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Fertilizing for High Yield and Quality

Cassava

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Cassava

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Contents

1 Introduction

1.1 Origin, botany and physiology

1.1.1 Origin and botany

Cassava (*Manihot esculenta* Crantz), a root crop in the Euphorbiaceae family, is native to the southern Amazon (Olsen and Schaal, 1999), specifically the border between Bolivia, Brazil, Guyana, Peru, Surinam and Venezuela (Allem and Postal, 1994). It is a perennial shrub whose storage roots can be harvested from 6-24 months depending on the cultivar, agronomic management and agroecological zone.

Cassava propagated from seeds have radicles which develop into taproots and adventitious roots, later forming storage roots. On the other hand, cassava propagated from cuttings have adventitious roots arising from the base of the buds. The roots then become fibrous with some (three to ten) forming storage roots. It is important to note that cassava is a true root crop and not a tuberous root as its roots cannot be used for vegetative propagation. The storage roots consist of three parts: 1) the bark (periderm), 2) the peel (cortex) and 3) the parenchyma (the edible portion accounting for 85% of the total weight).

Mature stems are woody and cylindrical with alternating nodes and internodes. The lobed leaves (around three to five lobes in a mature vegetative leaf) consist of a petiole and a lamina which have palmated veins. The stomatal pores, which occupy 1.4-3.1% of the total leaf area, are mostly located on the underside (abaxial) rather than the upperside (adaxial), even though the upperside stomata are bigger. Cassava produces both male (pistillate) and female (staminate) flowers on the same plant (monoecious), and forms fruits and seeds (Appendix, 1-5) (for more on botany see Alves (2002).

1.1.2 Physiology

Leaf area index (LAI) is a major determinant in photosynthesis. However, in cassava, a competition arises during growth – in partitioning of the photoassimilates – between the shoot and the storage roots (El-Sharkawy, 2004). Allocation of more photosynthates to the shoots could lead to a decline in root yields, although in evaluating 30 cassava cultivars El-Sharkawy *et al.* (2012) observed a positive significant relationship between LAI and root yield (Fig. 1a). Nonetheless, Splittstoesser and Tunya (1992) observed that a moderate LAI of 2.4-3 favored higher root yield. In unpublished fertigation studies on three cassava cultivars in Zambia, the LAI increased as fertigation solution concentration increased However, the relationship between LAI and dry root yield was curvilinear in medium and long duration varieties, Kampolombo and Nalumino respectively, and linear in the short duration variety – Mweru (Fig. 1b).

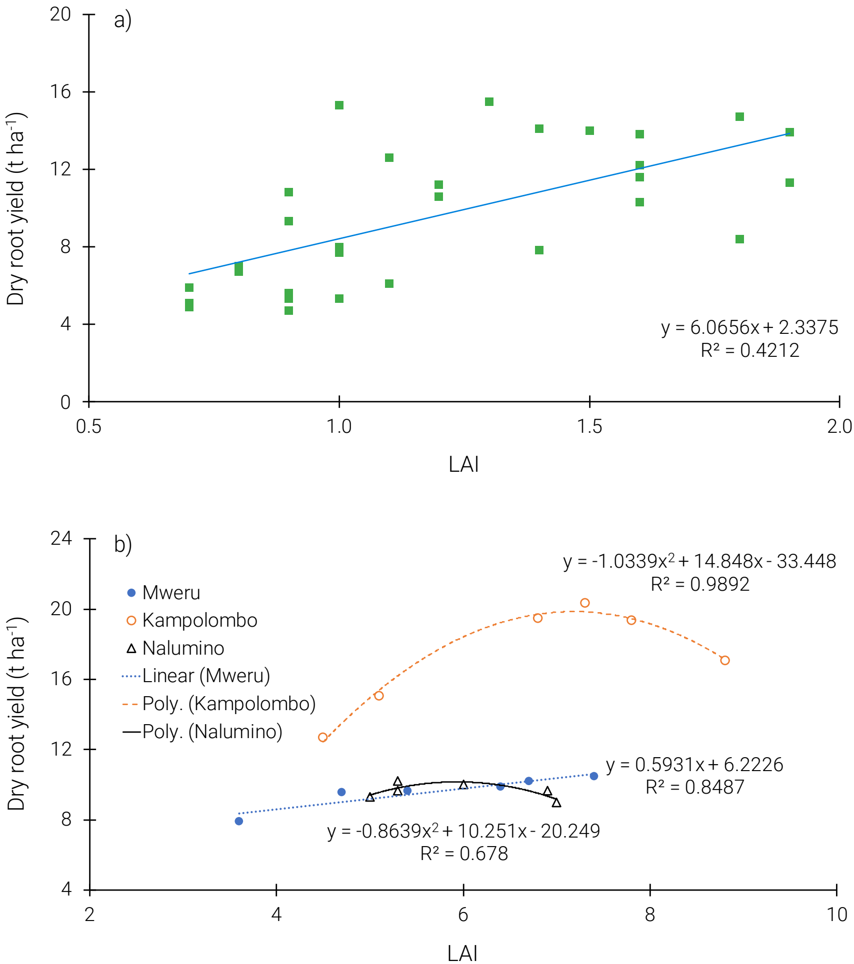

Fig. 1. Relationship between LAI and dry root yield of cassava. Observations in a) are from El-Sharkawy *et al.* (2012) while those in b) are from an unpublished fertigation study in Zambia. Poly means polynomial.

Earlier studies on photosynthesis of cassava showed that it was a C3-C4 intermediate crop due to a high leaf photosynthesis rate, low photorespiration and a chlorenchymatous bundle sheath. However, more recent studies have settled on cassava being a C3 plant with the maximum photosynthesis of improved cassava grown in the field being 50 µmol m^{-2} s^{-1} at a photon flux of 1,800 µmol m^{-2} s^{-1} (De Souza *et al.,* 2017). Previously, photosynthesis in greenhouses or growth chambers have ranged between 13 and 24 μmol CO_2 m^{-2} s^{-1} while, in the field, the range have been between 20 and 35 μmol CO_2 m^{-2} s^{-1} (Alves, 2002). The effect of temperature on photosynthesis has been suggested as determining which photosynthetic pathway cassava takes as it influences the enzymes involved in these pathways (Splittstoesser and Tunya 1992), even though the optimal temperature is 25-35°C (De Souza *et al.,* 2017).

Water stress during the early stage of cassava growth (initiated two months after planting and lasting for four months) greatly reduces LAI, shoot and root yields, however, alleviation of this stress improves growth and yield (El-Sharkawy and Cadavid, 2002). The response of cassava to drought has been described as isohydric in the early stages of soil water stress, maintaining relatively constant leaf water potential even when the stomata are closed (Alves, 2002). In these water stress conditions, stomatal CO_2 uptake is reduced leading to a reduction in total growth, although starch accumulation in the storage roots continues (Splittstoesser and Tunya, 1992). If water stress conditions become extreme, photosynthesis ranges between 7-20 mol CO_2 m^{-2} s^{-1}. Interestingly, if water stress continues, the C4 pathway is favored over C3 (Table 2). This was pronounced in cultivar CM 4063-6 tested by El-Sharkawy (2004).

Table 1. Water stress effect on root yield, shoot biomass and LAI of various cassava cultivars.

	Root yield (t ha^{-1} dry weight)				Shoot biomass (t ha^{-1} dry weight)				Mean LAI			
Cultivar	Control	Early stress	Mid-season stress	Terminal stress	Control	Early stress	Mid-season stress	Terminal stress	Control	Early stress	Mid-season stress	Terminal stress
CM 507-37	14.0	11.1	11.3	11.1	6.0	2.7	5.6	5.3	2.3	1.3	1.8	2.3
CM 523-7	13.8	12.8	12.1	9.7	5.3	4.2	5.2	4.5	2.3	1.4	1.3	2.0
CMC 40	10.0	10.4	12.1	14.6	7.8	3.9	5.7	6.7	1.7	1.1	1.1	1.7
M Col 1684	13.6	10.3	12.5	11.5	5.0	2.2	4.0	4.3	1.8	1.1	1.3	1.8
Average	12.9	11.2	12.9	11.7	6.0	3.3	5.1	5.2	2.0	1.2	1.4	2.0

Source: El-Sharkawy and Cadavid, 2002.
* Early water stress started two months after planting, mid-season water stress started four months after planting, and terminal water stress started six months after planting. The early and mid-season water stress treatments lasted for four months while terminal treatments lasted for six months.

Table 2. Effect of water stress on the photosynthetic pathways of cassava.

Clone	Water sufficient			Water stressed		
	PEPC (C4)	Rubisco (C3)	PEPC/ Rubisco (C4/C3)	PEPC (C4)	Rubisco (C3)	PEPC/ Rubisco (C4/C3)
CM 4013-1	0.86±0.12	0.28±0.10	3.10	1.18±0.17	0.30±0.01	3.9
CM 4063-6	0.89±0.05	2.30±0.03	0.39	1.42±0.26	0.62±0.02	2.3
SG 536-1	1.46±0.42	0.44±0.12	3.30	1.33±0.22	0.25±0.08	5.3
M Col 1505	1.09±0.10	0.57±0.13	1.90	0.96±0.16	0.89±0.14	1.1
Average	1.08	0.90	2.20	1.22	0.52	3.2

Adapted and modified from El-Sharkawy, 2004.

1.2 Production and importance

1.2.1 Production

Cassava is the third largest source of carbohydrates in the tropics and the sixth most important food crop in the world (Lebot, 2008). World production increased from 175.8 to 277.1 million tonnes between 2000 and 2016 – 57% from Africa, 31.9% from Asia, 11% from Americas and 0.1% from Oceania (FAO, 2017). Of the total 261.5 million tonnes produced globally in 2013, Nigeria's production accounted for 20.6% (on 3.85 million hectares), ahead of Indonesia and Brazil's production of 9.1% and 8.8% (on 1.12 and 1.69 million hectares) respectively. Despite the large total outputs from Nigeria, Indonesia and Brazil, the highest yields per hectare were achieved in India (36.4 t ha^{-1}), the Cook Islands (26.3 t ha^{-1}) and China's Taiwan province (24.2 t ha^{-1}) (Fig. 2) (FAO, 2017).

