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Nutrient Management Under Good Agricultural Practices for Sustainable Cassava Production in Northeastern Thailand

Derrick Keith Thompson [1], Ornprapa Thepsilvisut [1,*], Phanawan Imorachorn [1], Saowakol Boonkaen [1], Preuk Chutimanukul [1], Suthasinee Somyong [2], Wuttichai Mhuantong [3] and Hiroshi Ehara [4]

[1] Department of Agricultural Technology, Faculty of Science and Technology, Thammasat University Rangsit Center, Klong Luang 12120, Thailand; thompsonderrick30@gmail.com (D.K.T.); som.070244@gmail.com (P.I.); chomchom022@gmail.com (S.B.); preuk59@tu.ac.th (P.C.)
[2] National Omics Center, National Center for Genetic Engineering and Biotechnology (BIOTEC), National Science and Technology Development Agency (NSTDA), Klong Luang 12120, Thailand; suthasinee.som@biotec.or.th
[3] Enzyme Technology Research Team, Biorefinery Technology and Bioproduct Research Group, National Center for Genetic Engineering and Biotechnology (BIOTEC), Klong Luang 12120, Thailand; wuttichai.mhu@biotec.or.th
[4] International Center for Research and Education in Agriculture, Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan; ehara@agr.nagoya-u.ac.jp
* Correspondence: ornprapa@tu.ac.th

Abstract: Emphasis on sustainable cassava production is increasing, with aims to increase the net income of cassava farmers in an ecologically friendly way. This study examined the optimization of soil fertilizer management at two research locations (Nampong and Seungsang) in northeastern Thailand. The experiment was conducted as a randomized complete block design with five replications. Eight different fertilizer management protocols consisted of (1) no fertilizer application (control), (2) the recommended dosage of chemical fertilizer (RDCF), (3) 3.12 t ha^{-1} of chicken manure (CM), (4) 937.5 L ha^{-1} of swine manure extract (SME), (5) CM + SME, (6) ½ RDCF + ½ CM, (7) ½ RDCF + ½ SME, and (8) CM + PGPR (stake soaking with PGPR solution). At the Nampong site, the application of CM + PGPR has the most potential for increasing the cassava yield in terms of the fresh tuber yield when compared with no fertilizer and RDCF applications. At the Seungsang site, the application of CM gave the high fresh tuber yield, without significant differences from RDCF applications. Furthermore, compared to the RDCF treatment, both soil fertilizer management protocols produced positive marginal rate of return values, showing clear potential for contributing to sustainable cassava production.

Keywords: cassava; sustainable production; marginal rate of return; microbiome; fresh storage root yield

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1. Introduction

Sustainable cassava (*Manihot esculenta* Crantz) production is increasingly becoming a priority for tropical climate farmers worldwide [1]. The development of production models that help to maintain ecosystem functioning while generating worthwhile profits can be challenging because of the many factors involved in agroecosystem management. Farmers are faced with the need to maintain or improve yields on soils that are being degraded from cultivation practices and the overuse of synthetic fertilizers and pesticides [2,3]. Increasing synthetic fertilizer costs are making such a task continually more important as they often increase at rates faster than those of cassava crop selling prices, making synthetic fertilizer use less profitable than before [4].

Farmers often put little significance on overall soil health and the use of ecosystem services from soil microbes, microinvertebrates, macroinvertebrates, and other members of the soil food web [5]. This may be due to the fact that the benefits of these ecosystem services often take long periods to observe and do not always result in direct yield increases. Indirect benefits may include pest and disease suppression through competition, beneficial metabolite production, phytohormone modulation, and increases in soil nutrient availability [6]. The sustainability of cassava production going into the future will depend on more holistic approaches, which need to be studied to gain more understanding of how to apply them in real farm situations [7].

Thailand cassava production scored very well on the Social Life Cycle Assessment (SLCA) scale, an internationally recognized social sustainability assessment tool used to inform decisions on sustainable development [8]. Current trends in Thailand crop growth patterns suggest that cassava farming is becoming more popular in Thailand, partly due to the plant's ability to grow in poor soils and relatively low susceptibility to drought, an effect of climate change and unsustainable land use practices [9]. Climate change analysis predicts that the northeastern part of Thailand will have the greatest increase in cassava-growing season temperatures, and the cassava yield is projected to drop in this region [10]. Like any crop, when cultivated on the same land for long periods, cassava can deplete available nutrients, and production practices tend to erode soils, a fact that hinders its potential for ecological sustainability [11–13]. More ecologically friendly soil management practices may be used to mitigate the negative effects that these upcoming climate changes will have on northeastern Thailand cassava production.

Several studies have demonstrated yield advantages from incorporating farm wastes, organic fertilizers, and other amendments into cassava field soils [14,15]. Nutrients and organisms in manures can be beneficial for cassava production, both used solely and in combination with synthetic fertilizer [4,16–19]. Incorporation of both animal and green manures into soil can increase soil organic matter (SOM), which has been shown to buffer the adverse effects of extreme weather events, including those causing both excess water and drought [20,21]. Manure application can also improve soil fertility maintenance, an important aspect of farm sustainability [22]. While the nutrients in field soils and manures can be easily assessed, the microorganisms involved in these agroecosystems exist in dynamic symbiotic relationships that take place in extremely complex soil food webs [23]. Although the exact biochemical mechanisms controlling microbial–plant interactions are difficult to pinpoint, they can still be used in efforts to make cassava production more economically and ecologically sustainable. This can be conducted by limiting expensive off-farm inputs and improving overall agroecosystem functioning [24].

Many studies that involve limiting synthetic fertilizer and pesticide use have been conducted on organic cassava production, due to the strict organic production requirements and the higher selling price of cassava products when compared with those of non-organic cassava, making the endeavor financially more worthwhile [25,26]. Good agricultural practice (GAP) guidelines are based on many of the same sustainability principles as organic guidelines but are more lenient. While smallholding non-organic cassava farmers, who manage areas less than 10 ha [27] may not see organic production as feasible for their farming systems, GAPs may be adopted more if their profitability can be communicated to farmers.

Problems with cassava production profitability in Thailand have been linked to factors like volatile market prices, disease outbreaks, and increases in the costs of off-farm inputs, particularly synthetic fertilizer and pesticide products [25]. The presence of intensive livestock farming in many regions of Thailand provides an opportunity to replace synthetic fertilizer use with that of manure, without many additional transport costs. Farmyard

manure (FYM) and other agricultural byproducts, like green manure, also tend to have less price fluctuations. Some of the literature has reported popular organic amendments used in cassava production. In northeastern Thailand, chicken manure, cassava starch production waste [28], and liquid swine manure extract [29] have been particularly useful and their application has been observed to promote a greater fresh tuber yield, with values that were not significantly different from those resulting from synthetic fertilizer application at recommended doses. In some trials, the use of these organic amendments in combination with synthetic fertilizer application allowed for synthetic fertilizer rates to be reduced by half. Therefore, the promotion of using FYM or locally derived agricultural byproducts for amending cassava system soils may benefit farm profitability and the overall sustainability of cassava-based cropping systems.

Efforts are also underway to enhance cassava growth via the pre-planting treatment of stem cuttings by soaking with rhizobacteria that are known to be plant growth-promoting rhizobacteria, or PGPRs [30]. Even after decades of study, research teams from different regions continue to search for PGPR strains that are appropriate for use in their respective local environmental conditions [31–33]. Since cassava is the third most important source of calories in tropical and subtropical regions, after rice and corn, many government agencies have been employed to increase its productivity through improved farming methods in order to meet the rising demand for this root tuber crop. Yields have increased over time, mainly due to improved varieties and better agricultural practices. The average cassava yield in Thailand from 2014 to 2024 was estimated to be 19.4–22.6 t ha^{-1} [34–36]. This yield has been exceeded in studies that provided suitable growth conditions. For instance, in Thailand, optimal irrigation resulted in a yield of 56.9 t ha^{-1} from the Rayong 9 variety [37].

Better economic opportunities for farmers can be provided by formulating suitable efficient nutrient management practices to maximize production to input cost rations. This is exemplified by the study of Aravind et al. [38] in India which reported that an optimal nutrient application (25 t ha^{-1} of farmyard manure + 100% recommended dose of chemical fertilizer + cassava booster spray) produced 33.27 t ha^{-1} from the Vellayani Hraswa variety, which could be harvested in 6–7 months instead of the typical 9–24 months. These simple adjustments in crop management, using strategies that are suitable for each region under cultivation, have great potential for increasing production while also improving the livelihood of cassava farmers.

Given this background, and with the overall goal of developing guidelines for increasing cassava production's economic, ecological, and social sustainability, an integrative study was conducted to compare the use of chemical, chicken manure, swine manure, and PGPR-strain biological fertilizers in eight nutrient management treatments to determine their effects on cassava growth, yield components, and profitability, while also testing for correlations with nutrient uptake in an attempt to identify mechanisms by which growth and yield are affected by these different treatments. These eight management protocols were conducted at both of the two different field sites in Seungsang district, Nakhon Ratchasima province, and Nampong district, Khon Kaen province, two regions in northeastern Thailand. The findings of the current study will add to a bank of applicable knowledge that can be further tested and used for increasing the efficiency of cassava production.

2. Materials and Methods

2.1. Research Location and Soil Characteristics

Field trials were conducted at two locations in northeastern Thailand, the current dominant cassava-growing region of the country. The first field site is located in Nampong district, Khon Kaen province (Latitude: 16.823750, Longitude: 102.979556). The soil type belongs to the Nam Phong soil series (Loamy, siliceous, isohyperthermic Grossarenic

Haplustalfs). The soil of the experimental field has a sandy texture [21]. The chemical properties of the experimental plot's soil were as follows: pH 5.60 (moderately acidic), EC 0.12 dS m^{-1} (non-saline), 0.46% organic matter (very low), 0.02% total N (very low), 9.00 mg kg^{-1} available P (low), and 34.00 mg kg^{-1} available K (low). Throughout the experimental period, the study site's growth season temperatures averaged 27.1 °C, with a normal range of 23.0 °C to 30.5 °C.

The second field site is located in Seungsang district, Nakhon Ratchasima province (Latitude: 14.490722, Longitude: 102.508167). The soil type belongs to the Chokchai soil series (very fine, kaolinitic, isohyperthermic Rhodic Kandiustox). The soil of the experimental field has a silty clay texture [39]. The chemical properties of the experimental plot's soil were as follows: pH 6.15 (slightly acidic), EC 0.14 dS m^{-1} (non-saline), 2.98% organic matter (medium), 0.15% total N (low), 25.33 mg kg^{-1} available P (high), and 40.65 mg kg^{-1} available K (low). The temperatures of the study site during the growing season typically ranged from 23.5 °C to 29.5 °C, with an average of 26.8 °C throughout the experimental period.

Both locations are owned by smallholder farmers (less than 10 ha) who have been growing cassava for more than 5 years. The Nam Phong soil series in Nampong district and the Chokchai soil series in Seungsang district are two of the most studied soil series in Thailand for cassava cultivation [21,40–42].

The organic soil amendments used in this experiment were chicken and swine manure. The chemical properties of the chicken manure were as follows: pH 7.69, EC 7.29 dS m^{-1}, 41.88% organic matter, 2.67% total N, 0.97% total P, 2.24% total K, and a C/N ratio of 8.38. The swine manure chemical properties were as follows: pH 7.22, EC 4.99 dS m^{-1}, 44.79% organic matter, 1.22% total N, 1.25% total P, 1.05% total K, and a C/N ratio of 21.16 [43].

2.2. Plant Materials and Experimental Design

The commercial Rayong 72 cassava variety, which is well known for its high yield, high starch quality, good stem quality, and resistance to drought [44], was utilized because planting was planned for March, which is considered part of the dry season in Thailand. This variety is also known to perform well in the early rainy season (in May) and has been reported to have drought tolerance during a 4-month drought period in the mid-growth stage, as shown by the high storage root yield and high leaf retention [45].

