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Effect of combination fertilizer on growth and yield of Cassava cv. Rayong9 in Thailand

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Abstract The effects of combination fertilizer applications on cassava growth, yield, and starch content (cv. Rayong 9) were investigated. Plant heights were highest in chemical fertilizer only (T3) and combined chemical fertilizer with biofertilizer (T4) treatments. Stem diameter and SPAD chlorophyll readings were significantly higher in T4 at a key growth stage. After six months of harvesting, T4 yielded the highest fresh leaves (258.75 kg ha^{-1}) and rhizome yields (1184.75 kg ha^{-1}). T3 produced the highest fresh root yield in eight months of 15,937.50 kg ha^{-1}, while T4 outperformed all treatments at ten months (17,787.50 kg ha^{-1}). However, reducing the NPK fertilizer rate to half (12.5 kg ha^{-1}) combined with PGPR (T5) significantly enhanced cassava root yield at both the 6 and 10-month when harvested as compared to the full NPK fertilizer rate (T3, 437.5 kg ha^{-1}) only. Moreover, T5 showed the highest starch content at six months of growth (27.14%) and harvesting at ten months (19.67%). These findings indicated that integrating biofertilizers with reduced chemical fertilizer applications is a promising approach for promoting sustainable cassava production.

Keywords: Cassava, Bio-fertilizer, PGPR, Combination fertilizer, Starch content

Introduction

Cassava (*Manihot esculenta* Crantz) is a vital tropical crop, recognized as one of the world's most important sources of food and calories in tropical regions (Cock, 1985; Fregene *et al*., 2001). It ranks as the fourth most significant calorie crop in the tropics and has gained prominence for its role in food security and its expanding commercial and industrial applications (Amelework *et al*., 2021). In Thailand, cassava is an essential economic crop, with approximately 1.6 million

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hectares dedicated to its cultivation in 2022. Cassava exports during 2020, 2021, and 2022 reached 6, 10, and 11 million tons, respectively, generating revenue of 82,000, 123,000, and 150,000 million baht (The Office of Agricultural Economics, 2023a). This upward trend emphasizes its economic importance for both domestic consumption and export markets.

Cassava cultivation in Thailand relies heavily on chemical fertilizers to meet domestic and international market demand. This practice has led to increased production costs, environmental concerns, and long-term soil degradation (Wongsuwan *et al*., 2021; Rasool *et al*., 2021). As a sustainable alternative, integrating chemical fertilizers with organic or biological fertilizers has been proposed to improve soil fertility, enhance nutrient availability, and improve soil structure (The Office of Agricultural Economics, 2023b).

Bio-fertilizers, such as Plant Growth-Promoting Rhizobacteria (PGPR), play a crucial role in promoting plant growth. PGPR interacts with plant roots and other parts, such as stems and leaves, to facilitate nutrient uptake, produce plant growth hormones, and improve overall plant health (Chotinan, 2023; Vessey, 2003). Recent studies have shown that combining bio-fertilizers with chemical fertilizers can significantly improve cassava yields and growth performance. The study of Otaiku *et al*. (2019) demonstrated that combining bio-fertilizers with chemical fertilizers results in higher cassava yields and improved growth than using no fertilizers, while Shah *et al*. (2021) reported the role of PGPR in reducing dependency on chemical inputs while maintaining crop productivity. In response to the increasing concerns about soil degradation and the need for sustainable agricultural practices, this study investigates the effect of combining Bio-fertilizer with chemical fertilizers on the growth and yield of cassava cv. Rayong 9. The findings aim to provide insights into sustainable cassava production systems that improve productivity while reducing environmental and economic challenges.