1.2.2 Importance

The importance of cassava as a food crop cannot be underestimated, especially in the tropics where it is a source of starch for over 500 million people (Balagopalan, 2002). Its tuberous roots contain 50 mg $100g^{-1}$ of calcium (Ca), 40 mg $100g^{-1}$ of phosphorus (P) and 25 mg $100g^{-1}$ of vitamins such as ascorbic acid, niacin, riboflavin, thiamine etc. (Montagnac *et al.* 2009). However, these roots have low amounts of protein and other nutrients in contrast to the leaves which are a good source of protein if supplemented with amino acids e.g. arginine, histidine, leucine, lysine etc. (Odoemenem and Otanwa, 2011). Pro-vitamin A biofortified cassava has been introduced in several sub-Saharan Africa countries (Bouis and Saltzman, 2017) to combat 'hidden hunger' – micronutrient

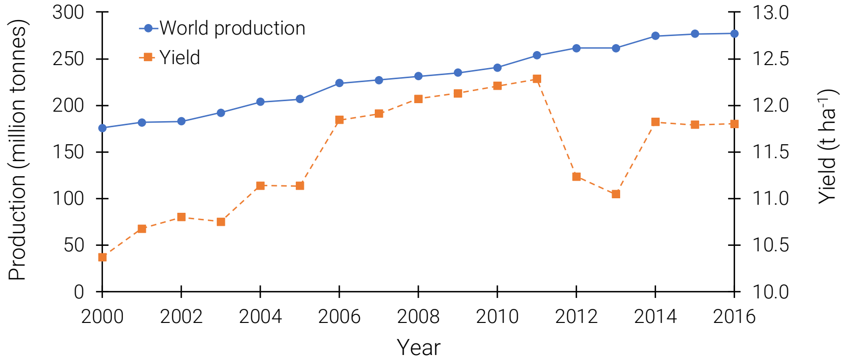

Fig. 2. Yield of cassava per hectare and total world production from 2000 to 2016. Data adapted from FAO, 2017.

deficiencies resulting from eating an unbalanced diet, mostly starchy staple crops (de Valenca *et al.,* 2017).

Cassava is not only vital for food security, but also for trade in different forms including chips; broken dried roots; meal; flour; and tapioca. In addition it is a source of commercial animal feed; fiber for paper and textile manufacturers; starch for pharmaceutical industries; and a raw material in beer production (Balagopalan, 2002; Odoemenem and Otanwa, 2011).

Despite cassava's importance as a food source, it contains cyanogenic glycosides which affects its consumption and quality. The crop is composed of 95% linamarin and 5% lotaustralin (methyl linamarin). The lethal dose of these cyanogenic glycosides for a human with a 60 kg body mass ranges from 30-210 mg of hydrogen cyanide (HCN) (Nhassico *et al.,* 2008). The concentration of linamarin is highest in the leaves and peels of the roots, usually 900-2,000 mg kg^{-1} HCN of fresh mass. However, this concentration varies for every cultivar, leading to the classification of cassava into 'sweet' and 'bitter'. 'Sweet' cassava have a cyanogenic potential (CNP) of less than 50 mg kg^{-1} as HCN from the fresh mass of the roots and is generally considered safe for consumption with only basic processing such as peeling and cooking. 'Bitter' cassava have a CNP greater than 100 mg kg^{-1} as HCN from the fresh mass of the roots, and hence must be processed before consumption to eliminate the cyanogens or reduce them to physiologically tolerable levels (Wilson and Dufour, 2002). Despite the toxicity of the cyanogenic glycosides when consumed in large quantities, they also play a significant role in plant defense mechanisms (Vetter, 2000; Riis *et al.*, 2003).

1.3 Agronomic practices, agroclimatic conditions and soils

Cassava can be grown as a sole crop, an intercrop or in rotation. Recently, the benefits of legume-cassava based intercropping have been shown, even though a second bean intercrop had no effect on the storage root yield of cassava (Pypers *et al.,* 2011). Intercropping of cassava, especially cultivar TME 1 in Nigeria, with oil crops such as sesame and sunflower have also proved to have a higher land equivalent ratio and area-x-time equivalency ratio (Adekunle *et al.,* 2014). This improvement in land equivalent ratio was previously observed in intercropping of cassava and cowpea (Olasantan, 1988). Such studies not only showed the improvement in land use advantage, but also soil fertility and the diversification of dietary options for smallholder farmers. These benefits of cassava cropping systems are dependent on certain factors, for example: Mutsaers *et al.* (1993) concluded that the success of a maize-cassava intercropping depended on the rate of recovery of cassava after the maize harvest, while that of legume-cassava intercrop depended on the growing duration of the legume (i.e. the amount of biological nitrogen (N) fixed by the legume that can later be used by cassava). Furthermore, in their study, Adjei-Nsiah *et al.* (2007) observed that the type of crop sequence in a rotational cassava based system was dependent on availability of resources and the needs of the farmers, for example cowpeas/maize-cassava was preferred by male farmers in comparison to pigeon pea/maize-cassava by female farmers.

Cassava is mostly cultivated in the tropics and sub-tropics between 30° N and 30° S (El-Sharkawy, 2004). It thrives in areas receiving annual rainfall of 1,000 mm or more in a period of six months with deep (at least 30 cm deep) well drained, non-saline, loam-clay soils (Hauser *et al.,* 2014). The temperature for optimal growth ranges from 25-29°C (Alves, 2002). Cassava can either be propagated through cuttings or seeds. If cuttings are used, they are 30 cm long with four to six internodes. These are planted slanting at an angle of 45 degrees, with two to three internodes underground, at a spacing of 1 m x 1 m. For a comprehensive guide on growing cassava see Abass *et al.* (2014).

2 Mineral Nutrition of Cassava

2.1 Role, uptake and accumulation of nutrients

2.1.1 Response to N

Of all the macro-elements, modern farming relies most heavily on N, which is both increasingly costly and highly effective. If plants are N-deficient, leaf elongation is stalled (Marschner, 2011), photosynthesis is inhibited (Gregoriou *et al.,* 2007), chloroplast size is reduced (Li *et al.,* 2013), and, overall, the plants are stunted. On the other hand, if the N level is increased, it is no longer a limiting factor to physiological processes and its effectiveness must be reassessed. In fact, most N applications in crop systems do not translate to increased yield (Lassaletta *et al.,* 2014) due to numerous parameters that affect its effectiveness, such as crop species and variety, the N form (i.e. nitrate or ammonium), soil type, water availability, and application method (El-Sharkawy *et al.,* 1998; Ospina *et al.,* 2014). Thus, N should be studied within the conditions and limitations of the farming environment as a whole to ensure that its application supports yield and profits.

Nitrogen fertilization is known to induce N concentration in the leaf blade (Nguyen *et al.,* 2002), LAI (Sangakkara and Wijesinghe, 2014), plant height, number of leaves, stem diameter, and number of roots (Uwah *et al.,* 2013) in cassava. However, its effect on root yield is still being debated. Initial studies suggested that N application induces cassava shoot growth at the expense of root formation (Cenpukdee and Fukai, 1991). More recently, Nguyen *et al.* (2002) observed a yield decline at 160 kg N ha^{-1} for the first year of application, whereas Kaweewong *et al.* (2013a) reported optimal root yields at N applications as high as 250 kg N ha^{-1}. On the other hand, Uwah *et al.* (2013) showed no yield response whatsoever to an increase from 80 to 120 kg N ha^{-1} (Table 3). These studies demonstrate that cassava responds to N fertilization, and that yields can improve, but also that N requirement differs with variety, agroecological zone, management and soils, and hence physiological bases for efficient N use (which are still obscure) are required.

Table 3. Rate of N at which maximum root yields were obtained from various varieties, regions and studies.

N rate (kg ha^{-1})	Fresh root yield (t ha^{-1})	Variety	Area/region	Source
0	8.7	Not provided	Vietnam (1990-1998)	Nguyen *et al.*, 2002
160	17.1			
% increase	96.55			
0	48.01	Kasetsert 50	Lopburi, Thailand (2009)	Kaweewong *et al.*, 2013a, b
250	64.1			
% increase	33.5			
0	34.76	Kasetsert 50	Supanburi, Thailand (2009)	Kaweewong *et al.* 2013a, b
187.5	47.5			
% increase	36.7			
0	30.0	Kasetsert 50	Chonburi, Thailand (2009)	Kaweewong *et al.*, 2013a, b
187.5	15.83			
% increase	89.5			
0	13.5	Sree Vijaya	Kerala, India (2005-2006)	Byju and Anand, 2009
200	27.4			
% increase	102.96			
0	12.9	M-4	Kerala, India (2005-2006)	Byju and Anand, 2009
200	21.5			
% increase	66.67			
0	25.8	MU51	Sri Lanka (2003-2004)	Sangakkara and Wijesinghe, 2014
90	43.9			
% increase	70.16			
0	20.59	TMS98/0581	Nigeria (2007-2008)	Uwah *et al.*, 2013
120	27.9			
% increase	35.5			

2.1.2 Effect of P

Another macronutrient, P, improves LAI, shoot biomass, net photosynthesis and root yield of cassava. However, the root yield response varies with cultivar, due to differences between vegetative growth and sink strength of the storage roots (Pellet and El-Sharkawy, 1993). Furthermore, the response to P diminishes over time (Nguyen *et al.,* 2002); significant maximum root yield was obtained at 80 kg P_2O_5 ha^{-1} whereas in successive years there was no significant difference in yield between 80 kg P_2O_5 ha^{-1} and 40 kg P_2O_5 ha^{-1} (Nguyen *et al.,* 2002) (Table 4). This lack of significance was attributed to accumulation of residual P.

