Nutrient use efficiency and harvest index of cassava decline as fertigation solution concentration increases

John Okoth Omondi[1]*, Naftali Lazarovitch[1], Shimon Rachmilevitch[1], Steve Boahen[2], Pheneas Ntawuruhunga[3], Eldad Sokolowski[4], and **Uri Yermiyahu[5]**

[1] French Associates Institute for Agriculture and Biotechnology of Drylands, Ben-Gurion University of the Negev, 84990, Beer Sheba, Israel
[2] International Institute of Tropical Agriculture, Mozambique
[3] International Institute of Tropical Agriculture, Zambia
[4] International Potash Institute, Switzerland
[5] Gilat Research Centre, Agricultural Research Organization, M.P. Negev 85280, Israel

Abstract

Response of cassava (*Manihot esculenta* Crantz) to fertigation as a form of nutrient delivery is unknown. The objectives of this study were to establish a balanced nutrition and to enhance agronomic nutrient use efficiency (ANUE) of cassava under fertigation. This study was conducted in the greenhouse and in the field. In both, the results showed a similar trend. There were six fertigation concentrations and three cassava varieties, selected for their duration of growth in the field. Shoot biomass of the long-duration variety (Nalumino) was the highest, even though its dry root yield was the lowest (10.18 t ha^{-1}) among the varieties. In contrast, the medium-duration variety (Kampolombo) produced the highest dry root yield (20.34 t ha^{-1}) and a lower shoot biomass. The highest root yield of the shortest-duration variety (Mweru) was achieved at 200 mg N, 30 mg P, and 200 mg K L^{-1} (155.0, 23.3, 155.0 kg N, P, K ha^{-1}), while Nalumino's was at 70 mg N, 7 mg P, and 70 mg K L^{-1} (54.3, 5.4, 54.3 kg N, P, K ha^{-1}). ANUE and harvest index of these varieties declined as the fertigation concentrations increased. Additionally, the correlation between concentrations of N in the youngest fully expanded leaf (YFEL) blades and dry root yields was the lowest (R^2 = 0.5488), whereas P and K were R^2 = 0.7237 and R^2 = 0.8006, respectively, an indication that nutrient concentrations in the leaf, especially N, cannot easily be used to predict root yield. When cassava reaches nutrient sufficiency, mainly N, its accumulation in the leaf continues without significant increase in the root yield.

Key words: irrigation / macro-nutrients / *Manihot esculenta* / root crops / starch

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1 Introduction

Cassava (*Manihot esculenta* Crantz) is a root crop in the Euphorbiaceae family and a native of South America (*Nassar*, 2007). It is the third largest source of carbohydrates in the tropics and sixth most important crop in the world (*Lebot*, 2008). It is a source of food to over 500 million people and its importance in commercial animal feed, fiber for paper and textile manufacturers, and starch for pharmaceutical industries (*Balagopalan*, 2002; *Tonukari* et al., 2015) is gaining prominence, hence the need to improve yield per unit area. Until recently, it was grown mainly in poor soils (*Howeler*, 2001) and under water-scarce conditions, resulting in minimum growth and root yield. However, lately, root yields have been improved through irrigation (*Amanullah* et al., 2006; *Odubanjo* et al., 2011) and application of nutrients (*Fermont* et al., 2009; *Byju* et al., 2012).

Balanced nutrient application enhances growth and yield. When cassava receives balanced nutrition, leaf area index (*Sangakkara* and *Wijesinghe*, 2014), plant height, number of leaves, stem diameter, and number of roots per plant increase (*Uwah* et al., 2013). If there is an imbalance in N, P, and K, the growth and yield decline. *Carsky* and *Toukourou* (2005) showed that withholding N, P, and K led to 3.0, 5.0, and 5.3 t ha^{-1} reduction in root yield, respectively. Moreover, changes over time in soil fertility influence root yield (*Nguyen* et al., 2002). In addition, balanced nutrition designed for specific agroecological zone and variety enhance yield, as was the case for the Sree Vijaya variety in Kerala, India (*Susan John* et al., 2007). In the above studies, balanced nutrition changed based on three things: soil fertility, agroecological zones, and varieties. Nevertheless, the mode of nutrient application in all these studies was banding.

The mode of nutrient application affects its uptake (*Blackshaw* et al., 2002; *Gaskell* and *Hartz*, 2011). For example, enhanced synergistic interaction of N, P, and K was observed when liquid fertilizer was applied compared to granular (*Layne* et al., 1996; *Kowalenko* et al., 2000; *Bryla* and *Machado*, 2011; *Tesfaye* et al., 2011). *Shah* et al. (2006) observed enhanced N and P uptake when liquid N was

* Correspondence: J. O. Omondi; e-mail: okoth05@gmail.com

applied through drip irrigation. These nutrients, N and P, play a major role in improving shoot growth (*Bryla*, 2016). Further, the liquid application of nutrients, especially N, reduces losses through leaching (*Hebbar* et al., 2004) and volatilization. It provides a pool of nutrients for root absorption, improving nutrient recovery, and allowing their management, particularly N input and residual soil N (*Darwish* et al., 2003). Fertigation as a mode of fertilizer application either in dry areas or areas receiving sufficient rainfall serves the purpose of efficient nutrient delivery and enhances nutrient use efficiency (*Badr* et al., 2010; *Liang* et al., 2014).

Benefits of fertigation have been observed for other root and tuber crops. These benefits include increased tissue N and tuber yield (*Janat*, 2007). However, in cassava, fertigation as a mode of fertilizer application is new and its effects on growth and root yields are unknown. We hypothesize that because potato has a vegetative sink component (tubers) comparable to cassava (roots), the mechanisms governing the yield are the same. This study was set out to establish balanced nutrition for cassava under fertigation. This is intended to form a baseline for nutrition recommendations for other cassava varieties, soils, and agroecological zones under fertigation. Therefore, the main objectives of this study were to establish a balanced nutrition and to enhance agronomic nutrient use efficiency of cassava under fertigation.

2 Material and methods

2.1 Experimental sites

This study consisted of greenhouse and field trials. Potted experiments were conducted in 2014 (Exp. 1) and repeated in 2016 (Exp. 2) in a greenhouse at Gilat Research Centre in Israel (31°20′ N and 34°39′ E). During the experiments, the average relative humidity was 77.4% and 82.0%, radiation was 133.2 W m^{-2} and 139.9 W m^{-2}, and temperature was 22.7°C and 23.7°C inside the greenhouse in 2014 and 2016, respectively.

