Agr. Nat. Resour. 58 (2024) 67–80

AGRICULTURE AND NATURAL RESOURCES

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

Research article

Effect of bentonite and cassava tails and stalk on cassava planted in an upland Grossarenic Grossarenic Paleustult and soil property changes

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Article Info

Article history:
Received 24 May 2023
Revised 1 January 2024
Accepted 16 January 2024
Available online 14 February 2024

Keywords:
Cassava,
Organic waste,
Soil amendment,
Soil property,
Tropical sandy soil

Abstract

Importance of the work: Cassava in Thailand is mainly planted in low fertility soils of the northeast with unsatisfactorily low yield in return. Treating the soils with soil amendments coupled with adequate fertilization can be a solution to sustainably improving the yield of cassava grown in these soils.

Objectives: To investigate the effects of bentonite (BTN) and cassava tails and stalk (CTS) on cassava yield and some soil properties.

Materials & Methods: A field experiment was conducted over 2 yr in a Grossarenic Paleustult. A split plot design was used, where the main plot consisted of BTN (1.25 t/ha and 2.5 t/ha), CTS (6.5 t/ha and 12.5 t/ha) and a mixture of BTN+CTS (1.25 t/ha + 6.25 t/ha and 2.5 t/ha + 12.5 t/ha), while subplots comprised ratios of N-to-P_2O_5-to-K_2O fertilization of 0:0:0 and 100:50:100 kg/ha.

Results: Almost all the amended plots with or without NPK chemical fertilizer addition interactively produced greater values for fresh tuber yield, starch yield and aboveground biomass than the non-amended plot, even with 100:50:100 kg/ha (N:P_2O_5:K_2O) added in both growing seasons. Overall, the addition of BTN+CTS at the rate of 2.5 + 12.5 t/ha with NPK fertilization induced the significantly highest N uptake in the tuber and in the leaf plus branch, P uptake in the leaf plus branch and K uptake in the tuber, the stem base and the leaf plus branch. In addition, soil amendments applied for two consecutive years increased the soil pH, total N and available P, K and Ca contents over the control that had no addition of these soil amendments.

Main finding: The BTN+CTS treatment, after application for two consecutive years clearly increased the yield of cassava and improved some major soil properties.

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https://doi.org/10.34044/j.anres.2024.58.1.08

Introduction

Cassava (*Manihot esculenta* L. Crantz) is one of the most important global economic crops. In Thailand, cassava production (29.0 m t/yr) is ranked third globally, following Nigeria (60.0 m t/yr) and the Democratic Republic of the Congo (41.0 m t/yr). Thailand is also the world's top exporter of cassava products, accounting for 7.1 million t/yr (Sowcharoensuk, 2023). This plant is grown in almost all regions of Thailand, with the largest cultivation area in the northeast, specifically in Nakhon Ratchasima province, where there were 243,870 ha in 2020 (Office of Agricultural Economics, 2023). In the 2021/22 growing season, the national average yield of cassava fresh tuber was 20.83 t/ha, with 21.09 t/ha and 20.88 t/ha for the northeast and for Nakhon Ratchasima province, respectively (North Eastern Tapioca Trade Association, 2023). However, the average yield could be much higher if proper soil and fertilizer management practices were applied, as reported in some field experiments, such as 52.35 t/ha when cassava starch waste along with 75 kg/ha of N were applied in an Oxic Paleustult, in Ubon Ratchathani province (Phun-iam et al., 2018) and 51.63 t/ha when 12.5 t/ha of chicken manure were added as an organic amendment in an Ustic Quartzipsamment, in Nakhon Ratchasima province (Chaem-ngern et al., 2020). The yield of casava in the northeast, especially in Nakhon Ratchasima province, is low due mainly to the nature of soils that have a rather coarse texture with low fertility status (Anusontpornperm et al., 2009; Boonrawd et al., 2021). The application of major plant nutrient fertilizer at a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha was recommended for light-textured upland Ultisols in the northeast with low organic matter and low available P and K contents (Sittibusaya, 1996). However, sole application of chemical fertilizer hardly improved the yield of this plant in the region because most soils used for cassava cultivation have low levels of organic matter (OM) and cation exchange capacity (CEC), resulting in low nutrient retention by these soils (Anusontpornperm et al., 2009; Boonrawd et al., 2021). Leaching and water erosion play a vital part in the loss of plant nutrients and the subsequent low efficiency of any fertilizer used by the growing plants (Howeler, 2014).

Soil amendments, such as cassava starch waste, chicken manure and burnt rice husk, have been proven successful in increasing the yield of cassava in this region (Phun-iam et al., 2018; Chaem-ngern et al., 2020; Prombut et al., 2022), particularly when enhanced with proper NPK fertilization (Howeler, 2014). Cassava tails and stalk (CTS) constitute waste from cassava starch manufacturing, accounting for 100–200 kg/t of fresh root processed (Thai Tapioca Starch Association, 2021). This waste is abundant in cassava-growing areas where cassava processing facilities are located. However, the waste can cause some adverse environmental impact as it cannot be used for any purposes but soil amendment. There is scarce information on CTS used as a soil amendment. A single year trial conducted in a sandy soil in northeast Thailand showed that the addition of CTS at the rate of 25 t/ha produced the highest fresh tuber yield of cassava (Jenwitheesuk et al., 2018). Mixing CTS with chicken manure at the rate of 6.25 t/ha for both materials produced the highest cassava fresh tuber yield of 33.94 t/ha (Nilnoree et al., 2016).

Bentonite (BTN) is a type of claystone composed mostly of smectite that is formed by the devitrification of volcanic ash or tuff (Jackson, 1997). It has a large surface area and high CEC and when used as a soil amendment, it can prevent the loss of nutrients, particularly $NH_4^+$and K^+, from the rooting zone in a loamy sandy soil and increase fertilizer use efficiency (Croker et al., 2004). It can improve the soil water retainability and water holding capacity of sandy soils (Mojid et al., 2012; Tahir and Marschner, 2016; Mohawesh and Durner, 2019) and be a source of micronutrients. The application of BTN as a soil amendment at the rate of 1.25 t/ha of a ratio of N-to-P_2O_5-to-K_2O fertilization at 200:100:200 kg/ha clearly induced the highest cassava fresh tuber yield, starch yield and aboveground biomass with values of 43.7, 12.4 and 15.8 t/ha, respectively (Boonrod et al., 2018). The low fertility status of most upland soils in the northeast, especially those sandy soils used for cassava cultivation, has prompted attempts to improve these soil properties to sustainably augment the cassava yield, which is crucial for cassava production in Thailand and neighboring countries where the plant is economically important for locally poor farmers (Asian Cassava Center, 2024). Without using proper soil amendments, the efficiency of chemical fertilizer used is expectedly low; consequently, the yield of cassava does not reach the expected optimum yield. Therefore, the current study was undertaken over two consecutive years to investigate the cumulative effect of CTS and BTN in combination with NPK fertilization on cassava's yield and NPK uptake, as well as the impact of these soil amendments on some soil properties. The outcomes of this study should be beneficial to local farmers who have been struggling due to low yields of cassava and the degradation of their own soils. In addition, the study should encourage transferable technology because the experiments were conducted in a farmer's field with repeated results.

