Agr. Nat. Resour. 58 (2024) 239–256

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Cumulative effect of perlite and chicken manure on NPK fertilization for cassava planted in Arenic Haplustult soil: Case study of continuous application for 8 yr

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Article Info

Article history:
Received 16 July 2023
Revised 8 February 2024
Accepted 7 March 2024
Available online 11 April 2024

Keywords:
Cassava,
Chicken manure,
Humid tropical sandy soil,
Perlite,
Soil properties

Abstract

Importance of the work: Long-term field trials are vital for sustainable improvement of cassava production in low-fertility sandy soils in northeast Thailand.

Objectives: To investigate the response of cassava to NPK fertilization and some soil properties following the application of perlite (PL) and chicken manure (CM) for 8 yr.

Materials & Methods: The 8 yr field experiment was carried out in an Arenic Haplustult soil, using a split plot design with the main plots comprising no application of soil amendment, compared to the addition of PL at 0.625 t/ha, CM at 3.125 t/ha or PL+CM at 0.625+6.125 t/ha and the subplots consisting of four rates of NPK fertilizer.

Results: In the 8th growing season, the significantly highest fresh cassava tuber yield (37.54 t/ha) was from the application of a ratio of N-to-P_2O_5-to-K_2O ratio fertilization (100:50:100 kg/ha, respectively) in the PL+CM amended plot. This amount was 64.7% and 220.3% greater than those obtained from the non-amended plot with the same NPK fertilizer added and without NPK fertilization, respectively. The continuous application of CM or the PL+CM mixture significantly increased almost all plant nutrients, pH and organic matter contents in both the topsoil and underlying subsoil compared to no soil amendment.

Main finding: The proper NPK fertilizer rates increased the cassava yield when the soil was continuously amended using modest amounts of PL, CM or PL+CM for several years. Furthermore, these soil amendments, which are recommended for use, improved the quality of the tropical upland sandy soil.

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https://doi.org/10.34044/j.anres.2024.58.2.09

Introduction

Cassava (*Manihot esculenta* L. Crantz) is a very important economic root crop to more than 800 million people in Thailand and other countries in the tropics (Howeler et al., 2013). Sowcharoensuk (2023) reported that Nigeria is the leading producer followed by DR Congo and Thailand, respectively; however, Thailand is the leading exporter of casava products (7.1 million tonnes), with data showing that approximately 55% of cassava in Asia was grown in Ultisols, 18% in Alfisols, 9% in Entisols and only 7% in the other soils combined (Howeler, 1992). Thailand is no exception, where cassava is dominant in upland Ultisols followed by Entisols; however, these soils in Thailand are poor physically and chemically (Anusontpornperm et al., 2009; Boonrawd et al., 2021), which may well be responsible for the stagnation in yield increase in the last decade, as shown by the country's average fresh tuber yield reported by Department of Agricultural Extension of 22.25 t/ha in 2014, with 21.00 t/ha predicted in 2023 (modified from OAE, 2023), even though the crop requires minimal inputs in marginal soil conditions and in moisture-deficit areas (Howeler, 2014). This was despite the recommendation for the past 30 yr for NPK fertilization of cassava grown in light-textured upland Ultisols in noreast Thailand obtained from a large nymber of field trials based on an N-to-P_2O_5-toK_2O ration of 100:50:100 kg/ha for soil containing organic matter, available P and K contents of ower than 6.5 g/kg, 5 mg/kg and 30 mg/kg, respectively (Sittibusaya, 1996).

Many attempts have been made to experimentally improve the yield of cassava planted in different soils through the use of soil amendments to enhance the efficiency of the chemical fertilizers applied (Howeler et al., 2014). The highest fresh tuber and starch yields were obtained from the combination of 75 kg/ha of N and 12.5 t/ha of cassava starch waste, respectively, as a soil amendment for cassava planted in an Oxyaquic Paleustult (Phun-iam et al., 2018). A study in a degraded Alfisol in Africa (Agbede, 2018) utilized Gliricidia, Moringa, Leucaena and Neem as types of green manure, with NPK (15-15-15 grade) fertilizer significantly increasing the fresh tuber yield (FTY) over the control with no green manure or NPK fertilizer application for two consecutive years. Planting cassava in an Ustic Quartzipsamment, in northeast Thailand (that had a light texture and very low fertility status with intense leaching) and amending this soil with 3.125 t/ha, 6.25 t/ha and 12.5 t/ha of chicken manure (CM) promoted greater FTY values of 14.9%, 24.2% and 31.6%, respectively, compared to the control with no CM addition, while the plants responded best to 100 kg/ha of K_2O (Chaem-ngern et al., 2020). Amending a Grossarenic Paleustult soil with 25 t/ha + 5 t/ha of cassava tails and stalk (CTS)+bentonite (BTN) along with the addition of 100 kg P_2O_5/ha, interactively produced the highest FTY (39.76 t/ha), with the overall results reaffirming that amending the soil with the proper rate of the CTS+BTN mixture enhanced the efficiency of P fertilizer and subsequently improved the yield of cassava (Leitch et al., 2023). A 2 yr field trial in a tropical sandy Typic Paleustult soil showed that in the second growing season, the addition of 25 t/ha of burnt rice husk (BRH) as a soil amendment along with 125 kg/ha of K_2O interactively produced the highest FTY that was 99.7% greater than that for the plot that received neither BRH nor K fertilizer (Prombut et al., 2022). In addition, the best performance of cassava planted in a Ferralsol soil in southern Cameroon in terms of FTY (51.78 t/ha) occurred with a mixture of *Tithonia diversifolia* fresh biomass and poultry manure with each applied at 10 t/ha (Bilong et al., 2022).

Perlite (PL), an amorphous volcanic glass with a rhyolitic composition and a relatively high-water retention, is important in the horticultural industry in the forms of a soilless growth medium and in potting mixes (Grillas et al., 2001; Papadopoulos et al., 2008). Several studies showed that PL used as substrate or medium increased the yield of plants such as strawberry (Ghazvini et al., 2007), crisp-head lettuce (Gül et al., 2005), tomato (Al-Shammari et al., 2018) and cucumber (Lee et al., 2014). It was found that used PL and new PL in substrates released Ca, Mg, K and P into solution at different rates, with the rate decreasing with time and with increasing pH of the suspensions (Silber et al., 2010). However, the use of PL for soil amendment in field crops has not been widely reported. In short-term studies, Kanjana et al. (2012) found that the PL effect on increasing cassava yield was inferior to ground limestone, bentonite and gypsum when used to amend a reddish sandy soil, which coincided with the results obtained by Lunlio et al. (2017).

CM is considered an excellent organic fertilizer due to its high contents of plant nutrients and organic carbon with a desirable pH, with nutrients being more abundant in CM than in pig and cattle manures (Howeler, 2001, 2002). CM, when applied to soils, improved the total porosity, soil water holding capacity and water infiltration rate and decreased the soil bulk density (Amanullah et al., 2010), assisted water-stable aggregate formation (Weil and Kroontje, 1979) and released macronutrients and micronutrients to growing plants (Agbede et al., 2008). In a low fertility Paleustult soil, the addition of CM at the rate of 3.125–6.25 t/ha without adding chemical fertilizer still produced a higher yield of cassava and the yield increased when the proper quantity of chemical fertilizer was added (Plengsuntia et al., 2012). The application of poultry manure at 10 t/ha also increased the cassava tuber yield by up to 54% over no application of the manure in a sandy soil in Nigeria (Anyaegbu et al., 2009). In addition, cassava responded to this manure in a Typic Quartzipsamment soil in a positive manner (Nilnoree et al., 2016). Amanullah et al. (2007) showed that cassava in a poultry manure plot had higher uptakes of all nutrients and a higher tuber yield, while post-harvest soil nutrients in the amended plot were higher than that in the control plot. A single-year field experiment in an Ustic Quartzipsamment soil revealed that amending the soil with 3.125 t/ha, 6.25 t/ha and 12.5 t/ha of CM induced a greater cassava fresh tuber yield than no CM addition, while the plants responded best to 100 kg/ha of K_2O. Soil pH and cation exchange capacity, and quantities of total N, available P and K and extractable Ca and Mg, were also increased by the addition of 6.25 t/ha or 12.5 t/ha of CM (Chaem-ngern et al., 2020). A single-year experiment showed that a sole chicken manure application or its combination with mineral fertilizer improved the soil nutrient status (in the 0–20 cm topsoil layer) of cassava fields in Zambia (Biratu et al., 2019).

