parameters (e.g., pH) were obtained by taking the mean of the four replicates (n=4). Significant differences (p<0.05) between the treatment means were determined by two-way ANOVA, using statistical software JMPIN (AS Institute Inc., SAS Campus Drive, Cary, NC, USA 27513) to compare the treatment means. If an interaction between the treatments and profile was found, one-way ANOVA with all combinations was performed using Turkey's HSD (honestly significant difference) and pairwise comparisons.

3. RESULTS

3.1 Effects of organic matter addition on soil properties

The soil organic matter (SOM) contents were significantly increased following the amendments when in the unamended soil decreased and NPK application had not much effect (Table 3). Nearly all the organic amendments, alone or in combinations, increased the SOM contents. The highest increase in SOM was measured in the soil amendment with NPK, CPH, and CM, followed by CPH, CM, and NPK, and CPH compared to that of the NPK+CM amended soil. The SOM content following NPK amendment was the lowest and had decreased compared to that of the control soil's SOM content. The overall results indicate that the SOM content has a direct influence on the SOC content. The addition of organic matter to the soil significantly increased the soil organic carbon (SOC) content, particularly when the amendment was made in combination (Table 3). A more than 6% increase in SOC was caused by a combination of NPK, CPH, and CM, followed by CPH+CM, CPH, NPK+CPH, and the rest of the treatments. In the NPK amended soil, a decrease in SOC of nearly 0.5% was measured compared to the unamended soil's content, which was approximately 2.0%. The overall changes corresponded to the changes in SOM.

Table 3: Changes in soil chemistry measured after five months of cocoa production following application of amendments.

Parameters (Soil)	**Treatments**							
	Control	**NPK**	**CPH**	**CM**	**CPH+CM**	**NPK+CPH**	**NPK+CM**	**NPK+CPH+CM**
SOM (%)	3.7 ± 0.34^{a}	2.7 ± 0.52^{a}	7.7 ± 0.53^{b}	5.8 ± 0.16^{c}	9.6 ± 0.40^{bcd}	6.1 ± 0.34^{bce}	4.8 ± 0.25^{acef}	11.4 ± 0.62^{dg}
SOC (%)	2.22 ± 0.36^{a}	1.58 ± 0.12^{a}	4.26 ± 0.23^{a}	3.23 ± 0.34^{ab}	5.33 ± 0.53^{ac}	3.49 ± 0.62^{a}	2.80 ± 0.23^{abd}	6.54 ± 0.22^{ce}
SOC_{stock} (t ha^{-1})	164.98 ± 2.32^{a}	85.68 ± 1.23^{b}	187.20 ± 3.56^{ac}	127.97 ± 4.24^{d}	183.41 ± 3.33^{ce}	129.38 ± 3.21^{df}	148.98 ± 2.36^{g}	173.18 ± 4.44^{ah}
WHC (%)	40.87 ± 2.22^{a}	38.16 ± 3.21^{a}	46.86 ± 1.23^{a}	52.52 ± 2.22^{b}	57.36 ± 2.21^{bc}	42.29 ± 1.12^{ad}	45.88 ± 2.3^{ade}	60.66 ± 1.3^{cf}
Moisture (%)	12.30 ± 0.59^{a}	11.40 ± 0.65^{a}	14.30 ± 0.87^{a}	18.40 ± 0.78^{b}	23.02 ± 0.98^{bc}	14.00 ± 0.69^{ad}	15.20 ± 0.87^{abde}	20.40 ± 0.69^{bcf}
pH	6.57 ± 0.52^{a}	5.99 ± 0.32^{a}	6.23 ± 0.70^{a}	6.40 ± 0.62^{a}	5.99 ± 0.33^{a}	6.17 ± 0.36^{a}	6.09 ± 0.25^{a}	6.20 ± 0.31^{a}
EC (dS cm^{-1})	0.17 ± 0.11^{a}	0.61 ± 0.03^{a}	0.26 ± 0.02^{a}	0.44 ± 0.03^{a}	0.33 ± 0.13^{a}	0.23 ± 0.11^{a}	0.50 ± 0.04^{a}	0.77 ± 0.02^{a}
BD (g cm^{-3})	1.70 ± 0.32^{a}	1.23 ± 0.42^{a}	0.81 ± 0.44^{a}	0.65 ± 0.36^{a}	0.56 ± 0.34^{a}	0.72 ± 0.22^{a}	0.79 ± 0.26^{a}	0.51 ± 0.34^{a}
TP (%)	35.72 ± 2.3^{a}	53.71 ± 1.32^{b}	69.56 ± 2.34^{c}	75.35 ± 3.34^{cd}	78.87 ± 2.32^{de}	72.83 ± 2.35^{def}	70.06 ± 3.33^{cfg}	80.63 ± 4.23^{eh}
CEC (cmol kg^{-1})	4.77 ± 0.22^{a}	7.40 ± 0.36^{a}	17.70 ± 0.33^{b}	13.57 ± 0.34^{c}	16.73 ± 0.13^{bd}	14.08 ± 0.32^{bce}	10.67 ± 0.13^{af}	20.53 ± 1.33^{bg}
BS (%)	38.81 ± 0.21^{a}	79.05 ± 0.33^{b}	85.54 ± 0.26^{bc}	85.87 ± 0.36^{bcd}	73.86 ± 0.43^{be}	78.08 ± 0.42^{bef}	69.84 ± 0.54^{g}	84.01 ± 0.39^{cdfh}

The values are mean ± standard error of four replicates (n=4). Different letters within the same row show statistical differences at p<0.05.

