EFFECTS OF POTASSIUM AND MAGNESIUM ON CASSAVA VEGETATIVE AND ROOT YIELD

BY

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DECLARATION

Declaration by student

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DEDICATION

This work is dedicated to:

My late father Sanginga Matabaro Jean-Marie, who planted cassava until his last days.

Thank you for everything papa.

&

Chief “*Aare*” Dr. Nteranya Sanginga, Dr. Pascal Sanginga, Mrs Justine Ndara, Chief “*Yeye*” Mrs Charlotte Kurara, Mrs Nabintu Bagalwa, Mrs Charlotte Sanginga, my siblings, relatives, friends and colleagues for the affection and unfailing support.

ABSTRACT

Cassava (*Manihot esculentum*) has a high potassium (K) demand and its application does not generally increase yields. Potassium may have antagonistic effects on magnesium (Mg) leading to deficiency of Mg in the soil. The objectives of this study were to (*i*) evaluate the vegetative growth of cassava under different K and Mg fertilizer combinations and (*ii*) determine the effects of K and Mg fertilizer on cassava storage root yield. A 2-cropping season experiment was conducted in a randomized complete block design (RCBD) to evaluate cassava variety TME419 at different combinations of K and Mg in Ibadan (7°2916N, 3.5302° E), southern Nigeria. Fertilizer treatments included 0, 90 and 180 kg ha^{-1} of K, 0 and 15.5 kg ha^{-1} of Mg and 20.5 kg ha^{-1} sulphur (S) to account for the S in Kieserite ($MgSO_4$) combined as follows: control (F_0), 90 K kg ha^{-1} (F_1), 180 K kg ha^{-1} (F_2), 0 K:15.5 Mg:20.5 S (F_0+Mg$_1$), 90 K:15.5 Mg:20.5 S kg ha^{-1} (F_1+Mg$_1$), 180 K:15.5 Mg:20.5 S kg ha^{-1} (F_2+Mg$_1$), 90 K:20.5 S kg ha^{-1} (F_1-Mg+S) and 180 K:20.5 S kg ha^{-1} (F_2-Mg+S). A uniform rate of 75 kg ha^{-1} nitrogen (N) and 20 kg ha^{-1} phosphorous (P) was applied to these treatments except on the control and F_0+Mg$_1$. Fertilizer treatments containing K had longer stem, fresh and dry total aboveground yield than the control and non-K treatment (F_0+Mg$_1$). Treatment F_1-Mg+S had the longest stem, higher fresh and dry stem yield, while treatment F_2+Mg$_1$ outyielded other treatments on both fresh and dry leaves yield and total aboveground yield. An average of 2 stems per plant were observed on cassava grown in all fertilizer combinations. The 2 cropping seasons were significantly ($p < 0.05$) different for all vegetative and yield attributes, with maximum vegetative yield in the first cropping season. Although there was no significance ($p > 0.05$) among the fertilizer treatments for storage root yield, the interaction between K ×Mg increased the fresh storage root yield and storage root dry matter yield (DM) by 14.58% and 20.8%, respectively, upon fertilization with F_2+Mg$_1$. Further, fresh storage root yield and storage root DM yield increased by 13.23% and 14.23%, respectively, in the plots fertilized with F_2. Cassava plants fertilized with F_0+Mg$_1$ recorded the highest root: shoot (R: S= 1.02) and harvest index (HI =0.90). The differences between the two cropping seasons on fresh storage root yield and root DM yield were 17.35% and 21.52%, respectively. The R:S and HI between the two cropping seasons also varied by 24.2% and 26.57%, respectively. Fresh storage root yield had significant positive correlations with the fresh total aboveground matter (r= 0.66*) in the first cropping season and (r= 0.51*) in the second cropping season. The interaction between K and Mg at the combination of 180 K:15.5 Mg:20.5 S kg ha^{-1} (F_2+Mg$_1$) highly enhanced the vegetative and root yield of cassava variety TME419. Therefore, the combination of 180 K:15.5 Mg:20.5 S kg ha^{-1} should be used by farmers to enhance cassava variety TME419 yield and balance the K and Mg fertility status of the soil.

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LIST OF ACRONYMS AND ABBREVIATIONS

CGIAR:	Consultative Group on International Agricultural Research
DM:	Dry matter
FAO:	Food and Agricultural Organization
IITA:	International Institute of Tropical Agriculture
MAP:	Months after Planting
R:S:	Root: shoot ratio
RMFTs:	Researcher Managed Field Trials
SSA:	Sub-Saharan Africa
SE:	Standard Error
SD:	Standard Deviation

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Cassava (*Manihot esculenta* Crantz) is a rain-fed crop grown in tropical and subtropical countries situated in the equatorial belt (Chua *et al.,* 2020). It is widely cultivated due to its versatility as food crop, feed, energy, and mainly due to its ability to thrive in poor soils unsuitable for most other food crops (Xiao, 2012; Howeler & Oates, 2018). Cassava is primarily grown for its edible starchy roots, which mainly constitute 62 % water, 35 % carbohydrate, 1-2 % protein, 0.3 % fat, 1-2 % fiber and mineral matter (Aiyelari *et al.,* 2019). The leaves are also consumed as green vegetables depending on the variety and crop age (Montagnac *et al.,* 2009). Cassava leaves have 7-18% protein, 7-18 g/100g carbohydrates and are also rich in vitamins such as B_1, B_2 and C (Xiao, 2012; Latif & Müller, 2015). These properties have made cassava the world's fourth most important staple and carbohydrate-enriched food after rice (*Oryza sativa*), wheat (*Triticum aestivum*) and maize (*Zea mays* L.), thereby feeding over 800 million people worldwide (El-Sharkawy, 2012).

The area under cassava is estimated to be more than 20 million hectares yielding over 300 million tonnes of fresh storage roots (El-Sharkawy, 2012; FAOSTAT, 2021). About 63% of the global cassava output is from Africa, with Nigeria accounting for 60 million tonnes, making it the first and largest cassava producing country worldwide (FAOSTAT, 2021). Despite being the largest cassava producer, low cassava storage root yields of up to 8.2 tonnes/ha fresh mass has been observed in Nigeria (FAOSTAT, 2021). The low cassava storage root yields have been attributed to poor agronomic practices, pests and diseases, nutrient imbalance and/or deficiency, and the use of old unimproved varieties. Among these yield limiting factors, nutrient imbalances and/or deficiencies have received little attention, yet, contribute to a large portion of the current yield gap (Huber & Jones, 2013; Yakimenko & Naumova, 2021). Cassava is perceived as a crop that either does not require or nonresponsive to nutrients application because it produces even on marginally nutrient depleted soils. However, recent findings have shown that cassava yields increase with the application of fertilizer (Biratu *et al.,* 2018; Adiele *et al.,* 2021). De Souza *et al.* (2017) report that the current average cassava storage root yield of 2.5 tonnes/ha dry matter (DM) in sub–Saharan Africa (SSA) smallholder farmers' fields is equivalent to only one-third of average yields produced in Asia. Indeed, with optimal growth conditions and agronomic practices, cassava yield potential can be as high as 90 tonnes ha^{-1} fresh storage roots equivalent to 27-32 DM tonnes ha^{-1} (Adiele *et al.,* 2020).

Ordinarily, equal amounts of nitrogen (N), phosphorus (P) and potassium (K) is recommended to be added in the soil to support optimal growth of cassava (FAO, 2013). However, continuous growth of cassava for many years in the same field requires modification of the N-P-K balance and supply of other vital nutrients to compensate for the depleted nutrients. This is because a tonne of cassava storage roots mines the soil of about 2.3 kg of N, 0.4 kg of P, 3.0 kg of K and 0.26 kg of Mg (Hauser *et al*., 2014, Howeler & Oates, 2018). In fact, due to cassava's high K demand, K becomes the most limiting nutrient when cassava is cultivated continuously in the same field for many years without replenishing the soil with adequate K fertilization (Imas & John, 2013). However, contradictory effects of increased K fertilization on cassava storage root yield have been observed. For instance, Adekayode & Adeola (2009) reported increased cassava storage root yield upon fertilization with K levels up to 150 kg ha^{-1}, while Chua *et al. (*2020) observed the highest storage root yield at 120 K kg ha^{-1}. Yet, Uwah *et al.* (2013) and Fernandes *et al.* (2017) showed that increasing K to levels higher than 80 kg and 90 kg ha^{-1} respectively, does not correspond to increased storage root yield.

This lack of response in cassava storage root yield despite the application of high levels of K could be attributed to K's ability to create an imbalance with other vital nutrients that have similar uptake mechanisms and hence they compete for the adsorption and absorption sites, transport mode, and various functions on the root surface or within the tissues (Fageria, 2001; Chua *et al.,* 2020). Generally, high level of K^+ has cationic antagonistic effects on the uptake of Mg^{2+} by typically blocking the unspecific Mg transporters at the root surface, resulting in relative Mg deficiency (Nejia *et al.,* 2016; Tränkner *et al.,* 2018; Wang *et al.,* 2020). Magnesium deficiency or low absorption affects plant growth and impairs the distribution of carbohydrates between the source and sink organs, which eventually reduces root growth and increases the shoot to root ratio (Ding & Xu, 2011, Xie *et al.,* 2020).

While it is evident that K^+ and Mg^{2+} show an antagonistic interaction, synergism has been observed depending on the proportion of each participating nutrient (Chaudrhy *et al.*, 2021). Therefore, there is a need to determine the appropriate amount of K: Mg fertilizers that can support cassava production.

1.2 Statement of the problem

Cassava has a high K demand, and therefore, supplying this element in adequate amounts is required for optimal production. However, the application of high doses of K does not increase cassava yields, owing to the fact that high K has an antagonistic effect on Mg leading to relative Mg deficiency. This K-Mg imbalance contributes to the large yield gap in African cassava production systems since Mg is a forgotten nutrient. Although it is evident that K^+ and Mg^{2+} show an antagonistic interaction, the two nutrients can also exhibit synergism depending on their proportion. The most effective proportion of K and Mg in African cassava production systems to spur the productivity of this food crop is not well known. This has left smallholder farmers to continue growing cassava using non-validated fertilizer combinations and, in the process, failed to increase yields.

1.3 Justification of the study

Due to the growing interest on cassava as a crop that can ensure food security in Africa, efforts must be made to maximize its production. Because there is so little reserve land suitable for cultivation, it is only possible to increase cassava production by increasing production per unit area, and one of the best ways to achieve this is through appropriate fertilization. Thus, with the reported lack of response to K fertilization associated with K-Mg antagonism, there is a need to provide a balanced K and Mg nutrition for cassava plants. Elucidating K–Mg interactions on cassava may help to clarify their physiological consequences on cassava growth and yield improvement, and provide a theoretical basis for balancing fertilization with K and Mg. Hence, the application of balanced K-Mg fertilizer by the farmers is likely to enhance cassava production in the African production systems.

1.4 Objectives of the study

1.4.1 Broad objective

The general objective of this study is to enhance production of cassava through the use of effective K and Mg fertilizer combinations.

1.4.2 Specific objectives

1. To evaluate the vegetative growth of cassava under different K and Mg fertilizer combinations.
2. To determine the effects of K and Mg fertilizer on cassava storage root yield.

1.5 Hypotheses

1. The interaction between K and Mg promotes the vegetative growth of cassava.
2. The interaction between K and Mg enhances cassava storage root yield.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of cassava

Cassava (*Manihot esculenta Crantz*), also known as manioc, tapioca, mandioca, and yuca, is a perennial woody shrub from the Euphorbiaceae family (Shackelford *et al.,* 2018). This high calorific crop has been domesticated for thousands of years, but it only became popular in the early 20th century during the colonial period when it drew the attention of colonists for its importance as an anti-famine and food security crop (El-Sharkawy, 2012).

Cassava is now widespread and grown in tropical countries situated in the equatorial belt (30˚ N; 30˚ S), with an altitude variation from sea level to 2000 m and annual precipitation ranging from 500 mm (in semiarid eco-zones) up to >2000 mm (in humid eco-zones) (El-Sharkawy, 2012; Guimarães *et al.,* 2017). Given this wide ecological diversity, cassava has the ability to adapt to a wide range of environments and ecosystems with highly varying temperatures, solar radiation, photoperiods and rainfall (Alves, 2002; El-Sharkawy, 2012). Furthermore, cassava is one of the most widely planted crops in tropical and subtropical countries, grown almost exclusively by smallholder and low-income farmers (Reincke *et al.,* 2018; De Souza *et al.,* 2020). This is due to its ability to tolerate prolonged drought and unpredictable rainfall, its high productivity even on low fertility and acidic soils, and its efficient production without mechanization or expensive inputs (De Souza *et al.,* 2020; Reincke *et al.,* 2018). In addition, cassava is also flexible to piecemeal harvesting for a period ranging between 8 and 24 months after planting; it can be inter-cropped and left in the ground to be used in times of unexpected food crisis and shortages (Baafi & Safo-Kantanka, 2008; Ano *et al.,* 2021). Due to this, cassava has become one of the most resilient food security crops of the 21st century feeding at least 800 million people worldwide and referred to as “the drought, war, and famine crop of the developing world” (Howeler, 2012; Shackelford *et al.,* 2018).

The global mandate for cassava is spearheaded by two centres of the Consultative Group on International Agricultural Research (CGIAR) (Hillocks, 2002). These are the International Institute of Tropical Agriculture (IITA) in Nigeria and the Centro Internacional de Agricultura Tropical (CIAT) in Colombia. In Africa, specifically in Nigeria, IITA and its marked collaboration with national research institutions have done extensive work on the development of cassava. The collaboration culminated in the development of highly resistant cassava varieties that can withstand and resist the virulence of different pests and diseases such as cassava mosaic virus disease (CMD), cassava anthracnose disease (CAD), cassava bacterial blight (CBB), cassava mealybug (CMB) and cassava green mite. Additionally, high-yielding varieties with minimal or free cyanide content were developed through the same collaboration (Ikuemonisan *et al.,* 2020).

Since cassava originated in South America, probably in the Amazon region, it is the only non-native African root crop that has the status of a major staple in the African continent (Baafi & Safo-Kantanka, 2008). Consequently, due to its robustness and versatility, cassava has gained importance, especially in these uncertain times, and the reliance upon it is expected to increase over the years as the climate changes and the human population grows (Anna *et al.,* 2010; Reincke *et al.,* 2018).

2.2 Cassava growth requirements and physiology

Cassava is a perennial shrub with a C_3-C_4 intermediate photosynthetic characteristic giving it a high ability to absorb carbon at very high rates in conditions of high humidity, solar radiation and temperature (El-Sharkawy & Cock, 1990; Alves, 2002). As a perennial shrub, cassava has no well-defined growth stages and can grow indeterminately, alternating phases of vegetative growth and carbohydrates storage in the roots (Alves, 2002; Moreno *et al*., 2021). Generally, the vegetative and storage root growth occurs simultaneously, although in two phases (Guimaraes *et al.,* 2017; Adiele *et al.,* 2021). The first phase (from planting to 8 weeks) is when stems and leaves are produced, and the roots begin to form. The second growth phase (8 to 72 weeks after planting) involves the growth of the shoot and the bulking of the roots that formed in the first phase. These two phases are followed by an interval of dormancy (Danielle, 2013). However, according to Alves (2007), storage root bulking starts after sufficient shoot growth, while Okogbenin and Fregene (2002) suggested that storage root bulking and shoot growth for certain cassava varieties occur simultaneously.

Nevertheless, since the vegetative and reproductive periods of cassava are generally not separated in time, there is literally competition for photoassimilates, forcing their distribution between the roots and shoot (Alves, 2002; Adiele *et al.,* 2021). However, depending on the environmental conditions and growth cycle, dry matter partitioning is directed either toward the production of the shoot or of the root (Alves, 2002; El-Sharkawy, 2004). Typically, during the first 3-5 months after planting, during canopy establishment, dry matter distribution is more concentrated in the shoot, and then the roots become store for the photoassimilates during the rest of the growth cycle (Alves, 2002; Adiele *et al.,* 2021). The efficiency of photoassimilates partitioning in the shoots and roots of cassava is highly depended of environmental conditions (Spollen *et al.,* 2000). For instance, when there is insufficient moisture, shoot growth is limited while root growth continues due to the selective allocation of photosynthates below the soil surface that allows maximum exploration of soil moisture while minimizing the loss of water through the shoots (Ober & Sharp, 2007). On the other hand, when more photoassimilates are allocated to the shoots, there will be less dry matter for storage root growth and filling, and thus a high shoot to root ratio (Alves, 2002; De Souza *et al.,* 2016). Since cassava yield is closely associated with storage root mass, achieving high yield would need to have a well-balanced growth and photoassimilates partitioning between the shoot and storage root (Ntawuruhunga & Dixon, 2010; Agahie, 2011). Thus, more photosynthetic products have to be translocated to the storage roots to achieve a high root to shoot ratio which is the indication of how much roots will be ultimately harvested (Boerboom, 1978).

For optimum cassava growth and yield, rainfall should be well distributed throughout the growing period, with at least an average of 50 mm rain per month spreading over 6 months in order to meet the plant water requirements (Ikuemonisan *et al.,* 2020). Unlike other crops such as beans (*Phaseolus vulgaris*), maize and rice that would die due to drought, cassava has a mechanism to overcome and is adapted to areas with unreliable rainfall (Cock & Howeler, 1978). Usually, cassava leaves would fall off, leaving the cassava dormant until the onset of the rain, when the carbohydrates in the stem and roots will be then used to produce new leaves (El-Sharkawy, 2007; Okogbenin *et al.,* 2013). In addition, cassava performs well on well-drained, loosely textured soils with pH varying from 5.5-6.5 (Danielle, 2013). The optimum temperature that allows adequate starch production in the leaves and maximum cassava root production ranges from 25 to 32°C (Danielle, 2013).