The field experiment was conducted at the International Institute Tropical Agriculture, Lusaka, Zambia (15°30′ S and 28°30′ E), at an altitude of 1190 m. The average radiation was 688.9 W m^{-2}, average relative humidity ranged from 85.9% to 46.8%, and temperature ranged from 24.8°C to 15.2°C. Rainfall amount during the experiment was 379.2 mm.

2.2 Treatments and procedures

In the greenhouse experiments, 20-cm cuttings with six nodes of an Israeli cassava (*Manihot esculenta* Crantz) variety (Tab. 1) were planted in 2-L containers filled up with water-saturated perlite. For a period of 28 d, the cuttings were hand-irrigated every 48 h using 0.5 L nutrient solution containing 100 mg N L^{-1}, 10 mg P L^{-1}, 100 mg K L^{-1}, 60 mg Ca L^{-1}, 30 mg Mg L^{-1}, and microelements (as described under the fertigation solution preparation).

All the rooted cuttings with 4–6 leaves were transplanted to 60-L containers of 40 cm diameter and 47 cm depth. These containers were filled up with 6 mm granular perlite substrate. Perlite has high porosity, hydraulic conductivity, and minimum interaction with nutrients. This substrate was successfully used in mineral nutrition studies of olive trees (*Erel* et al., 2015). The treatments were applied through uniform hand irrigation. In the first 4 weeks after transplanting, irrigation was 8 L per week, thereafter it was increased by 1 L per week. In 2014, 227 L of the solution were applied, while 347 L were applied in 2016. The experiments consisted of four fertigation solutions (Tab. 2) replicated five times in a complete randomized design. The shoots in Exp. 1 were trimmed to 20 cm height after 100 d of growth and allowed to regrow.

In the field, six fertigation concentrations were tested for three cassava varieties from 2015–2016 (Tab. 2). The treatments

Table 1: The morphology and agronomic traits of cassava varieties in the studies.

Trait	Israeli	Nalumino	Kampolombo	Mweru
Leaf tip color	Light green	Light green	Light purple	Light green
Leaf shape	Spear shaped	Spear shaped	Lanceolate	Lanceolate
Number of lobes per leaf	5	5	5	7
Stem color	Grey	Brownish	Reddish brown	Grey
Outer root skin color	Brown	Brown	Brown	Brown
Inner root skin color	White	White	Pink	Cream
Flesh color	White	White	White	White
Root shape	Cynical-cylindrical	Slender and long	Cynical-cylindrical	Fusiform/long
Plant architecture	Un-branching	Branching	Highly branching	Un-branching
Taste	Sweet	Flat	Sweet	Sweet
Flowering ability	Flowering	Profusely flowering	Flowering	Non-flowering
Maturity	13 months	18–24 months	16 months	12–14 months

Table 2: Treatments in the greenhouse and in the field.[a]

Treatment abbreviation	Fertigation solution concentration (NPK) (mg L^{-1})	Total N, P, and K in fertigation by the end of growth cycle (kg ha^{-1})	Cassava variety
Greenhouse			
N10P10K100	10, 10, 10		Israeli
N100P4K100	100, 4, 100		Israeli
N100P10K40	100, 10, 40		Israeli
N100P10K100	100, 10, 100		Israeli
Field			
N0P0K0 (Control)	0, 0, 0	0, 0, 0	Mweru, Kampolombo, and Nalumino
N20P2K20	20, 2, 20	15.5, 1.6, 15.5	Mweru, Kampolombo, and Nalumino
N70P7K70	70, 7, 70	54.3, 5.4, 54.3	Mweru, Kampolombo, and Nalumino
N100P10K100	100, 10, 100	77.5, 7.8, 77.5	Mweru, Kampolombo, and Nalumino
N150P20K150	150, 20, 150	116.3, 15.5, 116.3	Mweru, Kampolombo, and Nalumino
N200P30K200	200, 30, 200	155.0, 23.3, 155.0	Mweru, Kampolombo, and Nalumino

[a]The total number of treatments per replication was 18 in the field experiment. Applying the total NPK fertilizer applied at the end of the growth cycle was more practical for the field experiment than greenhouse, thus the missing values for greenhouse treatments.

were randomized in a split-plot arrangement, where fertigation concentrations were the main plots and cassava varieties were the sub-plots. The 18 treatments were replicated four times in a randomized complete block design. The varieties were selected for their differences in maturity period: Mweru was short duration, while Kampolombo and Nalumino were medium and long duration, respectively (Tab. 1). Lengthy Israeli plant protection regulations and importation processes hindered usage of similar varieties in the greenhouse, therefore, a variety available within Israel was used in the greenhouse.

Cuttings of 20 cm length were planted in a field nursery bed and irrigated uniformly with 0.5 L d^{-1} per stalk using compensated drip lines of 1.6 L h^{-1} spaced at 0.3 m. After 28 d, they were transplanted to the main field at a spacing of 1 m, each plot measured 5 m^2 containing 25 plants. On the 28^{th} day, application of treatments started. The cuttings were planted in the nursery because our unpublished results indicated faster sprouting in the nursery, ease in selection of plants with 4–6 leaves for transplanting and planning, *i.e.*, as the plants were growing in the nursery activities, such as plowing and layout of the field continued, thus shortening the preparation period and cycles of planting.