Materials and Methods

Site description and soil properties prior to experimental planting

The field trial was carried out in a farmer's field in Ban Supplu Noi, Huay Bong subdistrict, Dan Khun Thot district, Nakhon Ratchasima province, Thailand (15°11'5.04"N, 101°27'19.27"E) under rainfed conditions over two growing seasons. The area is a tropical savanna with an average annual rainfall (1999–2019) of 1,120 mm/y (Climate-Data.org, 2024). The experimental area was on an undulating surface with 3% slope and was located on the shoulder slope of a low hill. The soil representing the experimental area was Warin soil series, classified as Grossarenic Paleustults (Anusontpornperm et al., 2018). In soil genesis, rather use 'the wash over residuum of' which indicate washed material deposited on top of weahered conglomeritic sandstone. having a thick sandy layer extending to 100 cm from the mineral soil surface.

Properties of the soil (0–25, 25–45 and 45–60 cm) prior to conducting the experiment are presented in Table 1. This soil had a loamy sand texture throughout 0–60 cm depth. The soil pH extracted using a ratio of soil-to-water of 1:1 was strongly acid (pH 5.4) in the top layer and very strongly acid in the lower two layers (pH 4.9–5.0). All layers contained very low amounts of OM, total N and available P and K, with a moderately low CEC in the top layer and low-to-very low CEC levels in the layers below. In addition, the availability of other secondary and micronutrients was very low. Overall, this soil was rather acidic with a poor ability to retain plant nutrients, with the nutrient reserve being very low.

Experimental design

The experiment was arranged in a split plot design with four replications. The main plot, with individual plot sizes of 10 m × 8 m, consisted of seven treatments: the control = no soil amendment application (T1) and the additions of: BTN at 1.25 t/ha (T2), BTN at 2.5 t/ha (T3), CTS at 6.25 t/ha (T4), CTS at 12.5 t/ha (T5), BTN at 1.25 t/ha + CTS at 6.25 t/ha (T6) and BTN at 2.5 t/ha + CTS at12.5 t/ha (T7). The subplot was set up to compare the two rates of NPK fertilization, with ratios of N-to-P_2O_5-to-K_2O of 0:0:0 (CF0) and 100:50:100 (CF1) kg/ha. The latter rate was recommended for upland light-textured Ultisols with OM and available P and K contents of lower than 6.5 g/kg, 5 mg/kg and 30 mg/kg, respectively (Sittibusaya, 1996). The BTN was obtained from a mining site approximately 200 km away from the experimental area and the CTS was sourced from a cassava starch manufacturing plant nearby. The properties of both materials are shown in Table 2. Both materials had a very strongly acidic nature. Bentonite had very high CEC whereas CTS contained much higher organic carbon.

The specific rates of soil amendments were uniformly spread over the designed plots and then incorporated into the soil using a 3-disc plough (71 cm diameter) which ploughed to a depth of 40–45 cm (deep tillage). Two weeks after the incorporation, the soil was loosened using a 7-disc plough before making ridges (1.2 m between ridges) across the slope immediately afterward. Cassava (Huay Bong 80 variety) was planted on the ridges with 80 cm spacing between plants. Fertilization in the subplots was done when the plants were aged 2 mth by placing fertilizer into a hole dug between adjacent plants and covering with topsoil. Similar practices were undertaken on all main plots and subplots for two consecutive growing seasons.

Table 1 Soil texture and soil chemical properties prior to conducting experiment.

Property	0–25 cm	25–45 cm	45–60 cm
Texture	Loamy sand	Loamy sand	Loamy sand
pH (1:1 H_2O)	5.4	4.9	5.0
Organic matter (g/kg)	2.75	3.61	2.02
Total N (g/kg)	0.05	0.04	0.05
Available P (mg/kg)	4.83	4.76	3.67
Available K (mg/kg)	15.6	15.6	7.6
Available Ca (mg/kg)	170	180	116
Available Mg (mg/kg)	26.4	22.8	18.0
Cation exchange capacity ($cmol_c$/kg)	7.5	1.2	4.5

Table 2 Properties of bentonite and cassava tails and stalk used in experiment

Property	BTN	CTS	Property	BTN	CTS
pH (1:5 H_2O)	4.40	4.60	Total Mg (g/kg)	12.2	1.90
CEC ($cmol_c$/kg)	25.3	1.50	Total S (g/kg)	1.20	1.97
Organic carbon (g/kg)	1.10	156	Total Fe (mg/kg)	10,726	51.0
Total N (g/kg)	0.70	3.90	Total Mn (mg/kg)	85	290
Total P (g/kg)	0.10	0.30	Total Zn (mg/kg)	15.5	77.0
Total K (g/kg	19.6	6.2	Total Cu (mg/kg)	23.2	42.0
Total Ca (g/kg)	49.5	9.7	Total Na (g/kg)	1.88	0.50

CEC = cation exchange capacity; BTN = bentonite; CTS = cassava tails and stalk

Plant data and soil sample collection

The cassava crop was harvested at the age of 10 mth. At harvest time in both growing seasons, plant parameters were recorded: fresh tuber yield and aboveground fresh weight (stem base, stem, and leaf plus branch). The starch content was determined using 5 kg of fresh tuberous roots harvested from each plot, which were then weighed in air before weighing in water, and the content was read from a Riemann scale balance according to Bainbridge et al. (1996). The starch yield was calculated from the fresh tuber yield and the starch content. Four different plant parts (tuber, stem base, stem, and the leaf plus branch) from each plot were sampled and weighed separately, and known amounts of samples were collected from the field for dry weight measurements and plant analysis. Soil samples from each main plot were collected from depths of 0–30 cm and 30–45 cm at the time of harvest and used to investigate the impact of the BTN and CTS on some soil chemical property changes.

Methods of soil, plant, and soil organic amendment analysis

The soil samples were air-dried, gently crushed using an agate mortar and pestle, passed through a 2 mm stainless steel sieve, homogenized prior to analysis and used for measurements of soil chemical properties, except for soil organic carbon and total N that used 0.5 mm-sieved samples. A glass electrode pH meter was used to determine the pH (National Soil Survey Center, 1996) of aqueous suspensions (1:1 soil-to-solution ratio). Organic carbon was measured using the wet digestion method with 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. 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 K, Ca and Mg 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 using 1 M NH_4OAc at pH 7, then replacing exchangeable NH_4^+ ions with 10% NaCl, and distilling NH_3 into 2% H_3BO_3, followed by titration with 0.01 M HCl using bromocresol green-methyl red as an indicator.

