EVALUATING THE AGRONOMIC PERFORMANCE OF SELECTED YAM VARIETIES

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Professor Albert T. Modi

Date: 9 November, 2015

DECLARATION

I, Oluwadamilola Florence Alabi, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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a) their words have been re-written but the general information attributed to them has been referenced;

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(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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ABSTRACT

Food security ranks among South Africa's top ten priorities. While there is a range of crops, both major and minor, that are currently being exploited and explored for food security within South Africa, there is a need to explore other crop species currently not utilised within the country. Yam is a drought tolerant crop with ability to produce reasonable yields under severe environmental conditions. However, in order to promote yam as a possible food security option for South Africa, there is need for empirical information describing basic aspects of its agronomy. Therefore, the aim of this study was to evaluate growth and development of three yam species (*Dioscorea rotundata, Dioscorea cayenensis, and Dioscorea alata)* under environmental conditions in the province of KwaZulu-Natal, South Africa, where the crop is not normally produced. Secondary to this, the study aimed at determining the nutritional value of the yam species as a source of starch. The experimental design was a randomized complete block design with three replications. The experiment was provided with supplementary irrigation scheduled to provide 35 mm per week. Data collection included emergence, number of vine, and number of leaves, stomatal conductance, chlorophyll content index, chlorophyll fluorescence, yield and yield components. At harvest, moisture and starch content were determined. Results showed that, for most measured variables, water yam (*D. alata*) performed relatively better than white (*D. rotundata*) and yellow yam (*D. cayenensis*), respectively. Water yam emerged early (56 DAP) and produced the highest yield (24 t ha^{-1}). It also had the highest moisture (19.65%) and starch content (66.17%). Furthermore, water yam demonstrated a degree of phenological plasticity in response to environmental conditions throughout the growing season. Although, all three yam varieties performed reasonably well under KwaZulu-Natal conditions, water yam may be recommended for cultivation due to its ability to produce reasonable yields.

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DEDICATION

With all my heart, spirit and soul filled with gratitude, this dissertation is dedicated to the all sovereign God, the giver of wisdom, knowledge and understanding, “without you God, I am nothing, for by your grace I have run through a race, with your help I have overcome” and also to Hon. Ibrahim Gbodeniyi, I would never have done it without his financial support.

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CHAPTER 1

Introduction

1.1 Rationale for the Research

Food security ranks among South Africa's top ten priorities (United States Agency for International Development/ Southern Africa, 2013). There is food security, in relation with the global definitions, when the people in a society have sufficient food to live a good and healthy life at all times (United States Department of Agriculture, 2011). There are four pillars upon which food security is based: food availability, accessibility, utilization and stability (Hanson, 2013). Agriculture sectors can make a major impact on food security of a country, even in the world (Food and Agriculture Organization, 2008), being vital to livelihoods and important basis for human wellbeing, economic and social prosperity (Canadian International Development Agency, 2010). Due to the fact that the majority of people who are food insecure are small scale-farmers living in rural areas and mostly engaged in agriculture, CIDA (2010) implemented a food security strategy aimed at increasing the agricultural production and also reduction of immediate and long-term food shortages. Agriculture also plays a significant role in achieving food security in terms of food production to the population with the availability of adequate food (Du Toit, 2011). The Food and Agriculture Organization (2008) rate South Africa as a food secure nation which has the ability to produce enough food to meet national requirements. However, at the household level South Africa is food insecure (De Klerk *et al.,* 2004), especially when considering poor households in the rural areas. In rural households, most food is produced and consumed locally (Garrity *et al*., 2010), making household agricultural productivity critical to improving food security (Du Toit, 2011).

While there is a range of crops, both major and minor which are currently being exploited and explored for food security within South Africa, there is a need to also explore other crop species currently underutilised within the country (Modi and Mabhaudhi, 2013; Chivenge *et al.,* 2015). The main root and tuber crops grown in South Africa are the Irish potato (*Solanum tuberosum*), sweet potato (*Ipomoea batatas*) and taro (*Colocasia esculenta*), respectively (Allermann *et al*., 2004). Compared to other counties in sub–Saharan Africa, South Africa uses very few root and tuber crops. This may be in part due to the fact that the staple is a cereal crop – maize. However, dietary diversity is pivotal to achieving nutrition, especially in diets of rural poor people (Modi *et al.,* 2015). In this regard, it will be of great value to consider other root and tuber crops that are not cultivated in South Africa such as yam and cassava (*Manihot esculenta*). This would add diversity to the current range of root and tuber crops and broaden the food basket as a whole and hence increasing resilience to food insecurity. Most root and tuber crops can play a major role in rural households by providing income and employment due to the fact that a substantial quantity of the crop can be processed into more storable usage thereby reducing physical losses and leading to increased value of the product (Natural Resources Institute, 2014). Root and tuber crops occupy a significant role in the agriculture, food security and incomes of over 2.2 billion people in rural areas of developing countries of Africa, Asia and the Caribbean (Lebot, 2009; NRI, 2014).

According to Coursey (1967) and Lebot (2009), yam (*Dioscorea spp.*) is a staple food used by over a billion people in the tropical countries of Africa, Asia, the Caribbean and the Pacific region. Yam also provides food during periods of shortage while some of the species provide pharmacological components vital in traditional medicines (Mignouna *et al*., 2008; Lebot, 2009). It is more tolerant to drought, pests and diseases and tolerates different climatic and edaphic conditions (Degras, 1993). This means that it may be suited to a range of agro–ecologies making it possible to also cultivate it in South Africa.