Materials and methods

The experiments were conducted at the Khao Hin Son Research Station in the Khao Hin Son Subdistrict, Phanom Sarakham District, Chachoengsao Province. (Latitude, Longitude13°44'46.7"N 101°33'48.3"E). Soil analyses of the 0-30 cm depth indicated a sandy soil in mabbon series with low organic matter (0.77%),6.8 pH, Nitrogen (0.97 g kg^{-1}), high phosphorus (29 ppm), and moderate potassium (68 ppm). The experimental design was a randomized complete block design (RCBD) with four replications. The treatments consisted of five fertilizer applications: T1 = no fertilizer (control), T2 = apply Bio-fertilizer (PGPR) (12.5 kg ha^{-1}) only, T3 = chemical fertilizer 15-15-15 only (437.5 kg ha^{-1}), T4 = Chemical fertilizer 15-15-15 (437.5 kg ha^{-1}) combine with

Bio-fertilizer (PGPR) (12.5 kg ha^{-1}), and T5 = Chemical fertilizer 15-15-15 (218.75 kg ha^{-1}) combined with Bio-fertilizer (PGPR) (12.5 kg ha^{-1}). The biofertilizer (PGPR) used in this study was provided by the Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand. It consists of two bacterial species: *Azospirillum brasilense* and *Gluconacetobacter diazotrophicus*. Verified by certification standards, this formulation guarantees a minimum microbial density of 1×10^{6} colony-forming units (CFU) per gram of product. It was specifically developed for application in sugarcane (*Saccharum officinarum*) and cassava (*Manihot esculenta*) cultivation, to enhance agricultural productivity through biological nitrogen fixation and improved plant health (Agricultural Production Research and Development Division, 2021).

Land preparation was done by tractor plowing. The trial was conducted from June 2022 to June 2023 using cassava stem cuttings, Rayong 9 variety. Cassava was planted with a spacing of 100×100 cm on the flat ground. Each plot consisted of 6×11 cm^{2} total, 20 plots (1,320 plants). The Chemical (15-15-15) fertilizer and bio-fertilizer were applied and divided twice. The first time when the cassava was 45 days after planting and the second time when the cassava was 75 days after planting. The bio-fertilizer treatments are blended with chemical fertilizers and then gave immediately. The plots were hand-weeded regularly.

Data collection

Growth of cassava: Cassava height and stem diameters was measured 60 days after planting by randomly selecting eight plants per plot; plant height using a meter stick measured from the ground to the shoot. Stem diameters were measured by a vernier caliper. SPAD Chlorophyll Meter (SCMR) were measured 75 days after planting at three points upper, middle, and lower canopy.

Cassava yield: Cassava were harvested at 6, 8, 10 and 12 months after planting. Sixteen randomly selected plants per plot were collected in each harvest. Cassava yield was determined by digging up the root and separating from the stem. Each plant was separated into leaf, stem and storage root and then fresh weight was recorded immediately by an electronic balance. From each plot, 5 kg of storage root fresh weight was taken to measure starch content by specific gravity. Dry weight of leaf, stem and storage root were measured after placing them into a hot air oven at 80 ^{o}C for 72 hours.

Statistical analysis

The data obtained from the experiment were used to analyze statistical variance analysis (Analysis of Variance; ANOVA). Differences in means were compared using Fisher's Least Significant Difference (LSD) through the Rprogram version 4.0 (R Core Team, 2021).

Results

Rainfall

There was heavy rainfall in August after the cassava were planted on 28 July 2022. The total amount of rainfall during the 10-month study period (August 2022 to May of 2023) was 1,206 mm. During the study, the rainfall in August was 410 mm, representing 34% of the total rainfall during the period. The lower rainfall was found in January with 0.3 mm. (Figure 1). The average temperature was 30.0–33.0 °C (Figure 1).