In Thailand, long-term studies on the impact of soil amendment on the yield of cassava and soil properties are very rare. The cumulative effect of inputs should be different on a long-term basis compared to the short term, especially in very low fertility, coarse-textured soils. An Arenic Haplustult soil is rather similar to coarse-textured Typic Paleustults (Anusontpornperm et al., 2009; Boonrawd et al., 2021). This soil is characterized by a thick sandy layer (>50 cm) on the top with an argillic horizon underneath (Soil Survey Staff, 1999) and has low fertility status and a low ability to retain plant nutrients, resulting in poor performance of cassava when grown in this soil. Therefore, the current field study carried out over 8 yr was conducted in a farmer's field with the aim of investigating the cumulative effect of soil amendments, PL and CM on NPK fertilization of the cassava Huay Bong 80 variety and the changes in some soil properties following the long-term application of soil amendments. The results presented in this study were from the end of the 8 yr trial and should be beneficial for improving cassava production in the country and likely in other neighboring countries.

Materials and Methods

Site description and soil properties prior to conducting the experiment

An 8 yr on-farm trial was carried out in a farmer's field in Ban Non Somboon, Kritsana subdistrict, Sikhio district, Nakhon Ratchasima province, Thailand (15°6'20.31"N, 101°30'17.97"E) under rainfed conditions. The area is a tropical savanna with an average annual rainfall of 1,023.5 mm/yr. The terrain where the experimental area was located was undulating with 3% slope. The landform of this area was the upper mid slope-to-shoulder slope on a low hill. The soil representing the experimental area was in the Warin soil series, classified as Arenic Haplustults. This soil was derived from wash over a residuum of sandstone and had a thick sandy layer extending to 50 cm from the mineral soil surface.

Properties of the soil (at depths of 0–30 cm and 30–60 cm) prior to conducting the experiment in the 1st growing season are presented in Table 1. This soil had a loamy sand texture throughout 0–60 cm. The soil pH extracted with 1:1 water was strongly acid (pH 5.4) in the top layer and moderately acid in the layer underneath (pH 5.6). Both layers contained very low amounts of organic matter (OM), total N, available P and K, and extractable Ca and Mg, with low-to-very-low cation exchange capacity (CEC). Overall, this soil had low fertility and low nutrient retainability.

Table 1 Soil texture and soil chemical properties prior to conducting experiment in 1st year

Property	Soil depth 0–30 cm	Soil depth 30–60 cm
Texture	Loamy sand	Loamy sand
pH (1:1 H_2O)	5.4	5.6
Organic matter (g/kg)	5.4	1.6
Total N (g/kg)	0.21	0.14
Available P (mg/kg)	3.5	2.0
Available K (mg/kg)	12.2	13.9
Extractable Ca ($cmol_c$/kg)	1.56	1.09
Extractable Mg ($cmol_c$/kg)	0.21	0.16
Extractable Na ($cmol_c$/kg)	0.06	0.12
Cation exchange capacity ($cmol_c$/kg)	3.4	1.4

Experimental design

A split plot design with four replications was used. The main plot, with individual plots (12 m × 12 m), consisted of four treatments: control = no soil amendment application (T1); the addition of PL = 0.625 t/ha (T2); CM = 3.125 t/ha (T3); and PL+CM = 0.625+3.125 t/ha (T4). The subplots comprised four rates of NPK fertilization: 0:0:0 kg/ha (F0); 50:25:50 kg/ha (F1); 100:50:100 kg/ha (F2); and 200:100:200 kg/ha (F3) of N:P_2O_5:K_2O, respectively. The F3 treatment in the subplot was applied with the NPK fertilizer recommendation for upland light-textured Ultisols with OM, available P and K lower than 6.5 g/kg, 5 mg/kg and 30 mg/kg, respectively (Sittibusaya, 1996). Perlite was brought from a mining site approximately 150 km west of the experimental area and the CM was sourced from a chicken farm in Sikhio district, Nakhon Ratchasima province. The properties of both materials are shown in Table 2. The perlite was slightly alkali, whereas the CM had a slightly higher pH than PL. The CM was composed of much greater levels of CEC, organic carbon (OC) and primary and secondary plant nutrients, including Fe, while Mn, Zn and Cu were higher in the PL.

This study was undertaken in the 8th growing season, with all practices in the field being the same as had been done in the previous seven growing seasons as follows. Specific rates of PL and CM were uniformly spread out on the designed plots, and then incorporated into the soil using a 3-disc plough with a 71 cm diameter disc which ploughed to a depth of 40–45 cm (deep tillage). The experimental area was left for 2 wk, then the soil was loosened using a 7-disc plough, followed immediately by making ridges, spaced 1.2 m apart and across the slope. Cassava, Huay Bong 80 variety was planted with 80 cm spacing between plants. Chemical fertilizers in the subplots were applied at 2 mth after planting by placing the fertilizer in holes dug on the top of ridges in the middle between two plants and then covering with the topsoil.

Plant data and soil sample collection

The cassava was harvested at age 10 mth. Plant components (fresh tuber yield and aboveground fresh weight of the stem base, stem and leaf plus branch) were recorded at harvest time. The starch content was determined using 5 kg of fresh tuberous roots harvested from each plot, which were then weighed in the air before weighing in water, after which the amount was read from a Riemann scale balance according to Bainbridge et al. (1996). The starch yield was calculated from the fresh tuber yield and starch content. Four different plant parts (tuber, stem base, stem and the leaf plus branch) from each plot were sampled and weighed separately. In addition, known amounts of samples were collected from the field for dry weight measurements and plant analysis. Soil samples, the so-called post-harvest soil, of each main plot were collected from depths of 0–30 cm (topsoil) and 30–45 cm (subsoil) at harvest for the investigation of the cumulative effects of PL and CM on changes in some soil chemical properties.

Methods of soil, plant and soil amendment analysis

The post-harvest soil samples from the 8th crop were air-dried, gently crushed using an agate mortar and pestle, passed through a 2 mm stainless steel sieve, homogenized prior to analysis and the used for the measurements of soil chemical properties, except for soil organic carbon and total N that used samples that had been passed through a 0.5 mm sieve. The soil texture was classed based on the particle size distribution analyzed using the pipette method (Gee and Bauder, 1986). A glass electrode pH meter was used to determine the pH_{water} (National Soil Survey Center, 1996) of aqueous suspensions (1:1 soil-to-solution ratio). Organic carbon was measured using the wet digestion method and Walkley and Black titration (Walkley and Black, 1934; Nelson and Sommers, 1996), with the value being converted to soil OM content by multiplying the C percentage by 1.724.

Table 2 Properties of perlite and chicken manure used in experiment

Property	PL	CM	Property	PL	CM
pH (1:5 H_2O)	7.7	7.9	Total Mg (g/kg)	1.0	7.3
CEC ($cmol_c$/kg)	20.1	80.0	Total S (g/kg)	2.2	14.3
Organic carbon (g/kg)	nd	362	Total Fe (g/kg)	0.20	0.78
Total N (g/kg)	nd	28.8	Total Mn (g/kg)	0.30	0.05
Total P (g/kg)	nd	5.8	Total Zn (mg/kg)	0.40	0.04
Total K (g/kg	2.8	25.9	Total Cu (mg/kg)	0.10	0.02
Total Ca (g/kg)	1.2	18.3	Total Na (g/kg)	1.9	0.50

nd = not detected; CEC = cation exchange capacity; PL = perlite; CM = chicken manure

Total N was determined using the Kjeldahl method (Bremner, 1996). Available P was extracted using Bray II solution (Bray and Kurtz, 1945) and determined colorimetrically using the molybdic blue method and spectrophotometry. Available or extractable K, Ca, Mg and Na were analyzed using 1 M NH_4OAc at pH 7.0 extraction (Pratt, 1965) and measured using atomic absorption spectrophotometry. The CEC determination followed the procedure of Chapman (1965) with the removal of exchangeable bases with 1 M NH_4OAc at pH 7, then the replacement of exchangeable NH_4^+ ions with 10% w/v NaCl and distilled NH_3 into 2% w/v H_3BO_3, followed by titration with 0.01 M HCl using bromocresol green-methyl red indicator.