The separate samples of tuberous root, stem, stem base, and leaf plus branch were chopped and dried in the oven at 65–70°C until the weight of each sample was constant. Each samples was crushed and ground to a size smaller than 0.5 mm. The ground sample was digested using nitric-perchloric acid mixtures (HNO_3-to-$HClO_4$), 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 colorimetrically using the vanado-molybdenum yellow method (Westerman, 1990) and then measured using spectrophotometry (Murphy and Riley, 1992). 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 BTN and CTS were analyzed following the plant analysis procedures. For each plant part, the concentrations of N, P and K were multiplied by the total dry weight to obtain the nutrient uptake.

Statistical analysis

Statistical analysis of the data collected was performed using standard analysis of variance. The significance of treatments was determined using the F-test appropriate to the general linear model, as described by Gomez and Gomez (1984). Significant differences between the means of the treatments were tested at the 0.05 probability level ($p < 0.05$) using Duncan's multiple range test. Interaction effects between soil amendments and chemical fertilizer on the cassava's traits were tested for a significant difference based on the split plot design, if required. Only main effects were presented for a significant difference when the interactions of soil amendments and chemical fertilizer were non-significant. In this study, the interactive effect of soil amendment and chemical fertilizer was presented and discussed only for the fresh tuber yield and aboveground biomass, including the uptake of NPK in some plant parts of cassava. No statistical comparisons were carried out between the results from the two growing seasons.

Results

Cassava yield and plant attributes

Both BTN and CTS clearly had a positive impact on the Huay Bong 80 cassava variety in both the underground and aboveground plant parts. There was an interactive effect of soil amendments and chemical fertilizer on the fresh tuber yield; thus, the impact of soil amendments in the main plot and chemical fertilizer in the subplot was not discussed. Across all treatment combinations in non-amended plots, the addition of a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha did not significantly increase the fresh tuber yield compared to no fertilization (11.70 t/ha compared to 10.70 t/ha) in the 1st growing season; however, cumulatively, the NPK fertilization produced a significantly greater fresh tuber yield (6.57 t/ha) than no NPK addition in the following growing season (Fig. 1).

Among the BTN-amended plots, the addition of this inorganic amendment at the rate of 1.25 t/ha produced a slightly lower fresh tuber yield than the rate of 2.5 t/ha in both growing seasons. The addition of NPK fertilizer at a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha clearly elevated the fresh tuber yield of cassava over no NPK fertilization in the lower BTN rate-amended plot in both growing seasons; however, there was no significant impact of NPK fertilization on the yield from the higher rate of BTN amendment in both years (Fig. 1). However, the response of the yield to the combination between BTN and NPK fertilization in the latter growing season was inferior to that in the former growing season.

There was no significant difference in fresh tuber yield in the plots amended with CTS solely at both rates (6.25 t/ha and 12.5 t/ha), with or without NPK fertilization in the 1st growing season; however, incidentally, the addition of chemical fertilizer produced a lower fresh tuber yield than no NPK fertilizer addition in the 1st crop but significantly boosted this yield up to 38.39 t/ha in 12.5 t/ha BTN-amended plot compared to 28.46 t/ha in the same main plot without NPK fertilization (Fig. 1).

The soil amendment with BTN mixed with CTS at both rates (1.25 t/ha + 6.25 t/ha and 2.5 t/ha + 12.5 t/ha) produced a positive response on the fresh tuber yield of the cassava. The addition of NPK fertilizer at a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha slightly increased the yield over no NPK fertilization in both the amended plots, but there was no significant difference. The fresh tuber yield obtained from these combinations in both growing seasons was in the range of 33.87–41.26 t/ha. Notably, the use of BTN+CTS at the rate of 2.5 t/ha + 12.5 t/ha with a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha addition interactively promoted the highest fresh tuber yield of 41.26 t/ha in the second crop that was significantly greater than for the plot amended with one-half the amount of these mixed soil amendments that received the same content of NPK fertilizer (38.14 t/ha). The addition of BTN+CTS at the higher rate in this field experiment together with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha in the 2nd growing season cumulatively maintained the yield at 6.4% higher than for the same treatment combination in the former year (Fig. 1).

Growing cassava in the non-amended plot with no NPK fertilization resulted in the lowest fresh tuber yield among all treatment combinations, with values of 10.70 t/ha and 11.69 t/ha in the 1st and 2nd growing seasons, respectively. The sole application of BTN or CTS tended to produce lower yields than the mixture of these two materials applied at both rates, especially more clearly in the 2nd growing season. Additionally, the mixture of BTN and CTS had a cumulative impact on a slight increase in the yield in the latter crop, whereas the sole application of both soil amendments did not.

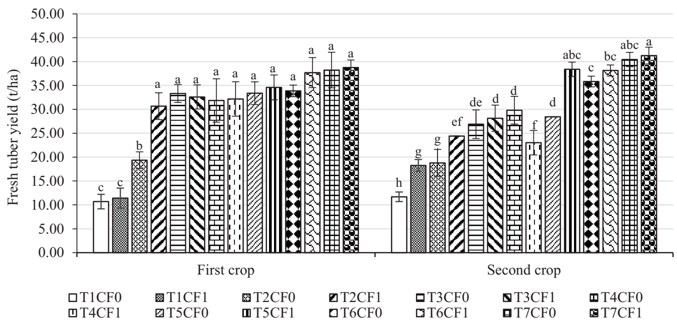

Fig. 1 Interactive effect of soil amendments and chemical fertilizer on fresh tuber yield of cassava, where different lowercase letters above bars grouped within the same crop are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment, T2 = BTN 1.25 t/ha, T3 = BTN 2.5 t/ha, T4 = CTS 6.25 t/ha, T5 = CTS 12.5 t/ha, T6 = BTN 1.25 t/ha + CTS 6.25 t/ha, T7 = BTN 2.5 t/ha + CTS 12.5 t/ha, BTN = bentonite, CTS = cassava tails and stalk, CF = chemical fertilization, CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha and CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha.

Soil amendments had no clear effect on the starch content in both growing seasons (Fig. 2A), whereas the plot fertilized with a ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha had a significantly higher starch content than the non-fertilized plot (Fig. 2B). There was an interactive effect of soil amendment and NPK fertilizer on the starch content only in the 1st growing season but with no clear trend regarding the impacts of soil amendment and NPK fertilizer rates on this yield parameter (Fig. 2C).

In addition, the soil amendments and chemical fertilizer interactively affected starch yield in a significant manner in both growing seasons (Fig. 3); hence, this was investigated regardless of the main impact of the soil amendment and NPK fertilizer additions. The effect trend was similar to that for the fresh tuber yield. In the non-amended plot, NPK fertilization did not significantly increase the starch yield compared to no NPK fertilization, with values of 2.68 t/ha and 2.96 t/ha, respectively, in the 1st growing season. In the next crop, the addition of a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha produced a significantly greater starch yield than for no NPK fertilizer addition, though only a 1.21 t/ha increase.