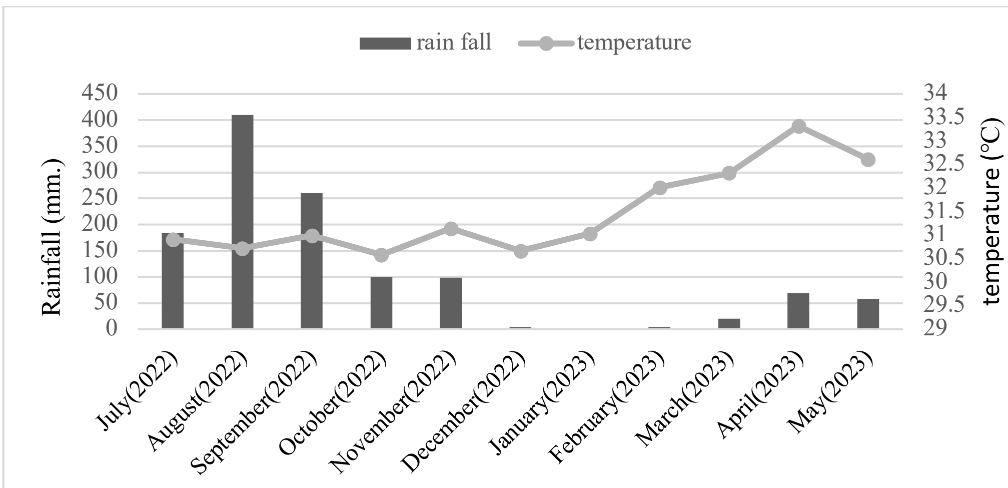

Figure 1. Average monthly rainfall and temperature from July 2022 to May 2023 at Hin Son Research Station in the Khao Hin Son Subdistrict, Phanom Sarakham District, Chachoengsao Province, Thailand

Plant growth

The plant height of the cassava showed significant ($p \leq 0.05$) differences in the various fertilizer applications. Mostly the tallest plants were from T3 and these varied from 83.94-178.75 cm while the shortest plants were from T1 (74.81-147.44 cm) and PGPR applied T2 (72.81-150.60 cm) (Table 1). However, the application of NPK combined with PGPR and applied deceased 50% of NPK combined Bio-fertilizer (84.50-167.81 cm and 85.63-164.72 cm, respectively) gave plant height not statistically ($p > 0.05$) different from T3 (Table 1).

Table 1. Effect of combination fertilizer on plant height and stem diameter of cassava cv. Rayong9

Treatments	Plant height (cm)								
	75 days	90 days	120 days	150 days	180 days	210 days	240 days	270 days	300 days
T1	74.78$^{ab1/}$	84.85^{ab}	89.18	91.81^{b}	98.41	110.35^{b}	111.32^{bc}	123.59^{b}	147.44^{c}
T2	72.81^{b}	83.34^{b}	98.90	95.32^{b}	125.46	105.38^{b}	110.81^{c}	123.01^{b}	150.60^{bc}
T3	83.94^{ab}	97.22^{ab}	101.33	113.61^{a}	125.69	135.38^{a}	138.66^{a}	142.21^{a}	178.75^{a}
T4	84.50^{ab}	98.99^{a}	107.20	116.10^{a}	118.02	132.10^{a}	131.25^{a}	141.94^{a}	167.81^{ab}
T5	85.63^{a}	97.74^{ab}	98.73	112.51^{a}	110.67	115.10^{b}	126.72^{ab}	133.66^{ab}	164.72^{abc}
f-test	*	*	ns	*	ns	*	*	*	*
CV %	10.20	11.10	19.66	9.71	20.96	9.01*	8.47	6.90	7.57
	Stem diameter (cm)								
T1	12.42^{bc}	13.44^{c}	14.89^{bc}	14.27^{b}	14.15^{ab}	13.18^{ab}	14.21^{bc}	15.79^{ab}	21.92
T2	11.78^{c}	13.10^{c}	14.52^{c}	14.31^{b}	13.61^{b}	12.56^{b}	13.46^{c}	14.40^{b}	17.82
T3	14.08^{a}	15.82^{a}	17.10^{a}	16.26^{a}	15.65^{a}	14.95^{a}	15.94^{a}	16.35^{ab}	19.30
T4	13.95^{a}	15.39^{ab}	16.54^{ab}	15.47^{a}	15.33^{ab}	14.44^{a}	15.19^{ab}	17.15^{a}	19.96
T5	13.65^{ab}	14.37^{bc}	15.88^{abc}	15.25^{ab}	14.60^{ab}	14.14^{a}	14.83^{abc}	16.83^{a}	18.98
f-test	*	*	*	*	*	*	*	*	ns
CV %	6.43	6.08	6.94	4.67	7.76	8.59	7.00	7.94	15.12

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test.
*= Significantly different at p<0.05, ns= non significantly different at p<0.05

From 75 days after plantings up until 270 days after plantings, the application of chemical fertilizer only (T3), NPK combined PGPR (T4) and deceased half of NPK combined Bio-fertilizer (T5) produced non-significant stem diameter as 14.08-16.35 mm, 13.95-17.15 and 13.65-16.83 mm, respectively but these were larger than stem diameters from control and PGPR only treatment (11.45-14.40 and 11.78-14.40 mm, respectively) (Table 1). but stem diameters in all the treatments were not different when the cassava reached 10 months old.