The experiment was arranged as a randomized complete block design (RCBD) with five replicates. At the two study sites, namely Nampong and Seungsang, the eight different fertilizer management protocols conducted were as follows: (1) no fertilizer application (control), (2) recommended dosage of chemical fertilizer based on soil analysis (RDCF) [46], (3) 3.12 t ha^{-1} of chicken manure (CM), (4) 937.5 L ha^{-1} of swine manure extract (SME), (5) 3.12 t ha^{-1} of chicken manure + 937.5 L ha^{-1} of swine manure extract (CM + SME), (6) 50% of the recommended dose of chemical fertilizers + 1.56 t ha^{-1} of chicken manure (½ RDCF + ½ CM), (7) 50% of the recommended dose of chemical fertilizers + 468.8 L ha^{-1} of swine manure extract (½ RDCF + ½ SME), and (8) 3.12 t ha^{-1} of chicken manure + stake soaking with plant-growth-promoting rhizobacteria (PGPR) solution (CM + PGPR). The description of the macronutrient contents from each fertilizer application is shown in Table 1.

After plowing using a 7-disc plough, 40 plots were prepared at both study sites, each having dimensions of 5 m wide by 6 m long (30 m^2). Rayong 72 cassava stakes, aged 12 months and 25 cm long, were planted at 1 m × 1 m standard inter- and intra-spacing (20 plants $plot^{-1}$). For the fertilizer application, chicken manure was produced from a mixture of chicken excrement, feathers, and rice husk bedding material, all of which was composted in sacks for one month before use. To limit erosion and volatilization, chicken

manure compost was incorporated into the soil by digging holes to a depth of 10 cm and thoroughly mixing the chicken manure compost into the soil two weeks before planting. These positions were marked so that cassava stalks could be planted directly into them two weeks later. The swine manure compost extract was made by soaking dry manure compost in tap water at a ratio of manure compost to water of 1:10, by weight. This procedure was adapted from the work reported by Kanto et al. [28]. The compost was soaked for 24 h, after which the water was filtered twice using cheesecloth. The resulting solution was then applied manually by misting the underside of cassava plant leaves to maximize uptake by stomata. This treatment was conducted monthly, from 2 to 5 months after planting (MAP), for a total of 4 applications. A chemical fertilizer combination was used to fulfill the recommended soil nutrient requirements based on soil analysis. In a single application, the fertilizer was incorporated into soil on both sides of each cassava plant 1 MAP. The PGPR-3 biofertilizer product was used to soak cassava stalks for 30 min before planting. The powdered product was mixed with tap water at a ratio of 1 kg of product to 20 L of water per hectare of planting area. This product was applied only once. Plants were irrigated equally by drip irrigation in all plots, as required to maintain vigorous growth. Specifically, the crops were partially irrigated during the rainy season and fully irrigated during the dry season. Natural extracts were sprayed to eliminate both diseases and insects when needed, and mechanical methods eliminated weeds every month until harvesting.

Table 1. Proportion of primary elements when various fertilizers were applied for each treatment.

Fertilizer Treatment	Application Rates	Soil Application			Foliar Application		
		N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Control (no fertilizer)	-	-	-	-	-	-	-
RDCF	CF 16-8-8 at 312.5 kg ha^{-1} CF 0-0-60 at 43.8 kg ha^{-1}	50.00	25.00	50.00	-	-	-
CM	CM 3125.0 kg ha^{-1}	83.11	30.31	70.00	-	-	-
SME	SME 937.5 L ha^{-1} × 4 times	-	-	-	4.58	4.69	3.94
CM + SME	CM 3125.0 kg ha^{-1} SME 937.5 L ha^{-1} × 4 times	83.11	30.31	70.00	4.58	4.69	3.94
½ RDCF + ½ CM	CF 16-8-8 at 156.3 kg ha^{-1} CF 0-0-60 at 21.9 kg ha^{-1} CM 156.3 kg ha^{-1}	66.72	27.66	60.00	-	-	-
½ RDCF + ½ SME	CF 16-8-8 at 156.3 kg ha^{-1} CF 0-0-60 at 21.9 kg ha^{-1} SME 468.8 L ha^{-1} × 4 times	25.00	12.50	25.00	2.29	2.34	1.97
CM + PGPR	CM 3125.0 kg ha^{-1} Stake soaking with PGPR	83.11	30.31	70.00	-	-	-

RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria (with PGPR-3 containing two types of bacteria: *Azospirillum brasilense* and *Gluconacetobacter diazotrophicus*).

2.3. Data Collection and Analysis

2.3.1. Plant Growth

Five randomly selected samples from the middle rows per each experimental plot were collected to determine vegetative growth, including plant height, plant width, and leaf number at 2, 4, 6, and 8 MAP. The plant height was measured using measuring tape, from soil level at the base of the plant to the terminal bud, while the plant width was collected as the average width measured at the widest point 90° to the plant. In addition, the leaf chlorophyll was measured from the central lobe of the fourth expanded leaf from

the top using a chlorophyll meter (SPAD 502Plus, Konica Minolta, Inc., Tokyo, Japan) every 2 months until 8 MAP.

2.3.2. Yield and Starch Content

Harvesting was conducted at 10 MAP, and the fresh tuber yield and starch content were recorded. After uprooting, the stumps were cut at 20 cm above the soil surface level, and then stumps and tubers were washed in running tap water to remove any adhering soil particles. The fresh mass of tubers was recorded in the field with a digital balance, and these values were used for the fresh tuber yield. The starch content of each sample was measured using the specific gravity method, which is based on the correlation between the starch content and the specific gravity of tubers using a Reimann scale balance according to Bainbridge et al. [47]. Briefly, the tubers were washed to remove excess soil, homogenized, and a 5 kg subsample per sample of fresh tubers was weighed in air and placed in water to obtain the specific gravity (SG), which is equal to 5 kg/(5 kg FWW) where FWW is the weight measured on a hydrostatic scale after submerging the tubers in water. Based on the obtained measurement results, the cassava density and the dry matter content are calculated. The cassava starch value is obtained by subtracting the content of non-starchy components from the dry matter content.

2.3.3. Sample Preparation and Nutrient Analysis

The leaf, stem, and tuber samples were chopped and dried in an oven (Thermotec 2000, Contherm Scientific Ltd., Lower Hutt, New Zealand) at 60 °C until constant sample weights were achieved. The samples were ground and then sieved through a 2 mm sieve before analysis of N, P, and K contents on a % dry weight basis. To determine the total N content, the Kjeldahl method was used, and for determining the P and K contents in the plant tissues, the standard protocol of the Association of Official Analytical Chemists (AOAC) [48] was followed with some modifications. Each sample, weighing 1.0 g, was digested in 15 mL of nitric-perchloric acid (HNO_3:$HClO_4$ at a ratio of 2:1 v/v). After digestion, the samples were diluted with distilled water until they reached a volume of 50 mL and were then stored in plastic tubes at room temperature. The P content in the diluted samples was analyzed by using a spectrophotometer (UV-1280, Shimadzu, Kyoto, Japan) at 420 nm. In contrast, the K quantification was analyzed using an atomic absorption spectrometer (PinAAcle900F, Perkin-ESMEer, Waltham, MA, USA).

2.3.4. Economic Analysis

Economic feasibility of the fertilizer management for cassava production in two study sites was determined by calculating net benefit and conducting an economic cost and benefit analysis, based on the partial budget techniques described by the International Maize and Wheat Improvement Center (CIMMYT) [49]. Prevailing market prices for inputs during planting time and outputs during harvesting time were used in calculations. All costs and benefits were converted to USD per hectare. The main equations used during the economic analysis by partial budgeting included the following:

$$TVC = FFC + AC + HPTC \quad (1)$$

$$GFB = AAY \times CFP \quad (2)$$

$$NB = (0.9 \times GFB) - (1.1 \times TVC) \quad (3)$$

where

TVC = total variable cost in USD ha^{-1};
FFC = fertilizer field cost in USD ha^{-1};

AC = fertilizer application cost in USD ha^{-1};
HPTC = harvesting, packing, and transport cost of fresh tubers in USD ha^{-1};
GFB = gross field benefit in USD ha^{-1};
AAY = adjusted average yield, which is 90% of the average yield in kg $plant^{-1}$ × planting rate (plant ha^{-1});
CFP = cassava field price in USD kg^{-1};
NB = net benefit in USD ha^{-1}.

After the TVC and GFB per ha were calculated for the treatments, dominance analysis was performed using the methods described by the CIMMYT [49]. Dominance analysis determined which treatments were dominated, meaning that they have net benefits that are less than or equal to those of treatments that have lower costs. The TVC and NB values of non-dominated treatments were then used for marginal rate of return (MRR) analysis to determine how much farmers would benefit when switching between economically beneficial treatments with a sequentially greater TVC. Non-dominated treatments were ranked from the lowest to highest TVC. MRR analysis was performed between treatment pairs, in order from treatments that had the lowest to highest TVC. The MRR calculation for each treatment pair was conducted with the following formula:

$$MRR = [(\Delta NB)/\Delta TVC] \times 100\% \quad (4)$$

where

MRR = marginal rate of return in percent;
NB = net benefit in USD ha^{-1};
TVC = total variable cost in USD ha^{-1}.

Using this method, a 100% MRR means that for every USD invested in switching between treatment pairs, there would be a USD 1 return on investment.

In order to make recommendations from economic analysis data, a minimum acceptable MRR value is required. In this study, a minimum acceptable MRR of 100% was chosen. This means that if a soil and plant management treatment results in an MRR of 100% or higher, that treatment would be recommended to farmers.

2.4. Statistical Analysis

Experimental treatment effects were analyzed using a randomized complete block design with five replications, and the statistical analysis of data collected was carried out using standard analysis of variance by using IBM SPSS Statistics, Version 26.0 software (IBM Crop., Armonk, NY, USA). To determine the significance of the difference between the means, Duncan's multiple range test was computed at the 0.05 probability level ($p \leq 0.05$). A correlation heatmap was made using Python visualization (version 3.11.7) to facilitate visual inspection for evaluating the relationships between different parameters at the two study sites.

3. Results

3.1. Plant Growth and Chlorophyll Content

At the two study sites, different soil management treatments were shown to affect traits related to cassava plant growth, including plant height and plant width, recorded at 2, 4, 6, and 8 MAP (Tables 2 and 3). At the Nampong site, different nutrient management treatments resulted in significantly different plant height at 4 MAP, with the plants from the ½ RDCF + ½ CM treatment having significantly greater height than those from the SME, ½ RDCF + ½ SME, and control treatments. At 2, 6, and 8 MAP, however, no significant differences in height were observed among the treatments. The plant height of cassava

at 2, 6, and 8 MAP was shown to be between 62.80 and 74.02 cm, 191.80 and 225.68 cm, and 210.00 and 240.66 cm, respectively (Table 2). At the Seungsang site, there were no significant differences between the plant height resulting from different treatments during any of the data collection periods. The cassava height at 2, 4, 6, and 8 MAP was in the range of 48.66–56.66 cm, 123.72–138.46 cm, 178.12–194.16 cm, and 181.34–205.60 cm, respectively (Table 3).

Table 2. Plant height and plant width of cassava at different months after planting (MAP) exposed to different fertilizer applications at Nampong site.

Treatment	Plant Height (cm)				Plant Width (cm)			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	66.78	156.98bcd [1]	202.34	232.66	87.14	100.32	79.32	58.64
RDCF	71.60	170.00ab	225.68	240.66	88.30	101.32	72.64	53.32
CM	65.58	167.34abc	219.98	236.68	89.54	102.14	73.34	62.64
SME	63.80	153.00d	191.80	222.00	82.74	94.32	75.34	70.68
CM + SME	68.46	166.66abc	216.12	231.34	89.76	102.00	72.00	51.36
½ RDCF + ½ CM	74.02	175.00a	210.66	239.00	94.26	101.34	75.02	59.32
½ RDCF + ½ SME	66.40	155.32cd	196.92	210.00	87.64	94.34	67.48	59.34
CM + PGPR	62.80	163.34a–d	217.32	234.66	85.26	98.32	77.30	65.34
Significance	ns	**	ns	ns	ns	ns	ns	ns
CV (%)	9.68	5.65	10.79	9.59	7.24	6.67	10.92	18.03

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; ** = statistical different at 99% level of confidence. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 3. Plant height and plant width of cassava at different months after planting (MAP) exposed to different fertilizer applications at Seungsang site.