The samples of the tuberous root, stem, stem base and leaf plus branch and soil amendments (PL and CM) were chopped and then dried in the oven at 65–70°C until the weight of each sample was constant. The samples were crushed and ground to a size smaller than 0.5 mm. The ground samples were digested using nitric-perchloric acid mixtures (HNO_3:$HClO_4$), according to Johnson and Ulrich (1959), except for total N which was extracted using a digestion mixture (H_2SO_4-Na_2SO_4-Se) and determined using the Kjeldahl method (Jackson, 1965). Total P was determined colormetrically using the vanado-molybyellow method (Westerman, 1990) and then measured using spectrophotometry (Murphy and Riley, 1962). Total K, Ca, Mg, Fe, Mn, Zn and Cu were determined using atomic absorption spectrophotometry (Westerman, 1990). Total S was analyzed using turbidimetry with $BaSO_4$ and the amount was determined using spectrophotometry with a 450 nm wavelength (Bardsley and Lancaster, 1965). The nutrient contents in PL and CM were also analyzed following plant analysis procedures. The uptake of NPK in different plant parts of cassava was calculated from the concentration of each nutrient multiplied by the dry weight per area of each plant part. The uptake in the whole plant was derived from the sum of each nutrient uptake in the tuber, stem base, stem and leaf plus branch.

Statistical analysis

Standard analysis of variance was applied to the data collected. The significance of treatments was determined using the F test appropriate to the general linear model as described by Gomez and Gomez (1984). Significance differences between the means of the treatments were determined at the 0.05 probability level ($p < 0.05$) using Duncan's multiple range test. The interaction effects of soil amendments and NPK fertilizer on the cassava components and on nutrient uptake were tested for significant differences (if any) based on the split plot design; however, only the main effects were tested for significant differences when the interactions of soil amendments and chemical fertilizer were not significant. The statistical software used in this study was the SPSS program version 21.0 (SPSS Inc.; Chicago, IL, USA).

Results

Cassava yield and plant components

Both soil amendments, continuously applied for eight consecutive years, and the NPK chemical fertilizer interactively affected the cassava fresh tuber yield, starch yield and aboveground biomass; however, there was no clear impact on the starch content. Without amending the soil throughout the 8 yr of conducting this field experiment, cassava performed rather poorly even though NPK fertilization was applied. In the non-amended plot, cassava responded best to the application of a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha, respectively, producing a fresh tuber yield of 22.80 t/ha; however, this was not significantly different to that applied with 50:25:50 kg/ha (21.14 t/ha) or 200:100:200 kg/ha (19.30 t/ha), whereas with no NPK fertilization only 11.72 t/ha of fresh tuber yield was obtained (Fig. 1A).

The use of sole PL as a soil amendment showed some pronounced cumulative impacts on enhancing the efficiency of NPK fertilizer. The addition of 100:50:100 kg/ha and 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O ratio, respectively) to the PL-amended plots promoted the fresh tuber yields of 31.48 t/ha and 31.94 t/ha, respectively, which were 38.1% and 65.5%, respectively, greater than for the same rates of NPK applied in the non-amended plot. However, adding 50:25:50 kg/ha in this PL-amended plot produced a far lower fresh tuber yield than for the former two rates of NPK; furthermore, there was no significant increase in this yield over that from zero NPK fertilization (20.88 t/ha compared to 20.44 t/ha) nor for the same rate of NPK in the non-amended plot (20.88 t/ha compared to 21.14 t/ha), as shown in Fig. 1A.

Among the plots amended with just CM at the rate of 3.125 t/ha, the plot with zero addition of NPK fertilizer had a significantly lower fresh tuber yield (23.15 t/ha) than from the other fertilized plots that had yields in the range 29.75–32.15 t/ha but these levels were not significantly different for the three rates of NPK fertilizer. Using a mixture of PL+CM to amend the soil, the application of 100:50:100

kg/ha (fertilizer ratio for N-to-P_2O_5-to-K_2O, respectively) produced the significantly highest fresh tuber yield of 37.54 t/ha (Fig. 1A). With the same soil amendment mixture applied, doubling the amount of NPK fertilizer adversely affected the fresh tuber yield (31.50 t/ha) which was not significantly different to the yield obtained from the plots fertilized with 50:25:50 kg/ha (27.63 t/ha) and with no NPK fertilization (27.52 t/ha).

Among the non-NPK fertilized plots, amending the soil with a mixture of PL+CM was the best statistically in the context of fresh tuber yield obtained, with the just CM-amended and PL-amended plots still producing far greater fresh tuber yields than the non-amended plot.

Neither the soil amendments nor the different rates of NPK fertilizer had no clear effect on the starch content, with the average starch content in the main plots and subplots being 23.53–24.95% and 23.71–25.16%, respectively (data not shown).

The starch yield as affected by the interaction of soil amendments and NPK fertilizer applications had a rather similar trend to that of the fresh tuber yield (Fig. 1B). Without using any soil amendment, NPK fertilization at all three rates (50–200:25–100:50–200 kg/ha of N-to-P_2O_5-to-K_2O, respectively) did not increase this yield any higher than that obtained from all amended plots, even the one with no addition of NPK fertilizer. Again, the lowest starch yield of 2.82 t/ha in this non-amended plot was observed when NPK fertilizer was not applied.

Cassava produced the significantly highest starch yield (8.93 t/ha) in the plot amended with a mixture of PL+CM when 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) fertilization was performed. Other rates of NPK fertilization and zero addition of these primary plant nutrients all produced significantly lower starch yields, in the range 6.55–7.27 t/ha. Notably, the addition of NPK fertilizer at the rates of 100:50:100 or 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) in the PL- and CM-amended plots also stimulated the starch yield that was not significantly different from the highest starch yield (Fig. 1B). In addition, it was clear that the use of just PL, just CM or a mixture of PL+CM could increase the starch yield when NPK fertilization was absent, whereas the addition of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) in the non-amended and amended plots was excessive and not suitable for increasing the starch yield of cassava planted in this sandy soil.

Regarding the aboveground plant parts, combining the stem base, stem and leaf plus branch as aboveground biomass, the results were quite different from those for the fresh tuber and starch yields. In the non-amended plot, the addition of 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) produced the highest aboveground biomass (9.58 t/ha) compared to the other rates that produced aboveground biomass values in the range 4.43–6.80 t/ha (Fig. 1C). In the PL-amended plot, the aboveground biomass increased rather exponentially with increasing rates of NPK fertilizer. However, the addition of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) in the plot amended solely with CM at the rate of 3.125 t/ha produced the significantly highest aboveground biomass (13.14 t/ha), while the other subplots within this main plot involving the addition of just CM were not significantly different. A rather similar trend was found in the plots amended with the PL+CM mixture; however, the amounts (8.81–12.57 t/ha) were not significantly different for the different rates of NPK fertilizer applied.

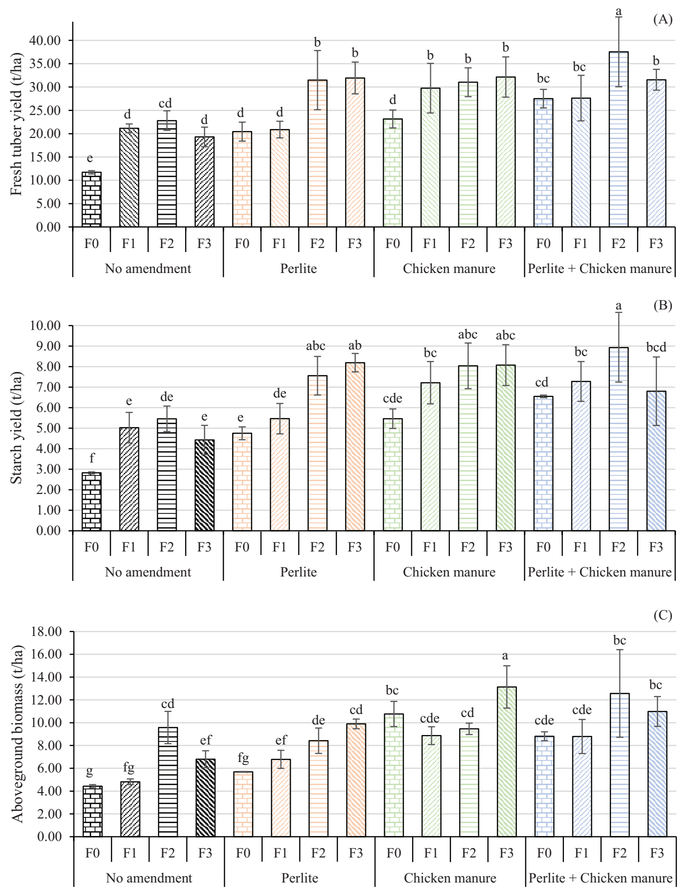

Fig. 1 Interactive effect of soil amendment and NPK fertilizer on cassava in the 8th growing season: (A) fresh tuber yield; (B) starch yield; (C) aboveground biomass (C), where different lowercase letters above columns indicate significantly ($p < 0.05$) different, error bars represent ± SD, F0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha of N:P_2O_5, F1 = ratio of N-to-P_2O_5-to-K_2O of 50:25:50 kg/ha, F2 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha and F3 = ratio of N-to-P_2O_5-to-K_2O of 200:100:200 kg/ha.