Cassava grown in low-P soils infected with the native vascular arbuscular mycorrhizae (VAM) benefits from their association (Howeler *et al.,* 1982a). The VAM improve P uptake, although inoculation with these fungi in P-fertilized cassava or increased application of P fertilizer may limit the fungus-cassava association and hence the P uptake (Sieverding and Howeler, 1985). Besides arbuscular mycorrhizae improving P uptake by cassava, Carretero *et al.*, (2009) showed its effectiveness in water uptake-this enhances adaptation of cassava to drought. The study by Sieverding and Howeler (1985) also indicated that at one site (Agua Blanca, Colombia) one variety, cultivar Barranquena, achieved the highest root yield at 50 kg P ha^{-1}, while another (M Col 113) at the same site reached its highest yield with an application of 200 kg P ha^{-1}. Indeed, this evidences how cultivars respond differently to nutrients applied. It is also interesting to note that another cultivar, M Col 1684, performed better with no P application (N and potassium (K) were applied at 100 kg ha^{-1} each) in the first cycle of growth (1989), while in the second cycle (1990) the highest root yield was at 100 kg P ha^{-1} (Table 4) (Pellet and El-Sharkawy, 1993). This is an indication that changes in soil fertility influence the nutrient requirement of a single cultivar and hence there is a need to continuously review nutrient recommendations.

Table 4. Rate of P at which maximum root yields were obtained from various varieties, regions and studies.

P rate (kg ha^{-1})	Fresh root yield (t ha^{-1})	Variety	Area/region	Source
0	12.9	Not provided	Vietnam (1990-1998)	Nguyen *et al.*, 2002
80	17.8			
% increase	37.98			
0	13.2	Barranquena	Agua Blanca, Colombia	Sieverding and Howeler, 1985
50	25.3			
% increase	91.67			
0	16.1	M Col 113	Agua Blanca, Colombia	Sieverding and Howeler, 1985
200	23.0			
% increase	42.86			
0	7.7	M Col 1684	Quilichao, Colombia (1989)	Pellet and El-Sharkawy, 1993
0 (with 100N, 100K kg ha^{-1})	12.9			
% increase	67.53			
0	5.4	M Col 1684	Quilichao, Colombia (1990)	Pellet and El-Sharkawy, 1993
100	11.5			
% increase	112.96			

2.1.3 Impact of K

The importance of K in crop growth and yield cannot be overestimated. Improving K nutritional status of a crop enhances its survival under biotic (Hendricks *et al.*, 2015) and abiotic stresses (Cakmak, 2005), such as high light intensity, drought, chilling, salinity (Amjad *et al.*, 2014) and iron toxicity. Further, it is a significant requirement for stomatal conductance, net photosynthesis, phloem loading of photo-assimilates and enzyme activity (see extensive review of K importance in crop production by Zorb *et al.*, 2014).

In root and tuber crops, K has been observed to improve root yields and increase cassava root yield by 90.8% compared to no K application (Adekayode and Adeola, 2009). Moreover, Ezui *et al.* (2016) described K as the most limiting nutrient in achieving high storage root yields. In their study, Alves and Setter (2004) concluded that cassava uses K as a primary osmolyte, enabling it to osmotically adjust and positively respond to water stress. Regardless of K's importance in tuber and root yields, a study from Mozambique observed the highest cassava root yields on zero K application and 60 kg ha^{-1} N and P application (Ivan *et al.,* 2017). Even as they observed this, they still recommended application of K (without giving quantities) to prevent substantial mining (Table 5). The source of K fertilizer has been observed to not be significant as long as the rate is right, applying 90 kg K ha^{-1} either from KCl or K_2SO_4 was observed to produce the highest non-significant root yield in Ghana (Boateng and Boadi, 2010).

Table 5. Rate of K at which maximum root yields were obtained from various varieties, regions and studies.

K rate (kg ha^{-1})	Fresh root yield (t ha^{-1})	Variety	Area/region	Source
0	2.8	Not provided	Vietnam (1990-1998)	Nguyen *et al.,* 2002
160	15.3			
% increase	546.43			
0	21.97	TMS98/0581	Nigeria (2007-2008)	Uwah *et al.,* 2013
80	27.89			
% increase	26.95			
0	14.7	Tapioca	Mozambique (2013-2014)	Ivan *et al.,* 2017
0 (60N, 60P kg ha^{-1})	27.7			
% increase	88.44			

2.2 Deficiency symptoms and nutrient toxicity

Macro and micronutrients are important for the growth and yield of cassava. However, for a long time cassava has been regarded as a crop which can grow and still produce reasonable yields in poor/degraded soils. This notion has resulted in low yields of cassava per unit area. It is only recently that awareness into effects of application of fertilizers to cassava was raised. Even so, few farmers can utilize fertilizers for a myriad of reasons, including the low purchasing power of fertilizers by most small-scale farmers who are the core growers and consumers of cassava.

Howeler (2002) reported that symptoms of nutrient deficiencies/toxicities in cassava tend to be difficult to identify early, as cassava does not readily translocate nutrients from its lower to upper leaves. Early deficiency symptoms manifest in reduced growth rates, fewer and smaller leaves and shorter internodes, therefore any visual identification needs to be confirmed by both soil and plant tissue analyses. Macro and micronutrient deficiency and toxicity symptoms in cassava are summarized in Table 6 and in Appendix (Photos 6-14).

Table 6. Symptoms of nutrient deficiencies and toxicities in cassava.

Nutrient deficiencies	Symptoms
Nitrogen (N)	Reduced plant growth. Uniform chlorosis of leaves, starting with lower leaves, but soon spreads throughout the plant.
Phosphorus (P)	Reduced plant growth, thin stems, short petioles; sometimes pendant leaves. Under severe conditions one or two of the lower leaves turn yellow to orange, become flaccid and necrotic and may fall off.
Potassium (K)	Reduced plant growth with excessive branching, resulting in prostrate plant type. Small, sometimes chlorotic upper leaves; thick stems with short internodes. Under severe conditions, premature lignification of upper stems with very short internodes, resulting in zigzag growth of upper stems.
Calcium (Ca)	Reduced root and shoot growth. Chlorosis, deformation and border necrosis of youngest leaves with leaf tips or margins bending downwards. Rare in the field.
Magnesium (Mg)	Marked interveinal chlorosis or yellowing in lower leaves.
Sulfur (S)	Often similar to N symptoms and seldom seen in the field. Uniform chlorosis of upper leaves, which soon spreads throughout the plant.
Boron (B)	Reduced plant height, short internodes, short petioles and small deformed upper leaves. Suppressed lateral development of fibrous roots. Purple-grey spotting of mature leaves in the middle part of the plant. Under severe conditions gummy exudates on stem or petioles – it is rare in the field.
Copper (Cu)	Deformation and uniform chlorosis of upper leaves, with leaf tips and margins bending up or down, petioles of fully expanded leaves bend down, and reduced root growth (occurs mainly in peat soils).
Iron (Fe)	Uniform chlorosis of upper leaves and petioles. Under severe conditions, leaves turn white with border chlorosis of youngest leaves. Reduced plant growth, small young leaves, but not deformed (occurs mainly in calcareous soils).
Manganese (Mn)	Interveinal chlorosis or yellowing of upper or middle leaves, uniform chlorosis under severe conditions (occurs mainly in sandy and high pH soils).

Zinc (Zn)	Interveinal yellow spots or white spots on young leaves. Leaves become small, narrow and chlorotic in growing points, necrotic spotting on lower leaves as well. Leaf lobes turn outwards away from the stem. Reduced plant growth, sometimes death of young plants (largely observed in high pH or calcareous soils, sometimes in acid soils).
Toxicities	
Aluminum (Al)	Reduced root and shoot growth. Under very severe conditions leads to yellowing of lower leaves, but only in very acidic soils.
Boron (B)	Necrotic spotting of lower leaves, especially along leaf margins (only observed after excessive B application).
Manganese (Mn)	Lower leaves turn yellow or orange with purple-brown spots along veins. Leaves become flaccid and drop off (mainly in acidic soils and when plant growth stagnates).
Salinity	Uniform yellowing of leaves, starting at the bottom of plants but soon spread throughout. Symptoms are very similar to Fe deficiency. Under severe conditions, border necrosis of lower leaves, poor plant growth and death of young plants.

Adapted and modified from Howeler, 2002.

2.3 Relationship between nutrients removed and root yield

It has long been believed that cassava mines nutrients from the soil more than other crops – and is called a ‘scavenger crop’ – however, a study by Putthacharoen *et al.* (1998) showed that N and P removal were lower than that of other crops while K uptake was similar. This contrasts Howeler (2002), who observed similar N and P removal between other crops and cassava, while more K was mined. In both studies, N and P required by cassava for production of a ton of dry matter was lower than other crops, while K was only higher for maize and sorghum (Table 7). Nonetheless, the above two studies agree on the increase in soil erosion when cassava is grown on slopes. They concluded that the amount of nutrients taken by cassava depended on the growth rate and the yield. These two components are influenced by climate, soil fertility and variety. Years later Fermont *et al.* (2007) confirmed that cassava which removes more nutrients from the soil also produces higher root yields (Table 8). The data from Howeler (2002) show a wide range of values, and the difference from those of Fermont *et al.* (2007) probably reflects the many different data sources Howeler (2002) used. Variation in factors including climate, variety, and agronomic management could be the reason for the major differences between the two data sets. Fermont *et al.* (2007) also provided equations which revealed a relationship between N, P, and K uptake and root yield, indicating that N had the least positive relationship with the root yield. This type of relationship between root yield and N content holds true even when the mode of fertilizer application changes, such as in fertigation. In their results, R^2 for N, P and K were 0.67, 087, 0.77 respectively (Fermont *et al.,* 2007), while the unpublished fertigation results (from seven months of greenhouse pot experiments at Gilat Agriculture Centre, Israel) showed 0.79, 0.90 and 0.87 for N, P and K respectively (Fig. 4).