The soil organic carbon stock (SOC stock) was significantly increased by CPH when combined with CM even when in the unamended soil was higher (Table 3). This was followed by CM when applied together with NPK, followed by CPH applied with NPK and CM. Comparatively, NPK, CM, NPK+CPH, and NPK+CM decreased the SOC contents when compared to the control, which had well over 160 t ha^{-1} SOC. The results showed CPH is a more effective contributor to SOC stock than CM in the soil. The application of NPK alone or with an organic matter source in the soil had no significant effect on the water-holding capacity (Figure 4) although there was an increased by 5% compared to the initial soil (Table 1). The most significant increase in water-holding capacity resulted from the addition of CPH and CM, together with or without NPK. The lone application of CPH and CM increased it too, but more so by CM. NPK application, with or without organic matter, generally decreased the soil's water-holding capacity.

The changes in moisture level measured were closely influenced by the water holding capacity of the soils (Table 3). Only the addition of organic matter increased the soil moisture level and among them, CM, CHP+CM, and their combination with NPK were the highest, followed by the other amendments. The overall changes measured being CPH+CM>NPK+CPH+CM>CM>NPK+CPH>CPH>NPK+CPH>NPK.

Compared to the control, the addition of CPH and CM alone, or in combination with NPK, decreased the pH to below 6.5 (Table 3). The NPK treatment reduced the pH to 6.0, CPH to 6.3, CM to 6.4, and the combined CPH+CM to 6.0, while the rest of the treatments had pH levels around 6.2. The decrease in pH was higher in the soil amended with NPK alone, and it was a bit higher when a combined application was made. Comparatively, the application of a combination of plant organic matter (CPH+CM) decreased the pH by 0.6, an effect similar to that of NPK. The changes in electrical conductivity (EC) measured are shown in Table 3. The highest changes in EC were measured in the soil where NPK and a combined NPK and organic matter was applied. This change in EC was followed by NPK, NPK+CM, CM, CPH+CM, CPH, and NPK+CPH. The least changes in EC were observed in the control soil, where no amendment was made, and only CPH and NPK+CPH were similar, measured at 0.2–0.3 $dScm^{-1}$.

All the organic matter amendments caused the bulk density to decrease to below 0.8 g cm^{-3} except for NPK compared to the control's 1.7 g cm^{-3} (Table 3). The order of decrease in bulk density, from the lowest to the highest, was as follows: NPK, CPH, and CM, CPH and CM, CM, NPK+CPH, CPH and NPK+CM. Among the organic matter amendments used, the combined CM and CPH was more significant, especially when NPK co-existed. The effects of the amendments on total porosity are shown in Table 3. Nearly all the amendments except NPK increased total porosity by 60% or more. The overall increase is NPK+CPH>CPH+CM>CM>CPH>the rest. Although the combined addition of NPK resulted in the highest, the lone effect of NPK addition, being low, indicates that its impact on total porosity was minimal.

3.2 Effects on macronutrients and micronutrients

The application of NPK contributed approximately 15 mg kg-1 of phosphorus, which was comparable to the content of the control soil (Table 4). The soil phosphorus content was significantly increased when organic matter was added to the soil, and this increase was more pronounced with CPH. The CM was most significant when NPK and CPH were combined. Nearly 40 mg kg^{-1} of phosphorus was added to the soil when the organic matter sources were applied together, and when NPK was included, the increase was even higher by another five percent. The addition of organic matter increased the soil's potassium content, particularly when combined with CPH alone or with NPK and CM (Table 4). The highest increase in potassium was caused by the combination of NPK and CPH, as well as CM. The effects of CM on potassium concentration were very much similar to NPK except when combined with NPK or CPH. These results show CPH is an important potassium source when the impacts are considered individually, and CM is much better when applied together. There was a fair amount of sulphur in the soil (Table 4), which decreased to near 200 mg kg^{-1} over the five months of cocoa production, especially in the control and soil amended with NPK (Table 4). There was little effect on soil sulphur content following NPK application, except with the organic matter combination. The CPH addition significantly increased the sulphur content compared to the CM, and the effect was even more pronounced when the combined addition was made in the soil, even when NPK was added along with them. In addition, the presence of NPK, whether alone or combined with the organic matter sources, decreased the contents by a certain amount.

Table 4: Changes in soil primary, secondary and micronutrients measured after five months of cocoa production following application of amendments.