2.3 Fertigation solutions preparation

Preparation of the fertigation solutions for the greenhouse experiments was done by dissolving NH_4NO_3, $NH_4H_2PO_4$, KH_2PO_4, K_2SO_4, KNO_3, $NaNO_3$, $MgCl_2$, in tap water with an electrical conductivity (EC) of 0.3–0.4 dS m^{-1} to make a stock solution for each treatment. One liter of the stock solution was diluted 200 times to form a final solution. Besides N, P, and K, other minerals were uniform among the treatments at 60 mg Ca L^{-1}, 30 mg Mg L^{-1}, 2 mg Zn L^{-1}, 0.3 mg Cu L^{-1}, 4 mg Mn L^{-1}, 3 mg B L^{-1}, 0.2 mg Mo L^{-1}, and 8 mg Fe L^{-1}. The microelements (from a commercial liquid fertilizer "Koratin" from Israel Chemicals Ltd., Israel) and Ca from liquid $Ca(NO_3)_2$ were added to the final solution. The nitrogen distribution in all the treatments was 90% NO_3^- and 10% NH_4^+. The pH and the EC in the final solution were 6.9 ± 3.0 and 0.95 ± 0.10 dS m^{-1}, respectively. To ascertain whether the concentration in the final solution matched that of the required treatments, samples of the stock solutions and the final solutions were analyzed for N, P, and K. Total N was determined following *Snell* and *Snell* (1949), while P was determined using an automated photometric analyzer (Thermo Scientific Gallery Plus) and K was analyzed using an atomic absorption spectrophotometer (Perkin Elmer). Each treatment concentration was allowed ± 5% deviation from the required concentration.

The fertilizers used for preparation of the fertigation solutions for the field experiment were: MAP 52, KNO_3, $Ca(NO_3)_2$, $MgSO_4$, urea, and liquid Mainstay Calcium™ (Redox Chemicals, LLC) containing 200 g Ca L^{-1}. The microelements were obtained from Super Trace™ (Amiran-Zambia). These fertilizers were dissolved in water to make stock solutions, except Mainstay Calcium™ and Super Trace™. Before dissolution, water was analyzed: pH 6.9, EC 0.7 dS m^{-1}, 1.56 mg K L^{-1}, 26.91 mg Na L^{-1}, 135.60 mg Ca L^{-1}, 51.60 mg Mg L^{-1}, 612.44 mg HCO_3^- L^{-1}, 10.08 mg SO_4^{2-} L^{-1}, 18.82 mg Cl^- L^{-1}, < 0.01mg PO_4^{2-} L^{-1}, < 0.01mg B L^{-1}, < 0.01 mg NH_4^+ L^{-1}, and < 0.01 mg NO_3^- L^{-1}. One liter of the stock solution was diluted 2500 times, and 30 mg Ca L^{-1}, 8 mg Zn L^{-1}, 3 mg Cu L^{-1}, 7 mg Fe L^{-1}, 3 mg B L^{-1}, 0.1 mg Mo L^{-1}, and 6 mg Mn L^{-1} were added to form the final solution. To ensure the required concentration of each treatment, solution samples were analyzed for N, P, and K. The fertigation solutions were applied uniformly in the field at daily 100% ET_0 (reference crop evapotranspiration) between 10.00–12.00 h using compensated drip lines of 1.6 L h^{-1} spaced at 0.3 m. Daily ET_0 was calculated using the Penman–Monteith equation in the WatchDog 2900ET weather station. At the end of the growth cycle, 7750 L of each treatment solution were applied.

2.4 Data collection and analysis

Soil was randomly sampled in the field from 0–30, 30–60, and 60–90 cm depths at the onset of the trial. Five samples were taken for each depth, mixed thoroughly, air-dried, and passed through a 2-mm sieve. The soil was analyzed for total N, P, K, Ca, Mg, S, Na, Fe, Mn, B, Cu, Zn, CEC, and OM (organic matter). Total N was analyzed using the Kjeldahl method (*Bremner*, 1960) and P, K, Ca, Mg, S, Na, Fe, Mn, B, Cu, and Zn using Mehlich 3 extraction (*Mehlich*, 1984). Soil pH was measured at a 1 : 2 soil : water ratio and texture using the hydrometer method. From the 0–30 cm depth, the soil was loam, while from 30–90 cm it was sandy clay loam. Its bulk density was 1.29 g cm^{-3}. The other pre-trial results are presented in Tab. 3. At the end of the trial, soil was sampled from each plot under five random drippers at 0–30 cm depths. They were processed and analyzed for N, P, and K, in the same way as soil samples at the onset of the trial.

Net photosynthesis and stomatal conductance were measured on a youngest fully expanded leaf of five plants within the net plot (4 m^2) in the field and on each plant in the greenhouse using an LI-6400 portable photosynthesis system (Li-Cor Inc., Lincoln, NE, USA). This was between 10:00 and 13:00 h at 88 and 122 d of treatment (DOT) in the greenhouse and the field, respectively. The measurements were made at photosynthetic photon flux density (PPFD, 400–700 nm) of 900–1000 μmol m^{-2} s^{-1}. On the same leaves and day, chlorophyll index was measured using chlorophyll meter (SPAD 502 Plus chlorophyll meter).

From each treatment in the field, five youngest fully expanded leaves (YFEL) of four plants within the net plot were sampled at 125 DOT and from each plant in the greenhouse at 88 DOT. The leaf blades were separated from the petioles, rinsed in deionized water for 15 s, dried using a paper towel, and oven-dried at 70°C to a constant weight. The dried leaf blades were ground in a stainless-steel coffee mill to 0.5 mm particle size. Total N concentration in the leaf blade was determined after digestion with sulfuric acid and peroxide. Phosphorus was determined using an automated photometric analyzer (Thermo Scientific Gallery Plus), while K was analyzed using an atomic absorption spectrophotometer (Perkin Elmer; *Snell* and *Snell*, 1949).

Heights of four plants from the net plot in the field and each plant in the greenhouse were measured from the 5^{th} internode from the ground/perlite to the tip of the newly formed leaf using a tape measure, whereas stem diameter was measured using a vernier callipers between the 5^{th} and 6^{th} internode from the ground/perlite on the same plants. Leaf area index was measured on the same plants at the base using Sunscan (SS1 Sunscan Canopy Analysis System).

Table 3: Soil characteristics of the field at the onset of the experiment.[a]

Depth (cm)	pH	EC (dS m^{-1})	P (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Mg (mg L^{-1})	S (mg L^{-1})	Na (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	B (mg L^{-1})	Cu (mg L^{-1})	Zn (mg L^{-1})	CEC (meq 100 g^{-1})	N (mg L^{-1})
0–30	6.3	58.5	13.6	103	881	219.5	15.05	18	97.9	171.5	0.150	1.965	1.620	7.775	900
30–60	6.0	21.0	4.8	50.8	726	180.5	8.39	30.6	117.0	120.5	0.125	2.055	1.185	6.795	950
60–90	5.6	16.5	1.8	39.4	507	129.0	11.85	29.35	98.2	128.5	0.084	2.065	0.945	5.685	800

[a]P and K determined after Mehlich 3 extraction.