In the sole BTN-amended plots, the starch yield of cassava responded significantly to a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha compared to no NPK fertilizer addition only in the 1st growing season; within each growing season, the higher rate of 2.5 t/ha gave a slightly greater starch yield (but not significantly so) than the lower rate (1.25 t/ha). The sole application of CTS at both rates (6.25 t/ha and 12.5 t/ha) produced somewhat similar starch yields in the range of 9.28–9.61 t/ha, no matter how much NPK fertilizer had been applied (Fig. 3). However, this yield factor significantly responded to NPK fertilizer added to 12.5 t/ha of only CTS, producing a 36.6% increase in the starch yield over no NPK fertilization.

Amending the soil with a mixture of BTN+CTS at the rates of 1.25 t/ha + 6.25 t/ha and 2.5 t/ha + 12.5 t/ha, with or without NPK fertilization, significantly stimulated the highest starch yield in the range of 9.29–10.97 t/ha in the 1st growing season and 8.65–9.42 t/ha in the next growing season, although these amounts were not significantly greater than the amounts obtained from other treatment combinations (apart from the non-amended plot with and without NPK fertilization and the sole BTN-plot with zero NPK fertilizer addition) in the 1st crop, while they were significantly greater than all other treatment combinations in the 2nd crop, with the single exception of the plot amended with CTS solely at the rate of 12.5 t/ha that had received a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha.

Bentonite and CTS not only increased the tuber yield but also accelerated the top growth of cassava in both growing seasons. Similar to the fresh tuber yield and starch yield, the main effect of soil amendment and NPK fertilization on aboveground biomass was ignored as there was an interaction between soil amendment and NPK fertilization. It was clear that the application of NPK fertilizer did not promote the top growth of cassava in both growing seasons and the amounts of aboveground biomass (3.63–4.40 t/ha in the 1st crop and 6.94 t/ha in the 2nd crop)

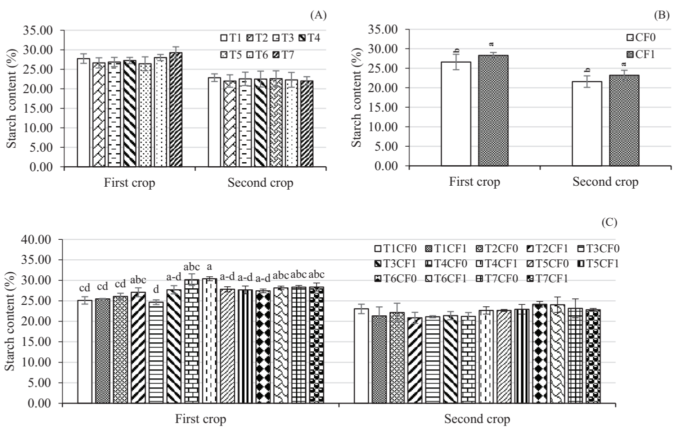

Fig. 2 Starch content in tuberous roots of cassava as affected by: (A) bentonite and cassava tails and stalk; (B) chemical fertilizer; (C) bentonite and cassava tails and stalk interaction, where different lowercase letters above bars grouped within the same crop are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment, T2 = BTN 1.25 t/ha, T3 = BTN 2.5 t/ha, T4 = CTS 6.25 t/ha, T5 = CTS 12.5 t/ha, T6 = BTN 1.25 t/ha + CTS 6.25 t/ha, T7 = BTN 2.5 t/ha + CTS 12.5 t/ha, BTN = bentonite, CTS = cassava tails and stalk, CF = chemical fertilization, CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha and CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha

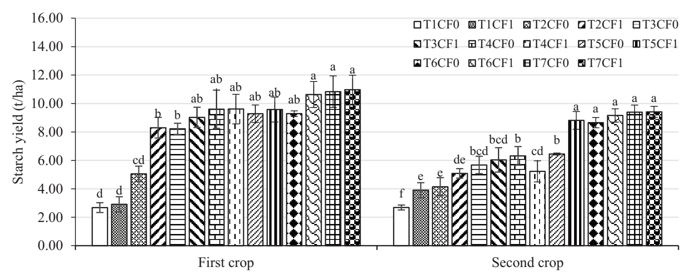

Fig. 3 Interactive effect of soil amendments and chemical fertilizer on starch yield of cassava, where different lowercase letters above bars grouped within the same crop are significantly ($p < 0.05$) different , error bars represent ± SD, T1 = no soil amendment, T2 = BTN 1.25 t/ha, T3 = BTN 2.5 t/ha, T4 = CTS 6.25 t/ha, T5 = CTS 12.5 t/ha, T6 = BTN 1.25 t/ha + CTS 6.25 t/ha, T7 = BTN 2.5 t/ha + CTS 12.5 t/ha, BTN = bentonite, CTS = cassava tails and stalk, CF = chemical fertilization, CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha and CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha

that were significantly lower than almost all values from the other treatment combinations in the 1st and 2nd growing seasons, respectively (Fig. 4).

In the sole BTN-amended plots, the addition of a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha significantly increased the aboveground biomass only in the 1st year when 1.25 t/ha of BTN was applied; however, the NPK fertilizer was less effective in the next crop as the fresh weight of aboveground parts from both no-NPK-fertilized and NPK-fertilized plots (11.12–12.84 t/ha) were not significantly different among the treatment combinations (Fig. 4).

When only CTS was used to amend the soil, cassava responded positively to NPK fertilization only in the plot added with 6.25 t/ha in the 1st growing season; however, in the latter year, a significant increase in the aboveground biomass was detected in the plot amended with 12.5 t/ha of only CTS with the addition of a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha. In addition, across all NPK subplots, the CTS amendment tended to have a cumulative impact on promoting more aboveground biomass in the 2nd growing season (Fig. 4).

Mixing the BTN with CTS as a soil amendment at both mixture rates (1.25 t/ha + 6.25 t/ha and 2.5 t/ha + 12.5 t/ha) slightly augmented the aboveground biomass over the sole application of each soil amendment in the 1st growing season; however, the the cumulative effect was clearer in the next crop as, apart from the plot amended with 12.5 t/ha of only CTS plus the addition of NPK fertilizer, there were significantly greater amounts of the top parts of cassava, particularly for the plot amended with 2.5 t/ha + 6.25 t/ha of BTN+CTS and treated with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha that produced the highest aboveground biomass of 22.92 t/ha (Fig. 4).

Nutrient uptake in cassava

The N, P and K uptake in the parts of the cassava plant (tuber, stem base, stem, and leaf plus branch) as affected by soil amendments and chemical fertilizer in the 2nd growing season are presented in Table 3.