2.3 Cassava as a food security crop

Sustainable production of sufficient food that can feed the increasing global population is currently one of the world's greatest challenges. According to Burns *et al.* (2010), food security is achieved only when "all people, at all times, have physical and economic access to sufficient safe and nutritious food to meet their dietary demands". Cassava is an important crop fulfilling a critical role in the global food security campaign, especially in sub-Saharan Africa (SSA), because of its high calorific content (Karlström *et al.,* 2016; Shackelford *et al.,* 2018). Except for sugarcane (*Saccharum officinarium*), cassava is the highest carbohydrates producer among crop plants, with a calorific value of 250×103 cal/ ha/day compared with 200 × 103, 176×103, 114×103 and 110×103 cal/ ha/day for maize, rice, sorghum and wheat, respectively (Bayata, 2019). Ironically, even though cassava is a high source of calories, it is still tagged as the "poor man's crop" due to many years of inadequate attention (Luar *et al.,* 2018). It is not only a food security crop because of its versatility as food, feed and energy, but also a cash crop for many households and smallholder farmers (Agiriga *et al.,* 2015).

Being a high calorific crop, cassava stands as the 6th most important crop globally and a major staple crop from which roughly two out of every five Africans get their daily calorific needs (Okogbenin *et al.,* 2013; Wellens *et al.,* 2022). About 70% of global cassava production is used for human consumption, and the rest of the output is used for animal feed and/or industrial uses (Adu *et al.,* 2018). In SSA, cassava's main economic value is its starchy storage root, albeit the leaves are also a source of proteins when consumed as vegetables (Okogbenin *et al.,* 2013; Adu *et al.,* 2018). For instance, in Nigeria, more than 65% of the population consume cassava at least once a day, either as *garri*, bread, *lafun*, flakes, or *fufu* (Ano *et al.,* 2021). Therefore, since cassava provides a stable food production base, there is an urgent need to sustain and/or expand its production in order to fulfill the food demand of the increasing human population (Burns *et al.,* 2010).

2.4 Cassava production trends in Nigeria

Cassava is grown on 35% of the world's agricultural land, and the area under cultivation rose by 44% between the years 1980 and 2011, from 13.6 million hectares to 19.6 million hectares (Howeler, 2014). Currently, cassava world production is estimated at 300 million tonnes, from which Africa's share is 63 % (FAOSTAT*,* 2021). In 2018, Nigeria's cassava output was 60 million tonnes (Figure 1) which was by far the largest in the world, followed by Thailand, Indonesia and Ghana with 31, 19 and 18 million tonnes of cassava, respectively (Ikuemonisan *et al.,* 2020).

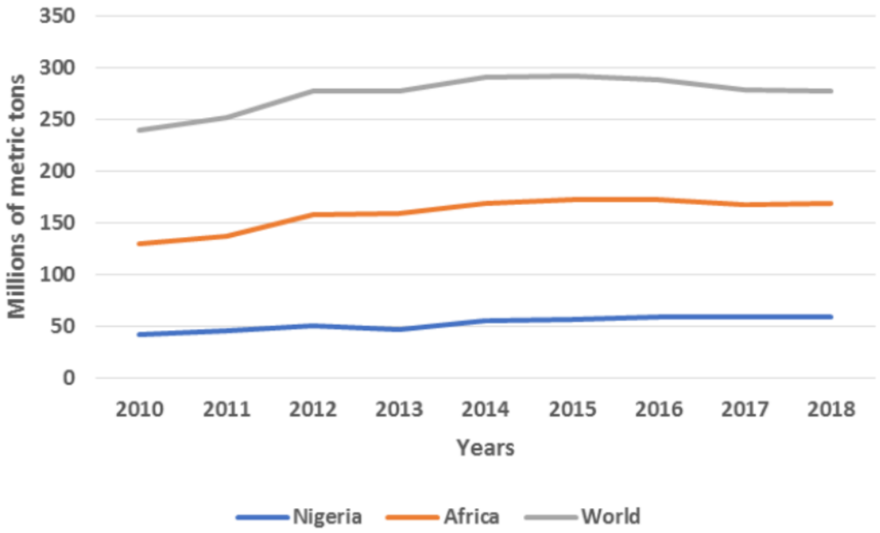

Figure 1: Global cassava output between 2010 and 2018 (FAO, 2020).

From 1970 to 2018, cassava output in Nigeria increased from 9 million tonnes to 60 million tonnes (Figure 2). However, this increase has been associated with the expansion of the cultivated areas rather than the actual farm yield (Ikuemonisan *et al.,* 2020). With the cassava arable space of 6.5 million hectares, Nigeria's production potential should range between 130 million to 156 million tonnes, reflecting a shortfall of 65.9% (Ikuemonisan *et al.,* 2020; Ano *et al.,* 2021). Other factors, often overlooked, have also contributed to the increased cassava production in Nigeria. Some of these are the rapidly growing population with many people embarking in cassava farming, the large internal market demand, the existence of improved processing technology, and the presence of IITA headquarters conducting extensive research on cassava and releasing new varieties (Ogunyinka & Oguntuase, 2020).

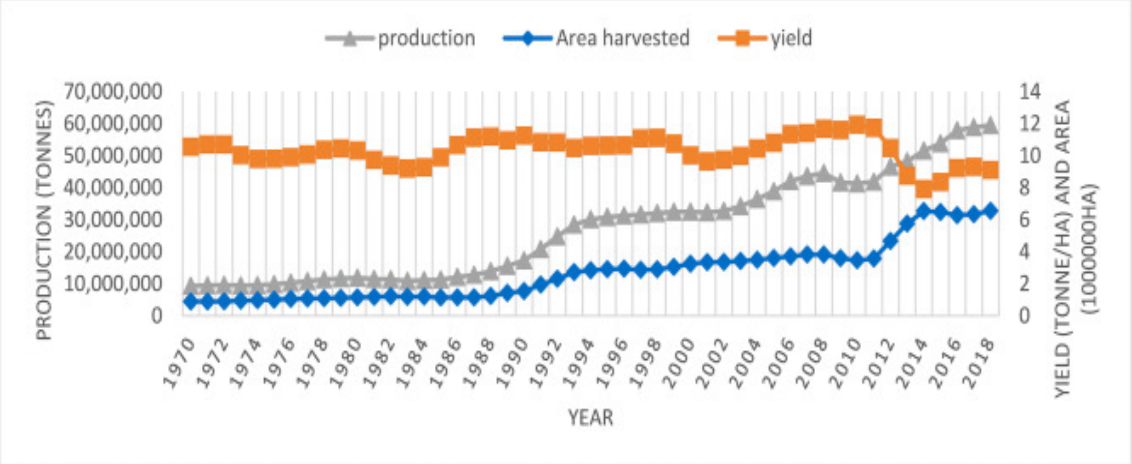

Figure 2: Cassava area, production, and yield trends in Nigeria between 1970 and 2018 (FAOSTAT, 2019).

2.5 Cassava Production Constraints

Even though cassava is the sixth most important crop in terms of annual output; it is reported that the yield has been in decline up to 8-fold below the potential and somehow stagnant for more than a decade (Burns *et al.,* 2010; Adu *et al.,* 2018). The low yield in cassava production systems, especially the 65.9% shortfall in Nigeria's yield, indicates that a myriad of biotic and abiotic constraints are impediments to optimal cassava production. These are notably the lack of varieties adapted to different edaphoclimatic conditions, use of landraces and traditional varieties, inadequate cultural and agronomic practices, lack of clean planting materials, susceptibility to diseases and pests, prolonged drought periods, and poorly fertile soils (Guimarães *et al.,* 2017; Adu *et al.,* 2018; Ano *et al.,* 2021). Furthermore, cassava has a long growth period with a lower annual turnover than that of food crops with shorter growth periods (Ikuemonisan *et al.,* 2020).

2.5.1 The lack of well-adapted varieties and quality planting material

Some farmers in many parts of the tropics where cassava is cultivated are still using landrace lines of cassava. Most of these local varieties bulk slowly and only attain maximum yield after 18 months, unlike the improved varieties that mature as early as six months after planting and attain their maximum yield at about 10-12 months after planting (Cucava *et al.,* 2017; Aiyelari *et al.,* 2019). These local varieties are also highly susceptible to abiotic and biotic constraints that ultimately reduce their yield. With the effort of plant breeders working tirelessly in developing, releasing and distributing the improved cassava varieties, this constraint is being circumvented.

Cassava production is also highly affected by the availability and quality of vegetative propagules. Many farmers do not plant healthy cuttings, which has been actually reported to be an important factor in the subsequent attainment of good yield. Additionally, the multiplication and distribution of cassava planting material (stem cuttings) is expensive and very demanding (Hillocks, 2002). The stems are bulky and highly perishable if they are not stored properly or planted as soon as they are harvested (Hillocks, 2002). Thus, circulation and use of cassava stem with low vigour and highly infested with pests and diseases is one of the major constraints to cassava production.

2.5.2 Pest and diseases

The major pests that have been observed in cassava fields and have had several incidences that threaten the future of cassava are cassava green mites (CGM; *Mononychellus* spp.), cassava mealybug (CM; *Phenacoccus manihoti* Matile-Ferrero), elegant grasshopper (*Zonocerus elegans* L. and *Zonocerus variegatus* Thunb.) and root mealybug (*Planococcus citri* Risso) (Howeler, 2012). Plant diseases such as cassava mosaic viruses (CMVs, Geminiviridae: Begomovirus {GEM2}), cassava anthracnose disease [CAD; *Colletotrichum gloeospoioides* f. sp. *manihotis* Henn. (Penz.) Sacc.], cassava bacterial blight (CBB; *Xanthomonas axonopodis* pv. *manihotis* Berthet and Bondar) and cassava root rots have also led to huge yield losses (Hillocks, 2002; Hayes, 2020). Other biotic constraints include attack of termites, nematodes and certain weed species. Luckily, there have been indeed massive efforts to fight these diseases, notably through the development of biological control methods, breeding and deployment of disease-resistant cultivars, phytosanitation such as roguing and use of clean or disease-free stem cuttings (Alonso *et al.,* 2021). Other control strategies include cultural practices such as intercropping and scheduled planting, but also vector control using insecticides (McCallum *et al.,* 2017).

2.5.3 Soil fertility

Cassava has high adaptability to various soil conditions, producing generally fairly good yields on marginal fields that are usually not suitable for other crops (Cuvaca *et al.,* 2017; Prasetyo *et al.,* 2021). This led to a belief that soil fertility is not a constraint for cassava production. However, it has been reported that cassava grown on fertile soils or with fertilizers inputs yield optimally; and yield increase by 35% can be achieved if soil constraints, such as low fertility are eliminated (Chua *et al.,* 2020).

Furthermore, cassava is also known to be a ‘’scavenger crop’’ or a high nutrient miner because of its high absorption capacity, which leaves low-nutrient soils poorer than before (Biratu & Ntawuruhunga, 2019). Roots harvest generally removes nutrients in the following order: K>N>P>Ca>Mg>S, and this excessive removal can lead to serious detrimental effects on the Physico-chemical characteristics of the soil (Howeler, 2012). The decline in soil fertility is severe in tropical regions characterized by low nutrients status and organic matter resulting from leaching and topsoil erosion by intense rainfall (Uwah *et al.,* 2013). Likewise, due to the high absorption capacity of cassava, the residual mineral nutrients left after each harvest on poor soils are never sufficient for subsequent crops to yield optimally (Biratu *et al.,* 2019). Nevertheless, soil fertility status in cassava production systems may be maintained by applying sufficient amounts of nutrients to balance off the depletion of nutrients (Howeler, 2012).

2.6 Soil nutrient balance in cassava production systems

Nutritional problems are widespread in cassava production systems since many farmers believe cassava does not need good fertility (Howeler, 2017). Hence, they seldom do organic or inorganic fertilization. However, soil fertilization has shown remarkable success in eliminating these nutritional problems that reduce cassava yield (Biratu *et al.,* 2018). FAO (2013) recommends equal amounts of N, P, and K to be added to the soil to support optimal cassava growth. However, continuous growth of cassava for many years in the same field requires modification of the N-P-K balance to make up for the removed nutrients. The rationale is that for every tonne of harvested roots, cassava extracts on average about 4.91N, 1.08P, and 5.83K kg (Imas & John, 2013). For example, cassava yielding 45 mt ha^{-1} fresh storage roots can mine the soil of 62 N, 23 P and 197 K kg ha^{-1} (Imas & John, 2013).

Because cassava is a heavy K feeder, many authors have reported cassava yield decline in K-deficient fields (Howeler, 2002; Fernandes *et al.,* 2017). On the other hand, cassava yield increases when appropriate level of K fertilizer is supplied, implying that K is one of the most limiting nutrients for cassava (Imas & John, 2013; Uwah *et al.,* 2013; Chua *et al.,* 2020). Albeit K's role in increasing cassava yield, its application can change the concentrations and availability of other nutrients by affecting their move to the roots, absorption, uptake and distribution or function such that they compete for the same uptake mechanism from the soil (Koch *et al.,* 2019). This phenomenon is often observed between ions such as K and Mg (Koch *et al.,* 2019). Hence, as K and Mg are vital nutrients in cassava production systems, knowledge of both their individual and interactive effects is essential.

2.6.1 Role of Potassium in cassava production

Potassium (K) is the only cationic nutrient that plants need in the largest proportion (Ding & Xu, 2011). This is due to the fact that it is a major player in many plant biochemical and physiological processes, such as photosynthesis, N metabolism, as well as the transport and uptake of other nutrients such as magnesium (Mg), calcium (Ca) and

Manganese (Mn) (Zhao *et al.,* 2014; Fernandes *et al.,* 2017). Additionally, K contributes to improving crop yield and quality, reestablishing the leaf area of a crop and enhancing the ability of a plant to survive adverse conditions (Zhao *et al.,* 2014; Fernandes *et al.,* 2017). Potassium is a vital nutrient for stem growth due to its role in cell multiplication and photosynthesis such that its deficiency reduces the photosynthetic rate ultimately leading to a lower shoot biomass production (Boateng & Boadi, 2010; Thummanatsakun & Yampracha, 2018; and Koch *et al.,* 2020). Furthermore, since cassava is a high carbohydrate producer, quite heavy doses of K are required in synthesising and translocating carbohydrates that can increase the root yield and improve the root quality (Imas & John, 2013; Chua *et al.,* 2020).

2.6.2 Role of Magnesium in cassava production

Magnesium (Mg) is also required in significant quantities by plants and serves as a cation in several physiological processes in plants, making it an indispensable element of plant mineral nutrition (Tränkner *et al.,* 2018; Koch *et al.,* 2019; Yakimenko & Naumova, 2021). It plays a crucial role in photosynthesis, chlorophyll formation, synthesis of proteins, as well as transport of carbohydrates between the source and sink organs (Ding & Xu, 2011; Nejia *et al.,* 2016; Ogura *et al.,* 2020). As Mg plays a significant role in the production and partitioning of photoassimilates to the roots; Mg deficiency would be more pronounced on root growth (Koch *et al.,* 2019)

It is good to note that, Mg availability and variation in an agricultural production system depend on factors such as cation exchange capacity and texture of the soil, competing cation concentration, site-specific anthropogenic and climatic factors, crop cultivation, and fertilizer regime (Nejia *et al.,* 2016; Wang *et al.,* 2021). Unfortunately, most soils, especially in SSA, are Mg deficient because Mg has not been given enough attention in crop production and is now referred to as "the forgotten nutrient" (Cakmak & Yazici, 2010). Hence, in order to support the optimal growth of cassava, SSA soils cropped with cassava must be supplied with adequate levels of Mg (Nejia *et al.,* 2016).

2.6.3 Interactive effects of Potassium and Magnesium on cassava

Nutrient interactions occur when the supply and availability of one nutrient affects the absorption, distribution, or function of another nutrient. Nutrients interaction occurs at the root surface or within plant tissues, affecting the plant growth and yield (Fageria, 2001; Rene *et al.,* 2017). Nutrient interaction is influenced by many factors such as: concentration of participating nutrients, crop species and their root architecture, soil type and aeration, water availability, soil pH, ambient temperature, light intensity, the respiration and transpiration rate of the plant, the internal concentration of nutrients of the plants, crop age and growth rate (Fageria, 2001; Neija *et al.,* 2016). These interactions start with changes at subcellular levels affecting the rates of photosynthesis, respiration, cell division and expansion, utilization and translocation of assimilates, all of which will produce the final crop yield (Fageria, 2001).

Nutrient interactions can be classified and are generally measured based on the outcome in terms of growth response (Fageria, 2001). A positive or synergistic interaction is achieved when adding two nutrients together increases crop yield than when each of them is supplied alone. On the other hand, when adding two nutrients yields less than when they are supplied alone, the interaction is negative or antagonistic. However, when both nutrients do not change crop yield, the interaction is neutral (Fageria, 2001).

Both synergistic and antagonistic interactions are observed between K and Mg, depending on their proportion in the growth medium. Generally, an antagonistic interaction is observed when there is an excess of K in the nutrient medium without simultaneous application of Mg, which leads to a shift in their ratio at the root surface to the disadvantage of Mg (Fageria, 2001). Conversely, a one-sided oversupply of Mg has no adverse effect on K uptake since plants can always meet their K requirements via specific transporters (Khan academy, 2022). These two nutrients affect each other because they compete for the site of adsorption, absorption, transport, and function on plant root surfaces or within plant tissues (Chua *et al.,* 2020). The cationic antagonistic effect of high K^+ on the absorption of Mg^{2+} is due to the fact that K blocks the unspecific transports of Mg to the roots, which results in Mg deficiency (Nejia *et al.,*2016; Tränkner *et al.,* 2018; Wang *et al.,* 2020). This phenomenon is aggravated by the fact that the putative transporters for Mg are unspecific and take up cations other than Mg, while the very specific K transporters do not transport Mg and ensure K transport under both high and low K concentrations in the soil (Senbayram *et al.,* 2015). Thus, under high K concentration in the soil, K uptake is advantaged by the Mg transporters while Mg uptake is blocked (Koch *et al.,* 2019). Further, under insufficient Mg supply, K can limit the translocation of Mg from the roots to shoots, while the supply of Mg can improve the uptake and movement of K from the roots to shoots (Chaudhry *et al.,* 2021). Additionally, according to Xie *et al.* (2021), the competition between K and Mg is governed by K^+, and their interaction is generally unidirectional as the antagonistic effect of K^+ on Mg^{2+} uptake is stronger than that of Mg^{2+} on K^+ uptake. Due to this, it is mostly called unilateral antagonism.