Harvesting of Exp. 1 was done 120 d after trimming the plants, while Exp. 2 was harvested at 158 d after transplanting. At 230 d after transplanting in the field, six plants within the net plot (4 m^2 area) were harvested. The plants were separated into tuberous roots, stem, and leaves, and their fresh masses were recorded. A known fresh mass of sub-samples was oven-dried at 70°C for 48 h, weighed again, and water content and dry mass of each compartment were determined. Part of the fresh tuberous roots was peeled, dried, ground, and analyzed for starch using a total starch assay procedure (ACCI method 76-13.01) of the American Association of Cereals Chemists (*AACCI*, 2017).

Agronomic nutrient use efficiency (specifically N, P, K, as they were the nutrients that changed among the treatments) was calculated following a modification of *Yasuor* et al. (2013) and *Fageria* and *Baligar* (2005) nitrogen use efficiency methodologies. In these methodologies, nitrogen use efficiency is the ratio between yield and applied nitrogen. This was modified to agronomic nutrient use efficiency being yield (tuberous roots in our study) from the plot with fertigation minus the plot without fertigation divided by the total nutrient applied. Volume of the nutrient applied was calculated as follows:

$$\begin{aligned}&\textit{Volume of irrigation solution applied}\\ &\textit{from transplanting to harvesting } (L)\\ &\times \textit{ concentration of each nutrient}\\ &\textit{in the irrigation solution } (mg\ L^{-1})\end{aligned} \qquad (1)$$

$$\begin{aligned}&\textit{Summation of the volume of nutrients},\\ &\textit{i.e., adding volumes of N},\\ &\textit{P and K to get total nutrients applied } (TNa),\end{aligned} \qquad (2)$$

$$ANUE = Ya - Yb\frac{kg}{TNa}(kg), \qquad (3)$$

where *ANUE* is agronomic nutrient use efficiency (kg kg^{-1}), *TNa* is total nutrient applied (kg), *Ya* is root yield (kg) of the plots that received fertigation, *Yb* is root yield of the plots without fertigation.

Harvest index was calculated following *Ojulong* et al. (2010) methodology. However, in our experiment the fresh weights were replaced by dry weights, thereby using the procedure: the dry root yield (t ha^{-1}) divided by the total mass (dry shoot mass plus dry root yield (t ha^{-1}). Data collected were subjected to a two-way analysis of variance (ANOVA) at 5% level of significance and means compared using LSD on SAS software (*SAS*, 2002).

3 Results

3.1 Leaf and soil nutrients and agronomic nutrient use efficiency

Concentrations of N and P in the youngest fully expanded leaf (YFEL) blade were not significantly different in the greenhouse experiments, so was YFELs' N concentration in the field. However, YFELs' P concentration was significantly different (Tab. 4). Concentration of K in the YFEL blade was different in the greenhouse (Fig. 1a), among the varieties

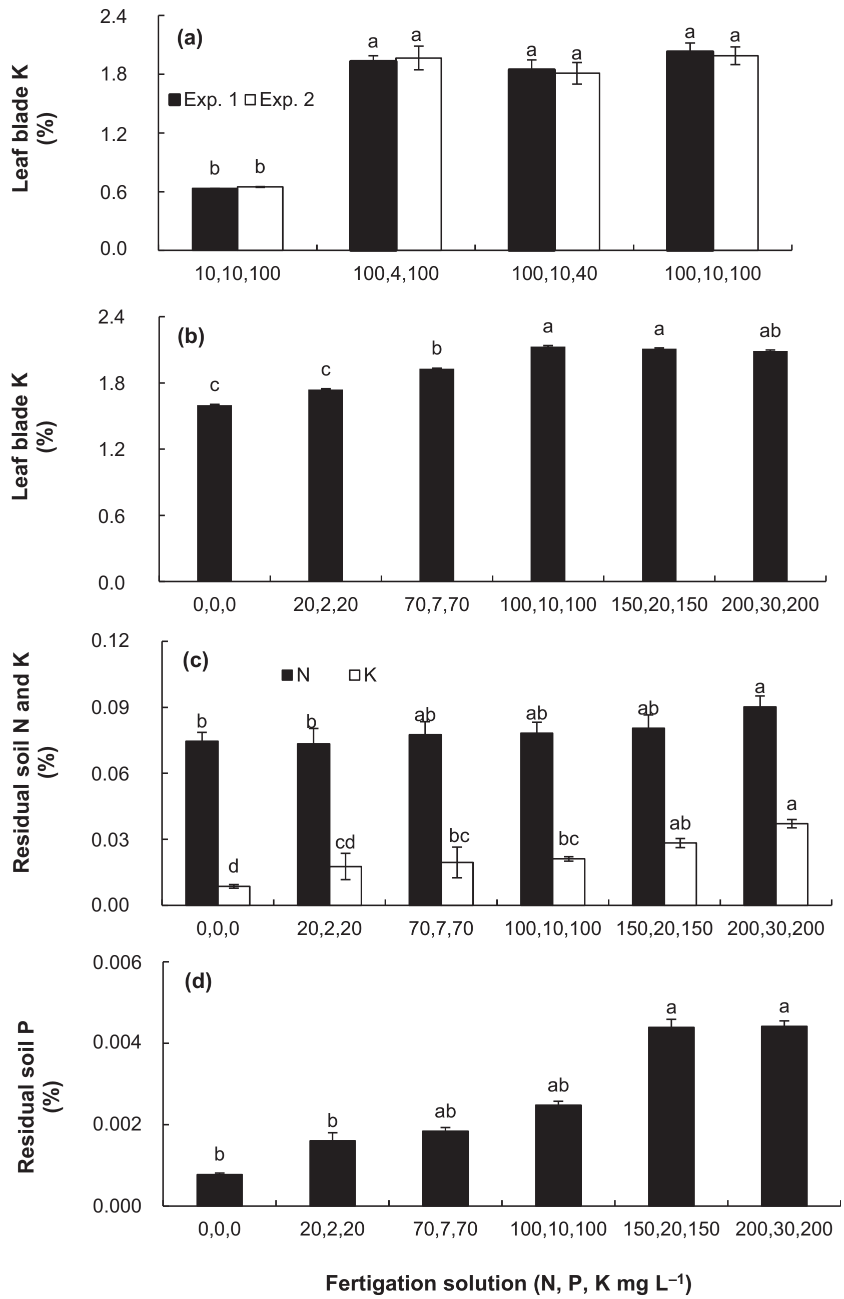

Figure 1: Effect of fertigation solution (main plot) on: (a) the concentration of K in the leaf blade (youngest fully expanded leaf–YFEL) in greenhouse, (b) K in the leaf blade in the field, (c) residual soil N and K, and (d) residual soil P. The error bars are ± SE (standard errors), $n = 4$. Means with different letters are significantly different at $P < 5\%$.