Treatment	Plant Height (cm)				Plant Width (cm)			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	50.94	128.54	186.92	197.00	100.48	157.92	161.78	134.92
RDCF	55.26	138.46	194.16	205.60	113.54	163.20	157.86	137.40
CM	54.72	137.00	188.48	197.28	107.26	160.06	151.40	126.18
SME	48.66	123.72	178.12	181.34	93.52	146.34	147.44	117.16
CM + SME	53.68	132.80	184.78	191.48	114.08	160.94	157.06	132.80
½ RDCF + ½ CM	53.00	130.26	177.94	184.06	105.14	149.26	139.92	108.74
½ RDCF + ½ SME	53.52	132.34	182.00	189.68	109.60	152.80	153.66	123.66
CM + PGPR	56.66	133.00	185.20	197.00	99.26	149.92	156.12	129.52
Significance	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	11.12	8.82	7.21	7.79	11.77	8.11	7.82	13.23

ns = no significant difference. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

For the plant width at both study sites, different soil management treatments did not significantly affect the plant width recorded at 2, 4, 6, and 8 MAP. At the Nampong site, the SME treatment resulted in the greatest plant width at 8 MAP (70.68 cm), while the CM + SME treatment resulted in the lowest width (51.36 cm) (Table 2). At the Seungsang site, cassava at 8 MAP grown under the RDCF treatment tended to result in the greatest plant width (137.40 cm), while the ½ RDCF + ½ CM treatment resulted in the lowest (108.74 cm) width (Table 3).

The leaf number of cassava plants at both sites tended to increase at 4 MAP and gradually decrease with plant age (Tables 4 and 5). At the Nampong site, the CM + PGPR

treatment resulted in significantly greater leaf number than the ½ RDCF + ½ CM, CM, and control treatments at 4 MAP. The CM + PGPR treatment also resulted in significantly greater leaf number than the CM + SME, ½ RDCF + ½ SME, ½ RDCF + ½ CM, CM, and control treatments at 8 MAP (Table 4). At the Seungsang site, the control and RDCF treatments resulted in the greatest leaf number at 6 MAP, both with an average value of 76.40 leaves, significantly higher than that resulting from the ½ RDCF + ½ CM treatment (Table 5). At 8 MAP, the RDCF treatment also resulted in the greatest leaf number (48.06 leaves), which was not significantly different from that resulting from the control and CM + PGPR treatments, while the lowest leaf number of cassava was observed in the SME treatment (Table 5).

Table 4. Leaf number and SPAD values of cassava at different months after planting (MAP) exposed to different fertilizer applications at the Nampong site.

Treatment	Leaf Number				SPAD			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	38.88	57.88c [1]	35.20	28.36cd	38.88b	57.88b	35.20b	28.36d
RDCF	45.56	64.70ab	30.68	32.60abc	45.56a	64.70a	30.68c	32.60bcd
CM	40.42	63.06bc	30.00	29.42bcd	40.42b	63.06a	30.00c	29.42cd
SME	45.08	68.22ab	31.34	35.06ab	48.22a	47.54c	46.72a	35.82abc
CM + SME	44.72	63.66ab	30.14	24.54d	47.04a	46.98c	47.98a	35.20abc
½ RDCF + ½ CM	38.52	57.74c	28.94	27.40cd	46.76a	46.36c	44.40a	38.98ab
½ RDCF + ½ SME	45.18	64.88ab	29.74	26.40d	47.74a	46.00c	46.72a	40.58a
CM + PGPR	40.94	69.00a	34.82	35.68a	45.84a	47.92c	44.28a	36.50ab
Significance	ns	**	ns	**	**	**	**	**
CV (%)	16.13	6.36	13.05	14.02	8.20	7.34	7.32	12.41

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; ** = statistical different at 99% level of confidence. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 5. Leaf number and SPAD values of cassava at different months after planting (MAP) exposed to different fertilizer applications at the Seungsang site.

Treatment	Leaf Number				SPAD			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	47.54	107.06	76.40a [1]	46.34ab	44.44	42.80bc	41.08ab	35.50bc
RDCF	50.66	111.58	76.40a	48.06a	43.56	45.44a	42.70a	38.42ab
CM	49.86	108.86	64.00ab	34.06cd	43.44	41.64c	39.18b	33.98c
SME	45.94	102.86	68.26ab	28.54d	39.86	42.92bc	43.20a	38.90a
CM + SME	52.40	114.52	69.46ab	40.68bc	42.76	42.42bc	40.70ab	37.80ab
½ RDCF + ½ CM	49.20	107.42	57.00b	35.14cd	40.56	41.64c	41.94a	35.64abc
½ RDCF + ½ SME	50.00	107.54	67.60ab	40.12bc	41.68	44.66ab	42.22a	37.04abc
CM + PGPR	47.68	104.82	67.80ab	44.28ab	39.92	42.84bc	40.90ab	38.66ab
Significance	ns	ns	*	**	ns	**	*	*
CV (%)	9.95	6.35	13.03	12.74	9.37	3.79	4.26	6.06

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; *, ** = statistically different at 95% and 99% level of confidence, respectively. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Nutrient management significantly affected chlorophyll content at both study sites (Tables 4 and 5). At the Nampong site, the control and CM treatments resulted in the lowest SPAD values at 2 MAP, with SPAD values of 38.88 and 40.42, respectively. During the other two times measured, 4 and 6 MAP, the highest SPAD values resulted from the

RDCF and CM treatments at 4 MAP, while the lowest SPAD values resulted from the RDCF and CM treatments at 6 MAP. In addition, at 8 MAP, the lowest SPAD value was observed in the control treatment (Table 4). At the Seungsang site, the RDCF treatments resulted in the highest SPAD value (45.44) at 4 MAP, but it was not significantly different from the ½ RDCF + ½ SME treatment (44.66). The SME treatment resulted in the highest SPAD values at 6 and 8 MAP, with SPAD values of 43.2 and 48.9, respectively, which were significantly higher than those resulting from the CM treatment at 6 MAP and the CM and control treatments at 8 MAP, respectively (Table 5).

3.2. Yield and Starch Content

Cassava tubers from both the Seungsang and Nampong study sites were harvested 10 MAP, and it seems that the cassava tubers at the Nampong site tended to be longer than those at the Seungsang site, (Figure 1).

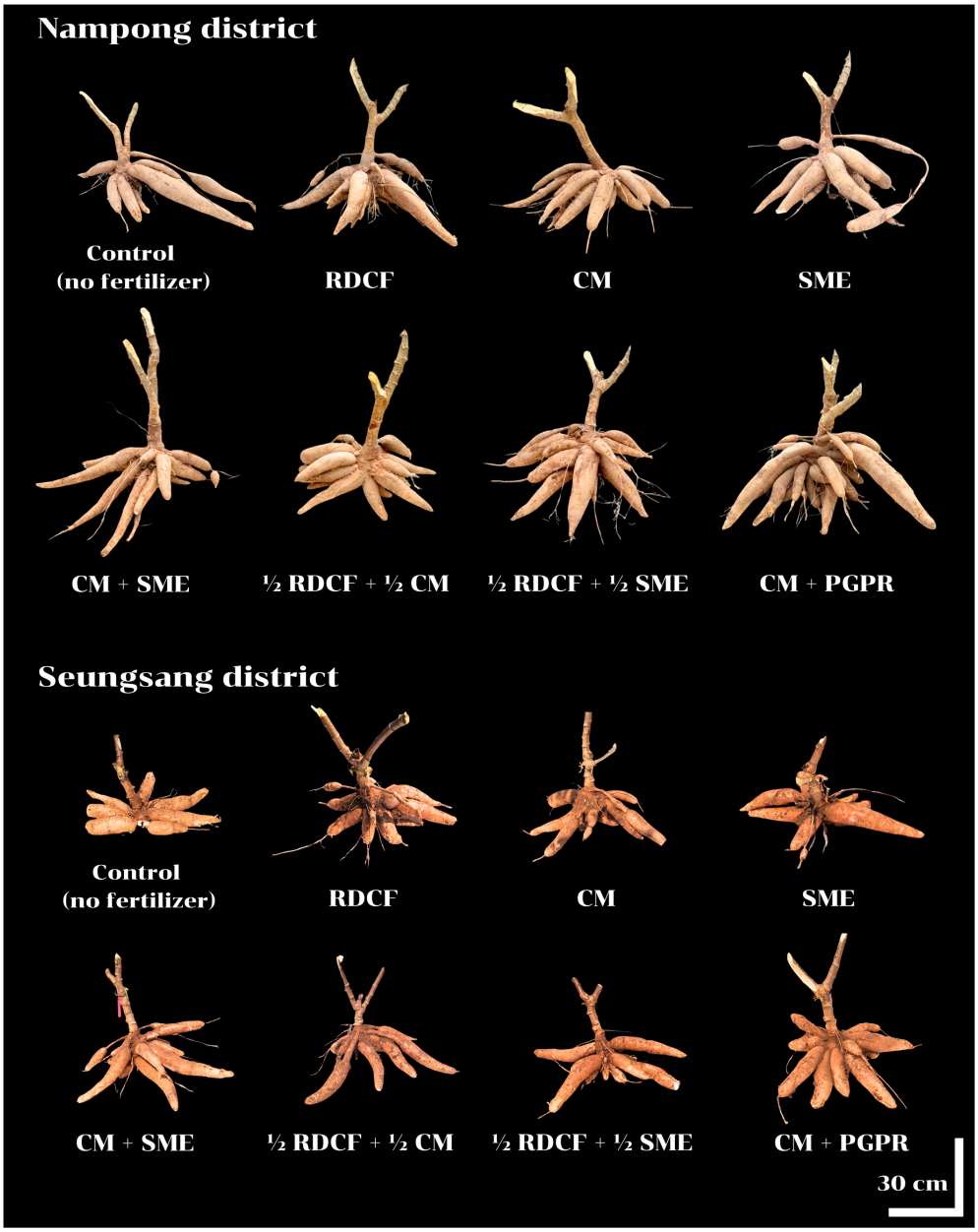


Figure 1. Tuber characteristics of cassava at 10 months after planting (MAP), when exposed to different fertilizer applications at two sites in northeastern Thailand. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

At the Nampong site, different fertilizer management had an influence ($p \leq 0.05$) on the fresh tuber yield. The highest fresh tuber yield was observed resulting from the CM + PGPR treatment (6.22 kg plant^{-1}) and was significantly greater than that resulting from all the other treatments. The CM and CM + SME treatments resulted in the next greatest average fresh tuber yield increase (4.79 kg plant^{-1}), but these values were not significantly different from the lowest fresh tuber yield, which resulted from the control treatment (4.25 kg plant^{-1}) (Table 6). At the Seungsang site as well, different fertilizer management had an influence ($p \leq 0.05$) on the fresh tuber yield. The highest fresh tuber yield was observed resulting from the CM treatment (5.19 kg plant^{-1}), followed by that resulting from the CM + SME treatment (5.11 kg plant^{-1}). These top two yield values were not significantly different, and they also were not significantly different from the yield values resulting from the RDCF, ½ RDCF + ½ SME, and CM + PGPR treatments, which were 4.66, 4.66, and 4.53 kg plant^{-1}, respectively (Table 6). The starch content of cassava grown at both study sites was revealed to not be influenced significantly by fertilizer management ($p > 0.05$). Starch content resulting from the different fertilizer management treatments at the Seungsang and Nampong sites was between 28.23–29.93% and 26.10–29.47%, respectively (Table 6).

Table 6. Fresh tuber yield and starch content of cassava exposed to different fertilizer applications at two sites in northeastern Thailand.

Treatment	Nampong		Seungsang	
	Fresh Tuber Yield (kg plant^{-1})	**Starch Content (%)**	**Fresh Tuber Yield (kg plant^{-1})**	**Starch Content (%)**
Control (no fertilizer)	4.25b [1]	28.23	3.70b	29.47
RDCF	4.72b	28.50	4.66ab	26.13
CM	4.79b	29.23	5.19a	26.40
SME	4.56b	28.47	4.02b	27.00
CM + SME	4.79b	29.93	5.11a	26.10
½ RDCF + ½ CM	4.65b	28.43	4.04b	29.25
½ RDCF + ½ SME	4.61b	28.80	4.66ab	29.47
CM + PGPR	6.22a	29.63	4.53ab	29.07
Significance	**	ns	*	ns
CV (%)	11.90	2.80	16.21	6.28

[1] Means with different letters in the same column indicate significant differences according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant different; *, ** = statistically different at 95% and 99% level of confidence, respectively. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

3.3. Macronutrient Concentrations in Plant Parts

Significant effects of soil nutrient management on the macronutrients in the leaf, stem, tuber (root), and whole-plant tissue of cassava at both study sites were observed (Tables 7 and 8). At the Nampong site, different nutrient management treatments had significant effects ($p \leq 0.05$) on the N, P, and K accumulation in cassava plants. The CM + SME, CM + PGPR, and CM treatments resulted in the top three total N values in leaves, with averages of 3.67%, 3.57%, and 3.53%. This was significantly greater than the total N resulting from the control, RDCF, ½ RDCF + ½ CM, and SME treatments. In whole-plant tissues, the CM + PGPR, CM, and CM + SME treatments resulted in the top three N concentrations, with 1.69%, 1.65%, and 1.63%, respectively (Table 7).