Nutrients (mg kg^{-1})	Treatments							
	Control	**NPK**	**CPH**	**CM**	**CPH+CM**	**NPK+CPH**	**NPK+CM**	**NPK+CPH+CM**
N	0.41±0.02^{a}	10.56±0.32^{b}	7.25±0.33^{c}	4.79±0.23^{d}	8.89±0.43^{bce}	13.33±0.33^{bf}	12.25±0.13^{bfg}	15.48±0.53^{fh}
P	286±31.23^{a}	262±42.33^{a}	2312±136.21^{b}	1174±136.54^{c}	3110±146.66^{d}	2220±142.25^{be}	1226±130.45^{cf}	3307±145.24^{dg}
K	7.23±1.21^{a}	16.25±2.55^{b}	126.45±2.20^{c}	60.47±1.38^{d}	172.33±2.25^{e}	137.25±2.32^{cf}	74.36±2.36^{g}	188.54±1.62^{fh}
S	298.56±21.21^{a}	256.22±25.03^{b}	1144±31.44^{c}	705±62.55^{d}	1605±45.36^{e}	1168±56.23^{ef}	725±23.30^{dg}	1639±21.33^{eh}
Mg	844±51.24^{a}	743±54.44^{b}	2696±45.23^{c}	1742±52.20^{d}	3691±41.63^{e}	2666±36.27^{cf}	1655±56.23^{g}	3452±31.39^{eh}
Ca	2346±142.22^{a}	2230±161.27^{a}	10567±156.32^{b}	5747±131.05^{c}	14148±126.27^{d}	8628±111.56^{e}	3581±119.06^{f}	12648±121.23^{g}
Zn	36.02±1.23^{a}	26.43±2.31^{b}	97.82±1.23^{c}	67.24±2.06^{d}	121.32±1.23^{e}	72.32±1.55^{f}	54.45±1.22^{g}	88.63±2.25^{ch}
Mn	6.12±1.23^{a}	3.62±0.86^{b}	58.92±0.76^{c}	29.53±2.11^{d}	87.83±1.14^{e}	42.23±2.20^{f}	20.63±2.09^{g}	70.24±2.66^{h}
Fe	7219±50.26^{a}	5761±61.24^{b}	8543±52.30^{c}	6724±61.33^{d}	10634±54.45^{e}	7226±53.36^{f}	5430±44.43^{bg}	9421±52.65^{h}
Cu	5.02±0.56^{a}	3.42±2.20^{a}	6.45±1.10^{ab}	8.75±2.13^{bc}	6.72±1.11^{bcd}	9.25±1.44^{ce}	11.06±1.52^{ef}	9.76±2.25^{ceg}
Mo	0.94±0.36^{a}	0.88±0.22^{a}	1.34±0.24^{b}	4.26±0.45^{c}	2.31±0.69^{d}	3.16±0.99^{ce}	3.95±0.68^{ef}	3.16±0.29^{efg}

The values are mean ± standard error of four replicates (n=4). Different letters within the same row show statistical differences at $p<0.05$.

When the organic matter sources were applied solely to the soil, CM significantly increased the concentration of magnesium compared to CPH (Table 4). The effects on the magnesium concentrations were more significant when CPH and CM were combined or NPK was co-applied. The impact of the organic matter when applied with NPK was not substantial, and the concentrations decreased when compared to the changes induced when the organic matter sources were applied without NPK. The calcium concentrations of the soil were significantly increased by all the organic matter sources, whether applied alone or in combination with NPK. Among the lone applications, CPH was more effective than CM when co-applied with NPK. The changes induced were more significant when CPH and CM were combined. In almost all cases, the presence of NPK resulted in a decrease in the soil's calcium concentration. Not much change in soil calcium concentration was measured in the NPK-amended and control soils, respectively (Table 4). The soil zinc concentrations were significantly increased by the organic matter sources alone or when combined and applied, and even with NPK (Table 4). The effects were more significant in the presence of CM than CPH, and the increase was by nearly 50% when the organic matter sources were combined. The results show that the application of NPK alone or in combination with an organic matter source resulted in a decrease in soil zinc concentrations (Table 4).

The effects on the manganese concentration were very similar to those of magnesium and calcium concentrations presented previously. The application of CM compared to the control and CPH significantly increased the magnesium concentrations, particularly when combined with CPH (Table 4). NPK application alone or even when combined with the organic matter sources decreased the soil manganese contents. These results indicate that CM is a crucial source of manganese, and the increase in soil manganese concentrations are more pronounced when CPH is combined with its application. The concentration of iron in the control soil was approximately 30 mg kg^{-1}, which decreased to near 20 mg kg^{-1} after NPK was applied (Table 4). When the CPH and CM were applied separately, the effects of CM were more pronounced, and the effects were even higher when used in combination. Again, the application of NPK with organic matter sources decreased the iron content compared to the impact of the lone or combined applications of the organic matter sources (Table 2).