Table 4: Fertigation solutions and variety effect on concentrations of N, P, and K in the YFEL blade in the field. [a]

Treatment abbreviation	N (%)	P (%)	K (%)
Mweru			
N0P0K0	5.31 ± 0.05a	0.85 ± 0.08b	1.44 ± 0.05e
N20P2K20	5.32 ± 0.04a	0.86 ± 0.05b	1.83 ± 0.10d
N70P7K70	5.32 ± 0.04a	0.88 ± 0.07b	1.91 ± 0.08cd
N100P10K100	5.39 ± 0.05a	0.92 ± 0.10ab	2.15 ± 0.09b
N150P20K150	5.41 ± 0.06a	0.93 ± 0.07ab	2.45 ± 0.04a
N200P30K200	5.42 ± 0.03a	1.08 ± 0.06a	2.05 ± 0.13bc
Kampolombo			
N0P0K0	5.36 ± 0.10a	0.73 ± 0.09b	1.49 ± 0.10c
N20P2K20	5.36 ± 0.08a	0.84 ± 0.08ab	1.53 ± 0.09c
N70P7K70	5.42 ± 0.07a	0.89 ± 0.10ab	1.62 ± 0.12bc
N100P10K100	5.59 ± 0.05a	0.93 ± 0.07ab	1.97 ± 0.13a
N150P20K150	5.51 ± 0.08a	1.17 ± 0.06a	1.97 ± 0.09a
N200P30K200	5.46 ± 0.06a	1.02 ± 0.08ab	1.92 ± 0.10ab
Nalumino			
N0P0K0	5.32 ± 0.04a	0.79 ± 0.07b	1.81 ± 0.09b
N20P2K20	5.34 ± 0.05a	0.89 ± 0.06ab	1.89 ± 0.09b
N70P7K70	5.36 ± 0.07a	1.01 ± 0.08a	2.18 ± 0.07a
N100P10K100	5.39 ± 0.12a	1.06 ± 0.08a	2.21 ± 0.10a
N150P20K150	5.44 ± 0.09a	1.02 ± 0.09a	2.25 ± 0.08a
N200P30K200	5.41 ± 0.06a	0.86 ± 0.05ab	2.15 ± 0.09a

[a]Means with different letters are significantly different at $P < 5\%$. The error bars are ± SE (standard errors), $n = 4$.

(Tab. 4) and among the fertigation solutions in the field (Fig. 1b). In the field, residual levels of N, P, and K in the soil were neither significantly different among the varieties nor among the interactions between fertigation solution and variety. However, they were different among the fertigation solutions (main plots), reaching maximum under N200P30K200 (Fig. 1c, d).

Agronomic nutrient use efficiency (ANUE) significantly declined as fertigation solution concentration increased ($P = 0.03\%$; Fig. 2b). Mweru's ANUE declined from 51.3 to 7.7 kg kg^{-1}, while Kampolombo's declined from 73.1 to 13.2 kg kg^{-1}, and Nalumino's decreased from 10.8 to –1.0 kg kg^{-1} from N20P2K20 to N200P30K200. Among the varieties, the greatest decline was under Kampolombo and lowest under Nalumino (Fig. 2b).

3.2 Growth and photosynthetic attributes

Differences in height, stem diameter, leaf area index, and shoot biomass were significant among the varieties, among the fertigation solutions, and under the interactions of fertigation solution and variety. Among the varieties in the field, Kampolombo was the shortest and Nalumino was the tallest (Tab. 5), while the highest height was achieved under N200P30K200. Stem diameter of Mweru was significantly the thinnest under no-fertilizer application and Nalumino was the thickest at N200P30K200 (Tab. 5). Leaf area index in the field followed similar trends as plant height and stem diameter. Leaves of the three varieties were significantly smallest under no-fertilizer and largest at N200P30K200. Kampolombo had the largest leaves (Tab. 5).

Dry shoot mass was significantly different in the greenhouse, among the varieties in the field, among the fertigation solutions and under interactions of fertigation solution and variety. Dry shoot mass of Mweru (13.1 t ha^{-1}) and Kampolombo (14.9 t ha^{-1}) were maximum at N200P30K200, while Nalumino's dry shoot mass (19.8 t ha^{-1}) was highest at N100P10K100 (Tab. 6).

The chlorophyll index was significantly different among treatments in Exp.1 and Exp. 2. Similarly, it was significantly different among the varieties in the field, the fertigation solution, and under the interaction of fertigation solution and variety (Tab. 5). Stomatal conductance was also significantly different in the greenhouse, among fertigation solutions, and under the