From the result in Table 2, it is apparent SPAD Chlorophyll Meter (SCMR) were significant different ($p < 0.05$) at 90, 120, 150 and 300 days. Application of chemical fertilizer combined Bio-fertilizer had significant difference compared to control and application of Bio-fertilizer only. The greenness leaf at 90 and 120 days found that used of NPK + Bio-fertilizer (T4) gave higher (51.51 and 51.51 SPAD unit, respectively than other treatments while at 120 and 300 days used of NPK + Bio-fertilizer gave higher (46.10 and 46.08 SPAD unit, respectively than control (48.33) and Bio-fertilizer only (46.07). However, the leaf greenness was not significant at 75, 180, 210, 240 and 270 days after planting in all treatments (Table 2).

After six months of cultivation, it was found that T4, which utilized a combination of chemical fertilizer and PGPR biofertilizer, resulted in significantly higher fresh leaf yield (258.75 kg ha^{-1}) (Table 3) and rhizome yield (1,184.75 kg ha^{-1}) (Table 4) compared to control; 143.50 kg ha^{-1} for leaves and 951.25 kg ha^{-1}for rhizomes ($P < 0.05$). However, no statistically significant differences when compared with methods T2, T3, and T5, which provided fresh leaf yields ranging from 178.50 to 218.0 kg ha^{-1} (Table 3) and rhizome yields were 1,027.0 to 1,037.0 kg ha^{-1} (Table 4).

Table 2. Effect of combination fertilizer on SPAD Chlorophyll Meter (SCMR) of cassava cv. Rayong9

Treatments	SPAD								
	75 days	90 days	120 days	150 days	180 days	210 days	240 days	270 days	300 days
T1	40.70	47.68$^{c1/}$	48.33^{c}	42.78^{bc}	42.78	40.62	44.72	43.62	42.78^{bc}
T2	40.63	46.07^{d}	46.07^{d}	41.87^{c}	43.65	41.17	46.43	42.70	41.87^{c}
T3	44.62	49.47^{b}	49.47^{bc}	45.23^{a}	43.45	43.42	47.58	45.41	45.23^{a}
T4	43.64	51.51^{a}	51.51^{a}	46.10^{a}	44.19	44.04	47.44	45.90	46.08^{a}
T5	41.83	49.85^{b}	49.85^{b}	44.39^{ab}	42.90	41.66	44.67	41.88	44.39^{ab}
f-test	ns	*	*	*	ns	ns	ns	ns	*
CV %	12.79	2.14	1.73	3.12	2.57	5.71	18.31	6.03	3.12

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

Table 3. Effect of combination fertilizer on leaf yield of cassava cv. Rayong9

Treatments	Leaf yield (kg ha^{-1})					
	6 months		8 months		12 months	
	fresh	dry	fresh	dry	fresh	dry
T1	143.50$^{b1/}$	42.55	128.75^{c}	32.75^{c}	1773.75^{ab}	429.78^{ab}
T2	178.50^{ab}	53.98	225.00^{ab}	59.88^{ab}	1396.25^{b}	362.55^{b}
T3	218.00^{ab}	62.73	288.75^{a}	74.30^{a}	2105.00^{ab}	475.63^{ab}
T4	258.75^{a}	73.73	287.50^{a}	70.85^{a}	2265.00^{a}	573.18^{a}
T5	197.50^{ab}	56.58	177.50^{bc}	46.43^{bc}	2116.25^{ab}	508.85^{ab}
f-test	*	ns	*	*	*	*
CV %	35.04	35.87	21.27	24.59	22.65	21.44

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

Table 4. Effect of combination fertilizer on rhizome yield of cassava cv. Rayong9