Table 7. Nutrients removed by cassava in comparison to other crops.

Crop	**DM ($t\ ha^{-1}$)**	**Removed nutrients**					
		$kg\ ha^{-1}$			**$kg\ t^{-1}$ of DM produced**		
		N	P	K	N	P	K
Cassava (roots)	5.185	48	7	60	9.26	1.35	11.57
Adapted from Putthacharoen *et al.*, 1998.							
Maize	8.782	118	44	87	13.44	5.01	9.91
Sorghum	5.097	79	25	51	15.50	4.90	10.01
Peanut (groundnut)	4.899	213	19	53	43.48	3.88	10.82
Mungbean	2.878	117	15	62	40.65	5.21	21.54
Pineapple	7.582	83	15	190	10.95	1.98	25.06
Adapted from Howeler, 2002.							
Cassava (roots)	13.53	55	13.2	112	4.50	0.83	6.6
Maize (dry grain)	5.56	96	17.4	26	17.30	3.13	4.7
Sorghum (dry grain)	3.10	134	29	29	43.30	9.40	9.4
Groundnut (dry grain)	1.29	105	6.5	35	81.40	5.04	27.1
Common beans[a] (dry grain)	0.94	37	3.6	22	39.60	3.83	23.4
Soybean (dry grain)	0.86	60	15.3	67	69.80	17.79	77.9
Sugarcane	19.55	43	20.2	96	2.30	0.91	4.4
Tobacco	2.10	52	6.1	105	24.8	2.90	50.0

[a] – *Phaseolus vulgaris*
DM – Dry matter

Table 8. Root DM yield and nutrient content in roots of cassava at harvest (adapted from Fermont *et al.*, 2007).

Root DM yield ($t\ ha^{-1}$)	Nutrient content					
	$kg\ ha^{-1}$			$kg\ t^{-1}$ of DM produced		
	N	P	K	N	P	K
10	26.2	2.5	19.1	2.62	0.25	1.91
20	55.4	6.0	30.4	2.77	0.30	1.52
30	83.1	9.6	47.4	2.77	0.32	1.58
40	110.9	13.4	73.9	2.77	0.34	1.85

DM – Dry matter

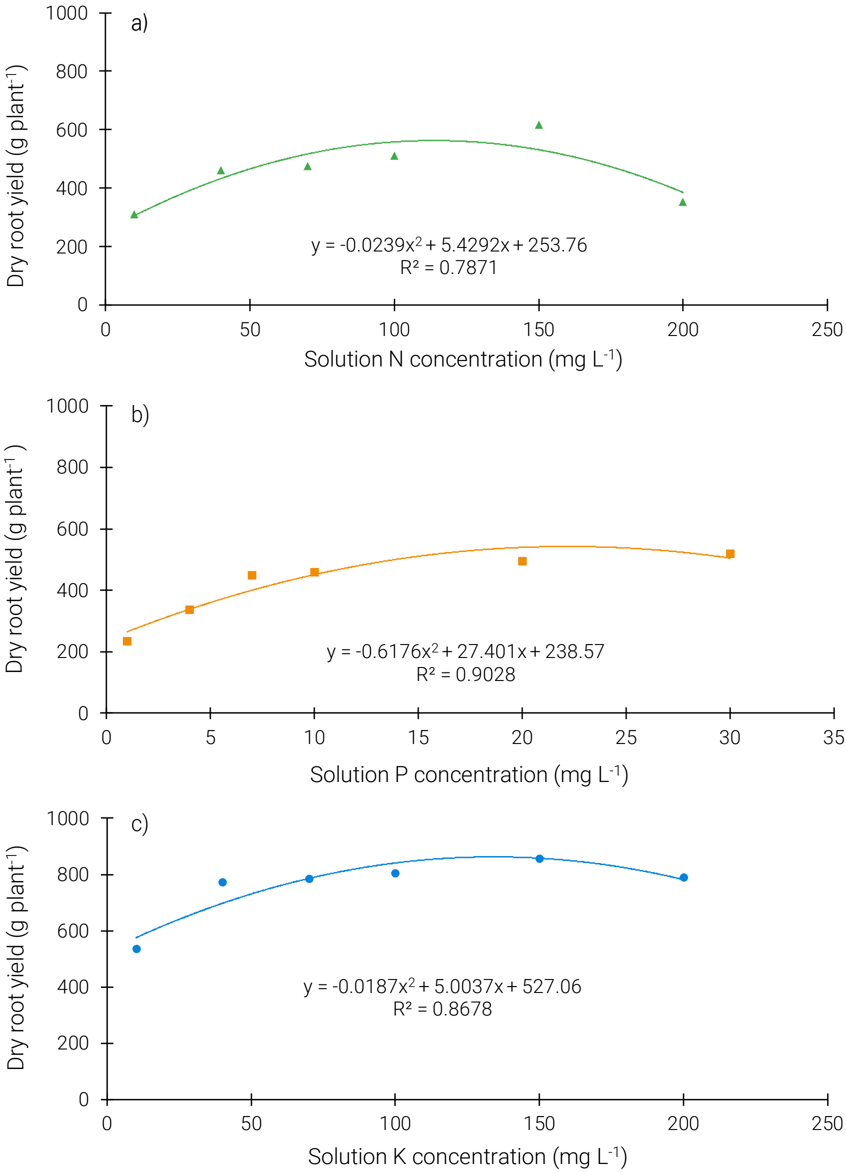

Fig. 4. Relationship between solution: a) N, b) P and c) K concentration and dry root yield. Adapted from unpublished fertigation studies on cassava in a greenhouse study at Gilat Agriculture Centre, Israel.

2.4 Plant nutrient diagnosis

2.4.1 Destructive method

Nutrient diagnosis in cassava has always been carried out using young fully expanded leaves (YFEL) as described by Howeler (2002) (Table 9). While nutrient diagnosis indicates the sufficiency or deficiency levels of nutrients (Table 9) and thereby predicts yields in many crops, in cassava a macronutrient such as N may be high in the YFEL but not lead to high root yields. This has been observed both when N is applied through banding or fertigation (Fig. 5a). Other root crops such as taro and sweet potato have shown similar characteristics, where increased N in the leaves has a curvilinear relationship with the root yield – higher leaf N concentration after optimum application leads to a decline in root yield (Hartemink *et al.,* 2000).

The other macronutrients (P and K), especially K in YFEL, have a higher positive relationship with root yields (Fermont *et al.,* 2007; Howeler, 2012) regardless of the method of application. There hasn't been much information on diagnosis of micronutrients in the YFEL of cassava except for Howeler *et al.* (1982b) and Howeler (2002). However, an interaction study between K_2SO_4 and micronutrients indicated that 30% of foliar applied micronutrients improved N, K and micronutrients (Zn, Mn, Fe and Cu) concentrations in cassava and its storage roots (Ali and Abd-Elkader, 2014). This is an indication of the importance of micronutrients in increasing root yields. Studies on tuber crops, including potato, have added further evidence of the increase in yields after the application of micronutrients (Mousavi *et al.*, 2007; Jawad, 2016) and even increases of these nutrients in the harvested tubers which enhances the crop's nutrition quality (Hadi *et al.,* 2015). However, application of micronutrients beyond optimum levels drastically reduces tuber yields, and this might also be the case in cassava – extensive studies on micronutrient effects on cassava are required. In Table 9, the levels at which macronutrients and micronutrients are sufficient and toxic to cassava are presented, however, there is a question as to whether the sufficiency levels diagnosed in the leaves would be able to predict the effect on the root yield as well.

In unpublished work on fertigating cassava with N in a greenhouse, results have indicated that using soluble carbohydrates in the YFEL could more effectively predict the effect of N on the root yield compared to using YFEL's total N (Fig. 5b). This is because N constitutes part of the carbon (C) sink (e.g. amino acids and proteins), so it has a positive effect on photosynthesis and transpiration (Leuning *et al.*, 1995; Bar-Tal *et al.*, 2001). Initially, N is critical at the leaf level, where it improves radiation-use efficiency and promotes photosynthetic productivity (Sinclair and Horie, 1989). Yet high levels of photosynthates, without corresponding transport, can signal that the capacity for non-structural carbohydrates has reached its maximum, and photosynthesis will be down-regulated (Goldschmidt and Huber, 1992). Moreover, as N also tends to promote vegetative growth (Kang *et al.,* 2004), it increases the plant's shoot-to-root ratio (Grechi *et al.,* 2007), and could exhaust its transpiration capacity. In fact, low N promotes root growth (critical for root crops such as cassava) and supports high transpiration demands (Marschner *et al.,* 1996). Hence, in a water-limited environment, high N levels could limit CO_2 sequestration and force plants to utilize their residual photosynthates in the canopy at the expense of root growth and reproduction. Thus, soluble carbohydrate levels indicate whether the N applied matches the transpiration capacity of the plant and root yield.

Table 9. Nutrient concentrations in the YFEL blades of cassava at three to four months after planting.