The application of NPK resulted in a decrease in copper concentration, whereas co-application with organic matter increased it instead (Table 4). The impact of CM was more pronounced than that of CPH, and this was particularly evident when a combined application was made. Again, in almost all cases, the presence of NPK resulted in a reduction of the copper concentrations. Molybdenum was another trace element whose concentration in the soil and the two organic matter sources was low (Table 4), and this has reflected in the changes in its concentration measured (Figure 19). The changes in the control soil and when NPK was applied were not as great as those when CPH and CM were used, both of which increased molybdenum concentration in proportion to their contents. A combination of organic matter sources increased the soil content, and NPK inclusion decreased it, with the most noticeable difference observed with CPH compared to CM (Table 4).

The cation exchange capacity (CEC) of the treatment soils, excluding the CEC of the individual cations (calcium, magnesium, potassium, and sodium), is shown in Table 4. The lowest CEC was measured in the control soil, followed by the NPK, NPK+CM, and NPK+CPH. In the soil, the organic matter was solely made, CEC was the highest under CHP amendment than CM, and was equally high when CPH+CM was the amendment. In almost all cases, the combined application of NPK with an organic matter source, either alone or in combination with another amendment, resulted in a decrease in CEC, most notably with CM compared to CPH (Table 4).

4. DISCUSSION

4.1 Effects of organic matter addition on soil properties

Cattle manure (CM) and cocoa pod husk (CPH) were considered as the organic matter sources from several perspectives: (i) the livestock industry in PNG has increased and the herd sizes have risen, producing a lot of wastes like manure and urine that need to be managed sustainably to address the environmental concerns and offers a lot of advantages in terms of soil health and productivity management if appropriately applied, and (ii) there is a lot of cocoa production related wastes produced by the more than 200,000 cocoa farmers, most of which are smallholder or family-based, and are not in a position to manage except burning them or stockpiling to save space. Research and development on how to sustainably utilize the various types of waste produced by the agricultural sector in PNG is a crucial concept for promoting a green economy and supporting the livelihoods of rural people who depend on agriculture. The findings of this study showed the importance of the use of CPH and CM (organic matter) application on soil properties that support general soil health and cocoa productivity, especially in aging (old) cocoa plantations.