Many authors have reported the antagonistic effect between K and Mg on rice, maize, potato, alfalfa (*Medicago sativa*), and sorghum (Omar & El-Kobbia,1966; Ologunde & Sorensen, 1982; Howeler, 2002; Ding, 2011; Neija, 2016; Wang *et al.,* 2020). Consequently, there has been indeed massive research reporting synergistic effects from a well-balanced concentration of K and Mg on high crop yields, such as rice and potatoes (Ding & Xu, 2006; Koch *et al.,* 2019). However, research on the recommended K/Mg ratio in soil have led to different results, owing probably to the different experimental conditions such as crop and soil types, source and rate of K and Mg supplied, age and position of leaves, and growth stage (Xie *et al.,* 2020). Little research has been done on cassava to assess the interaction between K and Mg. Therefore, the current study is set out to establish a balanced nutrition for cassava through a balanced use of K and Mg fertilizer in order to sustain high cassava storage root yield and alleviate the possibility of K-induced Mg deficiency.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Experimental sites

Field trials were conducted at the International Institute of Tropical Agriculture (IITA) in Oyo State, Southwest Nigeria (7°30′8″N, 3°54′37″E, and 243 m altitude) (Figure 3). The field used for this study had previously been cropped with yam in 2015, followed by cassava in 2016 and remained fallow until the establishment of this experiment. The site is in the humid tropical lowland zone with two seasons and a bimodal rainfall pattern which enables the planting of annual crops like cassava to take place twice a year. The first rainy season lasts from April to July, and the second rainy season starts in early September and ends around mid-November (Enesi *et al.,* 2021). After the first rainy season, there is usually a short dry period in August, and a long dry period of 4 months from mid-November to mid-March.

Cassava planting is normally scheduled in the first two months of either the long or short rains, and the plants remain in the field for about a year thereby receiving the two peaks of rain during the growth cycle. These researcher-managed field trials (RMFT) started at the onset of the first rainy season of 2019 and 2020, which were all in May. This period is ideal because the soil moisture is adequate, planting material is not scarce, and the crop can establish before the dry phase. Weather data for each cropping season were collected from planting to harvest in collaboration with the geographic informtaion system (GIS) unit of IITA, and presented in (Table 1).

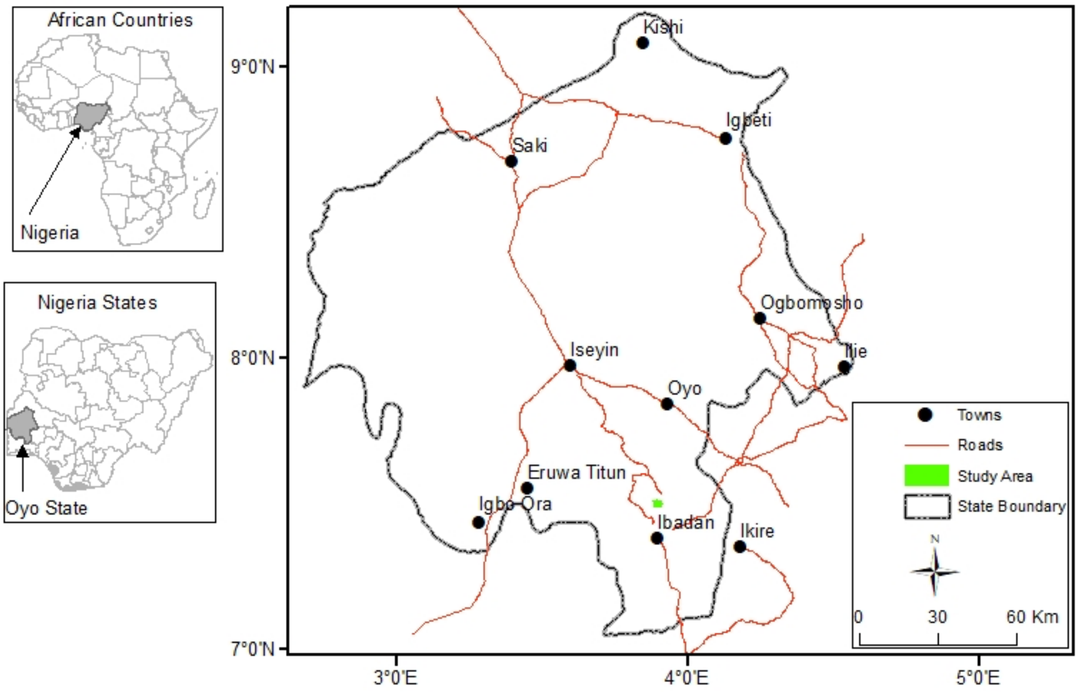

Figure 3: Map of the study area (Source: Author, 2022)

During the first cropping season, rainfall was more frequent and higher than in the second cropping season, with a total of 1777.4 mm and 1273.9 mm rain, respectively. The highest mean rainfall in the first cropping season was experienced in September (305.3mm), whilst no rain was received in January and February in the same season. Similarly, in the second cropping season, the month of June received the highest amount of rainfall (539.3mm) but no rains in August, January and February. The average temperature was 27.4 °C in the first cropping season and 27.7 °C in the second cropping season.

Table 1: Total monthly precipitation and mean (±SD) solar radiation, air temperature, relative humidity and wind speed of the Westbank in IITA from May 2019 to May 2021.

	2019-2020					2020-2021				
	Temperature	Rainfall	Windspeed	Solar Radiation	Humidity	Temp	Rainfall	Windspeed	Solar Radiation	Humidity
	(°C)	(mm)	(km/hr)	(MJ/m²/day)	%	(°C)	(mm)	(km/hr)	(MJ/m²/day)	%
May	27.4±1.3	242.2	2.8	17.5	77.4±4.0	28.1±1.2	70.0	3.2	21.2	82.0±2.7
June	26.2±1.2	212.0	2.1	16.1	83.4±4.3	28.2±1.2	119.6	3.1	20.3	82.2±2.6
July	25.7±0.9	206.2	2.1	15.2	85.1±4.6	26.1±0.5	539.3	3.3	15.2	85.2±3.4
August	25.6±0.8	236.9	2.2	14.7	82.2±4.3	25.8±0.7	45.2	5.3	15.1	80.1±1.9
September	25.6±0.8	305.3	1.8	15.7	81.1±7.2	26.1±0.8	0.0	5.7	18.3	82.0±2.5
October	25.6±0.9	300.0	1.8	16.9	79.1±7.1	27.0±0.8	194.5	4.4	15.4	81.1±2.1
November	27.8±1.0	32.4	1.6	18.2	70.1±7.6	28.4±0.5	138.1	2.7	18.3	91.6±11.1
December	27.7±1.2	9.0	1.6	18.6	60.4±8.2	28.4±0.6	11.0	2.2	18.2	99.8±0.2
January	28.1±1.4	0.0	2.0	9.8	69.1±11.1	28.4±1.5	35.2	2.7	18.3	67.5±5.6
February	29.5±0.9	0.0	2.8	13.8	70.7±10.7	29.4±1.5	0.1	3.0	11.2	65.0 ±7.0
March	29.4±1.2	31.0	4.8	20.4	79.0±2.9	29.1±2.0	0.0	4.7	8.5	74.3±8.4
April	28.8±1.5	142.3	4.0	20.3	79.1±3.1	28.7±1.7	54.4	5.1	12.1	77.4±6.3
May	28.5±1.1	60.1	3.2	21.2	82.0±2.5	28.0±1.2	66.5	5.9	16.1	81.4±2.9

3.2 Soil sampling and analysis

At the onset of every cropping season and before fertilizer application, soil was sampled at two depths (0-20 cm and 20-50cm) using a soil auger. Sampling at 2 depths was done because cassava is a deep-rooted crop that penetrates as far as 50 cm down the soil profile. Thus, any discontinuities in the soil can physically limit cassava roots penetration and nutrients uptake/availability (Abd-Elmabod *et al.,* 2017; CROPNUTS, 2022). The soil samples were air-dried at room temperature of about 27 °C, crushed, sieved through a 2 mm sieve and analyzed for texture, pH, organic carbon, total N, available P, exchangeable cations (K^+ and Mg^{2+}). All these analyses were done in the analytical service laboratory of IITA, Ibadan, Nigeria.

Soil pH which determines the solubility of minerals in the soil, was determined using a glass electrode pH meter (Metrohm Hersau E 520) (IITA,1978). This measurement was achieved by mixing 10 g of air-dried soil sample with 25 ml of distilled water mixed in a cap bottle and occasionally stirred for 30 minutes. Then, the glass electrode of the pH meter was immersed into the partly settled soil suspension to measure the pH and expressed as pH in 1:2.5 soil-water suspension.

The soil organic carbon was determined by chromic acid digestion (Heanes, 1984). A 100 ml graduated pyrex test tube measuring 200 mm by 30 mm was filled with air-dried soil (particle size < 0.15 mm). Next, 10.0 ml of N potassium dichromate ($K_2Cr_2O_7$) was added to the soil and carefully stirred while 20 ml of concentrated 98% sulfuric acid (H_2SO_4) was added gradually to prevent the soil and chromic acid from being lost due to localized boiling. The test tube containing the samples was put into a hole in the aluminum block hot plate digester at 135 °C after the mixture had been stirred for an additional 30 seconds.

The hot plate digester was removed after 30 minutes and let to cool. Distilled water was then added to top off the solution to the test tube's 50 ml mark, and it was swirled with a wash bottle. The sample solution was further topped up to 100 ml by adding distilled water to further mix the contents and dissipate the heat of dilution. The content was later allowed to cool to room temperature, and the final volume was adjusted to 100 ml with dH_2O, sealed with a rubber bung and inverted several times to mix the contents. This process was repeated for working standards and a blank solution. Then the soil suspension was left to settle before the supernatant liquor was added to a 15 ml centrifuge tube graduated at 10 ml and centrifuged for 15 minutes at 3 000 rpm. All supernatants had their absorbance measured at 600 nm, and a graph relating absorbance to the amount of organic carbon (mg) present was created. The amount of organic carbon (mg) which was equivalent to the absorbances of the sample and blank determinations was interpolated from the standard curve.

The total nitrogen was determined by *Kjeldahl* digestion and colorimetric determination on a Technicon AAII autoanalyzer (Bremmer, 1982). The soil was air-dried, sieved through 0.5 mm sieve. Approximately 5-10 g of soil sample was placed in a dry 500 ml macro-*Kjeldahl* flask, and 20 ml of distilled water was added to dissolve the soil contents. The flask was swirled for a few minutes after which it was left to stand for 30 minutes. One tablet of mercury catalyst and 10 g of potassium sulfate (K_2S0_4) were added to the mix, then 30 ml of conc. H_2SO_4 also through an automatic pipet. The flask was carefully put on low heat digestion stand, and when the water had drained and foaming had ceased, the heat was gradually increased until the digest was clear. The mixture was heated for 5 hours, and the heat was constantly adjusted during this process such that the H_2SO_4 could condense about half the way up the neck of the flask. After allowing the flask to cool, 100ml of water was slowly added into the flask. Because sand causes severe bumping during *Kjeldahl* distillation, the digest was carefully transferred into a second, clean macro-*Kjeldahl* flask (750 ml) while keeping all sand particles in the first digestion flask. The sand residue was rinsed four times with 50 ml of distilled water, and the aliquot was then transferred to the same flask. Approximately 50 ml boric acid (H_3BO_3) indicator solution was added into a 500 ml Erlenmeyer flask, placed under the distillation apparatus condenser. The 750 ml *Kjeldahl* flask was attached to the distillation apparatus and 150 ml of 10N sodium hydroxide (NaOH) added into the flask and the distillation process initiated. The distillation process stopped after 150 ml distillate had been collected, and the ammonium (NH_4-N) was estimated by titrating with 0.01N standard HCl using a 25 ml burette graded at 0.1 ml intervals and the N content in soil was then calculated.

Available phosphorous was determined by the Olsen method (Olsen *et al.,* 1954). To achieve this, a 125 ml Erlenmeyer flask was filled with roughly 2 g of soil, 1 teaspoon of carbon black, and 40 ml of the extracting solution. Then the flask was mechanically shaken for 30 minutes and the suspension was filtered using the Whatman No.40 filter paper. The flask was shaken again immediately before pouring the suspension into the funnel. Then the solution was stored for P determination using the colorimetric method.

Exchangeable K and Mg were measured by Mehlich-3 extraction (Jackson,1958). This analysis required the addition of 30 ml ammonium acetate (NH_4OAC) to 5 g of soil sample and the mixture mixed on a mechanical shaker for two hours. The mixture was centrifuged at 2,000 r.p.m for 5-10 minutes, and the clear supernatant carefully decanted into a 100 ml volumetric flask. Another 30 ml of NH_4OAC solution was added to the supernatant and mixed for 30 minutes, centrifuged and the supernatant was transferred into the same volumetric flask. This step was repeated once more and the supernatant transferred again into the same volumetric flask. The K was determined on a flame photometer and Mg on an atomic absorption spectrometer.

The soil particle size distribution analysis was determined by the hydrometer method (Bouyoucos,1951). Following this method, 51.0 g of air-dry soil passed through a 2mm sieve was transferred to a "milkshake" mix cup. Approximately 50 ml of 5.0% sodium hexametaphosphate $[(NaPO_3)_6]$ along with 100 ml of distilled water were added to the soil, mixed using a rod and left to set for 30 minutes. Then the soil suspension was stirred for 15 minutes with a multimix machine, and the suspension transferred from the cup to a glass cylinder. With the hydrometer in the suspension, dH_2O was added to 1130 ml to match the lower blue line, then the hydrometer removed. This process was followed by covering the top of the cylinder with a hand and inverted several times until all soil dissolved. The suspension in the cylinder was placed on a flat surface and the time noted. Then the hydrometer was immediately placed into the suspension by slowly sliding it until it floated. The first reading on the hydrometer was taken at 40 seconds (H1) after the cylinder had set down and the temperature of the suspension recorded with a thermometer (T1). The second reading (H2) along with the temperature (T2) of the suspension was taken after 3 hours. Then the percentages by weight were determined as follows:

Sand (%) = 100.0- [H1+0.2 (T1-68) -0.2.0] 2

Clay (%) = [H2+0.2 (T2-68) -0.2] 2

Silt (%) = 100.0 - (% sand + % silt)

Results of the soil physical and chemical properties of the study sites summarized in Table 2 revealed that the soil texture in both cropping seasons was sandy loamy, following the USDA soil classification (USDA, 1987). The sand content of the soil for the top 20 cm profile indicates that the sites had loose, well-drained soils which gave roots enough space to expand. The soil pH level (6.63 in the topsoil and 6.43 in the subsoil in the first cropping season) and (6.09 in the topsoil and 6.04 in the subsoil in the second cropping season) was within the acceptable range for optimum cassava growth (Howeler, 2012). However, the soils had low inherent fertility with relatively low organic carbon (OC), total nitrogen (TN), available P, exchangeable K and Mg which required additional fertilizer input for optimum yield (Table 2).

Table 2: Soil texture and chemical properties at two depths for Westbank site in the first and second cropping seasons

Year	**2019**		**2020**	
Depth	0-20 cm	20-50 cm	0-20 cm	20-50 cm
pH (H_20) 1:2.5	6.73	6.57	6.09	6.04
Org. C (%)	0.80	0.53	0.49	0.38
Total N (%)	0.08	0.05	0.04	0.03
Avail. P (mg kg^{-1})	1.55	1.23	2.05	1.54
Exch. K (cmol [+] kg^{-1})	0.30	0.28	0.10	0.14
Exch. Mg (cmol [+] kg^{-1})	0.22	0.24	0.28	0.32
Sand (g kg^{-1})	68.13	55.80	78.50	72.00
Silt (g kg^{-1})	9.60	9.27	5.90	6.90
Clay (g kg^{-1})	22.27	34.93	15.60	21.10

Note: mg Kg_{-}^{-1}= Milligrams per Kilogram; cmol/kg= centimoles per kilogram.

3.3 Cassava variety

The test crop used in this experiment was the cassava variety TME 419, locally known as "*Idileruwa*", an improved variety developed by the IITA cassava breeding team (Owoseni *et al.,* 2021). TME419 is highly tolerant to the cassava mosaic disease, high yielding, has a poor branching architecture, a minimal tendency to flower and bulks early and quickly (Aiyelari *et al.,* 2019; Enesi *et al.,* 2021). These properties make it popular and a variety of choice for Nigerian farmers because it can be harvested early and has low labour demand since it does not lodge.

3.4 Experimental Procedure

The fields were cleared of grass and weeds before cassava planting. Both sites were disc-ploughed to a depth of roughly 30cm furrow slice and harrowed then ridged at 1 m distance by a tractor. Field experiments were set up in a randomized complete block design (RCBD) using eight fertilizer treatments (Table 3) in 3 replicates for 2 consecutive cropping seasons. This design was used to control the fertility gradient of the sites so that any observed differences would be solely due to actual differences between treatments. A fresh field within the same land (same land history) was used every cropping season so as to maintain the same fertilizer treatments, given that this study only assessed the primary effect and not the residual effect of fertilization.

The experimental unit measured 7m × 5.6 m containing 49 plants, of which the inner 25 plants (5m x 4.5m) were used for growth evaluations and the final harvest. Planting stakes (stem cuttings) measuring around 25 cm in length were planted at 0.8 m intervals along the crest of the ridges by inserting the stakes to approximately two-thirds of their length at an angle of 45-60° relative to the soil surface. Hence, the plots had a rectangular planting pattern at 1 m × 0.8 m which translates into a plant density of 12,500 plants ha^{-1}.

Fertilizer treatments were composed of 75 kg N ha^{-1} from urea and NPK; and 20 kg P ha^{-1} from NPK which were applied uniformly to all plots except the control (Table 3).