Treatments	Rhizome yield (kg ha^{-1})					
	6 months		8 months		12 months	
	fresh	dry	fresh	dry	fresh	dry
T1	951.25$^{b1/}$	451.85	871.25^{c}	352.30^{b}	1,142.50^{bc}	393.05^{bc}
T2	1,037.50^{ab}	438.00	1,012.50^{bc}	418.70^{b}	878.75^{c}	296.30^{c}
T3	1,037.00^{ab}	478.92	1,347.50^{a}	538.32^{a}	1,270.00^{ab}	443.40^{ab}
T4	1,184.75^{a}	526.50	1,130.00^{b}	436.75^{b}	1,513.75^{a}	506.00^{a}
T5	1,027.00^{ab}	453.75	1,127.50^{b}	432.02^{b}	1,205.00^{b}	406.32^{b}
f-test	*	ns	*	*	*	*
CV %	10.04	17.56	12.72	14.53	16.30	15.76

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

Table 5. Effect of combination fertilizer on stem yield of cassava cv. Rayong9

treatments	Stem yield (kg ha^{-1})					
	6 months		8 months		12 months	
	fresh	dry	fresh	dry	fresh	dry
T1	1,129.50^{c} [1/]	432.63^{b}	895.00^{c}	245.80^{d}	2,572.50^{b}	647.58^{b}
T2	1,381.00^{bc}	443.20^{b}	1,336.25^{bc}	380.30^{cd}	1,677.50^{c}	417.50^{c}
T3	1,940.25^{a}	609.43^{ab}	2,832.50^{a}	685.75^{a}	3,197.50^{ab}	806.70^{ab}
T4	2,230.00^{a}	763.23^{a}	2,111.25^{ab}	553.00^{ab}	3,775.00^{a}	876.35^{a}
T5	1,715.75^{ab}	635.13^{ab}	1,651.25^{bc}	444.80^{bc}	2,740.00^{b}	646.08^{b}
f-test	*	*	*	*	*	*
CV %	22.62	26.82	29.97	24.04	19.77	19.98

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

Regarding fresh and dry stem yield, T4 produced the highest yield (2,230.00 and 763.23 kg ha^{-1}), which was significantly different ($P < 0.05$) from control (fresh weight 1,129.50 and dry weight 432.63 kg ha^{-1}) and T2 (1,381.00 and 443.20 kg ha^{-1}), although no significant difference compared with T3 with fresh yield of 1940.25 and dry yield of 609.43 kg ha^{-1} and T5 were 1,715.75 and 635.13 kg ha^{-1} (Table 5). In economic yield as storage root yield, there were statistically significant differences in fresh and dry cassava root yield. T4 exhibited produce with the highest fresh cassava root yield at 12,238.12 kg ha^{-1} than other treatments but not significant in dry root weight with T2 and T5 which produced 4730.15 and 4671.17 kg ha^{-1}, respectively (Table 6).

Table 6. Effect of combination fertilizer on root yield of cassava cv. Rayong9

Treatments	Root yield (kg ha^{-1})					
	6 months		8 months		12 months	
	fresh	dry	fresh	dry	fresh	dry
T1	8,713.13^{c} [1/]	3,718.93^{c}	7,071.87^{d}	2,830.72^{d}	10,765.62^{d}	3,444.83^{c}
T2	10,810.00^{b}	4,730.15^{ab}	10,509.37^{b}	4,205.36^{bc}	11,034.38^{cd}	3,411.40^{c}
T3	10,381.25^{b}	4,367.25^{b}	15,937.50^{a}	6,626.50^{a}	12,393.75^{bc}	3,814.72^{c}
T4	12,238.12^{a}	5260.03^{a}	11,268.75^{b}	4,350.09^{b}	17,787.50^{a}	5,501.67^{a}
T5	10,768.12^{b}	4671.17^{ab}	9,278.12^{c}	3,790.46^{d}	13,884.38^{b}	4,584.41^{b}
f-test	*	*	*	*	*	*
CV %	24.84	26.74	22.74	25.59	23.76	26.03

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

At 8-months of harvest, the treatment using chemical fertilizer 15-15-15 only (T3) showed the highest yield in all components (leaf, stem, rhizome, storage root fresh weight, and storage root dry weight), with significant differences compared to the other treatments (Table 3, 4, 5 and 6), but there were no significant differences in leaf yield and stem yield between T3 and T4. In terms of economic yield, significant differences were observed. The results showed that the application of chemical fertilizer (T3) produced a higher root yield than the other treatments, with a fresh cassava root yield of 15,937.50 kg ha^{-1} and a dry root weight of 6,626.50 kg ha^{-1} (Table 6).