Total P concentrations in leaf tissues were highest in plants resulting from the CM (0.110%) and SME (0.107%) treatments, followed by plants resulting from the RDCF (0.100%) and CM + PGPR (0.100%) treatments. The lowest total P concentrations in leaves resulted from the control treatment (0.057%). In stem tissues, the highest total P concentrations

resulted from the RDCF (0.077%) and CM (0.073%) treatments, without any significant difference between these values and those resulting from the SME treatment (0.060%). In tuber tissues, the highest total P concentrations resulted from the ½ RDCF + ½ CM (0.027%), ½ RDCF + ½ SME (0.030%), and CM + PGPR (0.030%) treatments, which were significantly higher than those from all other treatments. In the whole plant, the highest total P concentrations resulted from the RDCF (0.063%) and CM (0.070%) treatments, without any significant difference between these values and those resulting from the SME, ½ RDCF + ½ SME, and CM + PGPR treatments (0.060%) (Table 7).

Table 7. Macronutrient content in different plant parts of cassava exposed to different fertilizer applications at the Nampong site.

Treatment	Total N (%)				Total P (%)				Total K (%)			
	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant
Control	2.97d [1]	0.93	0.23	1.38f	0.057d	0.047b	0.020b	0.040c	0.41d	0.28d	0.34bc	0.34d
RDCF	3.27c	1.00	0.33	1.54cde	0.100ab	0.077a	0.020b	0.063a	0.37d	0.61a	0.37b	0.45c
CM	3.53ab	1.20	0.20	1.65ab	0.110a	0.073a	0.020b	0.070a	0.58b	0.53ab	0.45a	0.52b
SME	3.23c	1.00	0.30	1.51de	0.107a	0.060ab	0.020b	0.060ab	0.42cd	0.59ab	0.32c	0.44c
CM + SME	3.67a	0.97	0.27	1.63abc	0.087bc	0.050b	0.020b	0.050b	0.47c	0.50b	0.25de	0.41c
½ RDCF + ½ CM	3.27c	0.90	0.27	1.49e	0.083c	0.040b	0.027a	0.050b	0.41d	0.23d	0.23e	0.29e
½ RDCF + ½ SME	3.43b	1.00	0.27	1.58bcd	0.097abc	0.050b	0.030a	0.060ab	0.58b	0.40c	0.27de	0.41c
CM + PGPR	3.57ab	1.17	0.30	1.69a	0.100ab	0.050b	0.030a	0.060ab	0.92a	0.54ab	0.30cd	0.59a
Significance	**	ns	ns	**	**	*	**	**	**	**	**	**
CV (%)	2.63	12.30	17.56	3.06	9.08	20.17	8.88	9.48	5.86	11.05	7.84	5.85

[1] Mean with different letters in the same column indicate a significant difference according to Dun-can's multiple range test at $p \leq 0.05$. ns = no significant different; *, ** = statistical different at 95% and 99% level of confidence, respectively. Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 8. Macronutrient content in different plant parts of cassava exposed to different fertilizer applications at the Seungsang site.

Treatment	Total N (%)				Total P (%)				Total K (%)			
	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant
Control	2.93e [1]	0.90c	0.30a	1.39d	0.043cd	0.027bc	0.023	0.030b	0.40c	0.23cd	0.33c	0.32d
RDCF	3.50b	1.00a	0.30a	1.60a	0.040d	0.030b	0.030	0.030b	0.57ab	0.40b	0.36bc	0.45b
CM	3.83a	0.80d	0.23bc	1.61a	0.050b	0.040a	0.030	0.040a	0.42c	0.56a	0.37bc	0.45b
SME	3.30c	0.93bc	0.20cd	1.48b	0.047bc	0.020c	0.030	0.030b	0.63a	0.44b	0.48a	0.52a
CM + SME	3.20d	0.90c	0.27ab	1.45c	0.060a	0.040a	0.030	0.043a	0.38c	0.28c	0.33c	0.33cd
½ RDCF + ½ CM	2.87e	0.80d	0.20cd	1.28e	0.050b	0.030b	0.030	0.040a	0.64a	0.20d	0.42ab	0.42b
½ RDCF + ½ SME	2.93e	0.70e	0.17d	1.25e	0.050b	0.030b	0.027	0.040a	0.38c	0.27c	0.37bc	0.34cd
CM + PGPR	3.53b	0.97ab	0.27ab	1.59a	0.060a	0.047a	0.030	0.040a	0.52b	0.26c	0.32c	0.36c
Significance	**	**	**	**	**	**	ns	**	**	**	**	**
CV (%)	1.44	3.24	14.13	1.43	5.51	13.44	9.96	5.49	8.80	9.21	11.29	5.06

[1] Mean with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant different; ** = statistical different at 99% level of confidence. Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

The highest total K concentrations in leaves resulted from CM + PGPR (0.92%), which caused significantly greater K concentrations than all other treatments. The highest total K concentrations in stems resulted from the RDCF (0.61%), SME (0.59%), CM +PGPR (0.54%), and CM (0.53%) treatments. These four treatments resulted in significantly greater total K than the ½ RDCF + ½ SME (0.40%), control (0.28%), and ½ RDCF + ½ CM (0.23%) treatments. The highest total K concentrations in tubers resulted from CM (0.45%), which was significantly higher than those from all other treatments. Contrarily, the ½ RDCF + ½ CM (0.23%) treatment resulted in the lowest total K concentration in tubers, without any signif-

icant difference from those resulting from the CM +SME (0.25%) and ½ RDCF + ½ SME (0.27%) treatments. The highest total K concentrations in the whole plant resulted from the CM + PGPR (0.59%) treatment, whereas the lowest total K concentrations in the whole plant resulted from the ½ RDCF + ½ CM (0.29%) treatment (Table 7).

At the Seungsang site, total N concentrations in leaf tissues resulting from the CM treatment (3.83%) were significantly greater than those resulting from all other treatments. The lowest total N concentrations resulted from the ½ RDCF + ½ CM (2.87%), ½ RDCF + ½ SME (2.93%), and control (2.93%) treatments. In stem tissues, the significantly greatest total N concentrations resulted from RDCF treatment (1.00%) and were not significant different from those resulting from the CM + PGPR treatment (0.97%). In the tuber tissue, the greatest total N concentrations resulted from the control (0.30%), RDCF (0.30%), CM + SME (0.27%), and CM + PGPR (0.27) treatments, while the lowest N in tubers resulted from the ½ RDCF + ½ SME (0.17) treatment. In the whole plant, the highest N concentrations resulted from the CM (1.61%), RDCF (1.60%), and CM + PGPR (1.59%) treatments. These were all significantly greater than the lowest total N concentrations, which were observed in plants resulting from the ½ RDCF + ½ CM (1.28%) and ½ RDCF + ½ SME (1.25%) treatments (Table 8).

The greatest total P concentrations in leaves resulted from the CM + SME (0.060%) and CM + PGPR (0.060%) treatments, while the lowest leaf P concentrations resulted from the RDCF (0.040%) and control (0.043%) treatments. The greatest P concentrations in stem tissues resulted from the CM + PGPR (0.047%), CM (0.040%), and CM + SME (0.040%) treatments. Contrarily, the lowest total P concentrations in stem tissues resulted from the SME (0.020%) and control (0.027%) treatments. In tuber tissues, there were no significant differences between total P concentrations resulting from different fertilizer treatments. In whole-plant tissues, the lowest total P concentrations resulted from the control (0.030%), RDCF (0.030%), and SME (0.030%) treatments (Table 8).

Total K concentrations in leaves were highest in plants under the ½ RDCF + ½ CM (0.64%), SME (0.63%), and RDCF (0.57%) treatments. In stem tissues, total K concentrations were significantly highest in plants resulting from the CM (0.56%) treatment. In tuber tissues, the highest total K concentrations resulted from the SME treatment (0.48%), which were not significantly different from those resulting from the ½ RDCF + ½ CM (0.42%) treatment. In whole-plant tissues, the total K concentration was significantly greatest in plants under the SME treatment (0.52%), while the lowest total K concentration in the whole plant was observed in the control treatment (0.32%) plants, without any significant difference between values resulting from the CM + SME (0.33%) and ½ RDCF + ½ SME treatments (0.34%) (Table 8).

3.4. Correlations Between Macronutrient Concentration and Plant Productivity

To understand the relationships between the different traits recorded under different fertilizer management protocols at each study site, the correlations between the collected parameters were investigated and are shown in Figures 2 and 3. A positive relationship between parameters was assumed when the correlation coefficient (r^2) was 0.60 or higher. The total N concentration in the whole plant (r^2 = 0.64) and total K concentration in leaf tissues (r^2 = 0.67) displayed a higher positive correlation with the fresh tuber yield than other parameters. The starch content was positively correlated with the total N content in leaf tissues (r^2 = 0.60). However, these correlations were only observed at the Nampong site (Figure 2). Among the macronutrients in different plant parts and the whole plant in both study sites, the macronutrient concentrations in leaf tissues have the highest positive correlation (r^2 > 0.75) with the total macronutrient concentrations in the whole plant, compared with the stem and tuber tissue concentrations (Figures 2 and 3).

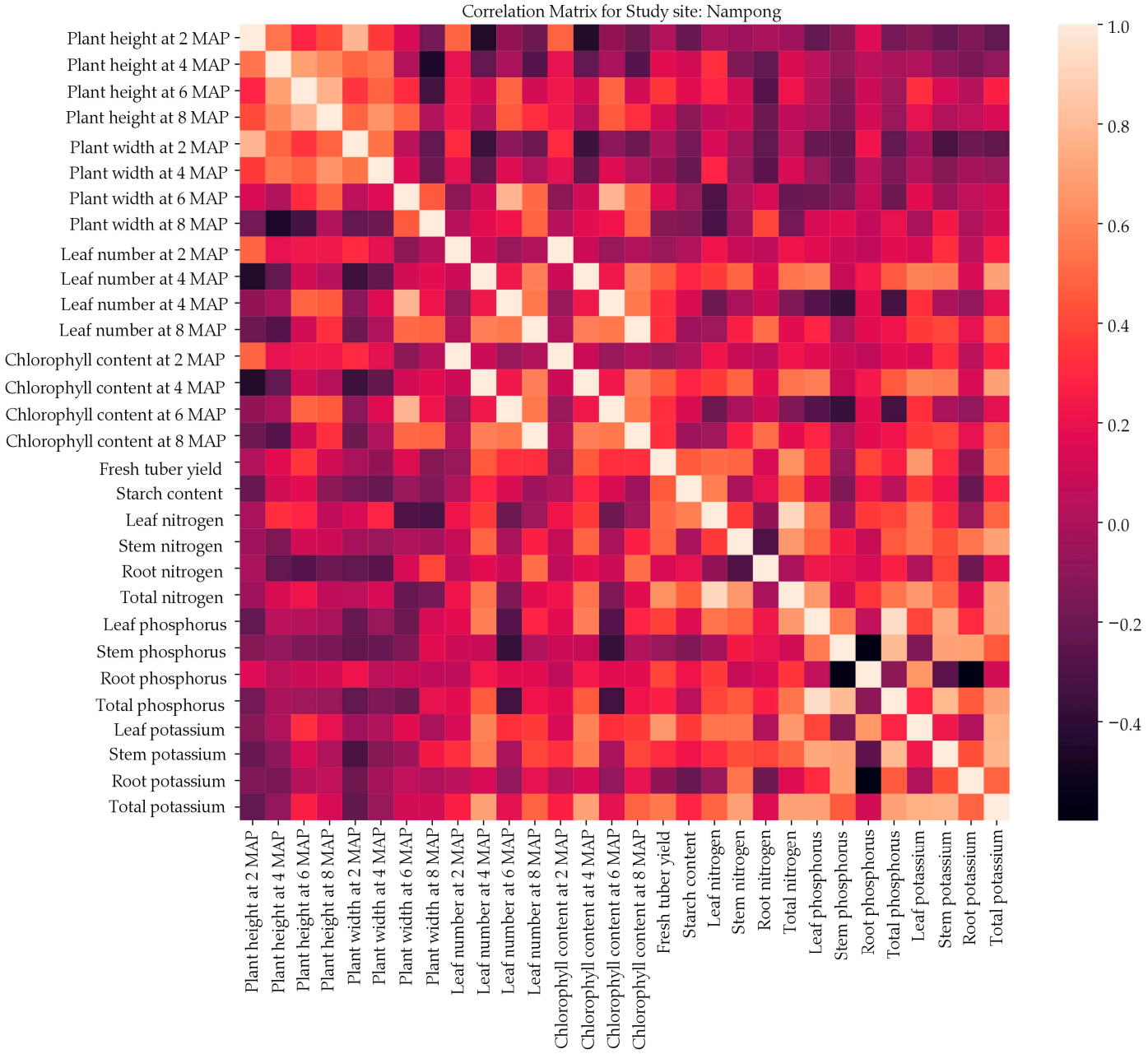


Figure 2. A correlational plot from 30 parameters recorded from cassava grown at the Nampong Site. MAP: months after planting.