The K rates were at 2 levels (90 and 180 kg ha^{-1}) applied alone as KCl giving the F1 and F2 treatment codes, while their combination with Magnesium (15.5 Mg-20.5S kg ha^{-1}) gave the treatments F_1+Mg_1 and F2+Mg1, respectively (Table 3). The Mg rate was also applied alone as 0K-15.5Mg-20.5S kg ha^{-1} denoted as F0+Mg1. Because the Mg fertilizer used was Kieserite which has large amounts of S, the treatments comprised two N, P, K levels in which no Mg was applied and the K was partially applied at K_2SO_4 to supply the same amount of S as was received with the $MgSO_4$. The 20.5 S kg ha^{-1} sourced from K_2SO_4 was combined with KCl to an equivalent amount of 90K:20.5S and 180K:20.5S which gave rise to the F1-Mg+S and F2-Mg+S treatments, respectively as shown in Table 3. Fertilizer application was by banding at 10 cm away from the planting line, in a 5 cm deep furrow, then covered with soil. Table 4 shows the schedule of fertilizer application and the formulation applied.

Table 3: Fertilizer treatments combination in kg ha^{-1}

Fertilizer treatments		**N**	**P**	**K**	**Mg**	**S**
1	F0 (control)	0	0	0	0.0	0.0
2	F0+Mg1	0	0	0	15.5	20.5
3	F1	75	20	90	0.0	0.0
4	F2	75	20	180	0.0	0.0
5	F1+Mg1	75	20	90	15.5	20.5
6	F2+Mg1	75	20	180	15.5	20.5
7	F1-Mg+S	75	20	90	0.0	20.5
8	F2-Mg+S	75	20	180	0.0	20.5

Table 4: Fertilizer application schedule

	Fertilizer combination (grams per plot)				
Code	**4WAP**	**8WAP**	**12WAP**	**14WAP**	**16WAP**
F0	0	0	0	0	0
F0+Mg1	0	308 MgSO4	308 MgSO4	0	0
F1	588 NPK	588 NPK, 256Urea	392 KCl	0	0
F1-Mg+S	588 NPK	588 NPK, 256Urea	446 K2SO4, 15KCl	0	0
F1+Mg1	588 NPK	588 NPK, 256Urea, 308MgSO4	308 MgSO4, 392KCl	0	0
F2	588 NPK	588 NPK, 256Urea	366 KCl	366 KCl	366 KCl
F2-Mg+S	588 NPK	588 NPK, 256Urea	446 K2SO4	361 KCl	361KCl
F2+Mg1	588 NPK	588 NPK, 256Urea, 308MgSO4	308 MgSO4, 366KCl	366 KCl	366 KCl

There was no phytosanitary control in both cropping seasons as no incidence of pests and diseases attack was recorded; hence the responses to fertilizer are not confounded by pest and disease stress. For an homogenous stand, cassava stakes that did not sprout were replaced at 4 WAP and weeding using hand hoes was regularly done when deemed required.

3.4 Data Collection

The number of stems per plant and stem height of all standing plants in the net plot were evaluated at 8 months after planting (MAP). Stem height was measured from the base of the plant to the tip of the newly developed leaf using a tape measure (cm). At 12MAP, a count of all standing plants in the net plot and their main stems that emerge from the planting stake was done. Then from each plot, the total fresh weight of the leaves was recorded from which a subsample of about 700-gram fresh was used to determine dry matter (DM). Further, the fresh weight of the main stems broken off the emergence point on the planting stake was determined from a sample of all plants from each plot. Then three stems that reflected the dominant stem diameter and length were selected, cut into small pieces of 20 -30 cm length from the base, the middle and the top. About 700-gram of stem pieces were subsampled for DM determination. The remaining planting stakes were weighed and discarded.

The storage roots in the net plot were cleaned of soil and sorted into marketable storage roots (sufficiently large and of good quality) and non-marketable storage roots (small or poor quality). Then, a count of the good storage roots was done separately, and the total fresh mass was recorded. Three good roots were selected from each plot, cut into roughly 1 cm thick discs from the top, middle and tip end of the root, then mixed. A subsample of

500-700gram from the root mix was taken for DM determination. Subsamples collected for DM determination were later oven-dried to constant weight at 80°C in an oven for about 72 hours. The number of marketable (good) tubers per plant was calculated as the ratio of the number of good roots to the number of standing plants in a plot.

Fresh and dry storage root yields were determined since fresh storage root yield is the most important information for traditional trading and domestic purposes such as cooking, while the dry matter in the marketable roots is the component of interest for commercial cassava producers and processors. Hence, the yield per hectare and dry matter (DM) content were determined as described by Misganaw & Bayou (2020) using the following equation below:

$$\mathbf{Y} = \frac{\mathbf{yp\ x\ 10{,}000\ m2}}{\mathbf{A\ x\ 1000}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{1}$$

Where Y = fresh yield per hectare in tonnes per hectare, yp= yield per plot, A=area per plot.

$$\mathbf{PDM} = \frac{dw}{Fw} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{2}$$

Where PDM= proportion of dry matter in the fresh yield, dw= dry weight, and fw= fresh weight

Dry matter yield in tonnes per hectare = **1 x 2**

The root: shoot ratio (R:S) = $\frac{W+Y}{AG}$

Where W= dry mass good roots t ha^{-1}*, Y= dry mass bad roots t ha*$^{-1}$*, and AG= dry mass total above ground t ha*$^{-1}$

Harvest index= $\frac{W}{AG}$

Where W= dry mass good roots t ha^{-1}*, and AG= dry mass total above ground t ha*$^{-1}$

3.6 Statistical analysis

Data on stem number, stem height, leaf mass, stem mass, total above-ground mass, number of roots and storage root mass were tested for normality using the *Shapiro–Wilk's* test (Shapiro & Wilk, 1965) applying the following formula:

$$\boldsymbol{w} = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation)}$$

where, $X(i)$ = are the ordered random sample values; Xi = smallest unit sample; ai = constants generated from the means, variance and covariance of the statistic sample of size n from a normal distribution.

Data was log-transformed in order to meet assumptions of ANOVA and statistically analyzed according to the procedure for a randomized complete block design using the following statistical model:

$$\boldsymbol{Y_{jkl} = \mu + S_i + \beta_j + F_k + SF_{jk} ++ \varepsilon_{ijkl}}$$

Where μ = Overall mean, Si= effects due to ith cropping season. β_j= effects due to jth replicate, F_k= effects due to kth fertilizer in jth replicate, SF_{ik}= interaction effect between ith season and kth fertilizer and $\varepsilon ijkl$ = Random component error.

Fertilizer treatment level was the first factor and cropping season the second factor. The linear mixed-effects model with the *lmer* function was used to assess the effect of fertilizer treatments and cropping season on vegetative and root yield. Statistically significant means were separated using Fisher's least significant difference (LSD) test at $p \leq 0.05$ using the following formula:

LSD 0.05=$\sqrt{\frac{2EMS}{r}}$. Where EMS =variance, r = number of replicates.

Furthermore, Pearson correlation analysis was done to determine the relationship between the vegetative yield and root yield using the pairs. Panel function of psych package. All statistical analyses were done using R software 4.1.2 version (R Core Team, 2022).

CHAPTER FOUR

RESULTS

4.1 Vegetative yield of cassava grown with different fertilizer treatments and cropping season

4.1.1 Analysis of variance for vegetative growth and yield

The vegetative parameters including stem height, stem number per plant, fresh and dry stem yield, fresh and dry leaf yield, fresh and dry total aboveground yield of cassava variety TME 419 did not differ significantly ($p > 0.05$) due to fertilizer treatments (Table 5). The interaction between fertilizer treatments and cropping season was also not significant for the vegetative traits. However, except the dry total aboveground yield, all other vegetative traits differed significantly due to the seasonal effect ($p < 0.05$).

Table 5: Analysis of variance of the vegetative characteristics of cassava variety TME 419 grown in different fertilizer treatments across two cropping seasons

Characters	**Mean squares Errors**				
	Replicate	Fertilizer	Season	Fertilizer x season	Error
Degree of freedom	2	7	1	7	32
Stem height		1852.2^{NS}	12976.3*	1251.9^{NS}	1136.4
Stem number		0.03^{NS}	0.38*	0.07^{NS}	0.89
Fresh stem		30.35^{NS}	102.14*	21.29^{NS}	17.26
Stem DM		2.28^{NS}	31.50*	2.21^{NS}	1.42
Fresh leaves		5.40^{NS}	752.6*	4.34^{NS}	6.03
Leaves DM		0.26^{NS}	30.06*	0.18^{NS}	0.30
Fresh total aboveground		51.18^{NS}	600.86*	36.54^{NS}	44.91
Total aboveground DM		3.19^{NS}	0.99^{NS}	3.98^{NS}	3.14

*NB: df = degree of freedom, F = Fertilizer treatment, C= cropping season, FT*C = interaction between fertilizer treatment and cropping season. *=Significant at p<0.05, NS=non-significant at p>0.05*

4.1.2 Effect of fertilizer treatment on stem height and number of stems per plant

The longest stems (237.79 cm) were observed on cassava plants fertilized with F_1-Mg+S (90K:20.5 S kg ha-^{1}) which was an increase of 13.58% over the control. Cassava plants fertilized with F_0+Mg_1 (0K:15.5Mg:20.5S kg ha-^{1}) had the shortest stems of 194.16 cm, thereby decreasing the stem height by 7.26%. Similarly, F_1 (90K kg ha-^{1}) and F_2 (180K kg ha-^{1}) increased stem height by 10.21% and 7.29%, respectively, compared with the control. Likewise, a 11.19%, 5.98% and 4.76% increment on stem height over the control was observed on cassava plants fertilized with F_2+Mg_1 (80 K:15.5 Mg:20.5 S kg ha-^{1}), F_2-Mg+S (180K:20.5S kg ha-^{1}) and F_1+Mg_1 (90K:15.5Mg:20.5S kg ha-^{1}), respectively (Figure 4). The average number of stems per plant at 8MAP was 2 at all fertilizer treatment levels.

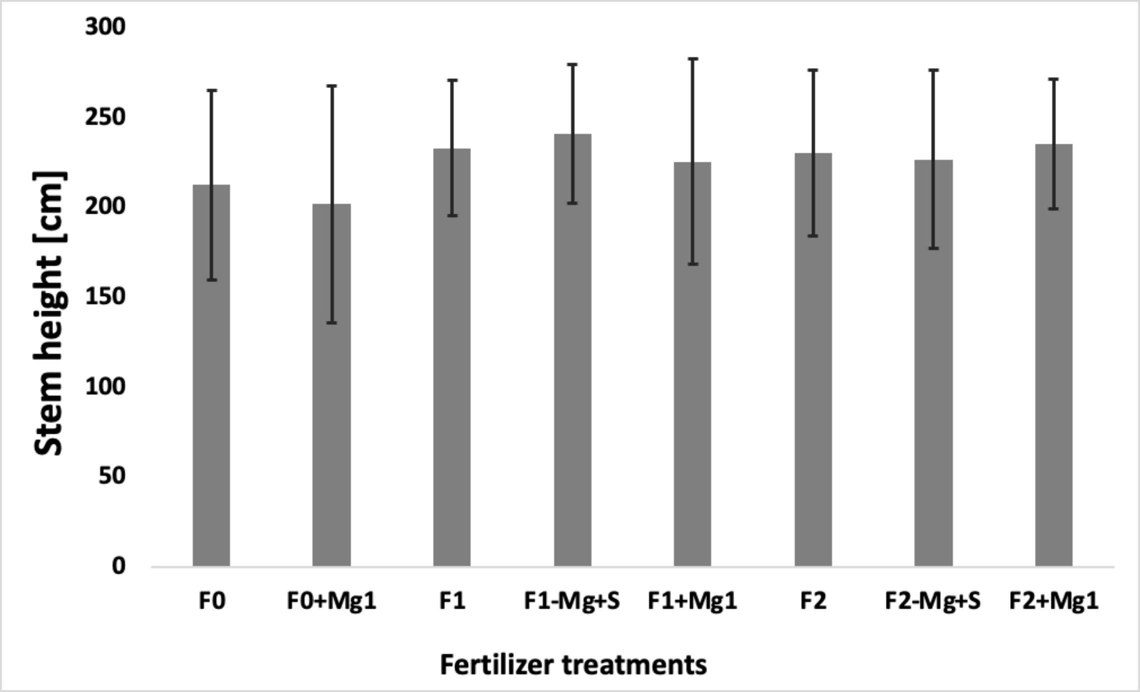

Figure 4: Stem height of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

4.1.3 Effect of fertilizer treatment on fresh and dry stem yield

Effects of F_1-Mg+S (90 K:20.5S kg ha^{-1}) on cassava increased the highest fresh stem yield of 30.2% followed by F_2+Mg_1(180 K:15.5Mg:20.5S kg ha^{-1}), F_2 (180K kg ha^{-1}), F_2-Mg+S (180K:20.5S kg ha^{-1}), F_1(90K kg ha^{-1}), and F_1+Mg_1(90K:15.5Mg:20.5S kg ha^{-1}) with 23.4, 23.1, 8.7,6.7 and 6.4 %, respectively. Cassava plants fertilized with F_0+Mg_1 containing 0K:15.5 Mg:20.5S kg ha^{-1} showed a decline in fresh stem yield by 20.9% compared with the control (Figure 5).

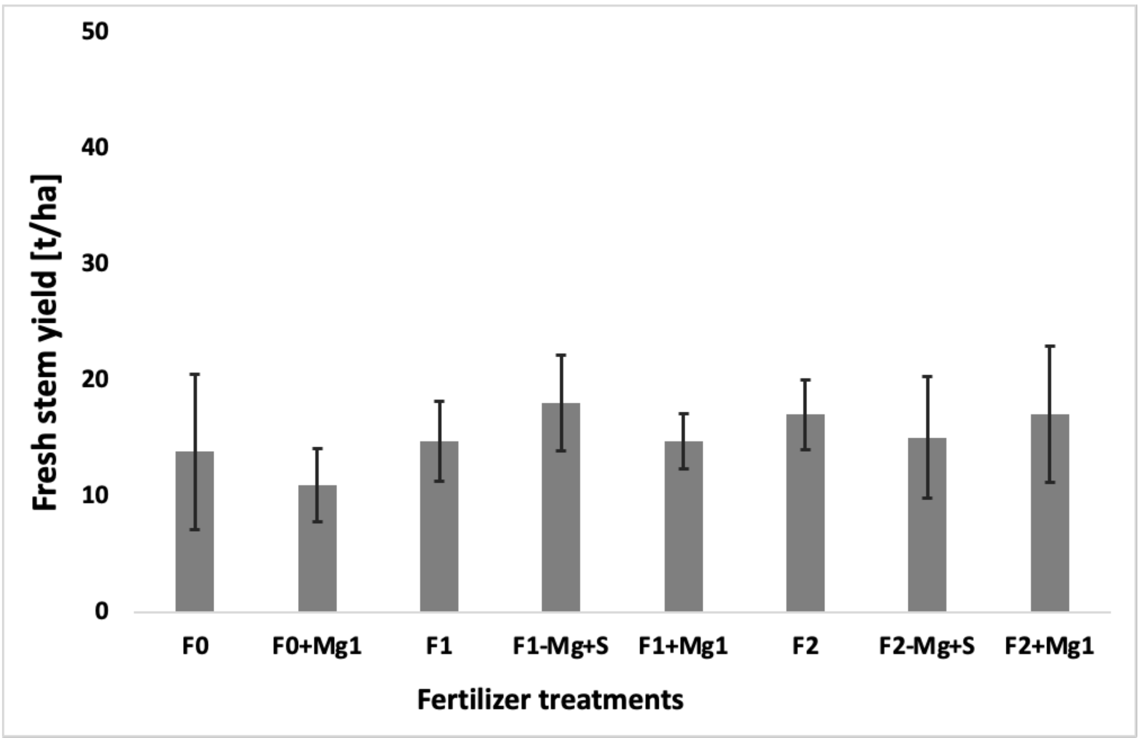

Figure 5: Fresh stem yield of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

Similarly, stem DM yield of cassava variety TME 419 increased by 24.6% over the control when supplied with F_1-Mg+S containing 90K:20.5S kg ha^{-1}. An increase of 20.2, 17.5, 10 and 3.1% over the control was observed in cassava plants fertilized with F_2 (180K kg ha^{-1}), F_2+Mg_1 (180K:15.5Mg:20.5S kg ha^{-1}), F_2-Mg+S (180K:20.5S kg ha^{-1}), and F_1+Mg_1 (90K:15.5Mg:20.5S kg ha$_{-1}$), respectively (Figure 6). Treatments F_1 (90K kg ha^{-1}) and F_0+Mg_1 (0K:15.5Mg:20.5S kg ha^{-1}) registered a decline of 0.9% and 20.8%, respectively compared with the control (Figure 6).