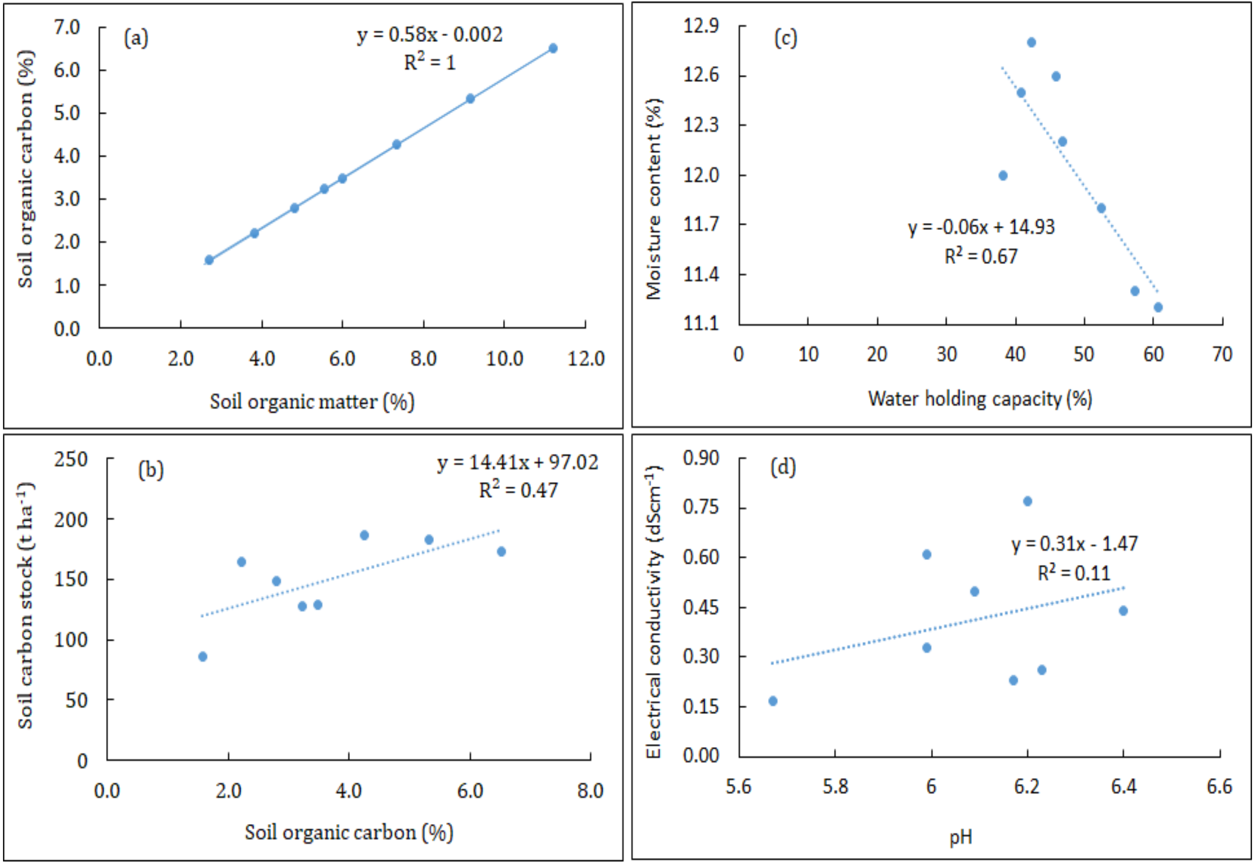

Figure 1: Interactions between SOM and SOC (a), SOC and SOC stock (b), WHP and moisture content (c) and pH and electrical conductivity (d). The values are means of four replicates (n=4).

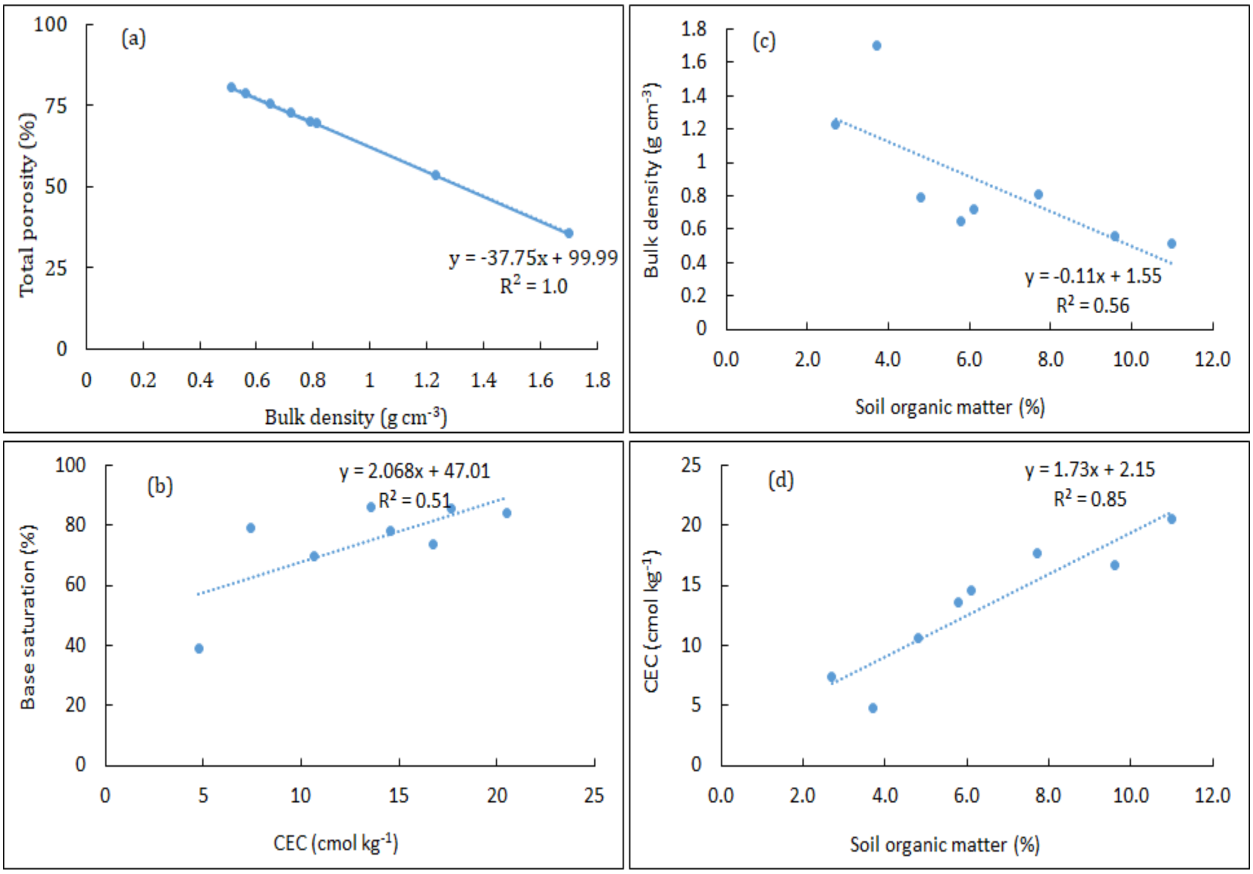

Figure 2: Interactions between bulk density and total porosity (a), CEC and base saturation (b), SOM and bulk density (c) and SOM and CEC (d). The values are means of four replicates (n=4).