	Nutritional status[a]					
Nutrient	Very deficient	Deficient	Low	Sufficient	High	Toxic
N (%)	<4.0	4.1-4.8	4.8-5.1	5.1-5.8	>5.8	-
P (%)	<0.25	0.25-0.36	0.36-0.38	0.38-0.50	>0.50	-
K (%)	<0.85	0.85-1.26	1.26-1.42	1.42-1.88	1.88-2.40	>2.40
Ca (%)	<0.25	0.25-0.41	0.41-0.50	0.50-0.72	0.72-0.88	>0.88
Mg (%)	<0.15	0.15-0.22	0.22-0.24	0.24-0.29	>0.29	-
S (%)	<0.20	0.20-0.27	0.27-0.30	0.30-0.36	>0.36	-
B ($\mu g\ g^{-1}$)	<7	7-15	15-18	18-28	28-64	>64
Cu ($\mu g\ g^{-1}$)	<1.5	1.5-4.8	4.8-6.0	6-10	10-15	>15
Fe ($\mu g\ g^{-1}$)	<100	100-110	110-120	120-140	140-200	>200
Mn ($\mu g\ g^{-1}$)	<30	30-40	40-50	50-150	150-250	>250
Zn ($\mu g\ g^{-1}$)	<25	25-32	32-35	35-57	57-120	>120

[a]Very deficient, <40% maximum yield
Deficient, 40-80% maximum yield
Low, 80-90% maximum yield
Sufficient, 90-100% maximum yield
High, 90-100% maximum yield
Toxic, <90% maximum yield; - no data.
Source: Howeler, 2002.

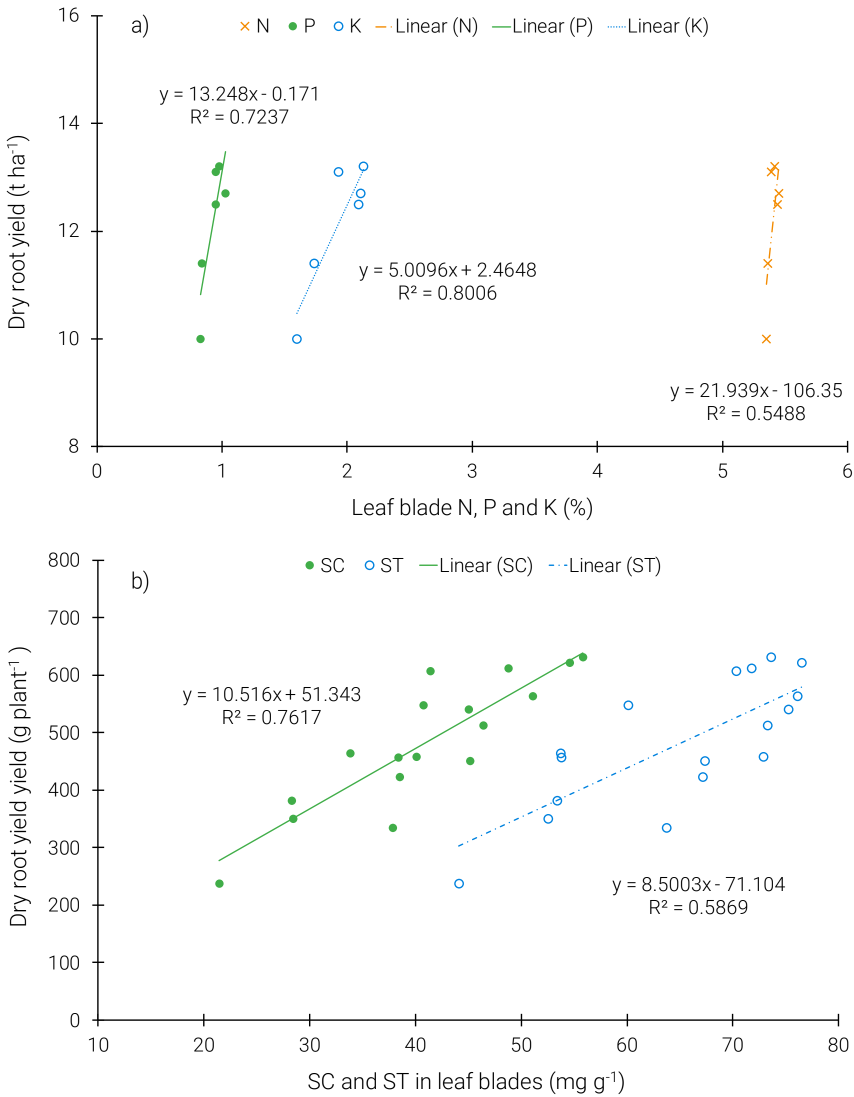

Fig. 5. Relationship between: a) N, P, K and dry root yield, b) soluble carbohydrates (SC), starch concentration (ST) and dry root yield. Dry root yield is per plant grown in 60-l perlite container. Adapted from Omondi *et al*, 2018, 2019.

2.4.2 Non-destructive method

The non-destructive method is another avenue that could be explored in nutrient diagnosis of cassava. For potato, SPAD meters (an indicator of plant greenness/ chlorophyll content) have been used to diagnose plant N status (Borhan *et al.,* 2017). This method has also been applied in cassava, indicating a positive relationship between N concentration in the leaves and SPAD readings (Fig. 6) (Haripriya and Byju, 2008). Besides the popular non-destructive SPAD method, other methods involving canopy assessment (sensors like Field Spec, CropScan, LI-1800 spectroradiometers, digital cameras), satellite mounted (for example QuickBird) and sap and electrical meters (such as nitrate test strips, nitrate ISE, electrical impedance spectroscopy) (Munoz-Huerta *et al.,* 2013) could be used. Such non-destructive methods, if developed for assessing the status of macronutrients, would be an effective and efficient method for cassava producers, leading to increased production.

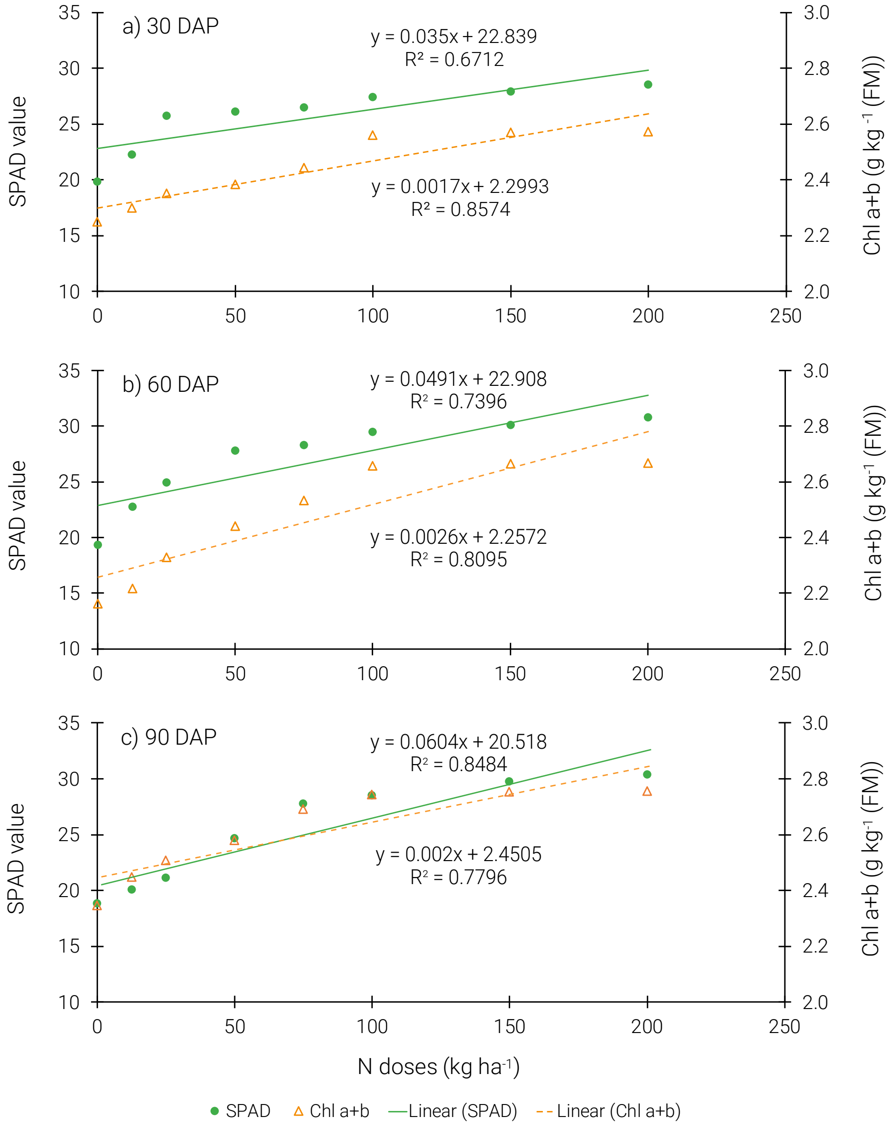

Fig. 6. The relationship between N applied to cassava and chlorophyll meter (SPAD) values and measured chlorophyll content (Chl a+b) in fresh mass (FM) of leaves at: a) 30 DAP, b) 60 DAP and c) 90 DAP. DAP – days after planting. Results presented in the graphs are adapted from a table in Haripriya and Byju, 2008.

2.5 Soil nutrient analyses

Soil nutrient availability is one of the factors that influences the concentration of a given nutrient in cassava tissue. An increase in soil nutrients through fertilization would reflect that in the tissues, especially the leaves, however, each nutrient has its optimal concentration within the leaf, beyond which further application could be toxic to the plant, lead to no yield change or even cause environmental pollution. Howeler (2002) presents classifications of soil nutrient characteristics required for cassava (Table 10).

Table 10. Approximate classification of soil chemical characteristics according to the nutritional requirements of cassava.