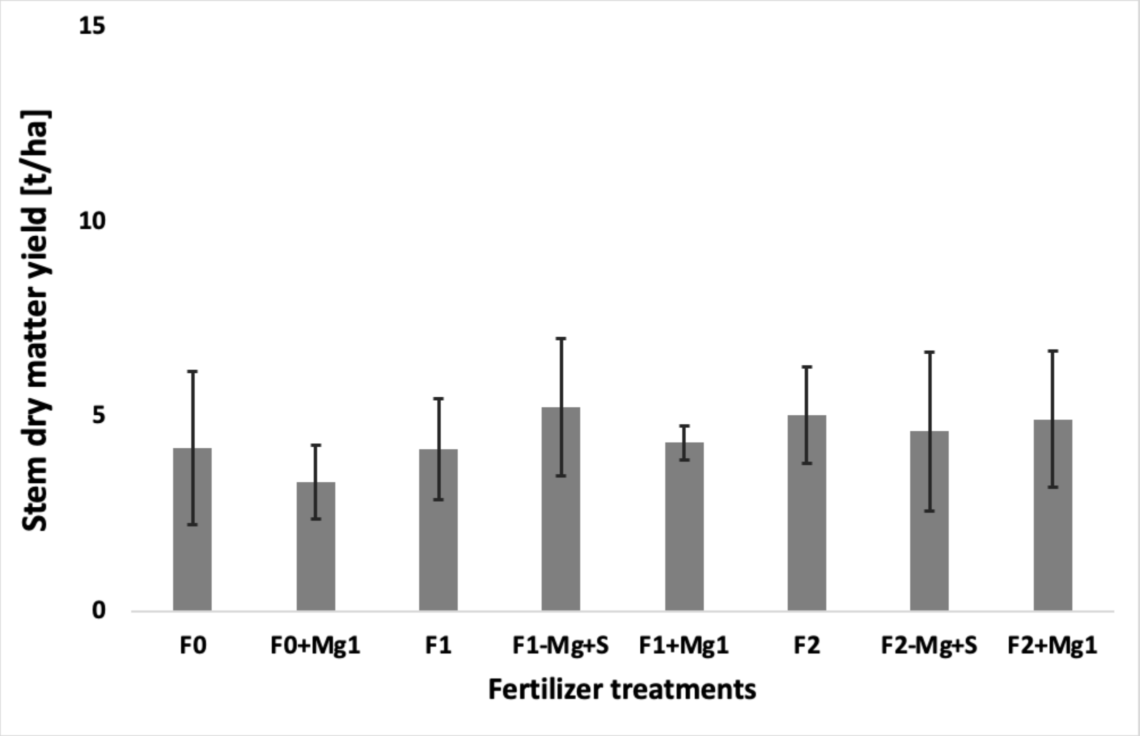

Figure 6: Stem dry matter yield of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

4.1.4 Effect of fertilizer treatments on fresh and dry leaves yield

Fresh leaves yield increment by 9.9% was found upon fertilization with 180K:15.5Mg:20.5S kg ha^{-1} (F_2+Mg_1), while a 1.9% and 0.8% increase was observed on cassava plants fertilized with 0K:15.5Mg:20.5S (F_0+Mg_1) and 90K:20.5S (F_1-Mg+S) respectively compared with the control. Treatments receiving 90K (F_1), 90K:15.5Mg:20.5S (F_1+Mg_1), 180K (F_2) and 180K:20.5S (F_2-Mg+S) reduced the fresh leaf yield by 4.2%, 12.3%, 2.48% and 19.45 %, respectively (Figure 7), compared with the control.

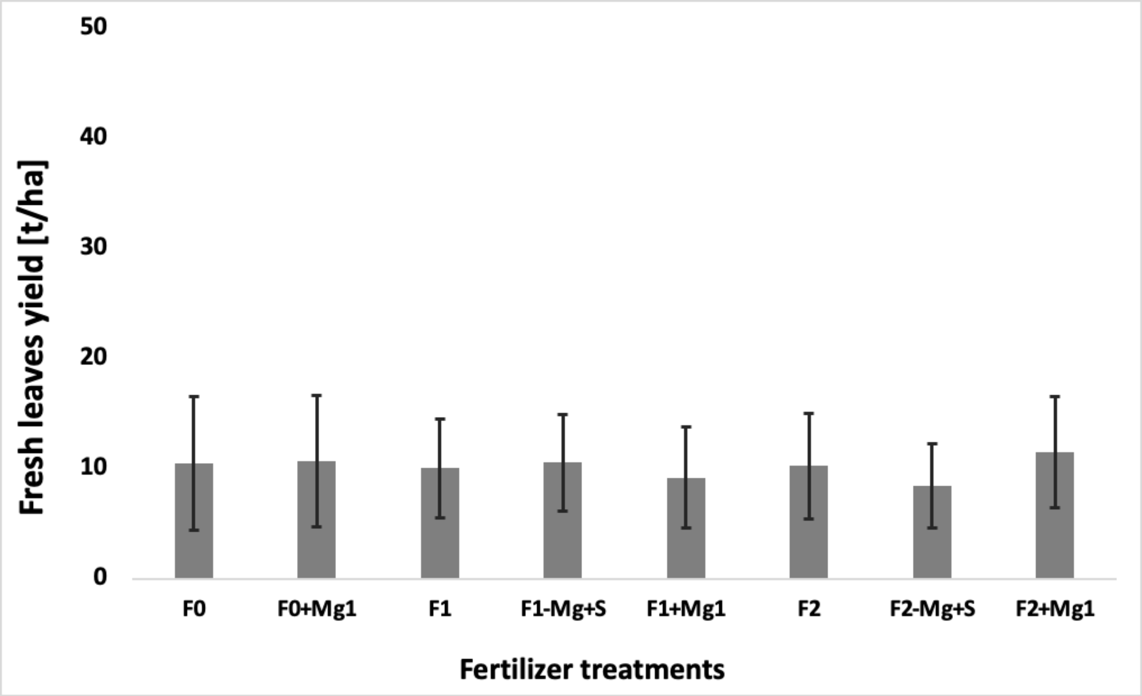

Figure 7: Fresh leaves yield of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

Similarly, leaves DM yield increased by 11.4%, 4.4%, 5.1% and 16.1% with 0K:15.5Mg:20.5S (F_0+Mg_1), 90K:20.5S (F_1-Mg+S), 180K (F_2) and 180K:15.5Mg:20.5S (F_2+Mg_1) respectively, over the control. On the other hand, a decrease of leaves DM yield by 2.2 %, 8.4% and 12.5 % was detected on cassava that received 90K (F_1), 90K:15.5Mg:20.5S (F_1+Mg_1) and 180K:20.5S (F_2-Mg+S), respectively (Figure 8) compared with the control.

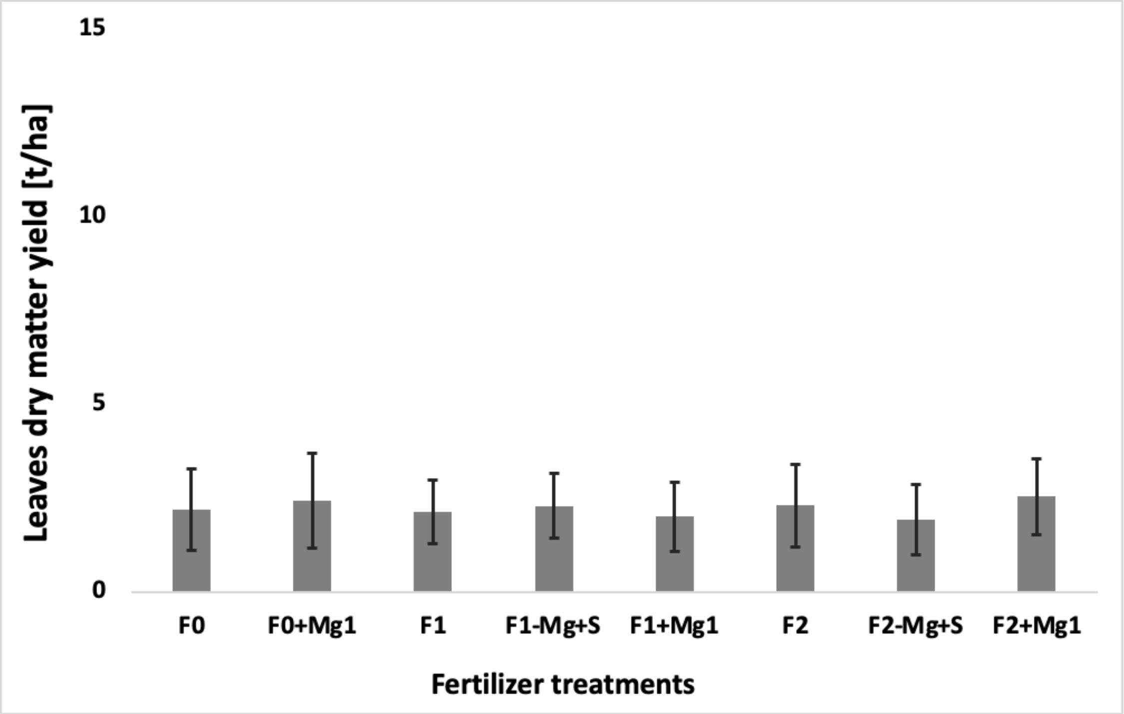

Figure 8: Leaves dry matter yield of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

4.1.5 Effect of fertilizer treatments on the fresh and dry total aboveground yield

Overall, the fresh total aboveground yield increased over the control by 16.5%, 15.2%, 11.9% and 2.67% with treatments composed of 180K:15.5Mg:20.5S (F_2+Mg_1), 90K:20.5S (F_1-Mg+S), 180K (F_2), and 90K (F_1), respectively. Treatments receiving 180K:20.5S (F_2-Mg+S), 90K:15.5Mg:20.5S (F_1+Mg_1) and 0K:15.5Mg:20.5S (F_0+Mg_1) decreased the fresh total aboveground by 4.6%, 2.2% and 10.5% respectively (Figure 9), compared with the control.

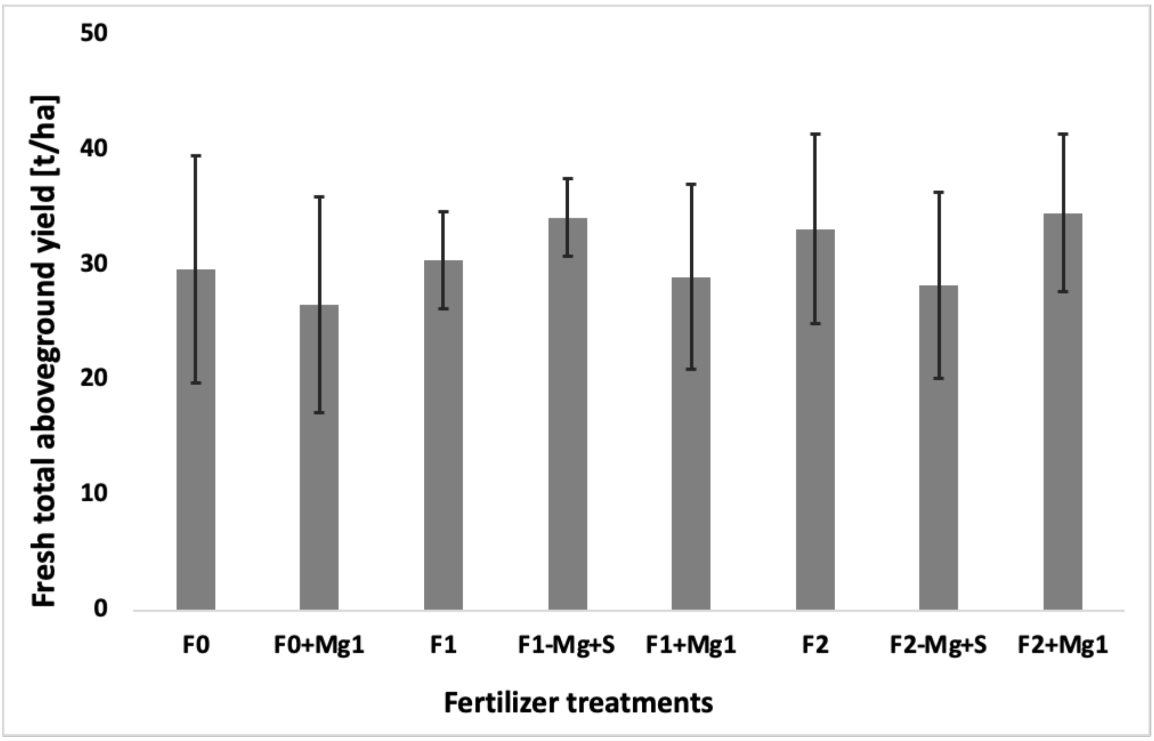

Figure 9: Fresh total above ground of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

The total above-ground dry matter yield of cassava variety TME 419 increased over the control by 15, 13.8 and 13.8% on the plots that were amended with F_2+Mg_1 (180K:15.5Mg:20.5S), F_1-Mg+S (90K:20.5S) and F_2 (180K), respectively. A slight decline of 0.2%, 1.4%, 2.2% and 9.4% was recorded with treatments combination of 180K:20.5S (F_2-Mg+S), 90K (F_1), 90K:15.5Mg:20.5S (F_1+Mg) and 0K:15.5Mg:20.5S (F_0+Mg_1), respectively (Figure 10) compared to the control.

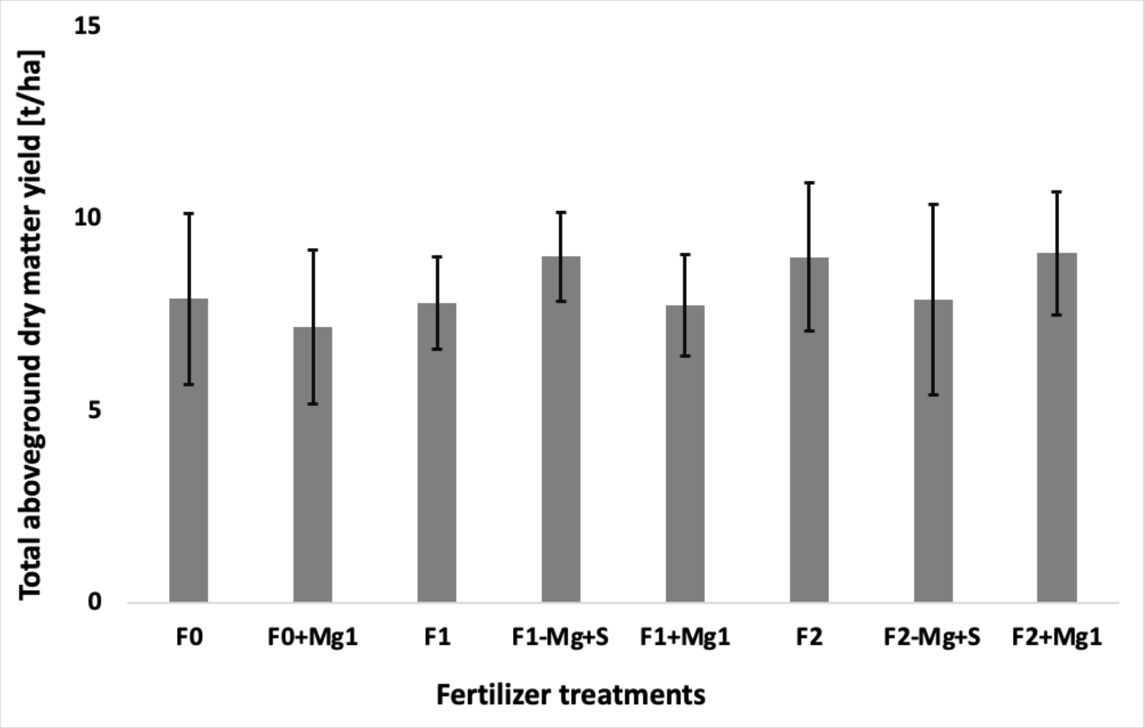

Figure 10: Dry total above ground of cassava variety TME 419 as affected by the application of different fertilizer treatments. Error bars are SE of the means

4.1.6 Mean effect of fixed factor cropping season on cassava vegetative yield

Vegetative yield response to fertilizer treatment was highly variable between the two cropping seasons (Table 6). Cassava stem height at 8MAP was found to be significantly ($p < 0.05$) higher in the first season than in the second, with a 15.9% difference between the two cropping seasons. The first cropping season had on average longer stem (245cm) than the second cropping season (188cm) at 8MAP. Stem height at 8 MAP was taller in all fertilized plots than in the control in the first cropping season, while in the second season amendment of soil with F_0+Mg_1 (0K:15.5Mg:20.5S) resulted in the shortest stem. Cassava that received F_2 (180K kg ha^{-1}) grew the highest attaining 266.5cm, followed by F_1+Mg_1 (90K:15.5Mg:20.5S) with 263.8 cm and F_1-Mg+S (90K:20.5S) with the height of 261.8cm in the first season (Table 6). On the other hand, the stems from cassava that were fertilized with F_1-Mg+S (90K:20.5S) grew the highest to the height of 213.8 cm followed by F_1 (90K) with 212.7cm and F_2+Mg_1 (180K:15.5Mg:20.5S) with 212.1cm, in the second season (Table 6).

For the control, the difference between the two cropping seasons was 7.2%, while a difference of 43.2% was observed on cassava supplied with 0K:15.5Mg:20.5S kg ha^{-1} (F_0+Mg_1). Similarly, for stems fertilized with 90 and 180 K Kg ha^{-1} (F_1 and F_2), a difference of 8.8% and 28.8% was recorded between the two cropping seasons, while a 7.5% and 12.2% difference was observed for stems receiving 90k:20.5S kg ha^{-1} (F_1-Mg+S) and 180K-20.5S kg ha^{-1} (F_2-Mg+S) respectively. Likewise, the combination of Mg at 90K:15.5Mg:20.5S (F_1+Mg_1) and 180K:15.5Mg:20.5S kg ha^{-1} (F_2+Mg_1) gave a difference of 7.5% and 1.4% respectively, between the two cropping seasons (Table 6). Further, in both cropping seasons, each plant had on average two stems at 8MAP, regardless of the fertilizer treatment applied.

Overall, the second cropping season outyielded the first on fresh and dry stem yield, while the first cropping season had more fresh and dry leaves which contributed to its high fresh and dry aboveground yield (Table 6). A difference of 19.11% and 35.89% in fresh and dry stem yield, respectively, was found between the two cropping seasons. The two cropping seasons recorded a difference of 78.03% in fresh leaf yield and 71.17% in leaves DM yield. The fresh total aboveground yield difference between the two cropping seasons was 23.07%, and the difference in total above-ground DM yield was 3.41%.

Treatments F_2 (180K), F_1+Mg_1 (90K:15.5Mg:20.5S) and F_1-Mg+S (90K:20.5S) produced the highest fresh stem yield of 17 t/ha, 15.02 t/ha, 14.67 t/ha, respectively in the first cropping season. These treatments also exhibited the highest stem dry matter yield (DM) of 4.62 tonnes/ha, 4.12 t/ha and 3.73 t/ha, respectively, in the same cropping season. The highest fresh leaf (15.92 t/ha) and dry leaf yield (3.57 t/ha) in the first season was observed on plants fertilized with F_0+Mg_1 (0K:15.5Mg:20.5S), followed by F_2+Mg_1 (180K:15.5Mg:20.5S) with 15.72 t/ha fresh leaf and 3.34 t/ha dry leaf yield. Similarly, the supply of F_2 (180K) resulted in the highest total aboveground fresh (38.23 t/ha) and dry yield (9.72 t/ha), followed by F_2+Mg_1 with 36.11 t/ha fresh and 8.76t/ha dry total aboveground yield (Table 6).