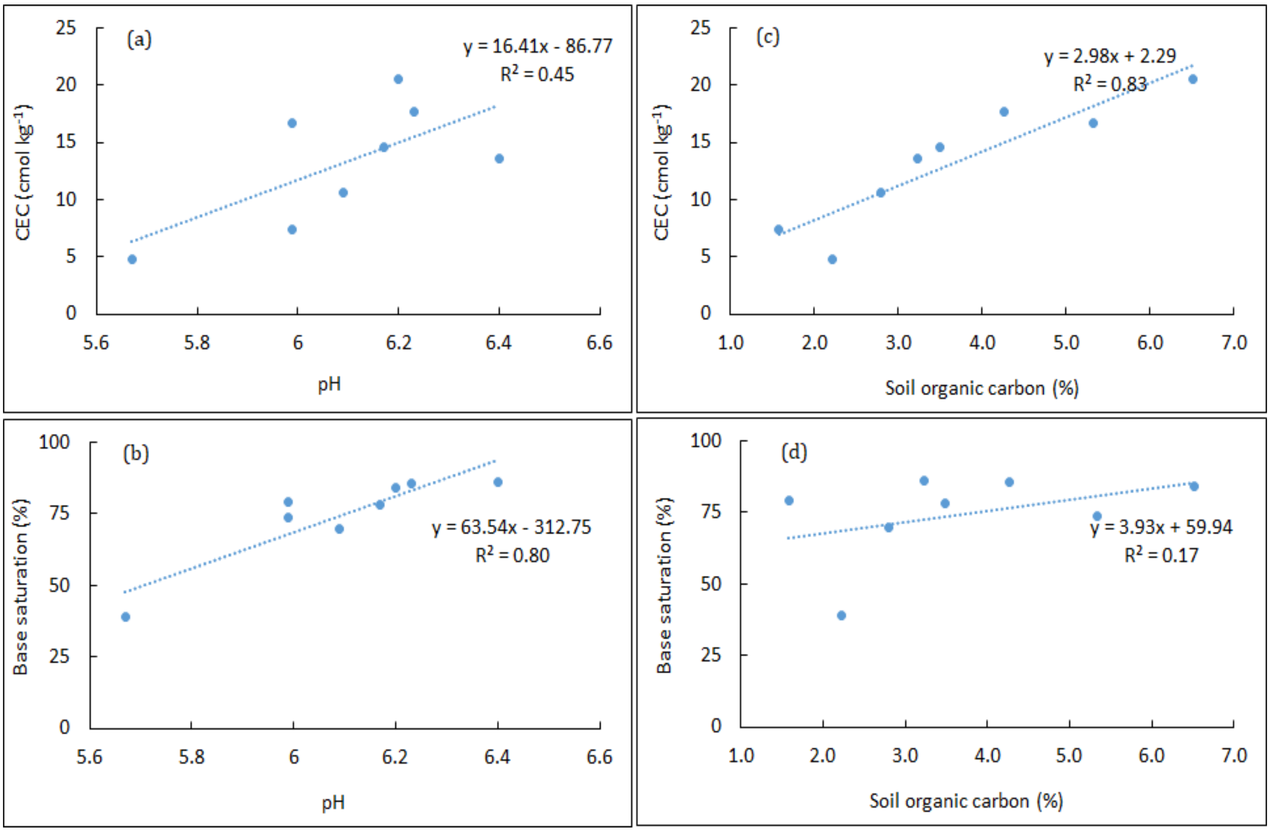

Figure 3: Interactions between pH and CEC (a), pH and base saturation (b), SOC and CEC (c) and SOC and base saturation (d). The values are means of four replicates (n=4).

The soil parameters of the plantation soil and nutrient contents of the two organic matter sources and NPK are presented in Tables 1 and 2. The changes in soil chemistry measured following their use as amendments are shown in Tables 3 and 4. Figures 1 to 3 show the positive interactions that existed following organic matter amendment that induced the changes in soil chemistry that were measured. Organic matter amendment increased the soil organic matter content, and more so when a lone CPH or combined CM and CPH were made (Table 3). The application of CPH increased SOM by 4%, and when combined, increased by 6%, and with NPK by 10%, respectively (Table 3). These results pointed out that the changes in organic matter content of the soil was dependent on the organic matter-type. The increase in soil organic matter in the presence of NPK tends to point out the need for readily available nitrogen for the microbial growth to act on the complex organic matter and in doing soil modify the soil environment conducive for the increase measured (Ouattara et al., 2021). The increase in the soil organic matter content by CPH resulted in significant changes in the soil organic carbon content (Table 3) and the soil organic carbon stock (SOC stock) (Table 3). The increase in the 4% soil organic matter resulted in a 3% increase in soil organic carbon content, which in turn led to a 30 t ha^{-1} increase in carbon stock compared to the control soil's content (Table 3). The application of NPK did not appear to significantly influence soil organic matter, soil organic carbon, or its stock, except when combined with the organic matter sources. These results suggest that the addition of organic matter was solely responsible for the changes in soil chemistry measured (Ogunlade and Orisajo, 2020). A more balanced soil microenvironment was created when carbon from organic matter served as an energy source and N from the NPK fertilizers was available for microbial growth, forming a balanced and healthy soil environment (e.g., Michael, 2020g; h). The changes in soil organic matter and the resultant balanced soil environment are the basis of the significant changes in the selected soil parameters measured. The changes in soil organic matter following amendment positively changes the soil organic carbon content (Figure 1a) and that influenced the soil carbon stock (Figure 1b). This also changed bulk density and cation exchange capacity (Figure 2c, d)