3.5. Economic Analysis

Since cassava plants were planted with 1 × 1 m spacing, 10,000 plants can be planted in 1 ha. Therefore, the average fresh tuber yield per plant was multiplied by this 10,000-plant ha^{-1} rate to obtain the average fresh tuber yield that would be harvested per ha using this same spacing. Tables 9 and 10 show the results of the partial budget, dominance, and MRR analysis for each of the fertilizer management treatments. At the Nampong site, the treatments of CM and CM + PGPR both resulted in positive MRR values. The control, CM, and CM + PGPR treatments resulted in net benefits of 2376.31, 2461.74, and 3237.07 USD ha^{-1}, respectively. The MRR when changing from the control (no fertilizer) to CM would be 30.97%. This means that for every USD invested in changing from the control treatment to the application of chicken manure at the recommended rate of 3125 kg ha^{-1}, local farmers would recover that dollar and make, approximately, an additional USD 0.31.

The MRR when changing from the application of CM to CM + PGPR would be 355.97%, meaning that the local farmers who already manage cassava field fertility by applying chicken manure compost at recommended rates (3125 kg ha^{-1}) would earn, approximately, an additional USD 3.56 for every USD that is invested in applying the PGPR product along with chicken manure compost (Table 10).

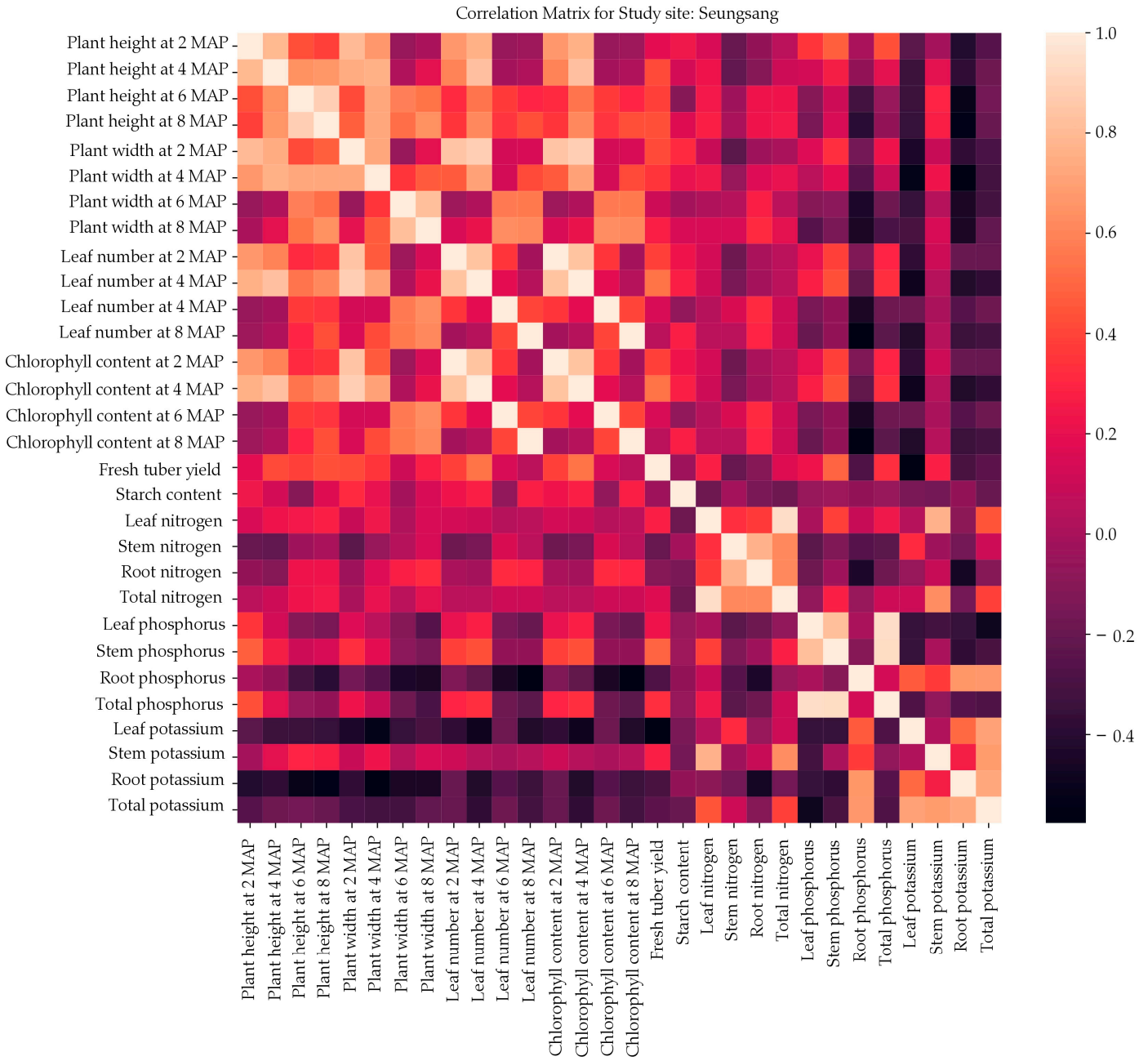


Figure 3. A correlational plot from 30 parameters recorded from cassava grown at the Seungsang Site. MAP: months after planting.

At the Seungsang site, the treatments of CM + PGPR, RDCF, and CM resulted in positive MRR values. The net benefits resulting from the control, CM + PGPR, RDCF, and CM treatments were 2070.40, 2291.41, 2375.65, and 2683.72 USD ha^{-1}, respectively. The MRR when changing from the control treatment to CM + PGPR would be 499.72%, meaning that for every USD invested in soil and plant management that utilizes chicken manure (3125 kg ha^{-1}) along with the inoculation of stakes with PGPR solution, there would be an around USD 4.99 return on investment. The MRR when changing from the application of

CM + PGPR to RDCF would be 1125.36% (Table 10), meaning that for every USD invested in changing from chicken manure treatment (3125 kg ha^{-1}) along with PGPR inoculation to the recommended dose of inorganic fertilizer (RDCF), there would be a USD 11.25 return for every USD invested. The MRR when changing from the application of the RDCF to CM would be 491.42%, which means that for every USD invested in changing from the RDCF to CM treatments, there would be a USD 4.91 return on investment (Table 10).

Table 9. Partial budget and net benefit of different fertilizer management treatments for cassava production at two sites in northeastern Thailand.

Study Site	Data	Control	RDCF	CM	SME	CM + SME	½ RDCF + ½ CM	½ RDCF + ½ SME	CM + PGPR
	Fertilizer field price (USD ha^{-1})	0.00	184.71	174.25	32.41	206.67	179.48	108.56	195.17
	Fertilizer application labor costs (USD ha^{-1})	0.00	26.14	26.14	139.40	165.54	52.28	165.54	26.14
Nampong	Total variable costs (USD ha^{-1})	586.09	862.25	861.92	801.14	1033.73	873.96	909.87	1079.73
	Average yield (kg plant^{-1})	4.25	4.72	4.79	4.56	4.79	4.65	4.61	6.22
	Average yield (kg ha^{-1})	42,467.00	47,200.00	47,933.00	45,600.00	47,933.00	46,533.00	46,067.00	62,200.00
	Adjusted average yield (kg ha^{-1}) *	38,220.30	42,480.00	43,139.70	41,040.00	43,139.70	41,879.70	41,460.30	55,980.00
	Gross field benefits (USD ha^{-1}) **	3356.68	3730.78	3788.72	3604.32	3788.72	3678.06	3641.23	4916.41
	Net benefit (USD ha^{-1}) **	2376.31	2409.22	2461.74	2362.63	2272.74	2348.90	2276.25	3237.07
Seungsang	Total variable costs (USD ha^{-1})	510.64	853.97	916.66	726.61	1077.44	789.32	917.23	846.49
	Average yield (kg plant^{-1})	3.70	4.66	5.19	4.02	5.11	4.04	4.66	4.53
	Average yield (kg ha^{-1})	37,000.00	46,600.00	51,900.00	40,200.00	51,100.00	40,400.00	46,600.00	45,300.00
	Adjusted average yield (kg ha^{-1}) *	33,300.00	41,940.00	46,710.00	36,180.00	45,990.00	36,360.00	41,940.00	40,770.00
	Gross field benefits (USD ha^{-1}) **	2924.55	3683.36	4102.28	3177.49	4039.05	3193.30	3683.36	3580.60
	Net benefit (USD ha^{-1}) **	2070.40	2375.65	2683.72	2060.46	2449.96	2005.72	2306.07	2291.41

Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria. * Adjusted average yield is 90% of average yield in kg plant^{-1} × planting rate (10,000 plant ha^{-1}). ** The price of cassava was 0.0878 USD kg^{-1} (USD 1 = THB 35.8670 on 15 March 2024).

Table 10. Dominance analysis and marginal rate of return for different fertilizer management treatments for cassava production at two sites in northeastern Thailand.

Fertilizer Management	Nampong			
	TVC (USD ha^{-1})	NB (USD ha^{-1})	Dominance Analysis	MRR (%) *
Control	586.09	2376.31		
SME	801.14	2362.63	Dominated	
CM	861.92	2461.74		30.97
RDCF	862.25	2409.22	Dominated	
½ RDCF + ½ CM	873.96	2348.90	Dominated	
½ RDCF + ½ SME	909.87	2276.25	Dominated	
CM + SME	1033.73	2272.74	Dominated	
CM + PGPR	1079.73	3237.07		355.97
Fertilizer Management	**Seungsang**			
	TVC (USD ha^{-1})	NB (USD ha^{-1})	Dominance Analysis	MRR (%) *
Control	510.64	2070.40		
SME	726.61	2060.46	Dominated	
½ RDCF + ½ CM	789.32	2005.72	Dominated	
CM + PGPR	846.49	2291.41		499.72
RDCF	853.97	2375.65		1125.36
CM	916.66	2683.72		491.42
½ RDCF + ½ SME	917.23	2306.07	Dominated	
CM + SME	1077.44	2449.96	Dominated	

Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria. TVC: total variable cost in USD ha^{-1}; NB: net benefit in USD ha^{-1}; MRR: marginal rate of return in percent. * MRR will only be shown when the treatment is not dominated.

4. Discussion

Despite being a resilient crop that can be cultivated in areas with inconsistent or low rainfall and with no inputs other than labor to provide a reasonable return, cassava requires careful management and may require some outside assistance to obtain larger yields and more significant financial gains [50,51].

Based on the background soil chemical properties at both study sites, Seungsang (silty clay texture) has a comparatively higher amount of the various nutrients than Nampong (sandy texture), which has lower levels of N, P, and K as well as six times less organic matter. The lower amount of nutrients in Nampong's soil is a result of the background soil properties, with sandy soils having less nutrients than soils with more clay content, especially in tropical regions [52]. In this study, the poor performance of cassava recorded from the unamended plots (control) was probably due to their low soil organic matter and nutrient content. The yield results at both the Nampong and Seungsang sites suggest that the CM + PGPR and CM treatments have a greater effect on the cassava yield than the absence of fertilizer (control), RDCF, and SME treatments. It seems that fertilizer treatments that contain combinations with CM have the most potential for increasing cassava tuber yields. Several investigations have revealed the enhancement of cassava production with poultry manure, either solely or mixed with chemical fertilizer, via improved soil physical and chemical characteristics [4,28]. Chicken manure application is also known to increase soil organic matter in soils, and soil organic matter facilitates cation exchange in soils and can help increase macronutrient availability [52,53]. These findings are consistent with previous research, which found that the chemical composition and C/N ratio of organic matter determine its quality, and that a combination of low- and high-C/N organic residues has a greater effect on soil fertility [54–56]. Biratu et al. [55] also reported that chicken manure application, both alone and in combination with NPK synthetic fertilizer, increased organic carbon, total N, and available P levels in cassava field soils. Higher levels of these nutrients in soils may have contributed to more uptake by the cassava plants. This dynamic may have played a role in the current study. However, chemical analysis of soil resulting from each fertilizer treatment would be required to support this hypothesis.