NPK uptake in cassava

The uptake of N, P and K in different plant parts (tuber, stem base, stem and leaf plus branch) of cassava as influenced by soil amendments and NPK fertilizer in the 8th growing season are shown in Tables 3–5. Overall, of these three elements, cassava took up K the most, which was slightly higher than N; however, both were far greater than P with average values across all plots of 100.60 kg/ha, 88.20 kg/ha and 41.11 kg/ha, respectively.

Nitrogen uptake

Cassava took up the most N in the tuber, followed by in the leaf plus branch, stem base and stem, respectively. Soil amendment and NPK fertilizer interactively impacted the uptake of N in all plant parts and in the whole plant. In the non-amended plot, increasing rates of NPK fertilizer did not increase the N uptake in all plant parts nor in the whole plant. Nonetheless, without NPK fertilization, the uptake of N in all plant parts and in the whole plant was the lowest (Table 3). The addition of NPK fertilizer at the rate of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) induced the significantly highest N uptake of 34.97 kg/ha in the leaf plus branch and of 127.32 kg/ha in the whole plant in the PL-amended plots, while this rate of NPK fertilizer also stimulated the significantly highest N uptake of 23.78 kg/ha in the stem base and of 15.32 kg/ha in the stem in the plots amended with just CM, as well as 68.95 kg/ha in the tuber in the PL+CM-amended plot. Across all rates of NPK fertilization in all main plots, the N uptake in almost all plant parts and the whole plant tended to decrease with a decreasing rate of the fertilizer. In addition, without NPK fertilization, the N uptake clearly increased in the plots amended with just PL, just CM or a mixture of PL+CM over the non-amended plot.

Phosphorus uptake

On average, the P taken up by cassava was mostly stored in the tuber. Without the use of soil amendments, the highest P uptake in all plant parts and the whole plant was observed when 100:50:100 kg/ha or 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) were added, especially in the leaf plus branch, in which, across all treatment combinations, the highest P uptake of 1.31 kg/ha was detected (Table 4). In the PL-amended plot, the addition of 50:25:50 kg/ha (N-to-P_2O_5-to-K_2O, respectively) induced the significantly highest P uptake of 5.33 kg/ha in the stem base, while in the PL+CM-amended plots, fertilizing the plant with 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) promoted the significantly highest P uptake of 74.25 kg/ha in the tuber and of 77.91 kg/ha in the whole plant. There was no interactive effect for soil amendment and NPK fertilizer on the P uptake in stem; however, the significantly highest P uptake in this plant part was observed in the plots amended with CM (0.96 kg/ha) or the PL+CM mixture (1.04 kg/ha), while the application of 100:50:100 kg/ha and 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) induced the respective significantly highest P uptakes of 0.97 kg/ha and 1.06 kg/ha in stem. It was clear that with no NPK fertilization, the P uptake in all amended plots was greater than that in the non-amended plot, while the addition of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) did not necessarily increase the P uptake compared to the application of 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) in most plant parts.

Table 3 Interactive effect of soil amendments and NPK fertilization on nitrogen uptake (kg/ha) in different plant parts of cassava in the 8th growing season

Soil amendment	NPK fertilization			
	F0	F1	F2	F3
Tuber				
T1	17.95^{h}	33.30^{g}	31.57^{g}	32.77^{g}
T2	39.35^{fg}	41.24^{efg}	54.89^{bcd}	65.30^{a}
T3	36.43^{g}	50.76^{cde}	61.40^{ab}	60.89^{ab}
T4	48.38d^{ef}	40.98^{efg}	59.46^{abc}	68.95^{a}
CV (%)	13.8			
Stem base				
T1	7.01^{e}	7.34^{e}	10.82^{de}	8.74^{e}
T2	9.53^{e}	13.76^{cd}	15.61^{c}	15.37^{c}
T3	21.35^{ab}	14.88^{cd}	17.14^{bc}	23.78^{a}
T4	15.28^{c}	17.92^{ab}	16.86^{c}	17.78^{bc}
CV (%)	19.3			
Stem				
T1	3.86^{e}	3.32^{e}	8.92^{d}	7.64^{d}
T2	4.56^{e}	7.07^{d}	7.26^{d}	11.68^{bc}
T3	12.37^{b}	8.29^{d}	9.47^{cd}	15.32^{a}
T4	8.13^{d}	8.77^{d}	11.83^{bc}	13.61^{ab}
CV (%)	19.3			
Leaf plus branch				
T1	3.54^{e}	12.51^{d}	22.86^{b}	14.97^{cd}
T2	13.84^{d}	12.57^{d}	22.54^{b}	34.97^{a}
T3	17.09^{bcd}	16.51^{bcd}	17.89^{bcd}	17.91^{bcd}
T4	17.09^{bcd}	12.98^{d}	33.32^{a}	21.73^{bc}
CV (%)	23.1			
Whole plant				
T1	32.36^{h}	56.46^{g}	74.17^{efg}	64.12^{fg}
T2	67.28^{fg}	74.65^{efg}	100.30^{cd}	127.32^{a}
T3	87.24^{de}	90.45^{cde}	105.91^{bc}	117.91^{ab}
T4	88.87^{cde}	80.64^{ef}	121.46^{ab}	122.08^{ab}
CV (%)	13.2			

CV = coefficient of variation; T1 = no soil amendment; T2 = perlite 0.625 t/ha; T3 = chicken manure 3.125 t/ha; T4 = perlite 0.625 t/ha + chicken manure 3.125 t/ha; F = chemical fertilizer; F0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha of N:P_2O_5, F1 = ratio of N-to-P_2O_5-to-K_2O of 50:25:50 kg/ha, F2 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha and F3 = ratio of N-to-P_2O_5-to-K_2O of 200:100:200 kg/ha.

Mean±SD superscripted with different lowercase letters indicate significant difference of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

Table 4 Interactive effect of soil amendments and NPK fertilization on phosphorus uptake (kg/ha) in different plant parts of cassava in the 8th growing season

Soil amendment	NPK fertilization				Mean±SD
	F0	F1	F2	F3	
Tuber					
T1	17.02^{h}	19.23^{gh}	25.78^{fg}	28.67^{ef}	
T2	26.81^{efg}	26.05^{fg}	35.51^{de}	29.68^{ef}	
T3	26.94^{efg}	40.58^{cd}	57.55^{b}	74.25^{a}	
T4	34.00^{def}	42.85^{cd}	65.55^{b}	45.42^{c}	
CV (%)	15.5				
Stem base					
T1	1.26^{fgh}	1.58^{d-h}	2.06^{def}	0.83^{h}	
T2	1.35^{e-h}	2.23^{d}	1.68^{d-g}	0.99^{gh}	
T3	5.09^{ab}	4.49^{b}	2.11^{de}	1.57^{d-h}	
T4	3.75^{c}	5.33^{a}	1.58^{d-h}	1.90^{def}	
CV (%)	21.0				
Stem					
T1	0.29	0.37	0.83	0.78	0.57±0.27B
T2	0.38	0.59	0.73	0.84	0.64±0.21B
T3	0.81	0.63	1.06	1.36	0.96±0.30A
T4	0.68	0.93	1.27	1.27	1.04±0.34A
Mean±SD	0.54±0.23B	0.63±0.23B	0.97±0.29A	1.06±0.32A	
CV (%)	20.5				
Leaf plus branch					
T1	0.20^{f}	0.40^{ef}	1.31^{a}	0.37^{ef}	
T2	0.46^{de}	0.38^{ef}	0.61^{b-e}	1.30^{a}	
T3	0.58cde	0.85^{b}	0.69^{bcd}	0.73^{bc}	
T4	0.84^{b}	0.61^{b-e}	1.10^{a}	0.74^{bc}	
CV (%)	21.9				
Whole plant					
T1	18.78^{h}	21.58^{gh}	29.98^{efg}	30.66^{efg}	
T2	29.00^{fg}	29.25^{fg}	38.53^{def}	32.80^{ef}	
T3	33.42^{ef}	46.56^{cd}	61.41^{b}	77.91^{a}	
T4	39.27^{de}	49.72^{c}	69.51^{ab}	49.33^{c}	
CV (%)	14.8				