Soil parameter	Very low	Low	Medium	High	Very high
pH[a]	<3.5	3.5-4.5	4.5-7	7-8	>8
Organic matter[b] (%)	<1.0	1.0-2.0	2.0-4.0	>4.0	
Al saturation[c] (%)			<75	75-85	>85
Salinity (mS cm^{-1})			<0.5	0.5-1.0	>1.0
Na saturation (%)			<2	2-10	>10
P[d] (µg g^{-1})	<2	2-4	4-15	>15	
K[d] (meq 100 g^{-1})	<0.10	0.10-0.15	0.15-0.25	>0.25	
Ca[d] (meq 100 g^{-1})	<0.25	0.25-1.0	1.0-5.0	>5.0	
Mg[d] (meq 100 g^{-1})	<0.2	0.2-0.4	0.4-1.0	>1.0	
S[d] (µg g^{-1})	<20	20-40	40-70	>70	
B[e] (µg g^{-1})	<0.2	0.2-0.5	0.5-1.0	1-2	>2
Cu[e] (µg g^{-1})	<0.1	0.1-0.3	0.3-1.0	1-5	>5
Mn[e] (µg g^{-1})	<5	5-10	10-100	100-250	>250
Fe[e] (µg g^{-1})	<1	1-10	10-100	>100	
Zn[e] (µg g^{-1})	<0.5	0.5-1.0	1.0-5.0	5-50	>50

[a]pH in H_2O
[b]Organic matter – Walkey and Black method
[c]Al saturation – 100 × Al (Al + Ca + Mg + K) in meq 100 g^{-1}
[d]P in Bray II; K, Ca, Mg and sodium (Na) in 1N NH_4-acetate; S in Ca phosphate
[e]B in hot water; and Cu, Mn, Fe and Zn in 0.05 N HCl + 0.025 N H_2SO_4;
Source: Howeler, 2002.

2.6 Improving cassava nutrient uptake

Gaining maximum uptake from applied nutrients is every researcher and farmer's target, even though this is just a mirage given the losses through volatilization, leaching and fixation. Despite this, enhancing plant uptake characteristics or nutrient management through placement and time of application have aided in improving the uptake of nutrients. Plant characteristics such as mycorrhizae have been shown to enhance P uptake. In cassava, VAM have been shown to increase P uptake and root yield. The uptake of P by the leaves and the roots increased by 17.4% and 91.6% respectively in VAM inoculated cassava, while the root yield increased by 55.5% (Osonubi *et al.,* 1995) (Table 11).

Application of reduced forms of P, such as phosphite (Phi) which is a biostimulator in horticultural crops, also improved P uptake through oxidation when applied to the soil by microorganisms to provide inorganic phosphate (Pi) (Gomez-Merino and Trejo-Tellez, 2015). Although, some studies have observed Phi as a sole source of P, others used it as a supplement (Loera-Quezada *et al.,* 2015). It is important to study this in more detail to determine whether it could enhance P uptake in cassava as well. Other biostimulants, such as humic and fluvic acids, seaweed extracts, protein hydrolysates and beneficial elements (Al, Co, Na, selenium [Se], and silicon [Si]), which also improve macro and micronutrients uptake (du Jardin, 2015), should also be explored in cassava. Indeed, *Bacillus subtilis* (GB03), a soil bacterium that actives Fe acquisition by plants, has been shown to increase Fe in cassava leaves (Freitas *et al.,* 2015). Microorganisms such as rhizobia have also proved to be useful, so additional research to explore the possibility of biological nitrogen fixing (BNF) in cassava, a non-legume, is important (Santi *et al*., 2013). BNF has been used to deliver nitrogen to maize and sugarcane through the application of naturally occurring N-fixing endophytes like *Gluconacetobacter diazotrophicus* (Gd) (Dent and Cocking, 2017), rather than rhizobial-host association, and could be tested in cassava. This could improve soil fertility for resource poor smallholders in particular.

Use of controlled and slow release fertilizers (Kaplan *et al*., 2013; Herrera *et al*., 2016) or polymer coated fertilizers (Yang *et al.,* 2016) also increases nutrient uptake and reduces losses through leaching or volatilization by synchronizing crop demand for the nutrient and its availability (Li *et al.,* 2017). Since other crops have shown improved growth and yields, cassava's response might be similar, so studies on the improvement of nutrient uptake through the application of such fertilizers to cassava are required.

Table 11. Effect of VAM on P uptake and concentration in the roots of cassava.

	Inoculated with VAM	Uninoculated with VAM
% root infection	48	37
P uptake by the roots (kg ha^{-1})	6.45	3.35
P concentration in the dry roots (ppm)	0.95	0.75

The values presented in the table are averages of three years for % root infection and two years for P uptake and concentration. Adapted from Osonubi *et al.*, 1995.

3 Fertilizer Usage

3.1 Current fertilizer usage

The use of fertilizers in cassava production is small in comparison to other crops which feed just as many people. These low levels stem from an outdated notion that cassava can grow in poor soils and still provide plausible yields. Recently, this mindset has begun to change with the introduction of improved cassava varieties, the need to improve root yields per unit area, and the growing population that requires food and alternative raw materials. Interestingly, world production of cassava has been increasing (Fig. 2), but yield per hectare has declined since 2010. Soil fertility is one factor that needs to be improved to enhance cassava yields.

Soil fertility is one of the most important factors for successful crop production. However, in many cases, crops do not receive the required amount of nutrition from the soil. Reasons cited for this in sub-Saharan Africa include poor inherent soils (Zingore *et al.,* 2007) and non-responsive soils (Rowe *et al.,* 2006). However, the major factor is poor fertilizer application (Crawford *et al.,* 2003) to replenish the nutrients that are taken up, leached or volatilized.

Finding statistics on global fertilizer usage in cassava is difficult, nonetheless, an estimated 2.3% of global NPK fertilizers are applied to roots and tubers (Table 12). Total global fertilizer consumption of all crops in 2014/15 was 181.9 million metric tonnes (Mt), of which 102.5 Mt was N, 45.9 Mt was P_2O_5 and 33.5 Mt K_2O (Heffer *et al.,* 2017). The 2.3% for roots and tubers is the lowest among the crops and categories presented, and potato is also likely to contribute to the largest part of this percentage. This further shows that application of fertilizers to cassava is scarce.

Table 12. Total fertilizer use by crops at the global level.

Crop	% of total consumption				'000 tonnes of nutrients			
	N+P+K	N	P_2O_5	K_2O	N+P+K	N	P_2O_5	K_2O
Wheat	15.3	18.2	14.6	7.4	27,866	18,699	6,699	2,467
Rice	13.7	15.2	12.5	11	25,001	15,561	5,762	3,679
Maize	16.2	17.8	13.9	14.2	29,429	18,283	6,391	4,755
Other cereals	4	4.7	3.6	2.7	7,327	4,783	1,647	897
Soybean	5.4	1.1	9.7	12.3	9,739	1,147	4,469	4,123
Palm oil	2.7	1.4	1.9	8	4,960	1,422	873	2,666
Other oilseeds	4.6	5.3	4.5	2.8	8,457	5,453	2,062	942
Fiber crops	3.7	4.1	3.8	2.4	6,746	4,200	1,729	817
Sugar crops	4.1	3.6	3.6	6.3	7,497	3,714	1,672	2,112
Roots and tubers	2.3	2.1	2.5	2.5	4,118	2,140	1,142	835
Fruits	7.2	6.1	8.8	8.5	13,118	6,221	4,050	2,847
Vegetables	8.6	7.4	9.9	10.6	15,658	7,572	4,530	3,556
Grassland	4.3	4.7	4	3.8	7,878	4,766	1,835	1,277
Residual	7.8	8.3	6.7	7.6	14,157	8,536	3,073	2,547

Residual includes pulses, nut trees, rubber, cocoa, coffee, tea, tobacco, forestry, fish ponds, ornamentals, turf, golf courses, homes, gardens, and other potential non-industrial/non-feed uses.
Source: Heffer *et al.*, 2017.

3.2 Rate of application, placements and timing of application

Addressing the 4R stewardship (right source, right rate, right placement, right time) of cassava is important if yields are to be improved in an ever-shrinking cropping area. The sources of fertilizers applied to cassava are varied, however the placement in most cases is usually through banding a few centimeters away from the planted cutting. The rate is applied at planting, even though some studies have shown benefits of using a split application, i.e. at planting and at 45 days after planting (Sangakkara and Wijesinghe, 2014).

Fermont *et al.* (2009a) observed an average yield of 8.6 t ha^{-1} of cassava in farmer managed fields and showed that this more than doubled to 20.8 t ha^{-1} with improved crop establishment, use of improved genotypes, and application of NPK of 100-22-83 kg ha^{-1}. They further noted that poor soil fertility was the major factor limiting yields of improved genotypes in improved crop establishment, reporting a 6.7, 5.4 and 5.0 t ha^{-1} reduction in yields under poor soils, early water stress and poor weed management respectively.

The amount of NPK fertilizer combination for maximum cassava root yield varies between agroecological zones, varieties, crop practices and soil fertility (Ezui *et al.*, 2016). Therefore, there is a need for every cassava grower to conduct initial soil analysis or follow the recommended basal NPK quantities for their agroecological zone. Despite having previously indicated the importance of micronutrients to cassava yields (Howeler *et al.,* 1982b), there is no evidence in the literature of microelements fertilizer application by cassava growers. Moreover, farmyard manure has been observed to improve soil micronutrients (Chaudhary and Narwal, 2005). In their study, Susan John *et al.* (2007) showed that there was a 19.2% increase in the fresh root yield of cassava after the application of NPK and farmyard manure compared to the application of just NPK.