In the second season, the highest fresh stem (21.47 t/ha) and dry stem yield (6.75t/ha) were observed in treatments F_1-Mg+S (90K:20.5S), followed by F_2+Mg_1 (180K:15.5Mg:20.5S) with 20.48 t/ha fresh, 6.21 t/ha dry. Cassava plants fertilized with F_2+Mg_1 had the highest fresh leaf yield (7.28 t/ha) and leaf dry yield (1.73 t/ha), followed by F_1-Mg+S (90K:20.5S) with 6.75 t/ha fresh leaf and 1.55 t/ha dry leaf yield in the second cropping season. The highest fresh total aboveground (32.79 t/ha) and dry total aboveground (9.48 t/ha) were recorded with F_2+Mg_1 (180K:15.5Mg:20.5S) in the same cropping season (Table 6).

Table 6: Mean values of vegetative attributes of cassava variety TME 419 as affected by application of different fertilizer treatments during two cropping seasons

Vegetative yield variables (t/ha)

First cropping season

Treatments	Stem height (cm)	Stem No	Fresh stem	Stem DM	Fresh leaves	Leaf DM	Fresh TAG	TAG DM
F0	233.25 ± 18.79	2.0 ±0.4 a	11.04 ± 1.89 b	2.99 ± 0.44 a	15.24 ± 4.15 ab	2.99 ± 0.77 a	32.31 ± 7.09 a	7.61 ± 1.60 a
F0+Mg1	250.00 ± 39.42	2.0 ±0.5 a	12.71 ± 3.80 ab	3.53 ± 1.30 a	15.92 ± 1.98 a	3.57 ± 0.001 a	34.80 ± 2.08 a	8.80 ± 1.40 a
F1	248.75 ± 37.53	2.0 ±0.5 a	12.79 ± 1.85 ab	3.39 ± 0.79 a	13.93 ± 1.53 ab	2.82 ± 0.49 a	33.30 ± 3.08 a	7.95 ± 1.34 a
F1-Mg+S	261.75 ± 23.84	1.9 ±0.5 a	14.67 ± 2.36 ab	3.73 ± 0.92 a	14.39 ± 0.85 ab	3.01 ± 0.27 a	35.61 ± 2.97 a	8.39 ± 1.33 a
F1+Mg1	263.75 ± 36.54	2.3 ±0.3 a	15.02 ± 2.89 ab	4.12 ± 0.52 a	12.68 ± 3.67 ab	2.67 ± 0.78 a	33.92 ± 8.18 a	8.49 ± 1.61 a
F2	266.50 ± 13.99	1.9 ±0.3 a	17.00 ± 4.67 a	4.62 ± 1.61 a	14.10 ± 3.51 ab	3.20 ± 0.73 a	38.23 ± 9.30 a	9.72 ± 2.41 a
F2-Mg+S	256.75 ± 39.66	2.0 ±0.2 a	13.11 ± 4.35 ab	3.37 ± 1.27 a	10.84 ± 3.96 b	2.49 ± 1.02 a	29.17 ± 9.05 a	7.19 ± 2.59 a
F2+Mg1	253.50 ± 9.57	2.0 ±0.2 a	13.77 ± 2.75 ab	3.67 ± 0.68 a	15.79 ± 1.67 ab	3.34 ± 0.52 a	36.11 ± 177 a	8.76 ± 0.99 a
	245.79 ± 24.26	**2.0 ±0.4**	**13.77 ± 3.20**	**3.68 ± 0.97**	**14.11 ± 2.93**	**3.01 ± 0.64**	**34.18 ± 5.82**	**8.36 ± 1.63**

Second cropping season

Treatments	Stem height (cm)	Stem No	Fresh stem	Stem DM	Fresh leaves	Leaf DM	Fresh TAG	TAG DM
F0	185.48 ± 75.94	2.0 ±0.3 a	16.71 ± 9.17 ab	5.42 ± 2.25 ab	5.74 ± 2.57 a	1.38 ± 0.59 a	26.82 ± 13.06 ab	8.24 ± 3.09 ab
F0+Mg1	138.32 ± 2.39	2.3 ±0.3 a	9.25 ± 1.36 b	3.13 ± 0.65 b	5.45 ± 1.63 a	1.30 ± 0.37 a	18.16 ± 2.65 b	5.57 ± 0.54 b
F1	212.72 ± 32.19	2.3 ±0.0 a	16.82 ± 3.77 ab	4.94 ± 1.33 ab	6.17 ± 1.53 a	1.45 ± 0.37 a	27.41 ± 3.06 ab	7.69 ± 1.32 ab
F1-Mg+S	213.84 ± 40.38	2.3 ±0.1 a	21.47 ± 1.70 a	6.75 ± 0.29 a	6.75 ± 2.00 a	1.55 ± 0.43 a	32.52 ± 10.26 a	9.67 ± 0.68 a
F1+Mg1	174.92 ± 31.86	2.1 ±0.1 a	14.51 ± 2.28 ab	4.55 ± 0.24 ab	5.72 ± 1.42 a	1.32 ± 0.36 a	23.93 ± 4.35 ab	7.02 ± 0.45 ab
F2	182.74 ± 8.41	2.2 ±0.1 a	17.16 ± 0.79 ab	5.49 ± 0.81 a	6.35 ± 0.87 a	1.39 ± 0.22 a	27.97 ± 2.26 ab	8.31 ± 1.39 ab
F2-Mg+S	186.99 ± 30.87	2.2 ±0.2 a	17.05 ± 6.18 ab	5.88 ± 2.00 a	6.06 ± 1.84 a	1.33 ± 0.38 a	27.24 ± 8.86 ab	8.64 ± 2.63 ab
F2+Mg1	212.07 ± 47.61	2.1 ±0.3 a	20.48 ± 6.74 a	6.21 ± 1.52 a	7.28 ± 2.49 a	1.73 ± 0.55 a	32.79 ± 10.26 a	9.48 ± 2.23 a
	188.38± 41.22	**2.2 ±0.2**	**16.68 ± 5.43**	**5.29 ± 1.55**	**6.19 ± 1.66**	**1.43 ± 0.38**	**27.11 ± 7.44**	**8.08 ± 1.97**

Note: figures in columns followed by different letters are significantly different at p<0.05. TAG means total above ground and DM means Dry matter

4.2 Effect of fertilizer and cropping season on cassava root yield

ANOVA analysis revealed that there was no significant ($p>0.05$) interaction between fertilizer treatment and cropping season on root yield, root: shoot (R:S) and harvest index (HI) (Table 7). However, both traits were significantly affected by the cropping season ($p<0.05$), while no significant differences were observed between the fertilizer treatments ($p>0.05$) (Table 7).

Table 7: Analysis of variance for root yield, root: shoot and harvest index of cassava variety TME 419 grown with different fertilizer treatments across two cropping seasons

Characters	Mean squares Errors				
	Replicate	Fertilizer	Season	Fertilizer*season	Error
	2	7	1	7	32
Fresh Root		21.88^{NS}	136.3*	3.69^{NS}	17.82
Root DM		1.79^{NS}	17.93*	0.73^{NS}	2.50
Root Number		1.29^{NS}	12.84*	0.46^{NS}	1.04
Root: Shoot		0.06^{NS}	0.47*	0.06^{NS}	0.04
Harvest Index		0.04^{NS}	0.44*	0.04^{NS}	0.04

*NB: df = degree of freedom, F = Fertilizer treatment, C= cropping season, F*C = interaction between fertilizer treatment and cropping season. *=Significant at p<0.05, NS=non-significant at p>0.05*

4.2.1 Effect of fertilizer treatments on storage root yield

Fresh storage root yield increment with fertilizer treatments receiving 0K:15.5Mg:20.5S (F_0+Mg_1), 90K (F_1), 90K:20.5S (F_1-Mg+S), 180K (F_2) and 180K:15.5Mg:20.5S (F_2+Mg_1) were by 5.4%, 1.2%, 0.7%, 13.9%, and 14.6% respectively, compared with the control. A decrease of 9.98% and 13.4% were recorded under treatments composed of

90K:15.5Mg:20.5S (F_1+Mg_1) and 180K:20.5S (F_2-Mg+S), respectively, compared with the control (Figure 11).

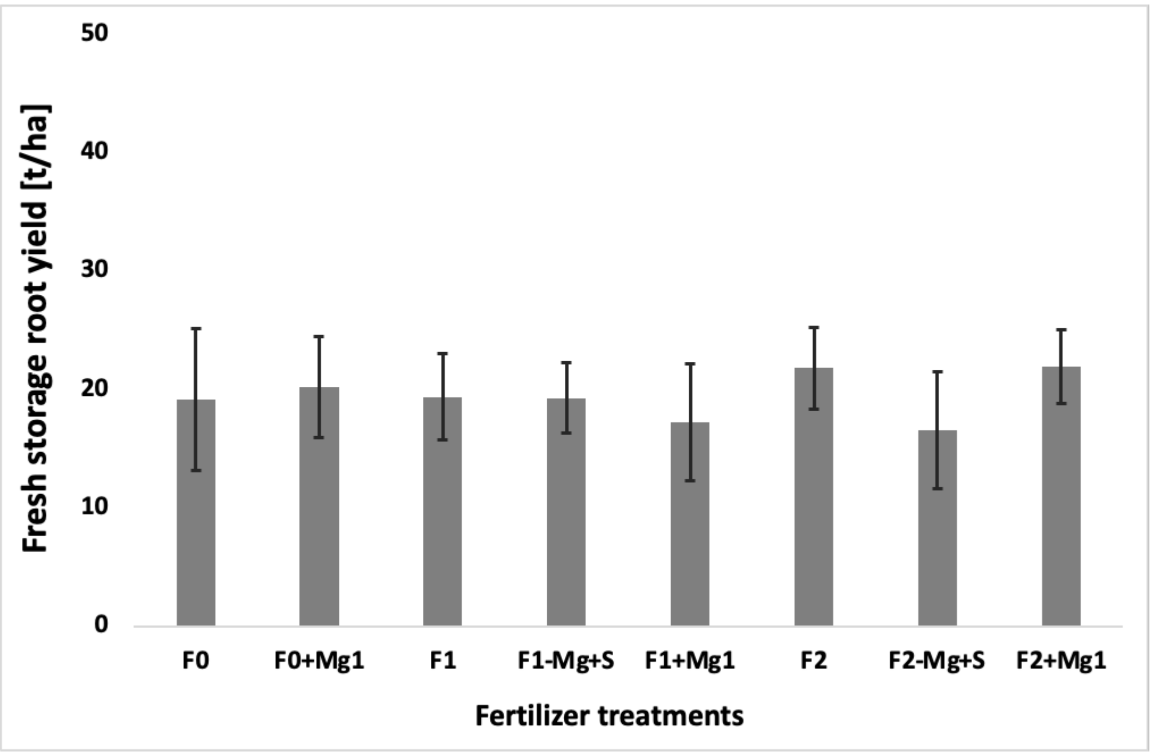

Figure 11: Fresh storage root yield of cassava variety TME 419 grown with different fertilizer treatments. Error bars are SE of the means

Similarly, results reveal a root DM yield advantage over the control of 20.4% with 180K:15.5Mg:20.5S (F_2+Mg_1), 14.61% with 0K:15.5Mg:20.5S (F_0+Mg_1), 14.23% with 180K (F_2), 10.5% with 90K (F_1) and 9.6% with 90K:20.5S (F_1-Mg+S). At the same time, treatments receiving 90K:15.5Mg:20.5S (F_1+Mg_1) and 180K:20.5S (F_2-Mg+S) reduced root DM yield by 9.6 and 6.2%, respectively, compared with the control (Figure 12).

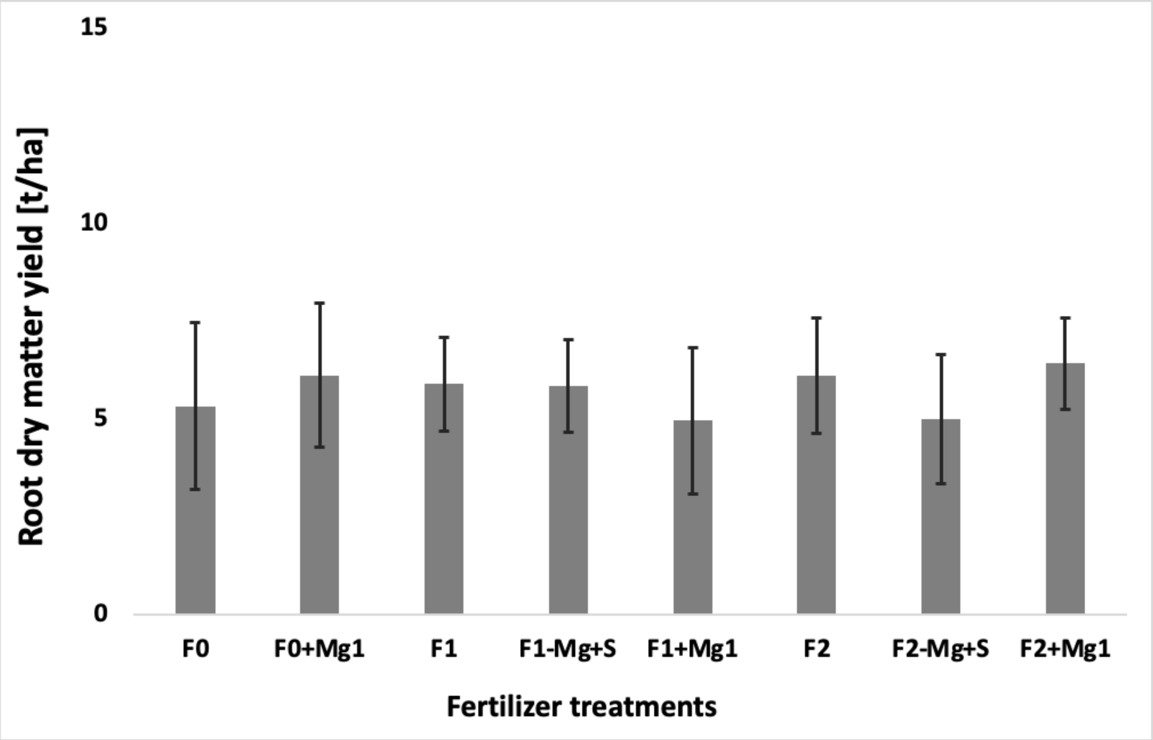

Figure 12: Root dry matter yield of cassava variety TME 419 grown with different fertilizer treatments. Error bars are SE of the means

All fertilized plots had on average high number of roots per plant than the control. Cassava fertilized with 0K:15.5Mg:20.5S kg ha^{-1} (F_0+Mg_1) recorded the highest number of roots per plant (Table 8).

Table 8: Number of roots per cassava plant grown with different fertilizer treatments across the cropping seasons

Treatments	Number of roots
F0+Mg1	5.31 a
F1	5.05 ab
F2-Mg+S	5.04 ab
F2	5.00 ab
F2+Mg1	4.85 ab
F1-Mg+S	4.85 ab
F1+Mg1	4.43 ab
F0	3.83b

Note: figures in columns followed by different letters are significantly different at p<0.05

4.2.3 Effect of fertilizer treatments on the root to shoot ratio and harvest index

Partitioning efficiency as measured by root: shoot (R:S) indicated that the root yield increased in parallel with the shoot yield by 36.1%, 11.6%, 6.6% and 1%, upon fertilization with 0K:15.5Mg:20.5S (F_0+Mg_1), 90K (F_1), 90K:15.5Mg:20.5S (F_2+Mg_1) and 180K (F_2), respectively. Plots that received 90K:20.5S (F_1-Mg+S), 90K:15.5Mg:20.5S (F_1+Mg_1) and 180K:20.5S (F_2-Mg+S) were 3.2%, 1.8% and 4.8% less efficient as compared to the control (Figure 13). Likewise, the harvest index (HI), representing parts of cassava plant that were harvested at 12MAP, revealed an advantage of 30.9% with 0K:15.5Mg:20.5S (F_0+Mg_1), 11.7% with 90K (F_1), 1% with 180K (F_2), and 5.4% with 180K:15.5Mg:20.5S (F_2+Mg_1). A decrease of 5.7%, 3.7%, 7% was found with cassava receiving 90K:20.5S (F_1-Mg+S), 90K:15.5Mg (F_1+Mg_1), 180K:20.5S (F_2-Mg+S) (Figure 14).