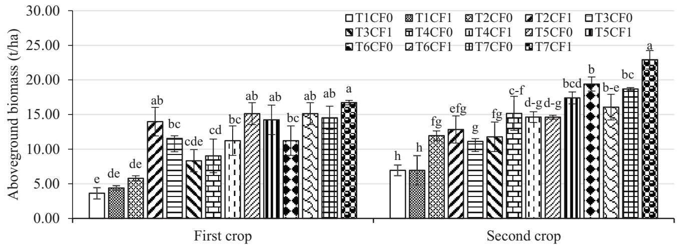

Fig. 4 Interactive effect of soil amendments and chemical fertilizer on aboveground biomass of cassava, where different lowercase letters above bars grouped within the same crop are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment, T2 = BTN 1.25 t/ha, T3 = BTN 2.5 t/ha, T4 = CTS 6.25 t/ha, T5 = CTS 12.5 t/ha, T6 = BTN 1.25 t/ha + CTS 6.25 t/ha, T7 = BTN 2.5 t/ha + CTS 12.5 t/ha, BTN = bentonite, CTS = cassava tails and stalk, CF = chemical fertilization, CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha and CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha

Table 3 Interactive effect of soil amendments and chemical fertilizer on NPK uptake (kg/ha) in different plant parts of cassava in 2nd growing season

Soil amendment	Chemical fertilizer					
	CF0	CF1	Mean±SD	CF0	CF1	Mean±SD
N uptake	Tuber			Stem base		
T1	10.8^{e}	35.0^{c}	22.9±13.2^{D}	3.0	13.8	8.4±6.3^{C}
T2	16.8^{de}	37.8^{c}	27.3±11.3^{CD}	3.2	13.0	8.1±6.8^{C}
T3	22.5^{d}	39.3^{c}	30.9±9.3^{C}	8.6	20.0	14.3±7.3^{B}
T4	39.5^{c}	41.6^{c}	40.5±1.4^{B}	12.7	27.3	20.0±8.9^{A}
T5	42.5^{c}	50.1^{b}	46.3±4.6^{A}	9.7	22.2	15.9±6.8^{AB}
T6	39.4^{c}	63.1^{a}	51.2±17.4^{A}	9.8	15.4	12.6±4.5^{B}
T7	43.0^{bc}	58.3^{a}	50.6±8.7^{A}	16.2	22.9	19.5±5.8^{A}
Mean±SD	30.6±13.5^{B}	46.5±11.5^{A}		9.0±5.2^{B}	19.2±6.4^{A}	
CV (%)	14.0			27.3		
N uptake	Stem			Leaf plus branch		
T1	2.9	12.9	7.9±5.8^{D}	65.9^{cd}	107.7^{ab}	86.8±26.1^{AB}
T2	3.1	10.8	7.0±4.9^{D}	77.8^{cd}	90.6^{bc}	84.2±17.3^{AB}
T3	7.2	16.1	11.6±5.8^{C}	74.4^{cd}	74.6^{cd}	74.5±12.8^{BC}
T4	14.0	21.8	17.9±5.6^{AB}	57.9^{de}	71.2^{cd}	64.5±12.1^{CD}
T5	12.9	18.6	15.7±3.7^{B}	38.6^{e}	64.1^{cde}	51.4±18.0^{D}
T6	9.8	18.9	14.3±5.6^{BC}	63.9^{cde}	108.6^{ab}	86.2±30.3^{AB}
T7	15.0	26.7	20.4±7.2^{A}	73.2^{cd}	131.7^{a}	102.4±38.7^{A}
Mean±SD	9.3±5.1^{B}	17.8±6.1^{A}		64.5±18.2^{B}	92.6±28.3^{A}	
CV (%)	25.1			21.4		

Table 3 Continued

Soil amendment	Chemical fertilizer					
	CF0	CF1	Mean±SD	CF0	CF1	Mean±SD
P uptake	Tuber			Stem base		
T1	21.5^{f}	26.2^{ef}	$23.9±3.4^{D}$	1.1	4.2	$2.8±1.7^{D}$
T2	33.6^{cde}	32.8^{cde}	$33.2±1.6^{C}$	1.5	5.0	$3.3±2.2^{D}$
T3	34.6^{cd}	34.3^{cd}	$34.5±3.5^{BC}$	3.8	7.6	$5.7±2.5^{C}$
T4	30.0^{de}	33.4^{cde}	$31.7±2.0^{C}$	5.4	10.1	$7.8±3.1^{AB}$
T5	31.6^{de}	40.2^{bc}	$35.9±4.7^{BC}$	4.4	8.2	$6.3±2.3^{BC}$
T6	28.8^{de}	60.3^{a}	$44.6±14.5^{A}$	4.5	7.5	$6.0±2.6^{C}$
T7	34.9^{cde}	43.7^{b}	$39.3±6.8^{B}$	6.8	10.9	$8.8±2.7^{A}$
Mean±SD	$30.7±5.7^{B}$	$38.7±9.1^{A}$		$4.0±2.0^{B}$	$7.6±3.0^{A}$	
CV (%)	13.3			27.9		
P uptake	Stem			Leaf plus branch		
T1	1.9	6.8	$4.4+2.9^{B}$	7.8^{efg}	12.3^{de}	$10.1+2.9^{BC}$
T2	2.0	7.7	$4.8+3.5^{B}$	9.2^{def}	10.6^{cde}	$9.9+2.0^{BC}$
T3	5.3	9.6	$7.4+3.0^{A}$	9.2^{def}	11.1^{cd}	$10.2+2.1^{BC}$
T4	6.4	10.9	$8.6+3.0^{A}$	6.9^{fg}	10.7^{cde}	$8.8+2.5^{CD}$
T5	5.0	10.3	$7.7+2.9^{A}$	5.2^{g}	9.3^{def}	$7.2+2.8^{D}$
T6	4.5	9.6	$7.1+3.3^{A}$	7.8^{efg}	14.5^{b}	$11.1+3.8^{BC}$
T7	5.4	12.6	$9.0+4.4^{A}$	11.0^{cd}	18.6^{a}	$14.8+4.6^{A}$
Mean±SD	$4.4±1.9^{B}$	$9.6+2.8^{A}$		$8.2+2.2^{B}$	$12.4+3.6^{A}$	
CV (%)	27.0			18.1		
K uptake	Tuber			Stem base		
T1	33.2^{d}	75.4^{b}	$54.3±23.3^{E}$	2.2^{g}	7.2^{f}	$4.7±3.0^{D}$
T2	51.8^{c}	88.3^{b}	$70.1±19.6^{D}$	2.4^{g}	8.7^{ef}	$5.5±4.0^{D}$
T3	79.0^{b}	87.4^{b}	$83.2±9.2^{C}$	7.4^{f}	10.6^{cef}	$9.0±2.8^{C}$
T4	83.7^{b}	82.2^{b}	$82.9±1.9^{C}$	12.2^{bcde}	14.5^{b}	$13.3±2.9^{B}$
T5	92.3^{b}	93.1^{b}	$92.8±6.0^{BC}$	8.1^{f}	12.8^{bcd}	$10.5±2.8^{C}$
T6	87.7^{b}	131.7^{a}	$109.7±34.7^{A}$	9.2^{def}	10.6^{cef}	$9.9±2.3^{C}$
T7	75.5^{b}	128.7^{a}	$102.1±29.0^{AB}$	14.1^{bcd}	25.6^{a}	$19.9±6.8^{A}$
Mean±SD	$71.9±22.7^{B}$	$98.1±23.8^{A}$		$8.0±4.7^{B}$	$12.8±6.2^{A}$	
CV (%)	13.9			22.8		
K uptake	Stem			Leaf plus branch		
T1	2.4	7.5	$5.0±3.2^{C}$	20.4^{cdef}	28.0^{b}	$24.2±5.3^{AB}$
T2	2.5	8.4	$5.4±3.7^{C}$	24.1^{bc}	23.1^{bcd}	$23.6±4.4^{AB}$
T3	9.0	13.2	$11.1±3.6^{B}$	23.5^{bcd}	18.2^{cdefg}	$20.9±4.3^{BC}$
T4	10.3	13.5	$11.9±3.0^{B}$	17.5^{defg}	16.6^{efg}	$17.1±2.6^{CD}$
T5	7.8	12.7	$10.2±2.9^{B}$	13.0^{bcd}	14.5^{fg}	$13.7±3.1^{D}$
T6	7.8	10.5	$9.1±3.0^{B}$	20.0^{cdef}	23.7^{bcd}	$21.8±4.0^{BC}$
T7	12.5	24.0	$18.2±8.1^{A}$	20.7^{cde}	34.0^{a}	$27.3±8.2^{A}$
Mean±SD	$7.5±3.9^{B}$	$12.8+6.3^{A}$		$19.9+4.7^{B}$	$22.6+7.35^{A}$	
CV (%)	30.5			17.7		