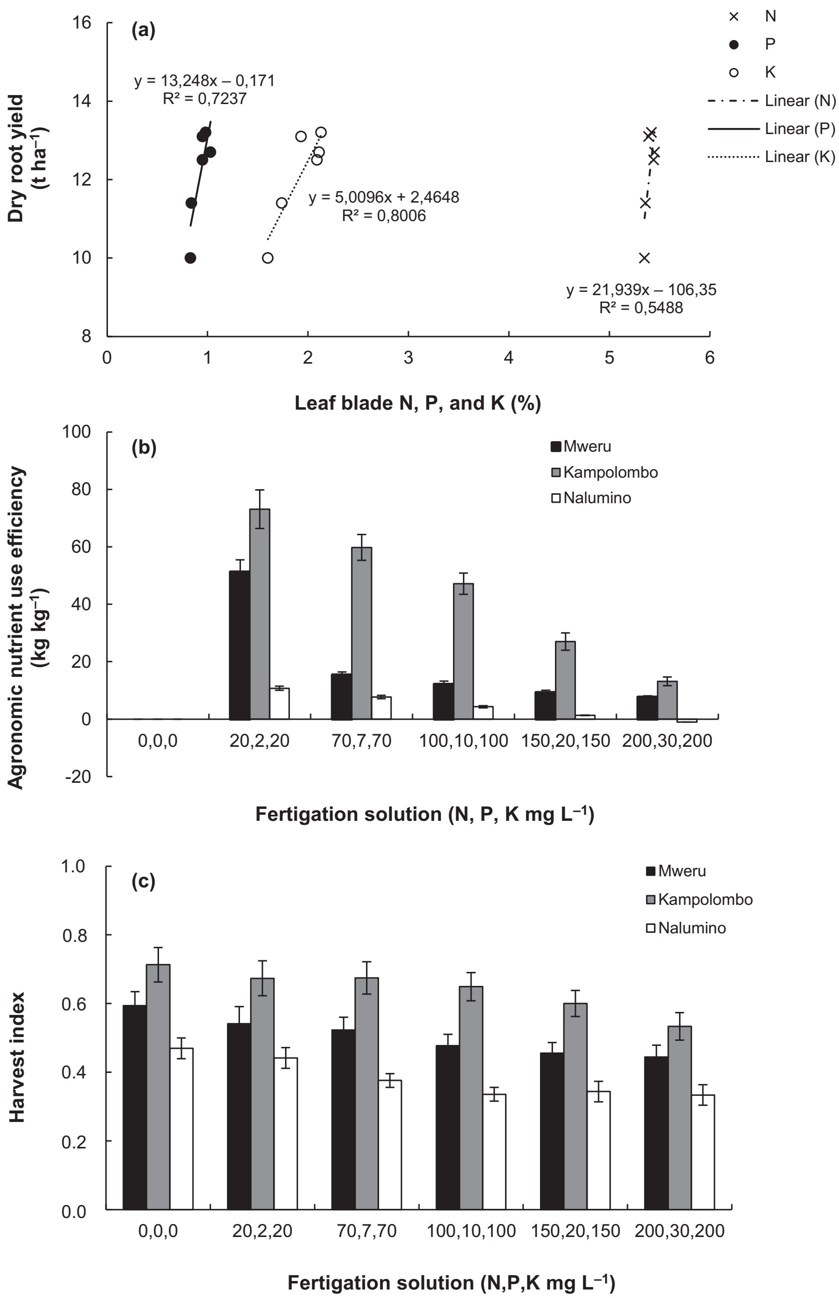

Figure 2: (a) The relationship between N, P, and K in the YFEL blade and the dry root yield in the main plot. Fertigation solution (main plot) effect on: (b) agronomic nutrient use efficiency and (c) harvest index of each variety in the field. The error bars are ± SE (standard errors), *n* = 4.

interactions between fertigation solution and variety in the field (Tab. 5). The trend of net photosynthesis was similar to that of stomatal conductance (Tab. 5). Dry root yields of the varieties were maximized under similar fertigation solutions (Tab. 6).

3.3 Root yield, starch concentration, and harvest index

Dry root yield was significantly different among the fertigation solutions in Exp. 1 and Exp. 2. Dry root yields of Mweru and Kampolombo were significantly different among the fertigation solutions, while Naluminos' were non-significant. Mweru's dry root yield increased from 7.89 t ha^{-1} under no-fertilizer to a maximum of 10.46 t ha^{-1} at N200P30K200, this maximum root yield was only different to no-fertilizer application, but similar to other fertigation solutions. Kampolombo's dry root yield rose from 12.67 t ha^{-1} under no-fertilizer and maximized at 20.34 t ha^{-1} at N100P10K100, then declined. However, this highest dry root yield of Kampolombo at N100P10K100 was not significantly different from root yield at N70P7K70 and N150P20K150 (Tab. 6).

The starch concentration of the dry roots followed a similar trend as root yields. Starch in the roots of Mweru reached a maximum of 78.50% at N200P30K200. However, this was only significantly different from the starch under no-fertilizer. Kampolombo's and Nalumino's root starch were maximum at N100P10K100 (85.06%) and N70P7K70 (77.55%), respectively (Tab. 6). The harvest index of the varieties significantly declined as fertigation solution concentrations increased (Fig. 2c).

4 Discussion

The results of the greenhouse and the field experiments showed similar trends, fulfilling this study's objective. In the field, the maximum physiological activity, as observed in stomatal conductance, net photosynthesis, concentration of starch in the roots, and the final yields, were achieved at N200P30K200, N100P10K100, and N70P7K70 for Mweru, Kampolombo, and Nalumino, respectively. These fertigation treatments, at which maximum root yields were achieved, offer a baseline for fertigation studies and ANUE of short, medium and long duration varieties of cassava.

The concentrations of N, P, and K in the YFEL blades of the three field varieties were within or above the sufficiency levels, being 5.1–5.8%, 0.4–0.5%, and 1.4–1.9% of N, P, and K, respectively (*Howeler*, 2002; 2012). This is an indication of an efficient uptake and accumulation of these macro-nutrients by cassava, since even at zero fertilizer application they were sufficient. Furthermore, the narrow range of total N, P, and K concentrations in the YFEL blades between zero fertilizer application and the highest fertigation treatment (Tab. 4) complicates N, P, K status analysis in cassava, as the range between deficiency and sufficiency is narrow. Even though, the macro-nutrients were above critical levels at the highest fertigation treatment, root yields declined, except those of Mweru. This shows that sufficiency of leaf nutrients, especially N, minimally correlates to root yield (Fig. 2a).

Table 5: Effect of fertigation on height, stem diameter, leaf area index, chlorophyll index, stomatal conductance, and net photosynthesis of cassava varieties in the greenhouse and the field.