At the Nampong site, PGPR inoculation along with chicken manure application at the full recommended rate significantly increased the fresh tuber yield by 26–42%, compared to all other treatments. Moreover, the CM + PGPR treatment also resulted in a greater leaf number (at 4 MAP and 8 MAP by 9% and 21%, respectively) than the CM application alone. This finding suggests that the organisms in the PGPR product may indeed be providing ecosystem services that help the aboveground and tuber growth in this location. This explanation is supported by previous work by Wongsuwan et al. [57] in Thailand, which showed 5.79% increases in fresh tuber weight resulting from the use of this same PGPR-3 product along with composted chicken manure, when compared with the application of composted chicken manure alone. The application of the PGPR-3 biofertilizer product alone, however, did not result in yield increases. According to Astuti and Mulyono [58], cassava stakes that were wounded and inoculated with PGPR and mycorrhizal fungus also produced more leaves. The mechanisms behind the growth and yield increases, therefore, may involve microbial interactions in the cassava rhizospheric region. The *Azospirillum brasilense* and *Gluconacetobacter diazotrophicus* bacteria strains present in the PGPR-3 product are thought to act by producing auxins, which stimulate root cell elongation, and by increasing water and nutrient uptake efficiency [59]. *Azospirillum brasilense* inoculation has also been shown to minimize the negative effects of excess N on cassava tuber development [60], a problem that some farmers face when applying soil amendments. Interestingly, based on the highest fresh tuber yield of cassava grown under the different fertilizer management of both study sites, the treatment with CM + PGPR produced the most significant fresh tuber yield

increase at the Nampong site (6.22 kg plant^{-1}), while CM produced the most significant fresh tuber yield increase at the Seungsang site (5.19 kg plant^{-1}). From this, the response of soil to PGPR at Nampong was greater, possibly because of the sandy soil there, which has less background soil nutrients and SOM. Application of organic fertilizers together with biological fertilizers containing PGPR microorganisms may be suitable for growing cassava in areas with degraded soils. Although it is obvious that PGPR application has beneficial effects in helping crops against biotic and abiotic stresses [61,62], the effectiveness of introduced PGPR inoculants is hard to predict without having site-specific background information about the PGPR activity because native PGPR, which appear to be considerably more prevalent in areas with high soil organic matter, may alter the relative performance of introduced PGPR inoculants [63]. Further microbiome and proteomics analysis may shed more light on the mechanisms behind how PGPR inoculation and PGPR inoculation along with fertilizer application affect cassava plant growth.

A high cassava fresh tuber yield has been observed in northeastern Thailand when chicken manure [28] and liquid swine manure extract [29] are applied, with results that are not significantly different from those obtained when synthetic fertilizer is applied at recommended doses. In this study, when compared to both synthetic fertilizer and chicken manure, nutrients from the monthly foliar application of swine manure may not be available to the cassava plants consistently. Whereas the plants growing under soil-applied fertilizer treatments would have continual access to the nutrients through the roots, at least at the beginning period after fertilizer/manure application, swine manure foliar application may cause a discontinuation of access to the nutrients in the manure and hence less potential for growth. This possibility is supported by the work of Janket et al. [64], which highlighted a temporal pattern of nutrient uptake and accumulation by cassava plants, with maximum rates occurring during early growth stages, from 1 to 6 months after planting. Discontinuous access to nutrients during this time of maximum absorption might be responsible for the significantly lower height observed at 4 MAP in plants that were only exposed to swine manure extract (Tables 2 and 3). This hypothesis would have to be tested by the investigation of nutrient levels in cassava plants under the different nutrient management treatments throughout the growing season for confirmation.

Although no clear consistent trend was found with the total macronutrient contents in each plant part in this study, their contents in whole plants resulting from different fertilizer treatments showed some clear patterns when related to different treatments. For the total N contents in cassava at the Nampong site, the CM + PGPR, CM, and CM + SME treatments resulted in the highest N concentrations in the whole plant. For the total N contents in plants at the Seungsang site, the CM, RDCF, and CM + PGPR treatments resulted in the greatest N concentrations. At both locations, the CM + PGPR and CM treatments resulted in the greatest total N accumulation. In addition, the cassava plants resulting from the CM treatments had some of the greatest total P contents in whole plants (Tables 8 and 9). While the highest total K value at the Nampong site resulted from the CM + PGPR treatment, the highest K at the Seungsang site resulted from the SME treatment (Table 9). Interestingly, a pattern was observed in the order of the highest total K concentrations and the highest fresh tuber yields resulting from different fertility treatments at the Nampong site, with both parameters being in the order of CM + PGPR > CM > RDCF > SME (Table 8).

Correlation analysis was conducted to test the significance of these correlations. Indeed, the N concentrations in the whole plant and the K concentration in the leaf tissue at the Nampong site are positively correlated with the fresh tuber yield there (Figure 2). In general, N is one of the key elements influencing the cassava yield [65]. This is consistent with the findings of Suwarto et al. [66] who reported that cassava requires sufficient N, P, and K nutrients to generate good tuber growth and productivity. Potassium (K) is also

widely known to be crucial for root growth. Janket et al. [64] reported that about half of all total K and 26–42% of P absorbed by cassava plants were sent to tubers. Lin et al. [67] also found the K application amount to have a significant positive correlation with the cassava yield. Furthermore, Prajapati and Madi [68] described K as being needed for sugar and starch translocation since it is a starch synthesis enzyme activator for tuber crops. This is why K almost always has to be supplemented in order to cultivate cassava long term, as the harvesting of tubers removes K from farms. Knowledge of these correlations could potentially be used to further develop the use of nutrient analysis and yield prediction techniques, such as the NIR technique, which could be used to predict the cassava yield from quick, noninvasive spectroscopy.

In the present study, at the Nampong site, the highest correlation between the starch content and the other data was observed with the total N accumulation in leaves (Figure 2). This result was consistent with the findings of other studies investigating the association between the level of leaf N content and starch accumulation in the tubers of other Thai cassava varieties, such as Huay Bong 80 [28,69]. However, the other literature demonstrated that very high rates of N fertilizer can be excessive and cause a reduction in tuberization and starch accumulation in cassava tubers. Omondi et al. [70] specified that excessive use of N would induce shoot (leaves and stems) vegetative growth but a poor tuber yield and a decrease in the tuber starch content. Nevertheless, our findings demonstrated that different nutrient management did not affect the tuber starch content at either study site. This was not surprising, as Pongsivapai et al. [14], Leitch et al. [15], Phun-Iam et al. [69], and Raksarikorn et al. [71] all reported that soil amendments, whether they were organic or inorganic fertilizers, had no clear influence on starch content. Previous studies have demonstrated that the starch content can vary according to varieties and environmental surroundings (temperature), harvest season (dry and raining seasons), storage time, or processing technology [72,73]. Generally, varieties that can provide high starch content accumulate starch quickly and maintain starch content as long as possible and are required for breeding and farming [74]. In this study, the Rayong 72 cultivar was utilized. This variety is renowned for its high yield, drought resistance, and high starch content, which ranges from 20 to 22% during the rainy season to 24% during the dry season [45]. Furthermore, this variety has been reported to have a starch content of 19.1% [75] and 24.8% [76] when grown in the same northeastern region of Thailand, or of 22.5% [77] and 22.9% [78] when grown in the northern region. Our results from the starch content in cassava tubers grown under different nutrient management at both study sites show up to 27% higher averages than those of the previous reports.

Although cassava can be planted in all months of the year, different planting dates result in different climatic conditions, such as temperature, relative humidity, and solar radiation, all of which are factors that cause yield differences of cassava [37]. The main planting times in Southeast Asia, including Thailand, are the early rainy season (May–June) and the late rainy season (October–December), with both having an optimal climate for cassava crop growth [45]. The current study used a drought-tolerant genotype (Rayong 72) and drip irrigation in an attempt to reduce the growth and yield differences that result from moisture levels. The findings in our study show that this strategy is useful for maintaining the cassava yield even though the crop was planted in the dry season. This is in agreement with the findings of Wongnoi et al. [79] who reported that an increase in soil moisture content by irrigation can increase the canopy size and leaf area, both important factors for photosynthesis and biomass accumulation, contributing to increases in the tuber yield due to optimal climate conditions during crop growth. Nonetheless, there is a 2–3-fold difference between the projected average yields from the current study and the Thai national average of roughly 21.3 t ha^{-1}. The highest projected yields were 62.2 t ha^{-1}

from the CM + PGPR treatment and 51.9 t ha^{-1} from the CM treatment at the Nampong and Seungsang sites, respectively.

Economic analysis from Nampong data shows that the marginal rate of return (MRR) when changing from the CM to CM + PGPR treatments would be greater than the minimum accepted value of 100%, meaning that this treatment may be recommended for local farmers to increase return on investment. The PGPR-3 product is relatively easy to apply and inexpensive. This option may be very attractive to local farmers if they knew about the economic possibilities that the product offers. All other experimental treatments resulted in greater fresh tuber yields than those of the control but only CM and CM + PGPR resulted in positive MRR values. For treatments that involved synthetic fertilizer, the cost of the fertilizer itself was high and the additional yield that resulted was not enough to make the treatment economically beneficial, due to the low field price of fresh cassava tubers. In treatments that involved the application of swine manure extract, the costs associated with the application of the swine manure were high and the resulting fresh tuber yields were relatively low. CM + SME, ½ RDCF + ½ CM, and ½ RDCF + ½ SME all involved more than one type of fertilizer application, which increased both the fertilizer costs and labor costs for those treatments (Table 10). The Nampong site results are similar to those of Bilong et al. [80] who found soil treatments with chicken manure to have greater benefit-to-cost ratios than treatment with synthetic fertilizer in two consecutive years in sandy clay soil. The authors attributed greater fresh tuber yields to improved soil quality index values, which resulted from improved soil physical and chemical properties, like porosity, bulk density, water holding capacity, OM, and cation exchange capacity.

At the Seungsang site, since the MRR when changing from the RDCF treatment to the CM treatment is greater than the minimum accepted value of 100%, it may be beneficial economically to recommend that local farmers who currently manage fertility by adding synthetic fertilizer alone change to using chicken manure at the rates used in this study. Like at the Nampong site, the additional costs associated with the application of SME and fertilizer combinations were high when compared with the change in net benefit (NB). However, at the Seungsang site, the difference between the NB resulting from the RDCF treatment and that resulting from the control treatments outweighed the additional costs required. Again, the low field price of fresh cassava tubers is a limiting factor in increasing gross field benefits.

At both research sites, the CM treatments resulted in a greater NB per ha than the RDCF treatments. This is an interesting result, in terms of both economic and ecological sustainability. Chicken manure is produced at local farms, making it very accessible. This would likely result in a lower carbon footprint, when considering the greater transport distance and manufacturing involved in synthetic fertilizer distribution. Locally produced manures also have less price fluctuations than synthetic fertilizer, and their purchase by local farmers benefits the local economy. For organic cassava production systems, protocols that focus more on using composted animal manures, farmyard wastes, and biofertilizers theoretically have relatively high gross field benefits because the cassava plant product selling prices are higher. However, the higher production costs for organic cassava systems, due to more strict soil amendment standard requirements and higher labor costs, may prohibit many smallholder farmers from organic cassava production [81]. While at the surface level it may seem that the soil and plant management treatments investigated in this study would be more applicable to organic cassava farmers, the marginal rates of return resulting from the CM treatments at the Seungsang study site and CM + PGPR treatments at the Nampong site may prove to be a powerful incentive for non-organic farmers in those regions to adopt these production protocols as well. In particular, farmers that are currently using production systems that only apply synthetic fertilizer may be

convinced to rely more on locally sourced composted chicken manure. In addition to the financial incentives provided by the viable treatments involving chicken manure compost application, or chicken manure compost application along with PGPR inoculation, farmers may benefit from the maintenance or increases in soil organic matter that are known to result from the application of composted manure amendments that contain carbon-rich materials [82]. This attribute is crucial to long-term soil health and soil food web stability, which is a requirement for sustainable agriculture [83].