In their nine years of studying the long-term response of cassava to N, P, and K fertilization in northern Vietnam on acrisols, Nguyen *et al.* (2002) found that the application of 160 kg N ha^{-1} in combination with 40 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1} significantly increased cassava yield during the final five years of their study. Despite this, their average root yield (with applications of between 80 kg N ha^{-1} and 160 kg N ha^{-1}) over the nine years was similar (17.1 t ha^{-1}). They attributed this phenomenon to differences in growing conditions from one year to the next and changes in soil fertility over time. A study on the effect of N, P, and K fertilizers on cassava cv. 53101 in Umudike, Nigeria by Odurukwe and Arene (1980) revealed that application of 30 kg N ha^{-1}, 15 kg P_2O ha^{-1} and 180 kg K_2O ha^{-1} enhanced root yield. A cassava yield maximization experiment through fertilizer use by Susan John *et al.* (2007) in Kerala, India, discerned higher root yields when N was applied at 100 kg ha^{-1}, P at 300 kg ha^{-1} and K at 300 kg ha^{-1}, compared to the recommended rates in that area of 100 kg N ha^{-1}, 50 kg P ha^{-1} and 100 kg K ha^{-1}. Wilson and Ovid (1994) studied the influence of fertilizer on cassava cv. Maracas Black Stick in Trinidad and Tobago and obtained the best yield with application of 400, 200 and 400 kg ha^{-1} of N, P, and K, respectively. In modelling cassava's response to fertilizer in India using the Quantitative Evaluation of Fertility of Tropical Soils model, Byju *et al.* (2012) developed a minimum and maximum range of root yields per kg of N, P, and K: 35 and 80 for N, 250 and 750 for P, and 32 and 102 for K (kg tuberous root per kg nutrient removed). Whereas, others have shown increases in response to fertilizer over time (Carsky and Toukourou, 2005).

3.3 Advances in fertigation studies of cassava

3.3.1 Baseline fertigation study for cassava (Adapted from Omondi *et al.,* 2018)

The mode of nutrient application affects its uptake (Blackshaw *et al.,* 2002; Gaskell and Hartz, 2011). For example, there is an enhanced, synergistic interaction of N, P, and K when liquid fertilizer is applied compared to granular fertilizer (Layne *et al.*, 1996; Kowalenko *et al.*, 2000; Bryla and Machado, 2011; Tesfaye *et al.*, 2011). In fact, Khursheed *et al.* (2006) observed enhanced N and P uptake when liquid N was applied through drip irrigation. These two nutrients play a major role in improving shoot growth (Bryla 2016). Furthermore, 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 enabling their management, especially N input and soil residual N (Darwish *et al.,* 2003). Indeed, fertigation as a mode of fertilizer application, in both dry areas and areas receiving sufficient rainfall, provides efficient nutrient delivery and enhances nutrient-use efficiency (Badr *et al.,* 2010; Liang *et al.,* 2014).

Benefits of fertigation have been observed in other root and tuber crops, including increased tissue N and tuberous yield (Janat, 2007). However, in cassava, fertigation as a mode of fertilizer application is new and its effects on growth and root yield are unknown. It is assumed that because potato has a sink component (tuber) that is similar to cassava (tuberous root), the mechanisms governing yield are the same and therefore the response of cassava to fertigation could be similar to that of potato.

Odubanjo and Olufayo (2011) studied the effect of drip irrigation on water use and yield of cassava cv. TMS 91934 in Nigeria; they achieved the highest root yield with the application of 100% available water in comparison to 50% and 25% available water. Amanullah *et al.* (2006a) also studied the response of cassava hybrid H 226 to surface irrigation in Tamil Nadu, India. They established that drip irrigation once every two days at 100% available water gave the highest fresh root yield of 36.0 t ha^{-1}. They also observed water savings of 75% under drip irrigation, while surface irrigation only saved 32%.

In a fertigation experiment in Zambia, the highest cassava fresh root yield of 43.2 t ha^{-1} was from a medium duration variety, Kampolombo, with an application of 100 mg N, 10 mg P, 100 mg K l^{-1} which translated to 77.5, 7.8 and 77.5 N, P and, K kg ha^{-1} respectively (Omondi *et al.* 2018). In the same experiment, a long duration variety, Nalumino, had a fresh root yield of 21.1 t ha^{-1} with an application of 70 mg N, 7 mg P and 70 mg K l^{-1} (54.3, 5.4 and 54.3 kg of N, P and K ha^{-1}), while the shortest duration variety, Mweru, produced a root yield of 22.2 t ha^{-1} with 200 mg N, 30 mg P and 200 mg K l^{-1}

(155.0, 23.3 and 155.0 kg of N, P and K ha^{-1}). In this study, with N, P, and K applied through fertigation to cassava, the varieties showed a decline in productivity as applied N, P, and K increased (Fig. 7). However, this productivity response differed among the varieties with medium duration Kampolombo having the highest productivity at the lowest nutrient application, i.e. 2.06 t kg^{-1} N, 20.6 t kg^{-1} P and 2.06 t kg^{-1} K.

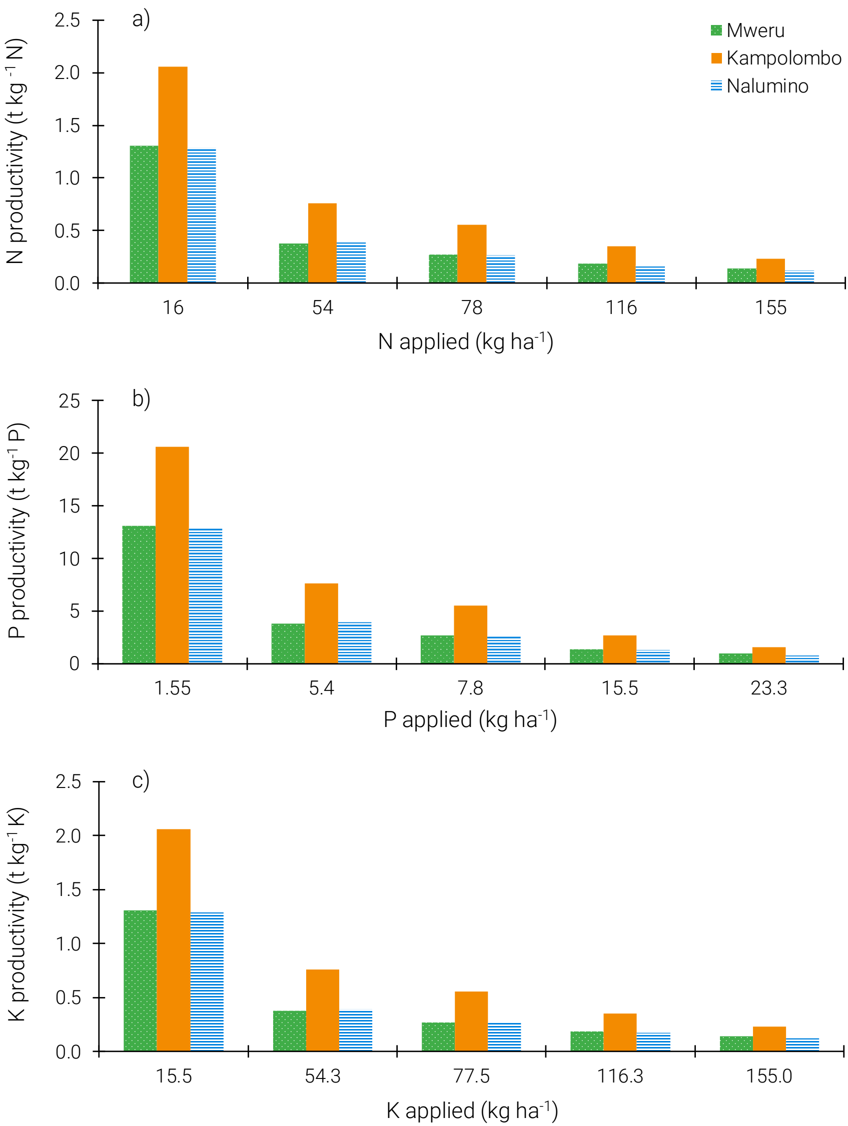

Fig. 7. Effect of applied N (a), P (b), and K (c) on the respective nutrient productivity on Mweru, Kampolombo and Nalumino cassava varieties. Adapted from unpublished fertigation studies on cassava in a field at the International Institute of Agriculture (IITA) - Zambia.

3.3.2 Optimizing root yield of cassava under fertigation

The method of fertilizer application chosen for crop production influences yield more than the method of irrigation. Therefore, Maisiri *et al.* (2005) recommended low-cost irrigation technologies with good water and nutrient management, such as drip irrigation. However, drip systems are expensive (Postel *et al.,* 2001). This reduces the purchasing power of smallholder farmers who are the major producers and consumers of cassava. Therefore, if smallholder farmers are to invest in fertigation of cassava, they need to reap the benefits. This is only possible if the yield per unit area of land is maximized.

Studies have already shown increased root yield with the application of fertilizers (Susan John *et al.*, 2007; Fermont *et al.*, 2009a, b; Byju *et al.*, 2012; Kaweewong *et al.*, 2013a) and irrigation (Amanullah *et al.,* 2006b; Odubanjo and Olufayo, 2011) separately. However, cassava is susceptible to low temperatures (El-Sharkawy, 2004). The cold period stagnates growth while consuming more fertilizer and irrigation water. What if one could escape the cold period entirely? Growth models can be used to predict when optimal root yield can be achieved to escape the cold season, and hence prevent wasteful application of fertilizers/irrigation with no significant increase in root yield. The logistic model allows for the prediction of when to harvest cassava for maximum root yield and evaluates the economic viability of fertigation technology for this crop.

Applying the logistic model to three varieties in Zambia showed minimum benefit (benefit is root yield increase between no fertilizer application and the fertigation concentration at which maximum root yield was achieved) of fertigation in one planting during two years (harvesting after 24 months). However, the benefit increased with the increasing number of plantings; for Mweru and Kampolombo this was after three plantings (harvesting every seven to eight months)—benefit and root yields were higher after three plantings. Conversely, for Nalumino the maximum benefit was after five plantings, 86.4% at five plantings compared to 6.4% at two plantings (Fig. 8). Additionally, the long duration varieties, in this case Nalumino, require minimum fertigation before seven months and thereafter require enhanced nutrition to increase development of the storage roots. These results led to the conclusion that fertigation could be used to shorten growth cycles of cassava varieties and probably other crops.