Treatment abbreviation	Plant height (cm)	Stem diameter (mm)	Leaf area index (LAI)	Chlorophyll index (SPAD)	Stomatal conductance (mmol H_2O m^{-2} s^{-1})	Net photosynthesis (μmol CO_2 m^{-2} s^{-1})
Exp. 1						
N10P10K100	169.0 ± 8.2c	13.6 ± 0.4c		43.7 ± 1.8c	0.21 ± 0.007c	18.2 ± 0.6
N100P4K100	209.1 ± 8.3b	14.8 ± 0.4b		48.3 ± 2.1ab	0.25 ± 0.010b	21.9 ± 1.7b
N100P10K40	215.0 ± 6.2b	17.7 ± 0.2a		49.8 ± 2.0ab	0.28 ± 0.017a	23.5 ± 1.9ab
N100P10K100	241.5 ± 5.6a	18.5 ± 0.3a		50.2 ± 2.5a	0.30 ± 0.020a	25.2 ± 0.9a
Exp. 2						
N10P10K100	257.2 ± 13.0b	14.3 ± 0.6b		42.1 ± 2.3c	0.23 ± 0.017c	20.3 ± 1.8c
N100P4K100	278.9 ± 11.4ab	17.2 ± 0.5a		47.4 ± 2.6b	0.27 ± 0.015b	27.2 ± 1.0b
N100P10K40	284.6 ± 5.4ab	18.4 ± 0.4a		48.6 ± 3.8ab	0.30 ± 0.022a	31.6 ± 2.3a
N100P10K100	302.2 ± 9.4a	18.7 ± 0.7a		51.2 ± 3.4a	0.31 ± 0.030a	33.1 ± 0.7a
Mweru						
N0P0K0	150.7 ± 1.5c	27.2 ± 0.4e	3.6 ± 0.1d	40.28 ± 3.3c	0.143 ± 0.007c	11.87 ± 1.1c
N20P2K20	174.6 ± 3.0b	32.0 ± 1.1d	4.7 ± 0.4cd	40.89 ± 3.1c	0.170 ± 0.010bc	12.41 ± 0.8c
N70P7K70	174.8 ± 0.3b	32.4 ± 0.3cd	5.4 ± 0.3bc	40.95 ± 3.3c	0.193 ± 0.011b	12.68 ± 0.8bc
N100P10K100	181.4 ± 1.3b	34.7 ± 0.4bc	6.4 ± 0.4ab	42.36 ± 3.8bc	0.257 ± 0.017ab	16.43 ± 0.7ab
N150P20K150	182.4 ± 2.4b	36.7 ± 1.3ab	6.7 ± 0.2a	45.59 ± 4.0a	0.270 ± 0.012a	16.53 ± 1.1ab
N200P30K200	191.7 ± 0.8a	37.8 ± 0.2a	7.4 ± 0.3a	44.46 ± 4.1ab	0.283 ± 0.008a	18.15 ± 1.4a
Kampolombo						
N0P0K0	113.1 ± 1.0e	25.9 ± 0.5d	4.5 ± 0.4c	39.06 ± 3.8c	0.134 ± 0.009c	9.06 ± 0.6c
N20P2K20	137.2 ± 2.1d	29.7 ± 0.9c	5.1 ± 0.1c	39.48 ± 3.2bc	0.137 ± 0.010c	10.98 ± 1.0bc
N70P7K70	147.9 ± 0.3c	30.5 ± 0.7c	6.8 ± 0.2b	42.28 ± 3.6ab	0.165 ± 0.016bc	12.80 ± 0.9b
N100P10K100	164.2 ± 5.3b	33.1 ± 1.9b	7.3 ± 0.2b	44.23 ± 4.2a	0.263 ± 0.015a	17.49 ± 1.2a
N150P20K150	162.6 ± 4.1b	33.7 ± 0.6ab	7.8 ± 0.1ab	44.15 ± 3.5a	0.257 ± 0.016a	15.33 ± 1.5ab
N200P30K200	176.1 ± 1.3a	35.6 ± 0.3a	8.8 ± 0.3a	41.75 ± 4.0abc	0.207 ± 0.014ab	12.67 ± 1.1bc
Nalumino						
N0P0K0	174.8 ± 1.8c	34.2 ± 0.3c	5.0 ± 0.1b	43.23 ± 2.2b	0.121 ± 0.006ab	9.39 ± 0.7cd
N20P2K20	186.1 ± 1.2b	35.8 ± 0.8c	5.3 ± 0.3b	44.27 ± 3.7ab	0.193 ± 0.013ab	14.98 ± 1.3ab
N70P7K70	190.8 ± 4.0b	38.9 ± 1.1b	5.3 ± 0.1b	44.58 ± 3.1ab	0.250 ± 0.019a	17.57 ± 1.4a
N100P10K100	200.9 ± 3.9a	39.7 ± 1.0b	6.0 ± 0.3ab	45.13 ± 3.3ab	0.231 ± 0.020ab	16.69 ± 1.3ab
N150P20K150	205.8 ± 3.1a	40.1 ± 0.9b	6.9 ± 0.4a	46.19 ± 2.1a	0.178 ± 0.017ab	12.25 ± 1.1bc
N200P30K200	209.2 ± 1.1a	42.9 ± 0.7a	7.0 ± 0.4a	46.60 ± 2.1a	0.120 ± 0.005b	6.20 ± 0.5d

[a]Means with different letters are significantly different at P < 5%. The error bars are ± SE (standard errors), $n = 4$. LAI of plants in Exp.1 and Exp. 2 were not measured.

The short (Mweru) and medium (Kampolombo) duration varieties achieving maximum shoot biomasses at higher fertigation treatments than the long-duration variety (Nalumino) was perhaps due to their internal demand for nutrients to complete their growth cycle within the shortest period. *El-Hawaz* et al. (2016) and *Kanmegne* et al. (2017) indicated that nutrition accelerates growth, thus, could be used to shorten the growth cycle. Certainly this was the case in the three varieties but more pronounced in Mweru.