CV = coefficient of variation; T1 = no soil amendment; T2 = BTN 1.25 t/ha; T3 = BTN 2.5 t/ha; T4 = CTS 6.25 t/ha; T5 = CTS 12.5 t/ha; T6 = BTN 1.25 t/ha + CTS 6.25 t/ha; T7 = BTN 2.5 t/ha + CTS 12.5 t/ha; BTN = bentonite; CTS = cassava tails and stalk; CF = chemical fertilization; CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha; CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 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 $p < 0.05$.

Nitrogen uptake

Overall, cassava took up the highest amount of N in the leaf plus branch, followed by the tuber, while the N uptake levels in the stem base and stem were far lower but similar. Soil amendment and NPK fertilizer clearly impacted the uptake of N in the tuber. The addition of BTN+CTS at both rates with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha interactively promoted the highest N uptake in this plant part (58.3–63.1 kg/ha). However, there was no interactive effect of soil amendments and chemical fertilizer on N uptake in the stem base and stem, while the addition of all soil amendments except BTN at the rate of 1.25 t/ha significantly promoted greater N uptake in these two plant parts than did no soil amendment addition. Amending the soil with BTN+CTS at the rate of 2.5 t/ha + 12.5 t/ha with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha had the interactive impact on the N uptake in the leaf plus branch, producing the highest content of 131.7 kg/ha.

Phosphorus uptake

On average, P was taken up in the highest amount in the tuber, with the amount being much lower in the other cassava parts. Phosphorus uptake in the different plant parts was clearly affected by soil amendments and NPK chemical fertilizer. The addition of BTN+CTS at the rate of 1.25 t/ha + 6.25 t/ha together with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha interactively stimulated the significantly highest P uptake in the tuber (60.3 kg/ha). There was no interactive effect of soil amendment and NPK chemical fertilizer on P uptake in the stem base and stem; however, the use of BTN+CTS at the rate of 2.5 t/ha + 12.5 t/ha to amend the soil along with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha interactively significantly augmented the highest P uptake in the leaf plus branch (18.6 kg/ha).

Potassium uptake

Potassium, across all treatments, was accumulated in tuber in the greatest quantity followed by in the leaf plus branch, while the amounts in the stem base and stem were far lower. There were interactive effects of soil amendments and NPK chemical fertilizer on K uptake in all cassava plant parts except the stem. The addition of BTN+CTS at both rates and with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha induced the significantly highest K uptake in the tuber (128.7–131.7 kg/ha). Amending the soil with BTN+CTS at the rate of 2.5 t/ha + 12.5 t/ha with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha interactively induced the significantly greatest K uptake in the stem base, and in the leaf plus branch parts (25.6 kg/ha and 34.0 kg/ha, respectively).

Soil chemical properties

The application of soil amendments for two consecutive years clearly affected some soil chemical properties in the topsoil (0–30 cm) and subsoil (30–45 cm). The addition of CTS at the rate of 12.5 t/ha significantly raised the soil pH to its highest level of 6.08 in the topsoil, while all treatments with CTS significantly increased the soil pH of the subsoil compared to the sole BTN-amended and control plots (6.15–6.30 and 5.66–5.91, respectively), as shown in Fig. 5A. The impact of soil amendments on the OM content in the topsoil was not clear since the addition of solely CTS, at either of the two rates produced OM (5.61 g/kg) at a level that was not significantly different from that in the control (5.02 g/kg). The addition of BTN+CTS at the rate of 2.5 t/ha + 12.5 t/ha cumulatively promoted the significantly highest OM level (6.23 g/kg) in the subsoil, whereas there were no significant differences among the other treatments (Fig. 5B).

Soil amendment quite clearly had an impact on the accumulation of N in both the topsoil and subsoil. The sole application of CTS at the rate of 12.5 t/ha produced the significantly highest total N content in the topsoil (0.90 g/kg), while the application of CTS alone at both rates promoted the significantly highest total N contents (0.88–0.90 g/kg) in the subsoil (Fig. 5C). Nonetheless, soil N in all plots was still very low, as would be expected in humid tropical sandy soils. Available P is normally lower than 5 mg/kg in most sandy soils in Thailand (Anusontpornperm et al., 2009; Boonrawd et al., 2021). In the current study, available P was clearly affected by the application of soil amendments in two consecutive years, especially in the topsoil. With the exception of adding solely BTN at either rate, the sole addition of CTS and the mixture of BTN and CTS added at either rate, stimulated a significantly greater available P content in the topsoil (10.96–13.27 mg/kg) than did no addition of soil amendment (8.23 mg/kg). The available P content in the subsoil was lowest in the control plot (9.12 mg/kg) but this was not significantly different to that in some other plots, whereas the sole addition of CTS at the rate of 12.5 t/ha and the sole application of BTN at the rate of 1.25 t/ha produced significantly more available P than in the control without any addition of soil amendment (Fig. 5D).