CV = coefficient of variation; T1 = no soil amendment; T2 = perlite 0.625 t/ha; T3 = chicken manure 3.125 t/ha; T4 = perlite 0.625 t/ha + chicken manure 3.125 t/ha; F = chemical fertilizer; F0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha of N:P_2O_5, F1 = ratio of N-to-P_2O_5-to-K_2O of 50:25:50 kg/ha, F2 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha and F3 = ratio of N-to-P_2O_5-to-K_2O of 200:100:200 kg/ha.
Mean±SD superscripted with different capital letters indicate significant difference of main effect and different lowercase letters indicate significant difference of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

Potassium uptake

Soil amendments and NPK fertilizer interactively affected K uptake in cassava. The plant took up this nutrient in tuber in the highest amount which was far greater than the amounts taken up in the other parts of cassava. In the non-amended plot, the augmentation of K uptake in all plant parts and in the whole plant was affected by NPK fertilization with the highest ones being obtained from the plots fertilized with 100:50:100 kg/ha or 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively), as shown in Table 5. The significantly highest K uptake of 133.11 kg/ha in tuber and 10.98 kg/ha in stem was found in the PL+CM-amended plots fertilized with 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively). In the PL-amended plot, the addition of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) significantly induced the highest K uptake of 9.00 kg/ha in leaf plus branch, and in the CM-amended plot, this amount of NPK fertilizer also stimulated the highest K uptake of 15.32 kg/ha in stem base. There was no interactive effect of soil amendment and NPK fertilizer on the K uptake in the whole plant. However, amending the soils with a mixture of PL+CM significantly promoted the highest K uptake of 130.59 kg/ha while the use of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) induced the highest K uptake of 124.78 kg/ha. Without NPK fertilization, the uptake of this major plant nutrient in all amended plots clearly increased over the non-amended plot.

Table 5 Interactive effect of soil amendments and NPK fertilization on potassium uptake (kg/ha) in different plant parts of cassava in the 8th growing season

Soil amendment	NPK fertilization				Mean±SD
	F0	F1	F2	F3	
Tuber					
T1	23.41^{h}	57.08^{fg}	67.98^{ef}	64.70^{ef}	
T2	43.28^{g}	53.60^{fg}	101.21^{bc}	86.90^{cd}	
T3	53.59^{fg}	79.35^{de}	111.67^{b}	109.72^{b}	
T4	77.50^{de}	80.78^{de}	133.11^{a}	131.69^{a}	
CV (%)	15.0				
Stem base					
T1	4.48^{f}	5.96^{ef}	9.24^{bcd}	6.41^{def}	
T2	4.22^{f}	7.02^{def}	8.33^{cde}	9.02^{bcd}	
T3	8.21^{cde}	8.03^{cde}	10.70^{bc}	15.32^{a}	
T4	8.06^{cde}	9.06^{bcd}	11.11^{b}	15.05^{a}	
CV (%)	20.3				
Stem					
T1	2.31^{fg}	1.79^{g}	5.05^{de}	5.47^{cde}	
T2	2.55^{fg}	5.36^{cde}	9.02^{ab}	5.64^{cde}	
T3	9.22^{ab}	7.30^{bc}	9.93^{a}	9.62^{a}	
T4	3.89^{ef}	6.87^{cd}	10.98^{a}	10.80^{a}	
CV (%)	20.2				
Leaf plus branch					
T1	1.24^{f}	2.86^{ef}	6.90^{bc}	4.19^{de}	
T2	3.98^{de}	2.83^{ef}	5.68^{bcd}	9.00^{a}	
T3	5.06^{cd}	6.20^{bc}	6.86^{bc}	8.97^{a}	
T4	5.35^{bcd}	4.34^{de}	7.13^{b}	6.64^{bc}	
CV (%)	21.1				
Whole plant					
T1	31.45	68.42	89.17	80.78	67.46±23.86D
T2	54.03	68.80	54.03	68.80	89.41±31.93C
T3	124.24	110.55	76.07	100.88	114.93±31.23B
T4	94.80	101.05	162.32	164.18	130.59±38.64A
Mean±SD	64.09±24.78C	84.79±19.59B	128.73±33.89A	124.78±35.20A	
CV (%)	14.4				

CV = coefficient of variation; T1 = no soil amendment; T2 = perlite 0.625 t/ha; T3 = chicken manure 3.125 t/ha; T4 = perlite 0.625 t/ha + chicken manure 3.125 t/ha; F = chemical fertilizer; F0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha of N:P_2O_5, F1 = ratio of N-to-P_2O_5-to-K_2O of 50:25:50 kg/ha, F2 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha and F3 = ratio of N-to-P_2O_5-to-K_2O of 200:100:200 kg/ha.

Mean±SD superscripted with different capital letters indicate significant difference of main effect and different lowercase letters indicate significant difference of interactive effect, according to Duncan's multiple range test at $p < 0.05$.

Cumulative effects of soil amendments on soil chemical property changes

Some chemical properties were tested only in the main plot. After amending the soil for eight consecutive years, some soil chemical properties in topsoil (0–30 cm) and subsoil (30–45 cm) had quite clearly changed. The just CM addition clearly increased pH_{water} in both soil layers compared to the control with no addition of soil amendment (Fig. 2A); however, the soil was still moderately acidic. The Soil pH_{KCl} significantly increased compared to the control plot, not only in the plot amended with just CM but also in the plot amended with PL+CM (Fig. 2B).

It was clear that organic amendment, such as CM, could augment the soil OM content. The plot amended with PL+CM had the significantly highest amount of OM in both the topsoil and subsoil (4.22 g/kg and 3.79 g/kg, respectively), while the addition of just CM also increased the OM content compared to the control plot (Fig. 2C). There was no clear effect of soil amendment on the total N content in the topsoil; however, all soil amendments significantly increased the total N content in the subsoil, with values in the range 1.72–1.84 g/kg compared to 1.21 g/kg in the control plot (Fig. 2D).

Phosphorus was greatly affected by the continuous addition of soil amendments, particularly just CM or PL+CM compared to the control, with the former increasing the available P content to 19.51 mg/kg in the topsoil and 19.67 mg/kg in the subsoil, while the latter boosted the available P content to 28.01 mg/kg and 18.78 mg/kg in the topsoil and subsoil, respectively (Fig. 2E). In a similar fashion, the available K levels in both the topsoil and subsoil increased following the consecutive addition of just CM or the mixture of PL+CM. The plot amended with just CM had available K of 27.84 mg/kg in the topsoil and 27.41 mg/kg in the subsoil, while amending the soil with PL+CM produced available K contents of 31.78 mg/kg and 28.11 mg/kg in the topsoil and subsoil, respectively (Fig. 2F).

The consecutive use of soil amendments also affected secondary and micronutrients in a positive manner. The addition of just CM or PL+CM both increased extractable Ca in both the topsoil and subsoil compared to the control, with values in the range 0.81–0.93 $cmol_c/kg$ in these two amended plots compared to 0.58 $cmol_c/kg$ in the control plot. Comparatively, the amount in the topsoil was higher than in the subsoil in all amended plots (Fig. 3A). A similar impact of soil amendments to that on extractable Ca was also observed for extractable Mg in both the topsoil and subsoil (Fig. 3B). Soil amendments only raised available Fe in the topsoil, with only the use of PL+CM producing the significantly highest available Fe content of 11.74 mg/kg (Fig. 3C). Both the topsoil and subsoil in all plots continuously treated with soil amendments had greater Fe contents (14.56–15.16 mg/kg) than the control plot (11.15–11.89 mg/kg) (Fig. 3D). This was also the case for the available Zn content in the topsoil and subsoil. All amended plots contained greater amounts of Zn than the non-amended plot, with the addition of PL+CM producing the highest amounts of 1.22 mg/kg and 0.96 mg/kg in the topsoil and subsoil, respectively (Fig. 3E). Only the available Cu in the topsoil was impacted by the addition of soil amendments. All amended plots, containing available Cu contents in the range 0.14–0.20 mg/kg, had a greater amount than the non-amended plot which had only 0.09 mg/kg (Fig. 3F).