Photosynthesis and root starch of the three varieties followed a similar trend as that of the root yields, an indication that nutrient concentrations influenced the source–sink relationship. The allocation of soluble carbohydrates from leaves to

Table 6: Dry shoot mass, dry root yield, and starch concentration of cassava varieties under different fertigation concentrations in the greenhouse and the field.[a]

Treatment abbreviation	Dry shoot mass (t ha^{-1})	Dry root yield (t ha^{-1})	Storage root starch (%)
Exp. 1			
N10P10K100	1.8 ± 0.15c	2.86 ± 0.10c	
N100P4K100	3.5 ± 0.24b	3.22 ± 0.17b	
N100P10K40	4.8 ± 0.37a	3.77 ± 0.14ab	
N100P10K100	5.2 ± 0.28a	4.05 ± 0.19a	
Exp. 2			
N10P10K100	3.7 ± 0.22c	1.97 ± 0.16c	
N100P4K100	6.7 ± 0.56b	5.28 ± 0.33b	
N100P10K40	7.8 ± 0.40ab	8.88 ± 0.51a	
N100P10K100	8.9 ± 0.48a	9.85 ± 0.44a	
Mweru			
N0P0K0	5.4 ± 0.4e	7.89 ± 0.6b	70.87 ± 2.99b
N20P2K20	8.1 ± 0.7d	9.56 ± 0.7ab	73.48 ± 2.37ab
N70P7K70	8.8 ± 0.6cd	9.65 ± 0.74ab	73.60 ± 1.96ab
N100P10K100	10.8 ± 0.8bc	9.86 ± 0.71a	73.97 ± 2.34ab
N150P20K150	12.2 ± 0.2ab	10.2 ± 0.54a	75.21 ± 2.37ab
N200P30N200	13.1 ± 0.5a	10.46 ± 0.46a	78.50 ± 2.97a
Kampolombo			
N0P0K0	5.1 ± 0.6e	12.67 ± 0.18c	73.16 ± 0.81c
N20P2K20	7.3 ± 0.7d	15.05 ± 0.73b	75.03 ± 1.07bc
N70P7K70	9.4 ± 0.8cd	19.48 ± 0.52a	75.56 ± 1.05bc
N100P10K100	11.0 ± 0.9bc	20.34 ± 0.18a	85.06 ± 1.79a
N150P20K150	12.9 ± 0.4ab	19.37 ± 1.20a	77.50 ± 1.05b
N200P30N200	14.9 ± 0.5a	17.06 ± 0.95b	73.65 ± 1.05c
Nalumino			
N0P0K0	10.5 ± 0.9c	9.30 ± 0.86a	67.82 ± 0.74d
N20P2K20	12.2 ± 0.8c	9.65 ± 0.82a	69.27 ± 1.01d
N70P7K70	16.9 ± 0.8b	10.18 ± 0.90a	77.55 ± 0.50a
N100P10K100	19.8 ± 0.7a	10.00 ± 0.80a	76.54 ± 0.74ab
N150P20K150	18.4 ± 1.0ab	9.63 ± 0.78a	75.53 ± 0.72b
N200P30N200	17.9 ± 0.9ab	8.96 ± 0.76a	73.26 ± 0.58c

[a]Means with different letters are significantly different at $P < 5\%$. The error bars are ± SE (standard errors), $n = 4$. The starch in storage roots in Exp. 1 and Exp. 2 are not presented as they were not measured.

roots was influenced by N and K. *Santiago* and *Tegeder* (2017) showed that N was involved in phloem loading, and *Armengaud* et al. (2009) and *Battie-Laclau* et al. (2014) observed the importance of K in carbon transport and storage. Moreover, this high positive relationship between K and root yield was observed in this experiment (Fig. 2a). However, these macro-nutrients can only influence the allocation of available photo-assimilates. Therefore, if photosynthesis declines, irrespective of N and K being sufficient as in our experiment, the photo-assimilates allocated to the roots will be lower. This prompts the starch build-up in the roots to be based on the quantity of available photo-assimilates for allocation.

Mweru's and Nalumino's agronomic nutrient use efficiency (ANUE) were lower than Kampolombo's. Kampolombo is described as highly branching with large leaves (*Chiwona-Karltun* et al., 2015), which was confirmed by the high leaf area index in this study (Tab. 5). This enhanced photosynthesis and starch accumulation in the roots. Furthermore, Kampolombo has the smallest height among the three varieties, thus, confirming *El-Sharkawy* and *De Tafur* (2010), who observed that short varieties have a high nutrient use efficiency and fill their storage roots earlier in the season than tall varieties.

The root yield of Nalumino had a minimum correlation with its shoot biomass in comparison to Mweru. This indicates that a long-duration variety such as Nalumino was either harvested early before it could translocate most sugars to the roots or it concentrated on building new leaves, expanding stems, and developing branches early in the season leading to the high shoot biomass observed in this study (Tab. 6). This build-up of vegetative plant parts consumed the sugars that would otherwise have been translocated to the roots. It has been observed that root diameter determines root bulking at the initial phases, whereas shoot biomass is most important for root bulking after 7 months of growth (*Okogbenin* and *Fregene*, 2002). This further explains why the high shoot biomass of Nalumino did not achieve a high root yield after 7 months of growth. Furthermore, the harvest index and ANUE of Nalumino were the lowest among the three varieties. As fertigation treatment increased, Nalumino's conversion of the nutrients into root yield was slow.

Indicating the importance of fertigation, the highest increase in root yield of Kampolombo was 60.5% with a fertigation rate of N100P10K100, corresponding to a total application of 77.5, 7.8, and 77.5 kg ha^{-1} of N, P, and K, respectively. In comparing this to banding, for example, *Fermont* et al. (2009) observed 43.4% and 76.9% (2004 and 2005) increase in root yield on banding of 100, 22, 83 kg ha^{-1} N, P, K. Even though their yield was higher compared to their no-fertilizer application, they banded more fertilizer compared to our experiment, in addition to higher soil nutrients at the beginning of their experiment and the longer cassava growth period. This indicates the importance of fertigation especially in enhancing nutrient uptake, thus, contributing to efficient nutrient use. Furthermore, managing higher root yields within 7 months of fertigation in our study as compared to the practice of harvesting in 12–15 months shows that fertigation plays a role in shortening the growth period in comparison to broadcasting or banding methods of fertilizer application. Moreover, the method of fertilizer application influences crop growth and yield (*Neilsen* et al., 1999; *Mohammad*, 2004).

5 Conclusion

The fertigation treatments at which varieties achieved their highest root yields are an indication of their specific nutrient requirements. However, the nutrient concentrations of the YFEL, especially N, were not well correlated with the final root yields. Furthermore, short varieties with large leaf area are more nutrient use-efficient than tall varieties. Even at sufficiency, nutrients, mostly N, in the leaf of cassava continue to accumulate without significant increase in the storage roots. Therefore, above sufficiency, there is luxury absorption of nutrients leading to a decline in both harvest index and ANUE.

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