Soil amendments had a positive impact on available K in both the topsoil and subsoil after application for two years in a row (Fig. 5E). The addition of BTN at the rate of 2.5 t/ha promoted the significantly highest available K content (60.90 mg/kg) in the topsoil while the amounts in the other amended plots (41.33–50.88 mg/kg) were significantly still higher than that in the control plot (32.89 mg/kg). On average, the available K content in the subsoil was lower than in the topsoil; however, the increment due to the soil amendments was evident, with the lowest amount (22.38 mg/kg) in the control treatment, while all treatments involving soil amendments produced amounts in the range 27.38–44.50 mg/kg. The use of BTN mixed with CTS at both rates significantly increased the amount of extractable Ca (1.10–1.30 $cmol_c$/kg) in the topsoil compared to the control with no addition of soil amendment (0.39 $cmol_c$/kg). A rather similar trend was observed in the subsoil, since the mixture of BTN and CTS produced a far greater level of extractable Ca (0.98–1.30) than did no soil amendment addition (0.33 $cmol_c$/kg), as shown in Fig. 5F.

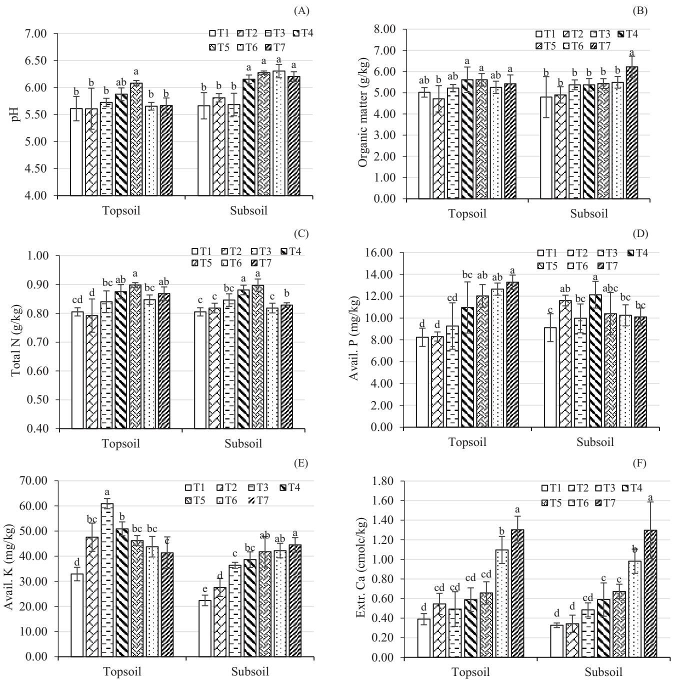

Fig. 5 Effect of bentonite and cassava tails and stalk on topsoil (0–30 cm) and subsoil (30–45 cm): (A) pH; (B) organic matter; (C) total N; (D); available P; (E) available K; (F) extractable Ca, where different lowercase letters above bars grouped within the same soil layer are significantly ($p < 0.05$) different, error bars represent ± SD, T1 = no soil amendment, T2 = BTN 1.25 t/ha, T3 = BTN 2.5 t/ha, T4 = CTS 6.25 t/ha, T5 = CTS 12.5 t/ha, T6 = BTN 1.25 t/ha + CTS 6.25 t/ha, T7 = BTN 2.5 t/ha + CTS 12.5 t/ha, BTN = bentonite, CTS = cassava tails and stalk, CF = chemical fertilization, CF0 = ratio of N-to-P_2O_5-to-K_2O of 0:0:0 kg/ha and CF1 = ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha

Discussion

Effect of soil amendments and NPK chemical fertilizer on cassava yields

The Grossarenic Paleustult soil, representative of the soil in the experimental area, has a sandy particle-size class throughout a layer extending from the mineral soil surface to the top of an argillic horizon at a depth of 100 cm or more. This Grossarenic subgroup was modified for use with Paleustults, with the latest 1999 soil taxonomy not providing any alternative subgroups (Anusontpornperm et al., 2018). This soil was categorized by a plethora of sand particles to great depth, demonstrating its poor nutrient retainability and low nutrient reserve (Table 1) in addition with possible moisture shortage during prolonged periods of dry season. The N, P, K, Ca and Mg contents in this soil prior to conducting the experiment were all at low-to-very-low levels throughout the 0–60 cm depth, suggesting that growing cassava in this soil without soil improvement or using solely NPK chemical fertilizer would always produce a poor return as shown by the results obtained in the current study (10.70 t/ha and 11.69 t/ha of fresh tuber yield, and 6.14 t/ha and 3.96 t/ha of starch yield in the 1st and 2nd growing seasons, respectively). Despite applying NPK fertilizer at the recommended rate (Sittibusaya, 1996), the yields did not increase over no fertilization in the former growing season, with only a slight increase in the latter growing season. Nonetheless, the yields were still far lower than the average yield for the region (North Eastern Tapioca Trade Association, 2023). This was in agreement with Parr and Hornick (1992), who reported that the use of a sole chemical fertilizer has not been helpful under intensive agriculture because it is often associated with reduced crop yield, soil acidity and nutrient imbalance, as was the case in the current study, where the soil had been used for cassava cultivation for a long time. In addition, some studies had reported the ineffectiveness of chemical fertilizers without the use of soil amendment (Phun-iam et al., 2018; Chaem-ngern et al., 2020; Prombut et al., 2022; Leitch et al., 2023).

The application of BTN at the rate of 1.25 t/ha was sufficient to improve the yield of cassava in the current study soil, especially when NPK fertilizer was applied at the recommended rate, with improvements in the fresh tuber yield by 168.6% and 33.6% over the control without the addition of BTN in the 1st and 2nd growing seasons, respectively. Amending the soil with CTS at both rates (6.25 and 12.5 t/ha) undoubtedly ensured the augmentation of cassava yields in both growing seasons even without NPK fertilization. However, the mixture of BTN and CTS at both rates illustrated a rather better positive impact on cassava yields in both growing seasons with and without NPK fertilization. This demonstrated that amending the soil with these materials for two consecutive years produced a cumulative impact that might lead to lowering the amount of NPK chemical fertilizer used slightly; however, this requires further study for confirmation. In other words, these mixed soil amendments positively enhanced NPK use efficiency and in turn induced greater yields of cassava.