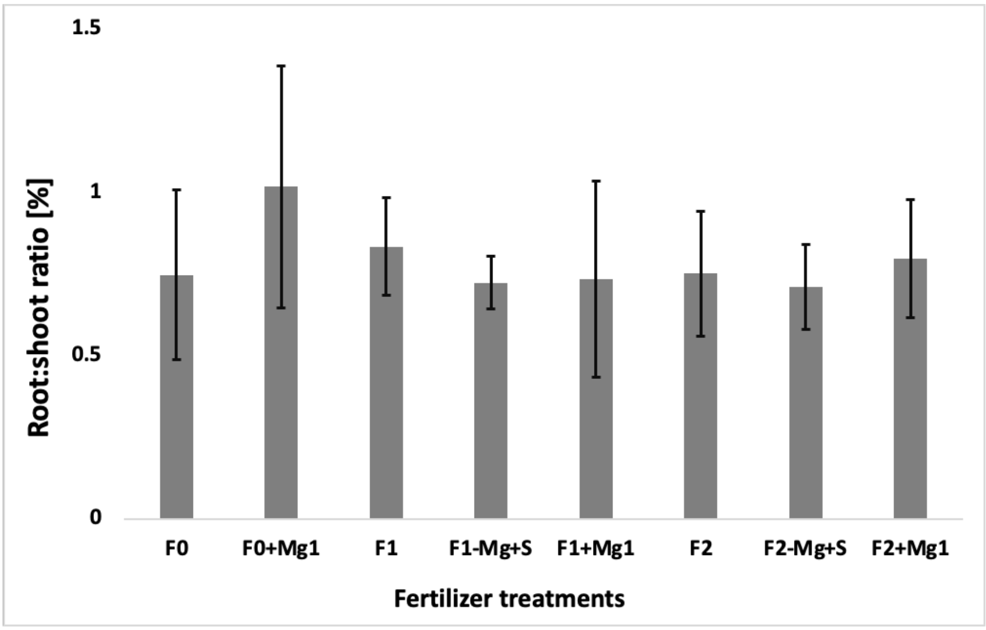

Figure 13: Root: Shoot of cassava variety TME 419 grown with different fertilizer treatments. Error bars are SE of the means

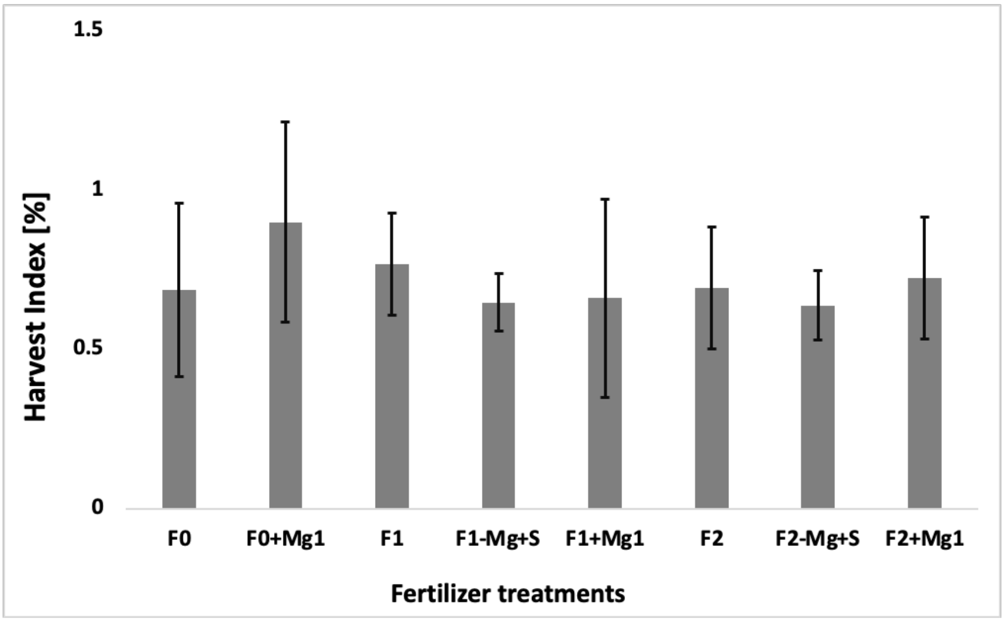

Figure 14: Harvest Index of cassava variety TME 419 grown with different fertilizer treatments. Error bars are SE of the means

4.2.3 Yield advantage with fertilizer treatments

The storage roots and stems are economically the most important part of cassava. Table 9 shows the relative advantage over the control attained by the different fertilizer treatments. Cassava that was grown on plots that received F_2+Mg_1 (180K:15.5Mg:20.5 S kg ha^{-1}) produced the highest advantage on storage root yield and a relatively high stem yield, while the highest stem yield was produced with treatment consisting of 90K:20.5S kg ha^{-1} (F_1-Mg+S) which also had a marginal increment on root yield (Table 9). The combination of 90K:15.5Mg:20.5S kg ha^{-1} (F_1+Mg_1) slightly increased stem yield with a decline in root yield, while 0K:15.5Mg:20.5S kg ha^{-1} (F_0+Mg_1) did the opposite by increasing root yield and highly decreasing stem yield. Further, application of 180K kg ha^{-1} (F_2) increased both the root and stem yield, while 90K kg ha^{-1} (F_1) also increased both the root and stem yield but at a relatively lower advantage compared to 180 K kg ha^{-1}. Treatment 180K:20.5S (F_2-Mg+S) only slightly increased stem yield, with a reduction in root yield (Table 9).

Table 9: Percent increases (%) of various treatments over absolute control

Treatments	Fresh root	Root DM	Fresh stem
F0+Mg1	5.44	14.61	-20.89
F1	1.15	10.49	6.70
F1-Mg+S	0.73	9.55	30.19
F1+Mg1	-9.98	-6.93	6.39
F2	13.85	14.23	23.05
F2-Mg+S	-13.43	-6.18	8.65
F2+Mg1	**14.58**	**20.41**	**23.41**

4.2.4 Effect of cropping season on cassava storage root yield, root: shoot and harvest index

A difference of 17.35% and 21.52% was found on fresh root and root DM yield, respectively, between the two cropping seasons. The root: shoot difference was of 24.20%, and a 26.57% difference on the harvest index was also recorded between the two cropping seasons (Table 10).

Table 10: Mean root yield, number of roots, root: shoot ratio and harvest index of cassava variety TME 419 grown with different fertilizer treatments during two cropping seasons

First cropping season					
Treatments	**Fresh root t/ha**	**Root DM t/ha**	**Root Nº**	**Root: Shoot**	**Harvest Index**
F0	16.56 ± 4.96 a	4.32 ± 1.15 a	3.48 ± 0.98 a	0.64 ± 0.08 a	0.57 ± 0.09 a
F0+Mg1	19.53 ± 6.02 a	5.84 ± 2.74 a	4.63 ± 1.14 a	0.70 ± 0.21 a	0.64 ± 0.19 a
F1	18.46 ± 2.59 a	5.48 ± 0.80 a	4.84 ±1.15 a	0.77 ± 0.18 a	0.71 ± 0.20 a
F1-Mg+S	17.17 ± 0.75 a	4.90 ± 0.71 a	4.37 ± 0.92 a	0.67 ± 0.05 a	0.59 ± 0.03 a
F1+Mg1	16.18 ± 4.22 a	4.30 ± 0.71 a	4.32 ± 0.65 a	0.61 ± 0.05 a	0.51 ± 0.06 a
F2	19.88 ± 2.11 a	5.97 ± 0.77 a	4.17 ± 0.79 a	0.69 ± 0.09 a	0.63 ± 0.13 a
F2-Mg+S	14.99 ± 2.93 a	4.59 ± 0.88 a	4.18 ± 0.16 a	0.75 ± 0.13 a	0.67 ±0.12 a
F2+Mg1	19.17 ± 0.28 a	5.44 ± 0.46 a	4.24 ± 0.42 a	0.69 ± 0.09 a	0.63 ± 0.11 a
	17.74 ± 3.39	**5.10 ± 1.21**	**4.28 ± 0.40**	**0.69 ± 0.11**	**0.62 ± 0.12**
Second cropping season					
	Fresh root t/ha	**Root DM t/ha**	**Root Nº**	**Root: Shoot**	**Harvest Index**
F0	21.71 ± 6.67 a	6.36 ± 2.63 a	4.18 ± 1.14 a	0.85 ± 0.36 b	0.80 ± 0.37 ab
F0+Mg1	20.82 ± 2.80 a	6.41 ± 0.85 a	6.00 ± 1.74 a	1.33 ± 0.06 a	1.15 ± 0.13 a
F1	20.25 ± 4.89 a	6.32 ± 1.57 a	5.27 ± 1.04 a	0.89 ± 0.12 b	0.82 ± 0.12 ab
F1-Mg+S	21.37 ± 2.85 a	6.81 ± 0.52 a	5.31 ± 0.81 a	0.78 ± 0.63 b	0.71 ± 0.09 b
F1+Mg1	18.27 ± 6.36 a	5.63 ± 2.64 a	4.53 ± 0.26 a	0.86 ± 0.42 b	0.81 ± 0.41 ab
F2	23.67 ± 3.79 a	6.24 ± 2.19 a	5.83 ± 1.28 a	0.81 ± 0.27 b	0.75 ± 0.25 ab
F2-Mg+S	18.13 ± 6.72 a	5.42 ± 2.34 a	5.90 ± 1.78 a	0.68 ± 0.15 b	0.61 ± 0.11 b
F2+Mg1	24.68 ± 1.31 a	7.43 ± 0.48 a	5.47 ± 0.22 a	0.91 ± 0.19 b	0.82 ± 0.23 ab
	21.11 ± 4.59	**6.33 ± 1.67**	**5.31 ± 0.65**	**0.88 ± 0.27**	**0.81 ± 0.25**

Note: figures in columns followed by different letters are significantly different at $p<0.05$.

4.3 Correlation between cassava root yield and vegetative yield

Correlations between cassava vegetative yield and root yield for the first and second cropping season is shown in Figure 15 and Figure 16. In the first cropping season, fresh root yield was significantly positively correlated with fresh stem yield (r= 0.49*, $p > 0.05$), stem DM yield (r= 0.45*, $p > 0.05$), fresh leaf yield (r= 0.52*, $p > 0.05$), leaf DM yield (r= 0.62*, $p > 0.05$), fresh total aboveground yield (r= 0.66*, $p > 0.05$) and total aboveground DM yield (r= 0.63*, $p > 0.05$). Similarly, the root DM yield was significantly positively correlated with fresh stem yield (r= 0.49*, $p > 0.05$), stem DM yield (r= 0.49*, $p > 0.05$), leaf DM yield (r= 0.44*, $p > 0.05$), fresh total aboveground yield (r= 0.52*, $p > 0.05$) and total aboveground DM yield (r= 0.56*, $p > 0.05$) (Figure 15). In the second cropping season, fresh root yield had significant positive correlation with fresh stem yield (r= 0.45*, $p > 0.05$), stem DM yield (r= 0.42*, $p > 0.05$), fresh leaf yield (r= 0.52*, $p > 0.05$), leaf DM yield (r= 0.53*, $p > 0.05$), fresh total aboveground yield (r= 0.51*, $p > 0.05$) and total aboveground DM yield (r= 0.49*, $p > 0.05$). The root DM yield had significant positive correlation with fresh stem yield (r= 0.42*, $p > 0.05$), fresh leaves yield (r= 0.46*, $p > 0.05$), leaf DM yield (r= 0.46*, $p > 0.05$), fresh total aboveground yield (r= 0.46*, $p > 0.05$) and total aboveground DM yield (r= 0.43*, $p > 0.05$) (Figure 16).

The R:S had significant negative correlation with fresh stem yield (r= -0.42*, $p > 0.05$), stem DM yield (r= -0.47*, $p > 0.05$) and the total aboveground DM yield (r= -0.42*, $p > 0.05$) in the second cropping season only (Figure 16). The harvest index (HI) had significant negative correlation with fresh stem yield (r= -0.43*, $p > 0.05$), stem DM yield (r= -0.48*, $p > 0.05$) and the total aboveground DM yield (r= -0.44*, $p > 0.05$) in the second cropping season (Figure 16).

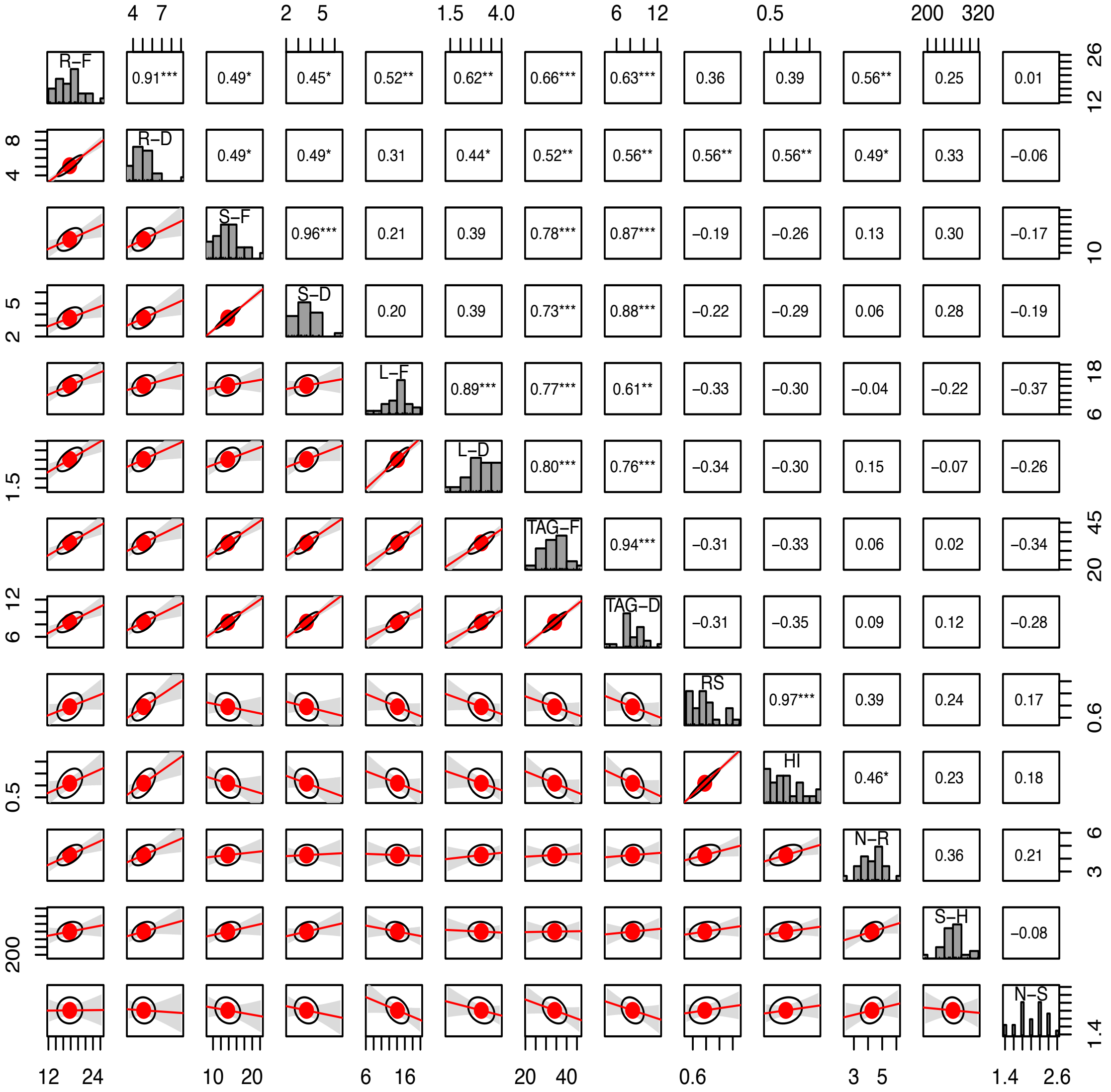

Figure 15: Correlation matrix between cassava yield and yield components as affected by the fertilizer treatments in the first cropping season. Correlation plots have smoothed regression lines, density functions histograms, and correlation coefficients with corresponding significance levels (Not significant if no *, while *, ** and * means significant at 10%, 5% and 1% levels, respectively). R-F=fresh root yield, R-D= Root Dry matter yield, S-F= Fresh stem yield, S-D=Stem Dry matter yield, L-F=Fresh leaves yield, L-D= Leaves Dry matter yield, TAG-F= fresh total aboveground, TAG-D=total aboveground dry, RS= Root: Shoot, HI= Harvest index, N-R= Number of roots, S-H=stem height, N-S= Number of stems.**

Figure 16: Correlation matrix between cassava yield and yield components as affected by the fertilizer treatments in the second cropping season. Correlation plots have smoothed regression lines, density functions histograms, and correlation coefficients with corresponding significance levels (Not significant if no*, while *, ** and * means significant at 10%, 5% and 1% levels, respectively). R-F=fresh root yield, R-D= Root Dry matter yield, S-F= Fresh stem yield, S-D=Stem Dry matter yield, L-F=Fresh leaves yield, L-D= Leaves Dry matter yield, TAG-F= fresh total aboveground, TAG-D=total aboveground dry, RS= Root: Shoot, HI= Harvest index, N-R= Number of roots, S-H=stem height, N-S= Number of stems.**

CHAPTER FIVE

DISCUSSION

5.1 Effect of treatments on vegetative yield

Vegetative responses to fertilizer application were variable, and cassava plants that were fertilized with K regardless of the rate and combination had longer stems (Figure 4) and high above-ground yield than plants from the control and 0K:15.5Mg:20.5S. This demonstrates that K and Mg had no discernible antagonistic effects on shoot development or yield. According to reports, K deficiency significantly reduces shoot biomass of various crops, notably cassava and potatoes, whereas Mg deficiency has little effect on stem height and shoot growth (Zhao *et al.,* 2014; Jákli *et al.,* 2017; Koch *et al.,* 2020). Given that K is a vital element for stem development owing to its function in cell division and photosynthesis, it is possible that the supply of K in this study's experiment increased the rate of photosynthesis, which eventually contributed to high stem production (Boateng & Boadi, 2010; Thummanatsakun & Yampracha, 2018; Koch *et al.,* 2019). The higher shoot growth and yield attained with K fertilizer is in agreement with the results of Kang & Okeke (1981), Okpara *et al.* (2010), Tang *et al.* (2016) and Uwah *et al.* (2018). On the other hand, the lack of K for plants that were fertilized with 0K:15.5Mg:20.5S might have contributed to the inhibition of some of the plants physiological processes related to the elongation and widening of the vegetative organs. This K deficiency may also have interfered with the formation of assimilate which were later used in leaves production (Chua *et al.,* 2020).

Leaf yield did not significantly differ with fertilizer application (Figure *7*). However, the high leaf yield produced with treatments composed of 0K:15.5Mg:20.5S and

180K:15.5Mg:20.5S could be linked to the $MgSO_4$. Since leaves are the part of the plant with the highest physiological Mg demand, the Mg supplied potentially contributed to the high leaf mass produced which in return might have provided the necessary tension in the xylem to extract soil water and nutrients via transpiration (Gransee & Führs; 2013; Cochard, 2014; Taiz *et al.,* 2017).

The production of average two stems per plant at 8MAP in both fertilized and control plots in both cropping seasons could be attributed to the poor branching architecture of TME419 which only produces a few number of main stems (Aiyelari *et al.,* 2019). Other varieties grown in Nigeria such as TMS581 branch more profusely (Enesi *et al.,* 2021), and produces more stems than TME419. Varieties such as Kelle, Hawassa-4 and Quelle, mostly grown in Ethiopia and introduced from Nigeria, have been reported to produce on average 1.6, 2.2 and 1.9 stems (Misganaw & Bayou,2020; Mulualem & Dagne, 2015). Therefore, the variation in each variety stem number could be linked to their physiological and genetic makeup.