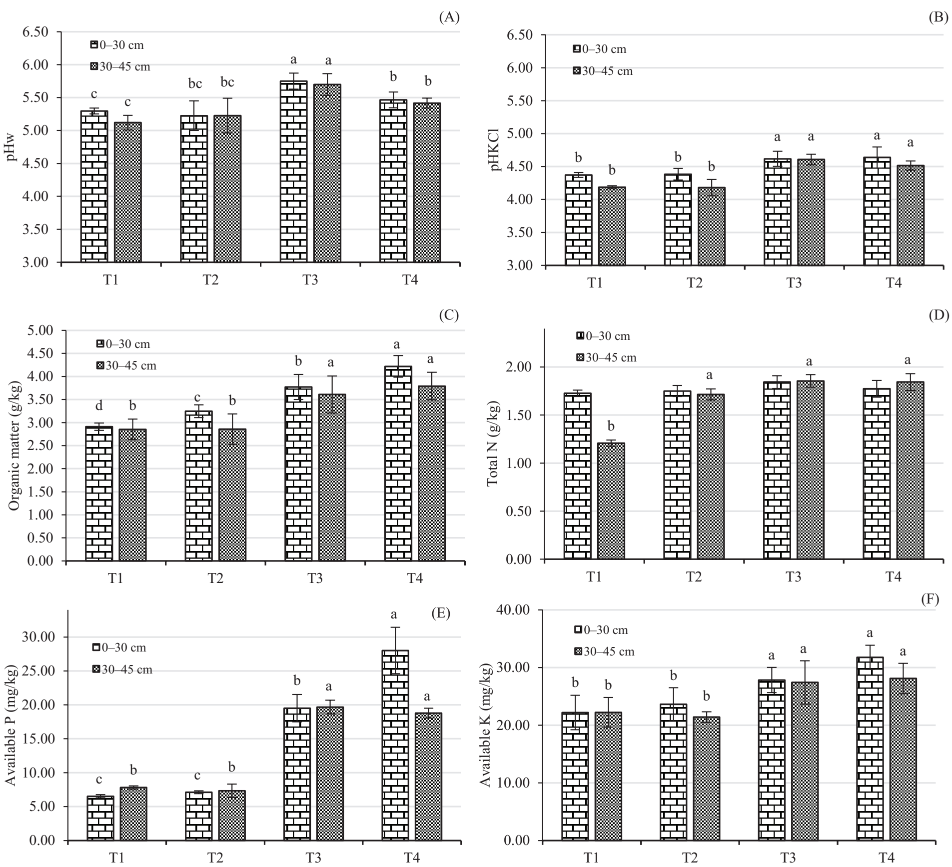

Fig. 2 Cumulative effect of soil amendments in topsoil (0–30 cm) and subsoil (30–45 cm) on: (A) $pH_{1:1water}$; (B) $pH_{1:1KCl}$; (C) organic matter; (D) total N; (E) available P; (F) available K (F), where different lowercase letters above columns grouped within the same soil layer are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment; T2 = perlite 0.625 t/ha, T3 = chicken manure 3.125 t/ha, T4 = perlite 0.625 t/ha + chicken manure 3.125 t/ha.

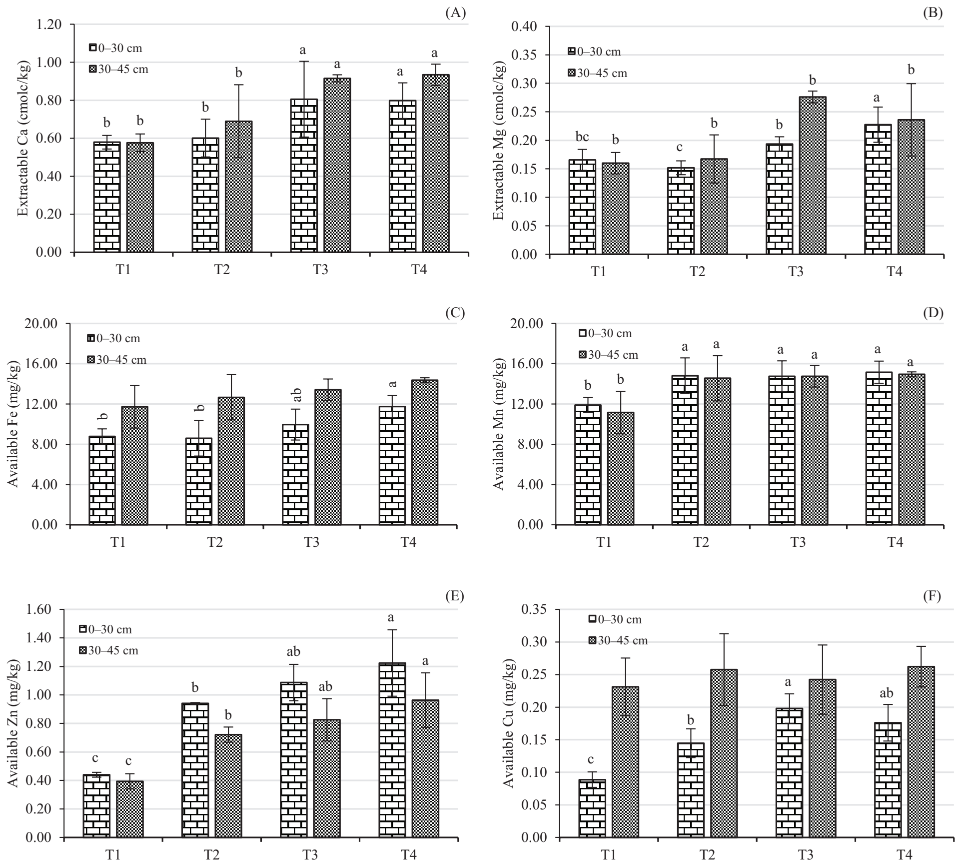

Fig. 3 Cumulative effect of soil amendments in topsoil (0–30 cm) and subsoil (30–45 cm) on: (A) extractable Ca; (B) extractable Mg; (C) available Fe; (D) available Mn; (E) available Zn; (F); and available Cu (F), where different lowercase letters above columns grouped within the same soil layer are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment; T2 = perlite 0.625 t/ha, T3 = chicken manure 3.125 t/ha, T4 = perlite 0.625 t/ha + chicken manure 3.125 t/ha.

Discussion

Effect of soil amendments and NPK chemical fertilizer on cassava components

The representative soil of the experimental area was classified as Arenic Haplustults, reflecting that this soil had a thick, sandy, textural class to a depth of at least 50 cm. This soil texture is favorable for the tuberization of cassava (Howeler, 2014) but is lacking in terms of nutrient reserves, coupled with a low base status and poor ability to retain plant nutrients, possibly in addition to moisture shortage that cassava can experience during a dry year. This poor soil was similar to the other soil groups, such as the Paleustults, which are found extensively in northeast Thailand (Anusontpornperm et al., 2009 and Boonrawd et al., 2021) as the thick sandy layer (>50 cm) overlying the argillic horizons of this Arenic Haplustult soil (Soil Survey Staff, 1999) can behave rather similarly regarding crop response.