At the 10-month harvest of cassava, the application of chemical fertilizer combined with bio-fertilizer (T4) resulted in significantly higher yields throughout all yield components. T4 produced a fresh root yield of 17,787.50 kg ha^{-1} and a dry root yield of 5,501.67 kg ha^{-1}, which were significantly higher than the other treatments. The fresh root yields of the other treatments ranged from 10,765.62 to 13,884.38 kg ha^{-1} while the dry root yields ranged from 3,411.40 to 4,584.41 kg ha^{-1} (Table 6). Regarding leaf yield, the treatments that included chemical fertilizers (T3, T4, and T5) provided higher fresh and dry leaf yields compared to the control and the treatment with PGPR bio-fertilizer alone (Table 3).

The starch content of cassava harvested at 6, 8, and 10 months after planting was analyzed using the Reimann scale balance method. The fresh starch content varied at each harvest time. The treatment with reduced NPK combined with bio-fertilizer (T5) showed significantly higher starch content ($p \leq 0.05$) than the other treatments at both the 6 and 10-month harvests. The average fresh starch content was 27.14% at 6-months and 19.67% at 10-months. At the 8-month harvest, the non-fertilizer treatment (control) had a significantly higher starch content (22.22%) compared to the other treatments ($p \leq 0.05$) (Table 7).

Table 7. Effect of combination fertilizer on the starch content of cassava cv. Rayong9

Treatments	% starch		
	6 months	8 months	12 months
T1	25.01$^{b1/}$	22.22^{a}	16.50^{c}
T2	25.81^{ab}	20.86^{b}	16.55^{c}
T3	24.87^{b}	22.81^{a}	17.08^{c}
T4	26.06^{ab}	20.93^{b}	18.53^{b}
T5	27.14^{a}	20.26^{b}	19.67^{a}
f-test	*	*	*
CV %	10.62	11.02	8.87

[1/] Means of the same column followed by the same letter were not significantly different at the 0.05 level using Duncan's multiple range test. *= Significantly different at p<0.05, ns= non significantly different at p<0.05

Discussion

The study examining the combined application of PGPR-3 biofertilizer and chemical fertilizer on the growth and yield of cassava (cv. Rayong 9) in the Mabbon soil series demonstrates that biofertilizer significantly influences cassava growth. The findings suggest that the integrated use of NPK fertilizer and PGPR-3 biofertilizer resulted in significantly greater growth rates compared to both the control and the biofertilizer-only treatments, indicating that application of biofertilizer only is insufficient to achieve optimal cassava growth. These results are similar to those reported in the study by Meunchang *et al*. (2011), which found a 5.06% increase in cassava height when biofertilizer was applied in combination with chemical fertilizer. The treatments of chemical fertilizer only (437.5 kg ha^{-1}), chemical fertilizer (437.5 kg ha^{-1}) combined with biofertilizer (12.5 kg ha^{-1}), and chemical fertilizer (218.75 kg ha^{-1}) combined with biofertilizer (12.5 kg ha^{-1}) showed no significant differences in growth throughout the study period. This suggests that biofertilizer PGPR can enhance cassava growth, even when chemical fertilizer inputs are reduced. According to Safriani *et al*. (2020), potential plant growth-promoting rhizobacteria (PGPR) were successfully isolated and identified from cassava rhizosphere soil. These PGPR isolates were found to have potential as plant growth promoters, suggesting their possible application in the field as plant growth promoters or biocontrol agents.