There was variation in the vegetative yield between the cropping seasons. Cassava plants in cropping season 1 produced the highest stem height, fresh and dry leaves, fresh and dry total aboveground yield than plants in the second cropping season (Table 6). This variation in the vegetative yield could be attributed to the differences in environmental conditions. The higher rainfall received in the first cropping season must have been more favourable for shoot growth since there was enough moisture that increased the rate of photosynthesis and transpiration (Meg, 2021). Due to the high rate of photosynthesis and transpiration, plants expanded their aboveground part especially leaves since they are the primary site of photosynthesis. On the other hand, less moisture in the second cropping season led to low leaf production to avoid high photosynthesis and transpiration which could have injured the plant by removing more water than the plant could take in (Stanley, 2017). Thus, the moderately high rain experienced in the first cropping season could have contributed to its high vegetative yield.

5.2 Effect of treatments on root yield

Root yield responses to fertilizer treatment were also highly variable (Figure 11, Figure 12). The root yield advantage of 13.9% fresh and 14.23% on DM, achieved with 180K kg ha^{-1} reveals that no K: Mg antagonism leading to decreased root yield was exhibited at such K level. These root yield results also confirm the assertion of others who reported cassava yield depression at K rates higher than 200 kg ha^{-1} applied as KCl (Kumar *et al.,* 1971, CIAT1974, Ngongi *et al.,* 1977). Other researchers have reported similar results in other tropical crops such as yam and sweet potato (Duncan *et al.,* 1959, Ferguson & Haynes, 1970). Putra *et al.* (2018) opined that yield decrease when K exceeds 255 kg ha^{-1} applied as KCl due to a high level of K which blocks the availability and uptake of Mg. However, the present study disagrees with reports that found yield depression starting at rates higher than 83K kg ha^{-1} (Kumar *et al.,* 1971), 80K kg ha^{-1} (Uwah *et al.,* 2013), and 90K kg ha^{-1} (Fernandes *et al.,* 2017). The discrepancies between these results could be attributed to factors like weather conditions, the source of K fertilizer used in the various trials and soil type. According to Kang & Okeke (1984), cassava yield response to K is highly dependent on soil type. Although it appears that the correct K source and rate could principally be the cause of the low yield as Hahlin & johansson (1973) reported that KCI is more efficient at low rates while K_2SO_4 is superior at high rates.

Further, the 5.4% fresh and 14.6% dry root yield increments reported with 0K:15.5Mg:20.5S could be due to the fact that Mg availability and uptake were not hampered by high K levels but also the SO_4^{2-} had a positive impact on Mg uptake or cassava roots formation. This could mean that, due to the lack of K: Mg antagonism, Mg increased the chlorophyll content and photosynthetic activity which promoted the formation of assimilates and the storage root yield (Subaedah *et al.,* 2016). Plants supplied with 0K:15.5Mg:20.5S had the highest R:S (≥1) (Figure 13) and consequently the highest HI (0.88) (Figure 14), most likely due to the supply of Mg as it is reported that Mg fertilization increases the root to shoot ratio (Ding & Xu, 2011). Thus, the 0K:15.5Mg:20.5S combination might have been superior over other fertilizer treatments in efficiently allocating assimilates to the roots. Further, due to the relatively low above-ground yield produced with 0K:15.5Mg:20.5S, it seems that the roots had priority and formed a preferential sink. Hence, the high root yield achieved under 0K:15.5Mg:20.5S could be the result of less competition of assimilates between the root and the shoot, a higher dry matter partitioning to the roots (R:S), and an increased sink capacity due to the high number of roots per plant produced (Table 8).

Similarly, the highest root yield increment of 20.8% demonstrated in this study with 180K:15.5Mg:20.5S could potentially be due to the supply of Mg, which might have upscaled the soil Mg level such that the high K supply did not block the Mg transporters to the roots (Table 9). But also, the SO_4^{2-} increased Mg uptake which promoted the CO_2 assimilation and the translocation of photoassimilates to the roots (Uwah *et al.,* 2013; Djabou *et al.,* 2018). Thus, the balanced level of nutrients with the combination of 180K:15.5Mg:20.5S promoted root yield as a result of the relatively high sink capacity (number of roots per plant), a high source supply (high above-ground biomass) and a slightly higher dry matter partitioning to the roots at a given aboveground biomass (R:S).

On the other hand, the low root yield reported with 90K:20.5S and 180K:20.5S would be due to their vigorous vegetative growth at the expense of the roots demonstrating their poor capacity to allocate the assimilates to the storage roots. Furthermore, it could also be that these treatment combinations were more efficient in expanding the aboveground part, which might have consumed the carbohydrates that would have otherwise been translocated to the storage roots. These results are in agreement with Alves (2002), who reported that when more photoassimilates are allocated to the shoots there will be less dry matter for storage root growth and filling. The low root yield, R:S, and HI reported with the combination of 90K:15.5Mg:20.5S seem not to have a practical explanation given that both K and Mg were supplied.

The fresh and dry matter root yield between the two seasons varied (Table 10), and on average, the second cropping season produced higher root yield than the first cropping season. This root yield variation between the two cropping seasons influenced the root to shoot ratio (R:S) which was higher in the second cropping season (0.88) and lower in the first cropping season (0.69). Similarly, the R:S influenced the harvest index (HI), whereby the low R:S recorded in the first cropping season resulted in its low HI (0.62), and the high R:S in the second cropping season enabled more carbohydrates to be accumulated in the roots which led to a higher HI (0.88). Given that the second cropping season had on average high root yield, R:S and HI compared to the first cropping season; the differences between the two cropping seasons could principally be linked to the level of total above-ground (shoot) production, the amount of rainfall received and varying soil properties status. Surprisingly, rainfall distribution was better in the first cropping season than in the second one where the plants endured more months without rain. It is reported that when there is insufficient moisture, shoot growth is limited while root growth continues due to the selective allocation of photosynthates below the soil surface that allows greater exploration of subsurface moisture while minimizing water loss through the shoot (Ober & Sharp, 2007). Thus, the climatic conditions in the second cropping season seem to have been more favourable for root growth. Additionally, the higher root yield recorded in the second cropping season may be due to the fact that soils had high sand content (Table 2) compared to the first one. Fasinmirin & Reichert (2011) and Enesi *et al.* (2021) opined that cassava performs well on loose soils which allow easy root penetration in soil and losses are minimized during harvest as the roots would not break when pulled from such sandy soil.

Further, the low yield recorded in the first season could be connected to the high leaf produced compared to the second season. Saitama (2017) and Isa *et al.* (2015) reported that high leaf production inhibits the process of tuber formation and development due to a large amount of carbohydrates allocated to leaf production and a relatively small portion left for the process of root development. This means that when more photoassimilates were being allocated to the shoots, there was less dry matter for root growth and filling (Alves, 2002; De Souza *et al.,* 2016). Other researchers have also reported variations in cassava yield between years and have attributed the differences to many factors, mostly rainfall and soil fertility (Fermont *et al.,* 2010).

The average number of roots per plant also varied between the seasons, with the second season producing the highest (5.3) while the first season had the lowest (4.2) (Table 10). The number of roots produced influenced the root yield given that roots are the sink of carbohydrates, hence the high root yield recorded in the second season was due to the increase in the sink capacity.

Overall, one possible reason for the lack of storage root yield response to fertilizer application could be due to the short rain period (approximately 5 months) as compared to the 12 months maturity period which might have led to fertilizer not being fully available to the plants due to dry soil conditions. It is reported that soil moisture and temperature significantly affect the ability of a plant to absorb and use nutrients more efficiently (Fermont *et al.,* 2009). Additionally, the low storage root yield may be caused by the fact that the cassava variety TME419 sheds all of its leaves in dry conditions and must rely on resources from its roots and stems to restore its canopy when there is sufficient moisture. Nevertheless, even though no statistically significant response to fertilizer was observed on storage root yield, applying a balanced fertilizer combination is recommended to avoid mining. Taking into consideration the fact that application of K+Mg resulted in higher root yield compared with those of K alone or K+S; and because cassava roots remove both N, P, K and Mg from the soil, $MgSO_4$ should be added into the fertilizer mix to avoid Mg mining.

5.3 Correlation between the vegetative parameters and root yield

Cassava's vegetative yield profoundly affected the final root yield. Correlation results reveal that the performance of the storage root yield in both seasons followed the same yield pattern as the total above-ground yield (stem and leaves) demonstrated by the positive correlation (Figure 15 and Figure 16). This implies that the root yield is a result of great photosynthetic capture. Further, the positive correlation between the root yield and the number of roots per plant indicates that the more roots produced, the more they contributed to the final root yield. Similar results have been reported by Amarullah *et al.* (2016). However, the negative correlation between the vegetative yield and the root: shoot (R: S) and the harvest index (HI) imply that when the above-ground yield was increasing the R:S and HI were reducing. This could have been due to the partition of assimilate to shoot growth rather than the roots (Misganaw & Bayou, 2020).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The results of this study show that K and Mg interaction promoted the vegetative yield of cassava TME419, as demonstrated by the high shoot yield recorded with 180K:15.5Mg:20.5S kg ha^{-1}.

Similarly, treatment 180K:15.5Mg:20.5S kg ha^{-1} demonstrated synergistic interaction on cassava root yield.

6.2 RECOMMENDATIONS

This study's results show that there is potential to increase cassava yield if Mg is included in fertilizer recommendations to balance the nutrient in the soil towards meeting the rising demand for cassava and to close the yield gap. Therefore, should cassava be planted in a similar production environment as our study area, 180K:15.5Mg:20.5S kg ha^{-1} fertilizer combination should be considered due to its maximum advantage on both vegetative and root yield as well as nutrient balance.

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APPENDICES

Appendix I: Aerial view of the experimental field

(Source: Author, 2020)

Appendix II: TWO-WAY ANOVA for fertilizer treatment and cropping season on cassava vegetative yield parameters

TWO-WAY ANOVA FOR VEGETATIVE YIELD						
1. Stem height (cm)	Source	DF	Adj SS	Adj MS	F-Value	P-Value
	Cropping season (C)	1	61546	61546.3	54.16	0
	Treatments (T)	7	6647	949.5	0.84	0.566
	C*T	7	10734	1533.4	1.35	0.26
	Error	32	36365	1136.4		
	Total	47	115292			
	Source	DF	Adj SS	Adj MS	F-Value	P-Value
2. Number of stems	Cropping season (C)	1	0.3763	0.37631	4.23	0.048
	Treatments (T)	7	0.2089	0.02985	0.34	0.932
	C*T	7	0.507	0.07243	0.81	0.582
	Error	32	2.8451	0.08891		
	Total	47	3.9373			
3. Fresh leaves yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	752.6	752.6	124.84	0
	Treatments (T)	7	37.82	5.404	0.9	0.521
	C*T	7	30.34	4.335	0.72	0.657
	Error	32	192.91	6.028		
	Total	47	1013.68			
4. Leaves DM yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	30.06	30.0596	100.87	0
	Treatments (T)	7	1.838	0.2626	0.88	0.532

	C*T	7	1.228	0.1755	0.59	0.76
	Error	32	9.536	0.298		
	Total	47	42.662			
5. Fresh stem yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	102.1	102.14	5.92	0.021
	Treatments (T)	7	212.5	30.35	1.76	0.131
	C*T	7	149	21.29	1.23	0.314
	Error	32	552.2	17.26		
	Total	47	1015.8			
6. Stem DM yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	31.5	31.502	22.22	0
	Treatments (T)	7	15.94	2.277	1.61	0.169
	C*T	7	15.46	2.208	1.56	0.184
	Error	32	45.37	1.418		
	Total	47	108.27			
7. Fresh total Above ground yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	600.9	600.86	13.38	0.001
	Treatments (T)	7	358.3	51.18	1.14	0.364
	C*T	7	255.8	36.54	0.81	0.583
	Error	32	1437	44.91		
	Total	47	2652			
8. Total Above ground DM yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season (C)	1	0.991	0.9907	0.32	0.578
	Treatments (T)	7	22.352	3.1932	1.02	0.439
	C*T	7	27.838	3.9769	1.27	0.298
	Error	32	100.523	3.1414		
	Total	47	151.705			

Appendix III: TWO-WAY ANOVA for fertilizer treatment and cropping season on root yield parameters

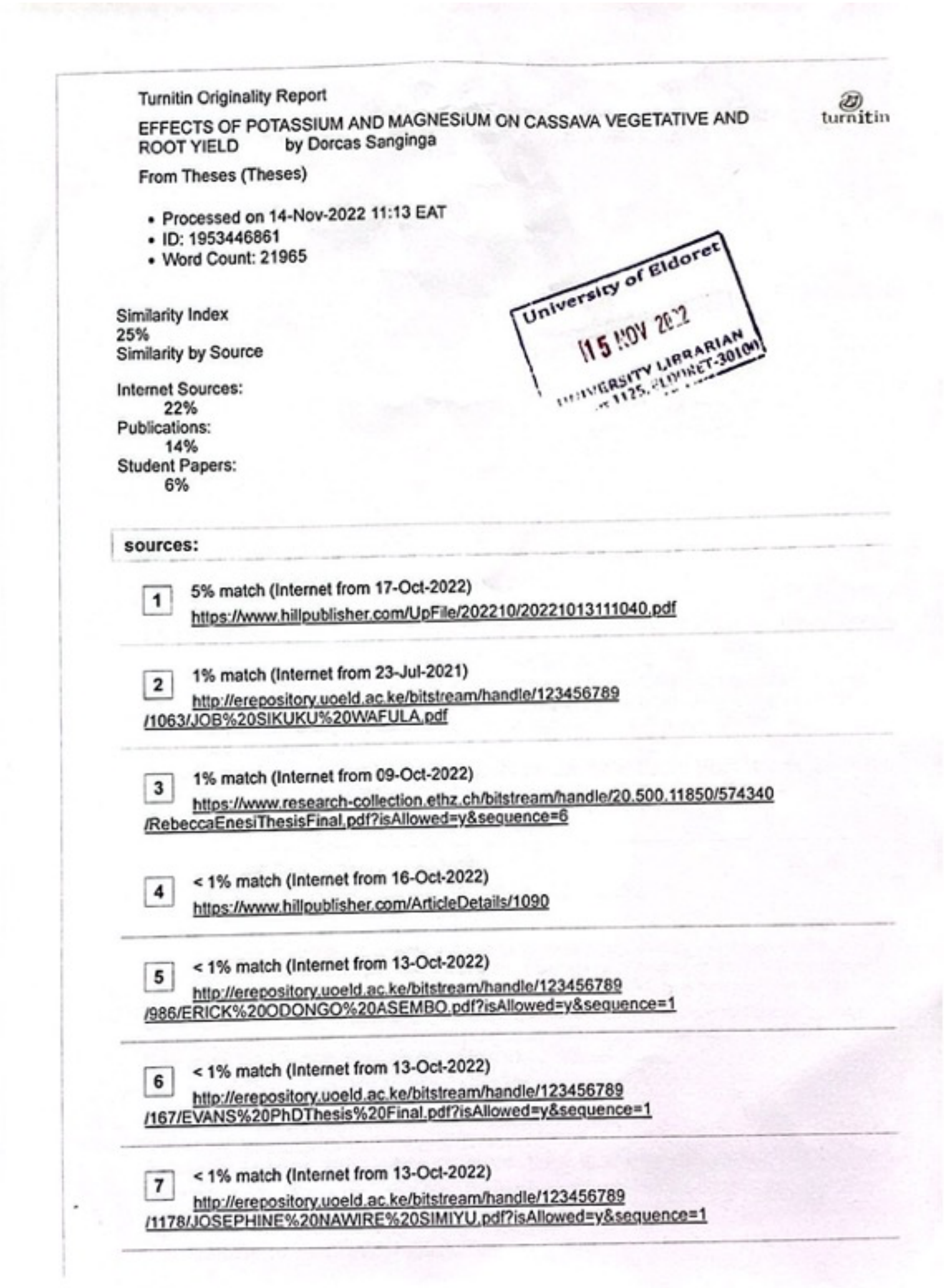
TWO-WAY ANOVA FOR ROOT YIELD

1. Fresh root yield (t/ha)

	Source	DF	SS	MS	F-Value	P-Value
	Cropping season	1	136.29	136.3	7.65	0.009
	Treatments	7	153.13	21.876	1.23	0.317
	Cropping season*Treatments	7	25.81	3.687	0.21	0.981
	Error	32	570.24	17.82		
	Total	47	885.47			
2. Root DM yield (t/ha)	Source	DF	SS	MS	F-Value	P-Value
	Cropping season	1	17.934	17.934	7.19	0.012
	Treatments	7	12.565	1.7949	0.72	0.656
	Cropping season*Treatments	7	5.107	0.7296	0.29	0.952
	Error	32	79.86	2.4956		
	Total	47	115.465			
3. R:S	Source	DF	SS	MS	F-Value	P-Value
	Cropping season	1	0.468	0.468	12.84	0.001
	Treatments	7	0.4224	0.0604	1.66	0.156
	Cropping season*Treatments	7	0.4154	0.0593	1.63	0.163
	Error	32	1.166	0.0364		
	Total	47	2.4718			
4. Harvest Index	Source	DF	SS	MS	F-Value	P-Value

	Cropping season	1	0.4359	0.4359	11.57	0.002
	Treatments	7	0.3073	0.0439	1.16	0.35
	Cropping season*Treatments	7	0.2914	0.0416	1.1	0.384
	Error	32	1.2062	0.0377		
	Total	47	2.2408			
5. N° of good root	Source	DF	SS	MS	F-Value	P-Value
	Cropping season	1	12.838	12.838	12.31	0.001
	Treatments	7	9.012	1.2875	1.23	0.313
	Cropping season*Treatments	7	3.242	0.4631	0.44	0.867
	Error	32	33.368	1.0427		
	Total	47	58.46			

Appendix IV: Similarity report



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