The soil parameters are soil organic matter (SOM), soil organic carbon (SOC), soil carbon stock (SOC_{stock}), water holding capacity (WHP), electrical conductivity (EC), bulk density (BD), total porosity (TP), cation exchange capacity (CEC) and base saturation (BS), respectively. The values are mean ± standard error of four replicates (n=4). Different letters within the same row show statistical differences at $p<0.05$.

The improvement in the soil organic matter enhanced the water-holding capacity compared to that of NPK (Table 3). The application of organic matter increased the soil's water holding capacity from between 10 – 20% compared to the unamended soil's, which is a significant result as cocoa prefers moderate to high (60 – 70% soil water contents, especially in well-drained soil. The moisture content under NPK remained nearly unchanged, and this was also improved in the organic matter-amended soils (Table 3). The increase in SOM content significantly enhances the water-holding capacity by 10 - 30% and soil moisture content by 2% in the CPH amended to 22% in the combined amendment, demonstrating the critical role of organic matter, agreeing to the findings of other studies. The resulted showed the higher the water holding capacity the higher was the soil moisture contents (Figure 1c).

The soil pH requirement for cocoa ranges between 6.0 and 7.5, which is slightly acidic to neutral, and the changes measured fell within this range (Table 3). The NPK and CPH+CM significantly lowered the pH, and the probable cause is the release of hydrogen ions from bacterial mineralization of nitrogen (e.g., Michael, 2021). The soil electrical conductivity range was within the optical range for plant growth (Table 3). The highest changes, as measured in the soil amended with NPK and the combination of NPK with the other two organic matter sources, showing that these amendments significantly contributed to the soil fertility status by increasing the soil nutrient content. That is, an increase in soil organic matter increased the soil pH and electrical conductivity, and the former influences the latter (Figure d). For instance, CM+CPH increased by the soil organic matter content by 6% compared to the control, resulting in an increase in electrical conductivity by 0.3 mS cm^{-1}. Similar positive results were evident in the changes in soil bulk density and total porosity (Figure 2a). Organic matter amendment decreased the bulk density of 1.7 g cm^{-3} soil in the control soil to 0.8 – 0.4 g cm^{-3} of the amendment soils (Table 3). The bulk density of the control soil indicated that it was compacted from an old plantation, and the results showed that incorporating organic matter into the soil significantly improved its density. The total porosity data supported the change measured. The changes in total porosity measured following organic matter amendment compared to the control were well over 45% and that of the NPK was 15 – 30% (Table 3). Cocoa requires loose and friable soil with high porosity and the overall increase in total porosity by nearly 50% showed that CM and CPH amendments are essential, and more so when a combination of the two is considered.

The cation exchange capacity is crucial for soil nutrient retention, availability, and management. It is influenced by soil organic matter, pH, and clay content, which depend on the negative charges available for cation exchange. In this study, all organic matter sources added to the soil, either alone or in combination, significantly affected the cation exchange capacity (Table 4). Comparatively, CPH increased the cation exchange capacity by 17 cmol kg^{-1}, which was the highest, followed by CM, at 10 cmol kg^{-1} (Table 4). These changes agree that CPH may contain more cationic nutrients (see Table 2), which indicates that CPH contained more nutrients than CM. Although the complete soil composition data were not presented, the soil contained 10% clay, which could be the probable reason there were sufficient negative charges available for cation exchange in the soil, in addition to those on the surface of the organic matter. In almost all cases, cocoa plants significantly reduced or altered the soil parameters and nutrients, regardless. This was quite evident in the control soil where no amendment was done. In contrast, the opposite occurred in the treated soils, indicating that plants utilized these resources and that the amendments provided supplementation. Our results agreed to the findings of several studies that increase in organic matter increases cation exchange capacity (e.g., Bonnet et al., 2024). For example, the highest organic matter content was measured in the soil where a combined NPK+CPH+CM was made and that corresponded to the highest cation exchange capacity measured (Table 4) and it correlated positively with soil pH (Figure 3a) and soil organic carbon contents (Figure 3c). An increase in cation resulted in an increase in the base saturation (Table 3) and strongly correlated with the soil pH (Figure 3) but the association was weak with the carbon content (Figure 3d).