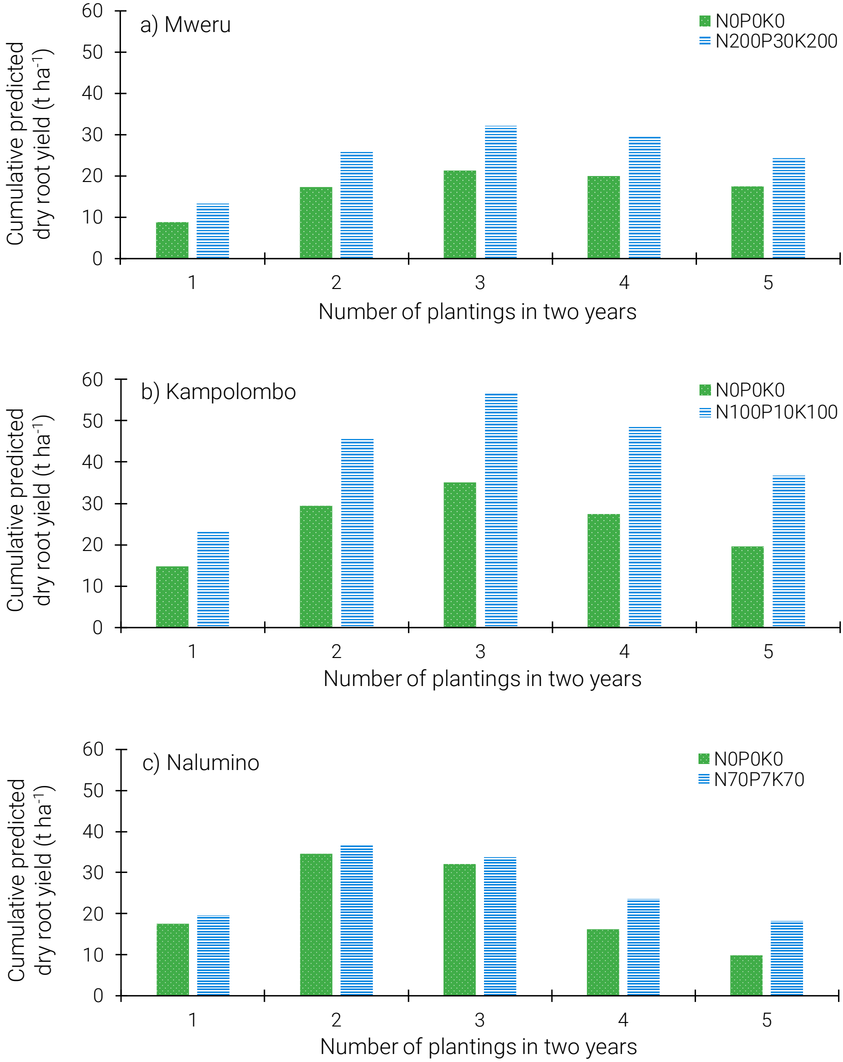

Fig. 8. Cumulative predicted dry root yield of: a) Mweru, b) Kampolombo and c) Nalumino under various number of plantings and fertigation concentrations. The legends indicate NPK solution concentration combinations. Cumulative is the total of yield within each planting number. Adapted from unpublished fertigation studies on cassava in a field at IITA, Zambia.

4 Environmental Impact

Reactive N, i.e. all N compounds besides N_2, contribute to environmental pollution (Kanter *et al.,* 2015). Good and Beatty (2011) predicted that by 2020 an excess of 20.2 Mt of N will be applied to agricultural lands around the world and this would cost the environment 8.7 billion US$ (Table 13). Knowing that fertilizer application to cassava has been lacking, there are low or no fertilizer risks such as leaching of N to the lower horizons leading to contamination of ground water. An unpublished fertigation study on the effectiveness of N application to cassava has shown that soluble carbohydrates in YFEL better predict root yield than total N. Such evidence precisely shows the optimal N rate for maximum root yields, thus alleviating the risk of applying excess N. The use of soluble carbohydrates is just one of the physiological methodologies that can be effective in reducing effects on the environment of applying excess nutrients. This soluble carbohydrate method of assessing N effectivity could be expanded to other nutrients, i.e. study other physiological indicators that are effective in revealing the relationship between nutrients and root yields.

Even though there is little or no environmental impact from nutrient application to cassava, there is a risk of excessive nutrient mining by cassava, especially K (Howeler, 2002). In addition to this, soil erosion could be exacerbated on slopes where cassava is often grown (Putthacharoen *et al.*, 1998; Howeler, 2002). With the need for increased production, increased fertilizer use is being promoted, so it is important to note that fertilizer usage should be judicious and synchronized with cassava growth to reduce environment impacts. While this is an avenue to reduce environmental degradation, other methods such as exploring alternative nutrient supply (for example BNF and VAM) should be explored extensively. Indeed, Kanter *et al.* (2015) proposed that fertilizer best management practices and or enhanced efficiency fertilizers, through the use of controlled/slow release fertilizers, could reduce environmental pollution immensely and improve fertilizer recovery efficiency.

Table 13. Total consumption of N, excess applied N and its environmental cost globally.

Year	Actual/predicted consumption (Mt N)	Value (US$B)	Excess N applied (Mt N)	Value (US$ x 10^9)	Environmental cost (US$ x 10^9)
1987	75.8	32.2			
2007	100.6	80.0			
2020	110.7	108.5	20.2	19.8	8.7
2030	126.9	154.8	46.4	56.6	24.9
2050	151.6	227.4	71.1	106.7	46.9

Adapted and modified from Good and Beatty, 2011.

5 Prospects

Since cassava feeds many people and offers an array of raw materials, its green revolution is inevitable. It is only prudent that while both farmers and researchers race to improve its production per unit area, fertilizer application should be judicious and synchronized with the respective cultivar's needs. This would reduce both environmental degradation and production costs. However, in order to do this, extensive studies are still required on the response of cassava to micronutrients, intermittent application of macronutrients, and when to apply them for maximum root yield. More emphasis should also be placed on slow/controlled release fertilizers.

To further enhance the success of fertilizer application, including fertigation, various growth models could be explored. So far, the Quantitative Evaluation of Fertility of Tropical Soils model has been studied (Byju *et al.*, 2012; Ezui *et al.*, 2016), though not extensively. Others such as the Decision Support System for Agrotechnology transfer (Jones *et al.,* 2003), Agricultural Production Systems Simulator (Keating *et al.*, 2003), and HYDRUS (Simunek *et al.,* 2016) among others need to be fully exploited for cassava.

Alternative tissue nutrient analysis that highly correlate or best predict root yields should be explored and, as already shown in this document, soluble carbohydrates in the YFEL is a better indicator of N use efficiency than total N. Such studies could be expanded to P and K. Further, studies on when cassava decides to start the allocation of sugars to the storage roots and which roots are designated for this will aid in revealing how nutrients influence this process. Finally, there are scarce, if any, studies on the influence of fertilizer on root starch characteristics of cassava (as starch is an emerging major industrial raw material), such as size, shape, solubility, etc. This is required if cassava is to appeal to a large market and be a significant crop for the 21st century, particularly in the face of global warming to which it is more adaptable to than most other crops.

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7 Appendix

Cassava plant

Photo 1. Cassava fruit. Photo by Shutterstock.com

Photo 2. Cassava leaf. Photo by J. Okoth Omondi.

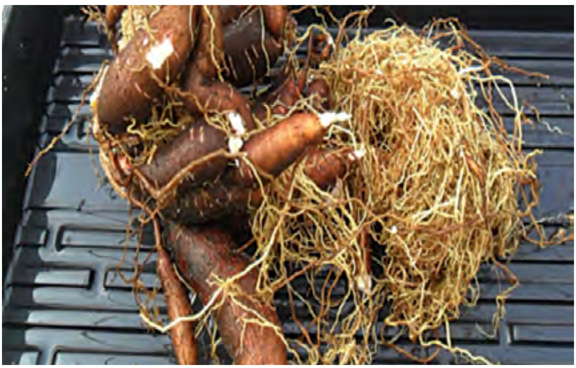

Photo 3. Cassava storage and fibrous roots. Photo by J. Okoth Omondi.

Photo 4. Cassava flowers.
Photo by Shutterstock.com

Photo 5. Cassava leaves, stems and storage roots.
Photo by Istockphoto.com

Visual sypmtoms of nutrient deficiency and toxicity

Photo 6. Nitrogen deficiency.

Photo 7. Potassium deficiency.

Photo 8. Magnesium deficiency.

Photo 9. Iron deficiency.

Photo 10. Iron deficiency.

Photo 11. Ca deficiency.

Photo 12. Boron deficiency.

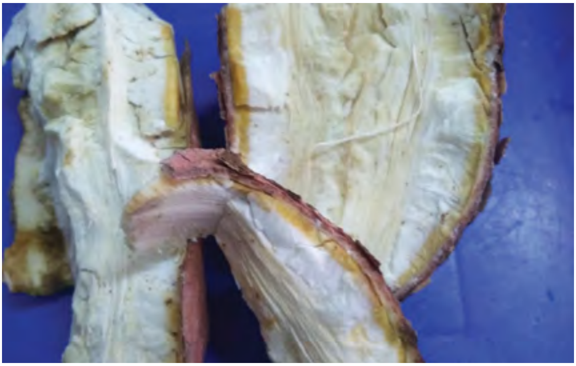

Photo 13. Boron deficiency.

Photo 14. Boron toxicity.

Photos 6-14 by Dr. Susan John, Principal Scientist (Soil Science), ICAR Central Tuber Crops Research Institute, Kerala, India.