5. Conclusions

Several relationships were found between the nutrient management protocols and the resulting cassava growth, yield components, macronutrient concentrations, and marginal rate of return. These relationships can be put to use to better understand cassava agroecosystem functioning, particularly in terms of what farmers can do to increase yields and what mechanisms may be behind those yield increases. At the Nampong site, the application of chicken manure at a rate of 3125.0 kg ha^{-1} and stake soaking with PGPR resulted in a higher fresh tuber yield than no fertilizer and the RDCF application. At the Seungsang site, the application of chicken manure at a rate 3125.0 kg ha^{-1} resulted in a high fresh tuber yield, which was not significantly different from the yield resulting from the RDCF application. Furthermore, compared to the RDCF treatment, both soil fertilizer management treatments produced a positive marginal rate of return values. The findings could be further substantiated by conducting similar investigations at more sites with varying climates and soil structures. All of the data resulting from these efforts may be used to make real-world recommendations for successful and sustainable cassava production.

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References

1. Kulkarni, S. Sustainable cassava: A case study of global sustainability. In *Global Sustainability: Trends, Challenges & Case Studies*; Kulkarni, S., Haghi, A.K., Eds.; Springer: Cham, Switzerland, 2024; pp. 211–222.
2. Belete, T.; Yadete, E. Effect of mono cropping on soil health and fertility management for sustainable agriculture practices: A review. *J. Plant Sci.* **2023**, *11*, 192–197. [CrossRef]
3. Dossa, K.F.; Miassi, Y.E. Advancing sustainable agriculture: A critical review of innovative strategies to decrease chemical dependency for environmental health. *J. Environ. Sci. Pollut. Res.* **2024**, *10*, 492–497.
4. Biratu, G.K.; Elias, E.; Ntawuruhunga, P.; Nhamo, N. Effect of chicken manure application on cassava biomass and root yields in two agro-ecologies of Zambia. *Agriculture* **2018**, *8*, 45. [CrossRef]

5. Khatoon, H.; Solanki, P.; Narayan, M.; Tewari, L. Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. *Int. J. Chem. Stud.* **2017**, *5*, 1648–1656.
6. Richardson, A.E.; Barea, J.M.; McNeill, A.M.; Prigent-Combaret, C. Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant Soil* **2009**, *321*, 305–339. [CrossRef]
7. Otaiku, A.A.; Mmom, P.C.; Ano, A.O. Biofertilizer impacts on cassava (*Manihot Esculenta* Crantz) rhizosphere: Soil microbiome engineering, genetic and sustainable agroecosystems, Igbariam, Nigeria. *World J Agri Soil Sci.* **2020**, *6*, 1–50. [CrossRef]
8. Prasara-A, J.; Gheewala, S.H. An assessment of social sustainability of sugarcane and cassava cultivation in Thailand. *Sustain. Prod. Consum.* **2021**, *27*, 372–382. [CrossRef]
9. Panyasing, S.; Yongvanit, S.; Nurmandi, A.; Prabnok, P. Collaborative partnership and new farm management for solving drought according to different geo-social environment in the Northeast of Thailand. *Int. J. Rural Manag.* **2023**, *19*, 64–88. [CrossRef]
10. Pipitpukdee, S.; Attavanich, W.; Bejranonda, S. Impact of climate change on land use, yield and production of cassava in Thailand. *Agriculture* **2020**, *10*, 402. [CrossRef]
11. Howeler, R.H. Long-term effect of cassava cultivation on soil productivity. *Field Crops Res.* **1991**, *26*, 1–18. [CrossRef]
12. Fermont, A.M.; Obiero, H.M.; van Asten, P.J.A.; Baguma, Y.; Okwuosa, E. Improved cassava varieties increase the risk of soil nutrient mining: An ex-ante analysis for western Kenya and Uganda. In *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*; Bationo, A., Waswa, B., Kihara, J., Kimetu, J., Eds.; Springer: Dordrecht, The Netherlands, 2007; pp. 511–520.
13. Aye, T.; Howeler, R. Integrated crop management for cassava cultivation in Asia. In *Achieving Sustainable Cultivation of Cassava*; Hershey, C., Ed.; Burleigh Dodds: Cambridge, UK, 2017; pp. 1–29.
14. Pongsivapai, P.; Thongjoo, C.; Jutamas, R.; Tawatchai, I. Effect of fertilizer management in combination with soil conditioner on yield of cassava cultivated on coarse-textured soil in Thailand. *Mod. Appl. Sci.* **2016**, *10*, 239–247. [CrossRef]
15. Leitch, A.; Anusontpornperm, S.; Thanachit, S.; Jindaluang, W.; Phun-Iam, M. Cassava response to phosphorus fertilizer in warin soil series amended with cassava tails and stalk-bentonite mixture. *Trends Sci.* **2023**, *20*, 4885. [CrossRef]
16. Pypers, P.; Bimponda, W.; Lodi-Lama, J.-P.; Lele, B.; Mulumba, R.; Kachaka, C.; Boeckx, P.; Merckx, R.; Vanlauwe, B. Combining mineral fertilizer and green manure for increased, profitable cassava production. *Agron. J.* **2012**, *104*, 178–187. [CrossRef]
17. Merumba, M.S.; Semoka, J.; Semu, E.; Msanya, B.M.; Kibura, J.K. Effect of tillage methods, farmyard manure and potassium rates on cassava yield and root quality in Kagera region, Tanzania. *Int. J. Plant Soil Sci.* **2022**, *34*, 33–50. [CrossRef]
18. Constantine, J.; Sibuga, K.P.; Hilbeck, A.; Shitindi, M. Influence of compost and farmyard manure on cassava growth, yield and dry matter partitioning at Mvomero and Masasi districts. *J. Exp. Agric. Int.* **2023**, *45*, 231–249. [CrossRef]
19. Aravind Ashokh, S.; Somasundaram, E.; Sanbagavalli, S.; Kavitha, P.S.; Venkatachalam, S.R.; Sunitha, R. Impact of organic nutrient management practices on growth dynamics and economics of short-duration cassava (*Manihot esculenta* Crantz.). *Agric. Sci. Dig.* **2024**, *44*, 212–218. [CrossRef]
20. Bakayoko, S.; Soro, D.; Nindjin, C.; Dao, D.; Tschannen, A.; Girardin, O.; Assa, A. Effects of cattle and poultry manures on organic matter content and adsorption complex of a sandy soil under cassava cultivation (*Manihot esculenta* Crantz.). *Afr. J. Environ. Sci. Technol.* **2009**, *3*, 190–197.
21. Kunlanit, B.; Khwanchum, L.; Vityakon, P. Land use changes affecting soil organic matter accumulation in topsoil and subsoil in Northeast Thailand. *Appl. Environ. Soil Sci.* **2020**, *1*, 8241739. [CrossRef]
22. Bilong, E.G.; Abossolo-Angue, M.; Ajebesone, F.N.; Anaba, B.D.; Madong, B.À.; Nomo, L.B.; Bilong, P. Improving soil physical properties and cassava productivity through organic manures management in the southern Cameroon. *Heliyon* **2022**, *8*, e09570. [CrossRef]
23. Jacoby, R.; Peukert, M.; Succurro, A.; Koprivova, A.; Kopriva, S. The role of soil microorganisms in plant mineral nutrition-current knowledge and future directions. *Front. Plant Sci.* **2017**, *8*, 1617. [CrossRef]
24. Busby, P.E.; Soman, C.; Wagner, M.R.; Friesen, M.L.; Kremer, J.; Bennett, A.; Morsy, M.; Eisen, J.A.; Leach, J.E.; Dangl, J.L. Research priorities for harnessing plant microbiomes in sustainable agriculture. *PLoS Biol.* **2017**, *15*, e2001793. [CrossRef] [PubMed]
25. Pannakkong, W.; Parthanadee, P.; Buddhakulsomsiri, J. Impacts of harvesting age and pricing schemes on economic sustainability of cassava farmers in Thailand under market uncertainty. *Sustainability* **2022**, *14*, 7768. [CrossRef]
26. Kumsueb, B.; Rattanasriwong, S.; Phommalath, S.; Nut, N.; Fan, J.; Do, H.X.; Jintrawet, A. scenarios for a scaling-up system for organic cassava production in the Mekong River Basin: A foresight approach. *Agriculture* **2024**, *14*, 600. [CrossRef]
27. Office of Assistant Director-General (Natural Resources Management and Environment Department). *Smallholders and Family Farmers*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013; 4p.
28. Nilnoree, T.; Anusontpornperm, S.; Thanachit, S.; Kheoruenromne, I.; Petprapai, P. Effect of chicken manure and organic wastes from cassava starch manufacturing plant on cassava grown on Dan Khun Thot soil. *Khon Kaen Agric. J.* **2016**, *44*, 167–178.
29. Kanto, U.; Jutamanee, K.; Osotsapar, Y.; Jattupornpong, S.; Kaewprasit, C. Effect of swine manure extract by foliar application and soil drenching on dry matter and nutrient uptake of cassava. *Agric. Nat. Resour.* **2011**, *45*, 995–1005.