The results observed in this study revealed that BTN played a part in cassava yield improvement by providing some secondary and micronutrients (Table 2) in addition to improving the nutrient retainability of the soil, which in turn increased fertilizer use efficiency (Croker et al., 2004), held plant nutrients against leaching (Noble et al., 2001) and retained soil moisture (Mojid et al., 2012; Tahir and

Marschner, 2016; Mohawesh and Durner, 2019). The increase of cassava yield as affected by BTN addition in a coarse-textured soil was also reported by Boonrod et al. (2018). The CTS waste contained plant nutrients to varying extents (Table 2); thus, using this waste as a soil amendment, slowly released primary plant nutrients for cassava during its early growth (Opachat et al., 2018), including some secondary nutrients and micronutrients during decomposition. Furthermore, the considerable amount of organic carbon in the CTS should additionally contribute to the activity of vesicular arbuscular mycorrhizae (VAM) which have been reported as important for cassava, which is heavily dependent on an effective VAM association for absorption of P from the soil (Yost and Fox, 1979; Zaag et al., 1979). The CTS impact on cassava obtained in this study was consistent with that reported by Nilnoree et al. (2016) and Jenwitheesuk et al. (2018) where these single year studies were also conducted in sandy soils, both derived from conglomeratic sandstone and classified as Typic Paleustults. Across the two-year trial, sole application of CTS produced better results than the sole application of BTN in the context of fresh tuber yield, particularly for the cassava in the second crop with the fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha; however, the CTS was applied in a much higher quantity than the BTN.

Effect of soil amendments and NPK chemical fertilizer on NPK uptake

The uptake of major plant nutrients in different plant parts of cassava was studied only in the 2nd crop. In the whole plant, N, P and K uptakes across all treatments varied in the ranges 82.6–238.5, 32.7–92.0 and 58.2–212.3 kg/ha, respectively, or an approximate ratio of 5:2:4. This was quite different to the 6:2:9 ratio reported by Imas and John (2013) and Prombut et al. (2022). The K uptake in the current study might not be sufficient, considering that K is necessary for cassava root initiation and increasing tuber size and number (Howeler et al., 2002; Ayoola and Makinde, 2007). Adequate K supply is also important for starch synthesis and translocation; in addition, it increases yield and improves tuber quality (Uwah et al., 2013; Ukaoma and Ogbonnaya, 2013; Prombut et al., 2022). Furthermore, while the NPK uptake ratio in the tuber has been reported as 5:1:10 (Chaem-ngern et al., 2020), the ratio observed in the current study was 1:1:2, which reaffirmed that K fertilization in this soil needs greater emphasis, while the rate of P fertilization can be reduced. This was evidenced by soil property changes when harvesting the 2nd crop, since the available P content had accumulated much more than 5 mg/kg (Fig. 5D), while the available K content had slightly decreased (Fig. 5E). As a result, K fertilizer should be increased whereas P fertilizer can be decreased.

Effect of soil amendments on soil properties changes

The sole application of CTS and the mixture of BTN+CTS addition at both rates resulted in an increase in soil pH owing to the effect of CTS rather than BTN. This organic waste increased soil pH by releasing low molecular weight organic acids during its decomposition to form a complex with aluminum (Al) in the soil solution (Bartlett and Riego, 1972; Hue et al., 1986). Al is adsorbed on the surfaces of the organic material (Asghar and Kanehiro, 1980) and may release organic anions that are attracted hydronium ions to form complexed organic compounds (Benssho and Bell, 1992).

Organic matter and total N increased slightly following the addition of soil amendments, especially the CTS. This was quite normal for sandy soils in general, as organic matter and N can be lost rather easily through leaching, with the former being decomposed quickly under a humid tropical climate and the latter also being lost rapidly with the removal of the cassava tubers from the field. The slight increases in the organic matter and N were similar to those observed in some studies undertaken in sandy soils in northeast Thailand (Nilnoree et al., 2016; Chaem-ngern et al., 2020; Prombut et al., 2022).

Clearly, the available P increased in both the topsoil and subsoil in almost all amended plots, indicating that both BTN and CTS could contribute to greater availability of this major plant nutrient, since some P was released from the CTS (Table 2) while the increase in the pH may also have increased P availability (Barrow, 2017). In addition, the uptake of P by cassava was lower than for N and K; thus, P fertilization might also be responsible for the P in the soil.

There were clear increases in the available K and Ca as affected by BTN and CTS in both the topsoil and subsoil. Apart from being taken up by growing plants, both K and Ca are generally lost very easily through leaching, especially in coarse-textured soils (Goulding et al., 2021). The accumulation of both nutrients in this study was attributed to the ability of both soil amendments to retain these cations. Bentonite has a high surface area and a CEC that can change the surface charge characteristics of degraded soil in the humid tropics (Noble et al., 2001); thus, when used as a soil amendment, it can decrease the loss of nutrients (particularly $NH_4^+$and K^+)

from the rooting zone in a loamy sandy soil and increase fertilizer use efficiency (Croker et al., 2004). The addition of CTS also affected K and Ca in a positive manner because of the mineralization of the waste releasing nutritive elements (Mengel and Kirkby, 2001), which were absorbed in the soil, particularly with the involvement of BTN that had a high CEC. The accumulation of organic matter, total N and available P, K and Ca after continuously applying BTN and CTS for two years is very important for cassava cultivation in sandy soils because the soils derived from sandstone in northeast Thailand are inherently low in fertility with a low capacity to retain most plant nutrients, especially cationic plant nutrients (Anusontpornperm et al., 2009).

Conclusion

Soil amendments using BTN and CTS improved the cassava yield from a crop in a Grossarenic Paleustult, with a low soil fertility level. The sole application of CTS and the mixture of BTN+CTS at both rates without NPK fertilization still increased the yield of cassava; however, the application of either BTN or CTS, and the mixture of these soil amendments at both rates (BTN at 1.25 t/ha and 2.5 t/ha; CTS at 6.25 t/ha and 12.5 t/ha), along with a fertilization ratio of N-to-P_2O_5-to-K_2O of 100:50:100 kg/ha significantly improved the cassava yield, especially in the 2nd growing season, where using both rates of BTN+CTS mixture, with or without chemical fertilizer application, cumulatively promoted the highest fresh tuber yield and starch yield. Continuously applying both soil amendments for two consecutive years improved the fertility level of both the topsoil (0–30 cm) and subsoil (30–45 cm). To sustain the yields of cassava in this type of soil, a sufficient quantity of BTN and CTS should repeatedly be added, while the amounts of organic matter and the available P and K contents should be monitored because NPK chemical fertilizer (as either the individual elements or in combination) can be reduced following the augmentation of these soil parameters. A longer-term field trial should be conducted to obtain results on a consistent basis and to investigate the cumulative impact of both soil amendment and NPK fertilizer additions on cassava and soil property changes.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This research was supported in part by the Graduate Program Scholarship from The Graduate School, Kasetsart University, Bangkok, Thailand, with major funding from the Kasetsart University Research and Development Institute (KURDI), through grant FF(KU)5.65. We would like to thank Thai Central Chemical Public Company Limited for providing NPK chemical fertilizer used in this study.

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