Considering the amount of NPK fertilizer required, cassava still responded best to 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) applied to the plot amended with PL+CM. This indicated that the soil amendments were acting just as a supplement, while this recommended rate of NPK fertilization for upland light-textured Ultisols in northeast Thailand (Sittibusaya, 1996) was still able to accelerate the highest cassava yields. However, with one-half of this NPK fertilizer applied, the fresh tuber and starch yields decreased by 39% and 22.8%, respectively, from their maximum values. Doubling the amount of this recommended rate was not suitable because the subsequent yield was lower likely because of the excessive N supply causing excessive top growth and no increase in tuber yield (Cenpukdee and Fukai, 1991). In addition, it has been reported that cassava Huay Bong 8 variety (the same variety used in the current study) produced significantly higher fresh tuber and starch yields when it received only 75 kg/ha or 100 kg/ha of N (Phun-iam et al., 2018). The yield of cassava in the other main plots that received this high rate of NPK fertilizer coincidently gave no better yield outputs than that receiving the recommended rate (Fig. 1).

For the just CM-amended plot, the ranges in fresh tuber yields (29.75–32.15 t/ha) and starch yields (7.21–8.07 t/ha) among the NPK fertilized plots were not significantly different, illustrating that the addition of 50:25:50 kg/ha (N-to-P_2O_5-to-K_2O, respectively) was economically sufficient. However, the highest fresh tuber and starch yields obtained from the PL+CM amended plot added with 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) were 26.2–16.8% and 23.9–10.7%, respectively, greater than those from the plots with added NPK fertilizer and only CM for soil amendment. Amending the soil with PL+CM or with just CM with one-half the recommended rate still produced a significantly greater starch yield than the non-amended plot fertilized with the recommended rate of NPK fertilizer. This indicated that the continuous use of CM at the rate of 3.125 t/ha as a soil amendment could possibly supply these major plant nutrients that had not been applied in the form of chemical fertilizer.

For the PL-amended plot, only the addition of 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) was sufficient to obtain quite satisfactory fresh tuber and starch yields from the cassava whereas one-half of this NPK fertilizer rate or zero NPK fertilization provided very low levels for these two yields. This was due mainly to PL containing a very low amount of mineralized NPK that was distinctly different from CM. Growing the cassava in this sandy soil without using any soil amendments (PL and CM in the current study), the plant performed poorly, producing a very low levels of yields and aboveground biomass. Fertilizing the plant with the recommended rate of NPK fertilizer (100:50:100 kg/ha of N:P_2O_5:K_2O, respectively) produced only 22.80 t/ha of fresh tuber, which was slightly higher than the average yield for Thailand for the past decade (OAE, 2023). In an economic sense, one-half of this recommended NPK fertilizer rate should be applied as the yield obtained (21.14 t/ha) was just slightly lower. Furthermore, without soil amendment incorporation nor NPK fertilization, the fresh tuber and starch yields observed were only 11.72 t/ha and 2.82 t/ha, which were 220.3% and 216.7%, respectively, lower than for the plot amended with PL+CM along with the addition of 100:50:100 kg/ha (N:P_2O_5:K_2O, respectively). The yield results in the current study indicated that soil amendments, such as PL and CM, with a proper rate of NPK fertilization can sustainably increase the cassava yield to a satisfactory level.

In this study, the amount of soil amendments used was only 0.625 t/ha and 3.125 t/ha for PL and CM, respectively. These amounts are quite low for the inorganic and organic amendments, respectively, compared to other soil improvement studies involving a cassava crop, such as 3 t/ha of lime (Tan and Chan, 1989; Tan, 1992), 2.5–5 t/ha of gypsum and lime (Anikwe et al., 2016), annual application of 2.65 t/ha of wood ash (Nayar et al., 1995), 10 t/ha of cattle and poultry manures (Bakayoko et al., 2016), 5–10 t/ha of cattle manure and compost (Utomo et al., 2010), 10–20 t/ha of poultry manure (Bilong et al., 2022), 3.125–12.5 t/ha of chicken manure (Chaem-ngern et al., 2020) and 3.125–25 t/ha of burnt rice husk (Prombut et al., 2022). Theoretically, the amounts of soil amendments used in the current study were possibly insufficient to produce an immediate yield improvement of cassava, albeit with the soil quality improvement; nonetheless, the levels and sources for soil amendment were chosen based on their affordability and practicality of application for farmers growing cassava in northeastern Thailand. In addition, NPK fertilizer was tested to investigate whether the amount initially recommended (Sittibusaya, 1996) should be changed after applying soil amendments for several years.

The results from the 8th growing season showed that all treatments involving soil amendment produced positive outputs. Clearly, cassava performed better in all the amended plots (even with just the application of PL) compared to the non-amended plot. The highest fresh tuber yield observed in this study was from the plot amended with the mixture of PL+CM with added 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively). This demonstrated that to obtain a satisfactory yield of cassava in the best possible manner in this sandy soil, proper soil amendment and NPK fertilization should be matched. In this case, CM played a role in providing some secondary nutrients and micronutrients that were otherwise in low amounts in this soil (Table 2), with the additional nutrients released from the added CM producing a higher yield, as well as, in part, probably improving some physical properties such as total porosity, soil water holding capacity, water infiltration rate, bulk density and water stable aggregates (Weil and Kroontje, 1979; Amanullah et al., 2010). The positive impact of CM has been affirmed by several short-term studies, especially in light-textured soils (Amanullah et al., 2007; Anyaegbu et al., 2009; Plengsuntia et al., 2012; Nilnoree et al., 2016; Chaem-ngern et al., 2020).

Combining CM with PL resulted in the PL additionally improving the nutrient retainability of the soil during the growth cycle of cassava more than by adding NPK fertilizer, as the PL amendment was shown to be a potentially useful material to improve sandy soil because PL had the ability to increase water holding capacity (Özenç, 2003; Samadi, 2011). Furthermore, PL is produced in Thailand and contains large amounts of various nutrients (Saisuttichai and Manning, 2007) as presented in Table 2. Silber et al. (2010) showed that used PL and new PL released Ca, Mg, K and P at different rates, with the rate decreasing over time and the pH increasing of the suspensions, indicating that previous application of PL could cumulatively affect the next crops by providing some additional nutrients, especially Mn, Zn and Cu, which were quite abundant compared to CM (Table 2). In particular, zinc as a micronutrient is vital to cassava as the plant is sensitive to Zn deficiency (Asher et al., 1980), with Zn deficiency symptoms being widely reportedly not only in alkaline soils but also in acidic soils in many countries, including Thailand (Howeler, 2011).

Effect of soil amendments and NPK chemical fertilizer on NPK uptake

The uptake of N, P and K in the whole plant across all treatments varied in the ranges 32.36–127.32 kg/ha, 18.78–77.91 kg/ha and 31.45–164.18 kg/ha, respectively, representing approximate proportion of 9:4:10 which was in good agreement with Imas and John (2013) and Prombut et al. (2022). In contrast, it has been claimed that among the soil nutrients, N is the most taken up by cassava (Ayoola and Makinde, 2007; Adjei-Nsiah and Sakyi-Dawson, 2012; Santos et al., 2014), perhaps because the cassava cultivars used in these studies were different from the one used in the current study. In the current study, the highest fresh tuber yield of 37.54 t/ha was obtained from the plot amended with PL+CM, which received 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively), with the NPK uptakes in the whole plant being 121.46 kg/ha, 69.51 kg/ha and 162.32 kg/ha, respectively. This proportion was closer to 6:2:9 as quoted by Ima and John (2013) and Prombut et al. (2022). Based on the report of International Fertilizer Association (1992), to attain a fresh tuber yield of 45 t/ha, the cassava had to take up 62 kg/ha of N, 23 kg/ha of P_2O_5 and 197 kg/ha of K_2O in the tuber, with 202 kg/ha of N, 73 kg/ha of P_2O_5 and 343 kg/ha of K_2O uptake in the whole plant. However, in the current study, the highest fresh tuber yield (37.54 t/ha) was obtained with 71 kg/ha, 79 kg/ha and 160 kg/ha of NPK, respectively, being taken up in the tuber and 148 kg/ha, 83 kg/ha and 274 kg/ha of NPK, respectively, being taken up by the whole plant. This demonstrated that N and P were possibly taken up in excessive quantities in the current study, which was reaffirmed by the results from the plots that received very high amounts of N and P (200:100:200 kg/ha of N-to-P_2O_5-to-K_2O, respectively), which despite being double the recommended rate (Sittibusaya, 1996), did not produce corresponding yield increases. In addition, this was supported by the buildup of OM, total N and available P in the plot amended with PL+CM as presented in Figs. 2C, 2D and 2E, respectively.