30. Li, H.; Yan, C.; Tang, Y.; Ma, X.; Chen, Y.; Chen, S.; Lin, M.; Liu, Z. Endophytic bacterial and fungal microbiota in different cultivars of cassava (*Manihot esculenta* Crantz). *J. Microbiol.* **2020**, *58*, 614–623. [CrossRef]
31. Panomkhum, P.; Rungthong, R.; Nittayachit, T.; Iwai, C.B.; Ta-Oun, M.; Lawongsa, P. Effects of pesticide on phenotypic characteristics of plant growth—Promoting rhizobacteria (PGPR) in cassava production systems. *Int. J. Environ. Rural. Dev.* **2014**, *5*, 125–130.
32. Safriani, S.R.; Fitri, L.; Ismail, Y.S. Isolation of potential plant growth promoting rhizobacteria (PGPR) from cassava (*Manihot esculenta*) rhizosphere soil. *Biosaintifika* **2020**, *12*, 459–468.
33. Zapata, T.; Galindo, D.M.; Corrales-Ducuara, A.R.; Ocampo-Ibáñez, I.D. The diversity of culture-dependent gram-negative rhizobacteria associated with *Manihot esculenta* Crantz plants subjected to water-deficit stress. *Diversity* **2021**, *13*, 366. [CrossRef]
34. Food and Agriculture Organization of the United Nations (FAO). *Save and Grow a Guide to Sustainable Production Intensification*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013.
35. FAOSTAT. Available online: https://www.fao.org/faostat/en/#data (accessed on 18 February 2025).
36. Kongsil, P.; Ceballos, H.; Siriwan, W.; Vuttipongchaikij, S.; Kittipadakul, P.; Phumichai, C.; Wannarat, W.; Kositratana, W.; Vichukit, V.; Sarobol, E.; et al. Cassava breeding and cultivation challenges in Thailand: Past, present, and future perspectives. *Plants* **2024**, *13*, 1899. [CrossRef]
37. Mahakosee, S.; Jogloy, S.; Vorasoot, N.; Theerakulpisut, P.; Banterng, P.; Kesmala, T.; Holbrook, C.; Kvien, C. Seasonal variations in canopy size and yield of Rayong 9 cassava genotype under rainfed and irrigated conditions. *Agronomy* **2019**, *9*, 362. [CrossRef]
38. Aravind, S.A.; Somasundaram, E.; Sanbagavalli, S.; Kavitha, P.S.; Venkatachalam, S.R.; Sunitha, R. Effect of organic nutrient management practices on growth and yield of short-duration cassava (*Manihot esculenta* Crantz). *Indian J. Agric. Res.* **2023**, *A-6114*, 1–7. [CrossRef]
39. Sirichuaychu, W.; Trisuwarn, N.; Bunpradup, S.; Pinjongsakuldit, A.; Srapet, A. *Miracle of Soil: Soil Series for Economic Plant Cultivation in Thailand*; Office of Soil Survey and Land Use Planning, Land Development Department, Ministry of Agriculture and Cooperatives: Bangkok, Thailand, 2005; pp. 106–107.
40. Kaweewong, J.; Kongkeaw, T.; Tawornprek, S.; Yampracha, S.; Yost, R. Nitrogen requirements of cassava in selected soils of Thailand. *J. Agric. Rural Develop. Trop. Subtrop.* **2013**, *114*, 13–19.
41. Limwikran, T.; Kheoruenromne, I.; Suddhiprakarn, A.; Prakongkep, N.; Gilkes, R.J. Fertility capability and responses of Oxisols to agricultural wastes biochar application. *Thai J. Agric. Sci.* **2018**, *51*, 42–54.
42. Buddhakulsomsiri, J.; Parthanadee, P.; Pannakkong, W. Prediction models of starch content in fresh cassava roots for a tapioca starch manufacturer in Thailand. *Comput. Electron. Agric.* **2018**, *154*, 296–303. [CrossRef]
43. Thepsilvisut, O.; Chandoung, N.; Srikan, N.; Chutimanukul, P. Study of chemical properties and heavy metals in pig manure in different farm management systems in Ratchaburi province. *Khon Kaen Agric. J.* **2023**, *51*, 617–633. (In Thai)
44. Sarakarn, S.; Limsila, A.; Watananonta, W.; Suparhan, D.; Suriyapan, P. Cassava breeding and varietal dissemination in Thailand—Major achievements during the past 25 years. In *Cassava's Potential in Asia in the 21st Century: Present Situation and Future Research and Development Needs, Proceedings of the Sixth Regional Workshop, Ho Chi Minh City, Vietnam, 21–25 February 2000*; Howeler, R.H., Tan, S.L., Eds.; The Nippon Foundation: Tokyo, Japan, 2020; pp. 161–166.
45. Polthanee, A.; Taboonmuang, R.; Manaonok, J. Root yield and nutrient removal of four cassava cultivars planted in early rainy season of Northeastern Thailand: Crop experienced to drought at mid-growth stage. *Asian J. Crop Sci.* **2016**, *8*, 24–30. [CrossRef]
46. Department of Agriculture. *Fertilizer Recommendation for Economic Crop*; Department of Agriculture: Bangkok, Thailand, 2005.
47. Bainbridge, Z.; Tomlins, K.; Wellings, K.; Westby, A. *Methods for Assessing Quality Characteristics of Non-Grain Starch Staples (Part 2: Field Methods)*; Natural Resources Institute: Chatham, UK, 1996; pp. 43–79.
48. AOAC. Official Method of Analysis. In *AOAC Official Methods of Analysis*, 18th ed.; AOAC International: Washington, DC, USA, 2005.
49. CIMMYT. *From Agronomic Data to Farmer Recommendations: An Economics Training Manual*; Completely Revised Edition; Mexico, D.F., Ed.; CIMMYT: El Batán, Mexico, 1988.
50. Howeler, R.H. *Sustainable Soil and Crop Management of Cassava in Asia: A Reference Manual*; Centro Internacional de Agricultural Tropical (CIAT): Cali, Colombia, 2014; ISBN 978-958-694-125-9.
51. CIAT (Centro International de Agricultura Tropical). *Cassava Research and Development in Asia: Exploring New Opportunities for an Acient Crop*; CIAT (Centro International de Agricultura Tropical): Bangkok, Thailand, 2007; pp. 288–301.
52. Yost, J. Soil organic carbon in sandy soils: A review. *Adv. Agron.* **2019**, *158*, 217–310.
53. Kaluba, P.; Mwamba, S.; Moualeu-Ngangue, D.; Chiona, M.; Munyinda, K.; Winter, E.; Stützel, H.; Chishala, B. Cropping practices and effects on soil nutrient adequacy levels and cassava yield of smallholder farmers in northern Zambia. *Int. J. Agron.* **2021**, *2021*, 1325964. [CrossRef]
54. Pimentel, M.L.; Reis, I.M.S.; Castro, J.S.; Portela, V.S.; Romano, M.L.P.C.; Vildoso, C.I.A.; Gasparin, E.; Sia, E.F. Cassava yield indicators and total organic carbon in tropical soils under different fertilization treatments. *Aust. J. Crop Sci.* **2021**, *15*, 1325–1331. [CrossRef]

55. Biratu, K.G.; Eyasu, E.; Ntawuruhunga, P. Soil fertility status of cassava fields treated by integrated application of manure and NPK fertilizer in Zambia. *Environ. Syst. Res.* **2019**, *8*, 3. [CrossRef]
56. Adekiya, A.O.; Ejue, W.S.; Olayanju, A.; Dunsin, O.; Aboyeji, C.M.; Aremu, C.; Adegbite, K.; Akinpelu, O. Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. *Sci. Rep.* **2020**, *10*, 16083. [CrossRef] [PubMed]
57. Wongsuwan, N.; Khaengkhan, P.; Sinsiri, N. Effect of biofertilizer (PGPR–3) organic and chemical fertilizers on growth yield and quality of Rayong 9 and Kasetsart 50 cassava varieties on Korat soil series. *Prawarun Agric. J.* **2021**, *18*, 103–111. (In Thai)
58. Astuti, A.; Mulyono, M. Adoption on cassava technology package to improve the plant growth in Kalasan, Yogyakarta, Indonesia. *BIO Web Conf.* **2024**, *137*, 01001. [CrossRef]
59. Prongjunthuek, K.; Sanoh, S.; Yenoum, W. Utilization of PGPR-I biofertilizer in waxy corn production in Chai Nat Province. In Proceedings of the 62nd Kasetsart University Annual Conference, Bangkok, Thailand, 5–7 March 2024; pp. 298–305. (In Thai)
60. Fernandes, A.M.; da Silva, J.A.; Eburneo, J.A.M.; Leonel, M.; Garreto, F.G.S.; Nunes, J.G.S. Growth and nitrogen uptake by potato and cassava crops can be improved by *Azospirillum brasilense* inoculation and nitrogen fertilization. *Horticulturae* **2023**, *9*, 301. [CrossRef]
61. Vejan, P.; Abdullah, R.; Khadiran, T.; Ismail, S.; Nasrulhaq Boyce, A. Role of plant growth promoting rhizobacteria in agricultural sustainability—A review. *Molecules* **2016**, *21*, 573. [CrossRef]
62. Mohanty, P.; Singh, P.K.; Chakraborty, D.; Mishra, S.; Pattnaik, R. Insight into the role of PGPR in sustainable agriculture and environment. *Front. Sustain. Food Syst.* **2021**, *5*, 667150. [CrossRef]
63. Khoso, M.A.; Wagan, S.; Alam, I.; Hussain, A.; Ali, Q.; Saha, S.; Poudel, T.R.; Manghwar, H.; Liu, F. Impact of plant growth-promoting rhizobacteria (PGPR) on plant nutrition and root characteristics: Current perspective. *Plant Stress* **2024**, *11*, 100341. [CrossRef]
64. Janket, A.; Vorasoot, N.; Toomsan, B.; Kaewpradit, W.; Theerakulpisut, P.; Holbrook, C.C.; Kvien, C.K.; Jogloy, S.; Banterng, P. Quantitative Evaluation of Macro-Nutrient Uptake by Cassava in a Tropical Savanna Climate. *Agriculture* **2021**, *11*, 1199. [CrossRef]
65. Kang, L.; Liang, Q.; Jing, Q.; Yao, Y.; Dong, M.; He, B.; Gu, M. Screening of diverse cassava genotypes based on nitrogen uptake efficiency and yield. *J. Integr. Agric.* **2020**, *19*, 665–974. [CrossRef]
66. Suwarto; Diaguna, R.; Santosa, E.; Hartono, A.; Pramuhadi, G.; Nuryantono, N. Analysis of NPK nutrient content and the nutrient balance of cassava for sustainable high productivity in Ultisols soil. *Aust. J. Crop Sci.* **2023**, *17*, 206–214. [CrossRef]
67. Lin, H.; Yuan, Z.; Liu, R.; Xiao, Y.; Huang, X.; Wang, R. Effects of different N, P and K treatments on yield, nutrient accumulation and utilization and economic benefit of cassava. *J. Plant Nutr. Fertil.* **2012**, *18*, 1459–1468.
68. Prajapati, K.; Modi, H.A. The importance of potassium in plant growth: A review. *Indian J. Plant Sci.* **2012**, *2*, 177–178.
69. Phun-Iam, M.; Anusontpornperm, S.; Thanachit, S.; Kheoruenromne, I. Yield response of cassava Huay Bong 80 variety grown in an Oxyaquic Paleustult to cassava starch waste and nitrogen fertilizer. *Agric. Nat. Resour.* **2018**, *52*, 573–580. [CrossRef]
70. Omondi, J.O.; Lazarovitch, N.; Rachmilevitch, S.; Yermiyahu, U.; Sperling, O. High nitrogen availability limits photosynthesis and compromises carbohydrate allocation to storage in roots of *Manihot esculenta* Crantz. *Front. Plant Sci.* **2019**, *10*, 1041. [CrossRef]
71. Raksarikorn, C.; Pumisak, I.; Ruankuan, I. Influence of organic granular fertilizer, chemical and granular organic fertilizer with hormone mixed formula (ho), and chemical fertilizer to the yield and starch content of cassava. *Rev. Gest. Soc. Ambient.* **2024**, *18*, e05410. [CrossRef]
72. Benesi, I.R.M.; Labuschagne, M.T.; Herselman, L.; Mahungu, N.M.; Saka, J. The effect of genotype, location and season on cassava starch extraction. *Euphytica* **2008**, *160*, 59–74. [CrossRef]
73. Gu, B.; You, Q.; Li, K.; Chen, S. Change in physicochemical traits of cassava roots and starches associated with genotypes and environmental factors. *Starch* **2013**, *65*, 253–263. [CrossRef]
74. Maraphum, A.; Saengprachatanarug, K.; Wongpichet, S.; Phuphaphud, A.; Posom, J. In-field measurement of starch content of cassava tubers using handheld VIS-near infrared spectroscopy implemented for breeding programmes. *Comput. Electron. Agric.* **2020**, *175*, 105607. [CrossRef]
75. Polthanee, A.; Janthajam, C.; Promkhambut, A. Growth, yield and starch content of cassava following rainfed lowland rice in Northeast Thailand. *Int. J. Agric. Res.* **2014**, *9*, 319–324. [CrossRef]
76. Watananota, W.; Tangsakul, S.; Kamhung, M. The response of micronutrients on cassava root yield of Rayong 72 and Kasetsart 50. *Thai Agric. Res. J.* **2004**, *22*, 24–38. (In Thai)
77. Mondet, E.; Muakphet, P.; Suwichien, Y. Varietal testing of cassava varieties suitable in soil series 35 and arid areas in Kamphaeng Phet province. *VRU Agric. Food J.* **2024**, *2*, 28–35. (In Thai)
78. Kittipadakul, P.; Rodjanaridpiched, C.; Vichukij, V.; Changlek, P.; Malumpong, C.; Keawtrakulpong, K. Cassava stability of Thai cassava. In Proceedings of the 42nd Kasetsart University Annual Conference: Plants, Agricultural Extension and Communication, Bangkok, Thailand, 3–6 February 2004; Kasetsart University: Bangkok, Thailand, 2004; pp. 191–201. (In Thai)

79. Wongnoi, S.; Banterng, P.; Vorasoot, N.; Jogloy, S.; Theerakulpisut, P. Physiology, Growth and yield of different cassava genotypes planted in upland with dry environment during high storage root accumulation stage. *Agronomy* **2020**, *10*, 576. [CrossRef]
80. Bilong, E.G.; Abossolo-Angue, M.; Nanganoa, L.T.; Anaba, B.D.; Ajebesone, F.N.; Madong, B.A.; Bilong, P. Organic manures and inorganic fertilizers effects on soil properties and economic analysis under cassava cultivation in the southern Cameroon. *Sci. Rep.* **2022**, *12*, 20598. [CrossRef] [PubMed]
81. Somkid, S.; Thongros, M.; Chansrakoo, W.; Phompanja, P.; Kumsap, K.; Lersuwanaro, D.; Karnnasuta, K. System development of organic cassava starch supply chain of Ubon Ratchathani farmers. *Thai Agric. Res. J.* **2021**, *39*, 73–86.
82. Song, M.; Li, J.; Gao, L.; Tian, Y. Comprehensive evaluation of effects of various carbon-rich amendments on overall soil quality and crop productivity in degraded soils. *Geoderma* **2023**, *436*, 116529. [CrossRef]
83. Fageria, N.K. The role of soil organic matter in maintaining sustainability of cropping systems. *Commun. Soil Sci. Plant Anal.* **2012**, *43*, 2063–2113. [CrossRef]

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