The harvest yield of cassava cv. Rayong 9 at six months showed that T4 produced the highest fresh leaf and rhizome yields, significantly outperforming the control. This indicates that biofertilizers PGPR may promote early-stage growth through mechanisms as nitrogen fixation and phytohormone production, as reported by Vessey (2003). Amawan (2012) also reported that the Bio-fertilizer were increased plant growth and yield for cassava because Bio-fertilizer act as bio-fertilizer provide nitrogen via nitrogen fixation moreover phytostimulators can directly promote the growth of plant, usually by the production of hormones. Plant hormones are ethylene, jasmonic acid (JA) and salicylic acid (SA) Teaumroong *et al*. (2005). The significantly higher stem yield observed with T4 (Table 5) supports the potential of biofertilizers to stimulate vegetative growth (Mohanty *et al*., 2021). The integration of chemical fertilizer with PGPR biofertilizer (T4) significantly increased fresh cassava root yield (12,238.12 kg ha^{-1}), outperforming other treatments. This emphasizes the synergistic effects of biofertilizers in enhancing nutrient uptake and soil fertility (Bhattacharyya *et al*., 2016). However, dry root yield was not significantly different from treatments containing biofertilizer T2 and T5, suggesting a plateau in dry matter accumulation under similar nutrient conditions (Lin, 2023). This finding is similar to Wongsuwan *et al*. (2021) who reported that the impact of Bio-fertilizer on cassava yield is more than non-fertilizer. The cassava yield tends to increase by 16.2%. These findings demonstrate the potential of integrated fertilizer management for improving cassava productivity sustainably (Kumar *et al*., 2019). At eight months harvested, T3 (chemical fertilizer 15-15-15) produced the highest yields across all components, with fresh and dry root yields of 15,937.50 kg ha^{-1} and 6,626.50 kg ha^{-1}, respectively (Table 6), significantly surpassing other treatments. This reflects the efficiency of chemical fertilizers in providing readily available nutrients critical for root development (Lin, 2023). Comparable leaf and stem yields between T3 and T4 suggest biofertilizers in T4 support vegetative growth but offer less impact on mid-stage root yields, while T3 maximizes economic yield, integrating biofertilizers may enhance long-term soil fertility (Bhattacharyya *et al*., 2016). When harvested at ten months, the integration of chemical fertilizer with PGPR biofertilizer (T4) significantly outperformed other treatments in all yield components, including fresh and dry root yields of 17,787.50 kg ha^{-1} and 5,501.67 kg ha^{-1}, respectively. The enhanced performance of T4 play the symbiosis of biofertilizers, which enhance nutrient availability, promote root development, and support long-term soil fertility (Bhattacharyya *et al*., 2016). Interestingly, it was found that reducing the NPK fertilizer rate by half (12.5 kg ha^{-1}) combined with PGPR (T5) significantly increased cassava root yield at both 6- and 10-month harvest stages compared to applying the full rate of NPK fertilizer (T3, 437.5 kg ha^{-1}) only. This demonstrates the accumulative effect of PGPR in enhancing nutrient availability, root development, and nutrient use efficiency, compensating for reduced chemical fertilizer application. Similar results have been reported by Bhattacharyya *et al*. (2016) and Meunchang *et al*. (2011), where biofertilizers improved soil fertility and plant growth by promoting microbial activity and nutrient cycling. Integrating biofertilizers with reduced chemical fertilizers enhances root growth and nutrient uptake, boosting productivity with lower inputs (Calvo *et al*., 2014). PGPR also supports sustainable agriculture by improving yields, reducing chemical use, and mitigating environmental impacts (Andrade *et al*., 2023). This corresponds to integrated nutrient management, which optimizes yields, preserves soil fertility, and lowers costs (Srinivasarao *et al*., 2021). The analysis of starch content revealed variable responses among treatments. The higher starch content observed with reduced NPK combined biofertilizer (T5) at the 6 and 10-month harvests suggests that reduced nitrogen rate, coupled with enhanced microbial activity, may redirect resources toward starch accumulation. Similar findings were reported by Gao *et al*. (2020) that biofertilizer application improved carbohydrate metabolism and starch synthesis. Interestingly, the control treatment exhibited the highest starch content at 8 months, potentially due to stress-induced starch accumulation, as previously noted in cassava under suboptimal nutrient conditions (Janket *et al*., 2020).

These findings suggest that combining biofertilizers with reduced chemical fertilizers can be an effective strategy for achieving sustainable cassava production. Future studies should investigate the long-term impacts of biofertilizer application on soil fertility and its economic feasibility for large-scale cassava production.

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