Without using soil amendments for eight consecutive years, the NPK uptake increased purely due to the added NPK fertilizer; however, the increasing proportion of the uptake was far lower than that of the amended plots. Likewise, the cassava yield did not increase that much. This was in agreement with the fact that the efficiency of chemical fertilizer usage is low in this type of soil (Anusontpornperm et al., 2009; Boonrawd et al., 2021). It was reaffirmed by the amounts of NPK taken up in the whole plant which were only 74.17 kg/ha, 29.98 kg/ha and 89.17 kg/ha, respectively, for the plots fertilized with 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) or 64.12 kg/ha, 30.66 kg/ha and 80.78 kg/ha, respectively, for the plot supplied with 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively). It was evident that the quantities of NPK taken up were lower than the amounts applied. Nutrient losses through leaching in this sandy soil could have been responsible for this; thus, nutrient use efficiency can hardly be improved without using soil amendments consecutively for a number of growing seasons.

Furthermore, with respect to the highest fresh tuber yield mentioned above, K uptake in the tuber and whole plant was much lower than the amounts reported by International Fertilizer Association (1992); however, it is not clear whether the K uptake in the current study was sufficient as the study was conducted in an Ustic Quartzipsamment with the highest fresh tuber yield of 51.63 t/ha and the K uptake in the tuber and whole plant also being lower than in the report mentioned (Chaem-ngern et al., 2020). This is worth further investigation, especially using a ratio of NPK fertilizer with lower N and P, considering that K is essential for cassava root initiation which, in turn, increases tuber size and number (Howeler et al., 2002; Ayoola and Makinde, 2007), as well as being important for starch synthesis and translocation that leads to increasing the yield and improving the tuber quality when adequate K is supplied (Ukaoma and Ogbonnaya, 2013; Prombut et al., 2022).

Effect of soil amendments on soil property changes

After applying soil amendments for eight consecutive years, particularly just CM or PL+CM, the soil pH_{water} and pH_{KCl} increased compared to the non-amended plot (Figs. 2A and 2B). Past studies have shown that the incorporation of CM into some sandy soils on a short-term basis did not increase soil pH (Nilnoree et al., 2016; Chaem-ngern et al., 2020); however, in the current study, despite using only 3.125 t/ha of CM, which had a quite high pH of 7.9 (Table 2), this manure showed a positive cumulative effect on lifting soil pH because the low molecular weight organic acids released during the decomposition of this manure formed a complex with aluminum (Al), with the Al being absorbed on organic material surfaces and perhaps complexed organic compounds were formed between organic anions and hydronium ions (Bartlett and Riego, 1972; Asghar and Kanehiro, 1980; Hue et al., 1986; Benssho and Bell, 1992). It was also found that ΔpH (pH_{water} - pH_{KCl}) was positive, showing that this soil had negatively charged clay colloids (Tan, 2011). Furthermore, the ΔpH for both the topsoil and subsoil increased slightly in the plots amended with just CM and PL+CM compared to the non-amended plot, illustrating that long-term application of the manure could increase negative charges in this soil to some degree. As a result of the pH increase due to CM or PL+CM additions and a subsequent increase in the negative charge sites in the soils, these conditions should be more favorable for cassava to perform better and to efficiently use NPK, due to the loss of nutrients through leaching being minimized, respectively.

Organic matter in both the topsoil and subsoil in the plots amended with just CM or PL+CM significantly increased compared to the non-amended plot (Fig. 2C); however, the amounts across all plots were still at very low levels, indicating the possibility of OM buildup in sandy soils but only slowly. In addition, all the soil amendments increased the total N in the subsoil (Fig. 2D), which was in line with other studies conducted in rather similar sandy soils (Nilnoree et al., 2016; Chaem-ngern et al., 2020). This might be beneficial to cassava in the following season as the current study used deep tillage as the first ploughing that could mix soil material at depths in the range 30–45 cm with the topsoil, making N more available to the plant.

The continuous application of just CM or PL+CM clearly augmented P availability in this soil (Fig. 2E) due mainly to the P component in the manure (Table 2) and the P fertilizer, along with the lift in the soil pH (Barrow, 2017). The plots continuously amended with these materials for eight consecutive years contained available P above the threshold (5 mg/kg of available P; Sittibusaya, 1996) used to determine the amount of P fertilizer. This suggested that P fertilizer could be reduced in the next crop grown in these plots. In addition, the accumulation of P (Fig. 2E) in these plots was surely responsible for the very high P uptake in the tuber and whole plant.

Generally, the K content in sandy soils is very low, as was the case for the soil in the current study. Although the continuous application of just CM or PL+CM improved the level of available K compared to the control with no addition of soil amendment (Fig. 2F), the amounts were marginally close to the threshold used for estimating the K fertilizer rate (30 mg/kg of available K; Sittibusaya, 1996). This might also have been responsible for the low K uptake by cassava in the current study. In other words, as K fertilizer was also applied in varying amounts, the K use efficiency was likely low. This is normal in upland coarse-textured soils, where leaching always governs the loss of this nutrient (Mengel and Kirkby, 2001). In addition, excessive N fertilizer application might have played a role in this case, as NH_4^+ can compete with K^+. It has been reported that there are physiological changes associated with NH_4^+ assimilation and ion imbalances, resulting from the decreased uptake of essential cations such as K^+, Mg^{2+} and Ca^{2+} (Barker et al., 1967; Gerendás et al., 1997; Roosta and Schjoerring, 2007). It was also found that net fluxes of K^+ and NH_4^+ were negatively correlated, as were their tissue concentrations, suggesting that there is direct competition during uptake in roots of barley (*Hordeum vulgare* L.) and Arabidopsis seedlings (ten Hoopen et al., 2010). However, this requires further investigation.

Again, compared to the control with no application of soil amendment, the continuous application of just CM or PL+CM significantly raised extractable Ca and Mg (Figs. 3A and 3B), with only the amendment using PL+CM increasing the available Fe in the topsoil (Fig. 3C), and available Mn and Zn (Figs. 3D and 3E) in both the topsoil and subsoil, along with available Cu (Fig. 3F) increasing in all the amended plots. This was because the PL and CM contained large amounts of these nutrients and the mineralization of the soil amendments released the nutritive elements (Mengel and Kirkby, 2001) which in the long-term were more absorbed in the soil. The findings regarding soil property changes in the current study are very important for improving cassava production in this type of soil in northeast Thailand and possibly in neighboring countries. The modest, affordable amounts of these soil amendments, if repeatedly applied, clearly not only increased the cassava yield but also improved the soil fertility level. The interaction of soil amendments and NPK fertilizer indicated the potential of using less NPK fertilizer while maintaining the cassava yield. Thus, it is vital to encourage Thai farmers who are growing cassava to practice such techniques because most cassava-growing soils in northeast Thailand are reportedly very poor, physically, and chemically (Anusontpornperm et al., 2009; Boonrawd et al., 2021).

Conclusions

The cassava yield and NPK uptake in the different parts of the cassava plant responded best to the recommended rate of NPK fertilizer (100:50:100 kg/ha of N:P_2O_5:K_2O, respectively) when the cassava was grown in this upland low fertility Arenic Haplustult soil with or without the use of soil amendments for eight consecutive years. However, 100:50:100 kg/ha (N-to-P_2O_5-to-K_2O, respectively) fertilization promoted the highest fresh tuber and starch yields when the soil had been continuously amended with a mixture of PL+PM at the rate of 0.625 t/ha + 3.125 t/ha. Despite the slightly lower fresh tuber yield, applying one-half of the recommended rate produced a rather acceptable yield compared to the recommended rate when applied to soil amended with only CM; however, this was not the case for the non-amended, PL-amended and PL+CM-amended plots. The addition of 200:100:200 kg/ha (N-to-P_2O_5-to-K_2O, respectively) could be deemed economically excessive in terms of the yield obtained. The soil pH, OM and most plant nutrients in both the topsoil (0–30 cm) and subsoil (30–45 cm) increased following the continuous addition of PL and CM. The modest amount of these soil amendments along with proper NPK fertilization can be strongly recommended to farmers growing cassava in Thailand, especially in soils with a sandy texture and low fertility status.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This research was funded by Kasetsart University, Bangkok, Thailand through the Graduate School Fellowship Program and grant FF(KU5.65) from the Kasetsart University Research and Development Institute (KURDI). The Thai Central Chemical Public Company Limited provided the NPK chemical fertilizers.

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