4.2 Effects on macronutrients and micronutrients

The critical nutrients of cocoa include primary (N, P, and K) and secondary (Ca, S, and Mg) macronutrients, as well as essential trace elements. The effects of organic matter on these nutrients are presented in Table 4. The results generally showed that adding the two organic matters to the soil to manage soil fertility under cocoa production is important and superior to commercial NPK as pointed out by other studies (Bolinder et al., 2020). Compared to the control, NPK addition increased N, P and K as expected and CPH addition increased N by 20, P by 30, and K by 900 mg kg^{-1}, and that of the CM addition was somewhat similar to the NPK (Table 4). These results suggest that organic matter addition is essential for primary macronutrients and, depending on the source, superior to commercial NPK. The increase in primary macronutrients was much higher when a combination of NPK and organic matter was added together, indicating a balanced availability of soil nutrients (Michael, 2021). The changes induced on the primary and secondary macronutrients (Table 4) were closely related to the nutrients supplied by them. The NPK contains none of the secondary macronutrients; therefore, what was measured in the control and NPK amended soils were those that were in the original soil shown in Table 1. The two organic matter sources equally affected the secondary macronutrients, even when combined, demonstrating their superiority as a secondary macronutrient source (Table 4).

The effects on the micronutrients of NPK application were negligible since there are none present in it (Table 4). The combined effects were significantly higher on all micronutrients, and the lone contribution of CM was substantially higher than that of CPH. A probable reason for the lesser contribution of CPH to soil micronutrients is the same as that discussed for primary and secondary macronutrients, and it is related to the type of microbial ecology established. The CM was wholly or partially digested material, which was readily subjected to soil microbes. In contrast, the CPH, being coarse and complex, required more time for the microbes to act on it and release the nutrients. This observation supports the general knowledge that nutrient availability in soils with less complex organic matter (CM) is shorter-lived than in those with more complex organic matter (CPH), the main reason being that complex organic matter sources take a longer time to establish a reliable microbial ecology. Another general observation was the resultant decrease in all nutrients when NPK was added to the soil, either individually with organic matter or in combination. This observation was not pronounced for the primary and secondary macronutrients, but rather for the micronutrients when all the nutrient sources were combined. For example, when CPH+CM was used, the increase in P was by 50 mg kg^{-1} (Table 4). This increased to 55 mg kg^{-1} when applied with NPK, and such changes were evident in all the other primary and secondary macronutrients. When micronutrients were taken into consideration, the opposite occurred; the concentrations decreased instead (Table 4). For example, when CPH and CM were added to the soil alone, the zinc concentration increased by 4.12 and 16.54 mg kg^{-1}, respectively. When combined, the increase was 30 mg kg^{-1}. When a combination of organic matter and NPK was applied, the increase in micronutrients decreased. For example, the 30 mg kg^{-1} increase measured decreased by nearly 43% (13 mg kg^{-1}). Similarly, the other micronutrients resulted in a certain degree of decrease when NPK co-existed in the soil.

The decrease in concentrations of macro- and micronutrients in the presence of NPK is interesting, and there could be several reasons. The general principle is that the NPK supports the growth and development of the microbial ecology, and the C from the organic matter is the primary energy substrate for the microbe's respiration (e.g., Michael et al., 2015; Michael, 2021). This said, when NPK is applied with a single energy source, such as CPH or CM, the single energy source appears to attract and establish a specialized microbial ecology that acts on it and releases the nutrients thereafter, within a matter of months. When a combination (CM+CPH) is available in the soil, the need for a more complex microbial ecology to act on the complex mixture of organic matter arises, making nitrogen (N) the most limiting factor compared to carbon (Michael, 2021). The differences in the establishment of microbial ecology, the limitations of N and C availability at different times, and the impacts of these on the decomposition of organic matter seem to be the reasons for the decrease in nutrients when NPK and organic matter co-existed in the soil.

5. CONCLUSION

Amending the soil with organic matter under cocoa generally improves all the parameters that regulate soil nutrient status and availability, the nature of the change being dependent on the type of organic matter. The CPH application significantly improved soil organic matter, soil organic carbon, and soil organic carbon stock. On the other hand, the CM application improved water holding capacity, moisture, pH, electrical conductivity, bulk density, and total porosity. The CPH application significantly increased the phosphorus, potassium, and calcium contents, whereas the CM application increased the contents of magnesium, zinc, manganese, iron, and copper, respectively. Based on these, CPH is an essential source for primary and secondary macronutrients, while CM is a crucial source for micronutrients. The sole application of an organic matter source with NPK results in the immediate establishment of a specialized microbial ecology, faster action of the organic matter, and quicker release of nutrients in the soil, leading to a decrease in soil nutrients over time due to the use of cocoa. The application of organic matter in combination with NPK results in a much slower establishment of a specialized microbial ecology, enhancing the slow release of nutrients to the soil for cocoa use, thereby increasing the concentration of nutrient availability.

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Author Contributions

SA and PSM designed the study, conducted the experiment, collected the data, processed the data, performed a literature review, and wrote the manuscript, and NP and JA contributed to field work and the final manuscript. All the authors read the final manuscript.

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Availability of Data and Materials

The data that support the findings have been included in the manuscript.

Ethical Considerations

The study did not involve humans or animals.

Competing Interest

There is no conflict of interest from the authors to declare.

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