In the tropics and subtropics of Africa, especially in West Africa, yam plays an important role in food security and livelihoods of at least 60 million people and also serves as a source of income for many small scale farmers (Mwiringi *et al*., 2009). Therefore, it would be beneficial to small scale farmers in rural areas of South Africa to grow another root and/or tuber crop that has adaptation to a range of environments, especially adverse conditions and can contribute to food security and income. However, in order to promote yam in South Africa as an alternative crop, there is a need to conduct agronomic experiments that can be used to definitively answer the question of yam suitability under South African conditions. This study is an attempt to evaluate the agronomic performance of popular yam species under KwaZulu-Natal conditions.

1.2 Justification

Yam (*Dioscorea spp*) is a drought tolerant tuber crop capable of producing good yield under water scarce conditions (Asiedu and Sartie, 2010). This is an important attribute given that South Africa is a water scarce country with much of the country being classified as semi–arid (RSA, 1998). In this regard, yam cultivation could be promoted in such environments and contribute to food security of people living in marginal areas of agricultural production.

South Africa faces household food insecurity which is partly due to the narrow food basket consumed by rural households (Modi *et al.,* 2015). Yams represent a large pool of agro biodiversity, which also confers them wide environmental plasticity. The promotion of yam as an alternative to the existing suite of root and tuber crops would provide a low cost alternative for rural households and contribute to broadening of the food basket in the country.

In addition, yams are linked with traditional agriculture system worldwide because they are vital crops (Tamiru *et al*., 2008,). This suggests that the crop can be part of agro-forestry and multicrop systems which typify the rural landscape. Their reported tolerance to shading (Lebot, 2009) makes yams suitable for such systems. Diversification of cropping systems in rural areas would also contribute to building resilience whilst contributing to food and nutritional goals. Therefore, it was hypothesised that given its wide environmental plasticity, yam cultivars could be adapted to South African growing conditions, especially in the coastal hinterland where it is relative, taro is also produced by rural farmers.

1.3 Aims and Objectives

The aim of this study was to compare agronomic performance of three yam species (*Dioscorea rotundata, Dioscorea cayanensis, and Dioscorea alata*). The specific objectives of the study were to:

- determine plant growth and development,
- determine yield and yield related components,
- determine the nutritional value, in terms of starch content and
- determine “seed” value of harvested material.

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CHAPTER 2

Literature Review

2.1 History, Origin and Production of Yam

Yam (*Dioscorea spp*) originated in three continents: Africa, Southeast Asia, and South America (Alexander and Coursey, 1969). It reached West Africa in the 16^{th} century (International Institute of Tropical Agriculture, 2009). Yam is mainly grown in tropical and sub-tropical regions on about five million hectares in almost forty-seven countries (IITA, 2010). It is widely cultivated in the exotic, damp, and southern Guinea savannah of West Africa (Maroya, 2014). The cultivation of yam on fertile soils with well–distributed rainfall gives good detailed variants in crop production in different agro-ecologies of the world (Akanbi *et al*., 2007).

In terms of area under production in Africa for root and tuber crops, cassava is the largest in production, followed by yam, sweet potatoes, Irish potatoes and taro, respectively (FAOSTAT, 2013). In West Africa, five nations, Benin, Côte d'Ivoire, Ghana, Nigeria, and Togo contribute 96% of global supply of yam (*Dioscorea spp*) and it is produced from four million hectares every year (FAOSTAT, 2013, Table 2.1). Nigeria alone contributes 70% of global yam supply (Maroya, 2014, Table 2.1). The production area of root and tuber crops in South Africa is low and there are no figures available for yam (Table 2.2). Sweet and Irish potatoes are produced by both subsistence and commercial farmers. Taro is mainly a subsistence crop whose production is mainly done by resource-constrained farmers although it is at early stages of commercialisation (Shange, 2004; Mabhaudhi and Modi, 2015).

Table 2.1: The major world top 10 yam producers in 2012 (FAOSTAT 2013).

Rank	Country	Production in tons
1	Nigeria	38,000,000
2	Ghana	6,638,867
3	Ivory Coast	5,674,696
4	Benin	2,739,088
5	Togo	864,408
6	Cameroon	520,000
7	Central African Republic	460,000
8	Chad	420,000
9	Papua New Guinea	345,000
10	Colombia	361,034

Table 2.2: Yield and production area of root and tuber crops in South Africa 2013. [1]FAOSTAT (2013), [2]Shange (2004), [3]Mabhaudhi and Modi (2015).

Crop	Production Area	Yield (kg ha^{-1})
[1] **Sweet Potatoes**	56 000	29474
[1] **Potatoes**	2 252 000	341212
[2,3] **Taro**	No Data available	No Data available
Yam	No Data available	No Data available

2.2 Taxonomy and Botany of Yam

Yam (*Dioscorea spp*) belongs to the genus *Dioscorea* and family *Dioscoreaceae* with approximately 600 species (Coursey, 1967) of which ten are staple yams (Lebot, 2009). The ten staple yam species can be grouped into five divisions which are *Enantiophyllum*, *Combilium*, *Opsophyton*, *Macrogynodium* and *Lasiophyton* (Table 2.3). Some of the species like *D. cayenensis, D. rotundata and D. bulbifera* are said to have originated from Africa, and *D. alata, D. esculenta, D. bulbifera, D. nummularia, D. pentaphylla,* originated from Asian and Melanesia, while *D. trifida* originated from America, *D. opposita* originated from Japan and China, and *D. transversa* originated in Australia and Melanesia (Lebot, 2009). Three widely grown species are white yam (*Dioscorea rotundata*), water yam (*Dioscorea alata)* and yellow yam (*Dioscorea cayenensis)* (Ike and Inoni, 2006; Zaknayiba and Tanko, 2013).

Table 2.3: Important cultivated *Dioscorea* species. Sources: Coursey (1967, 1976), Alexander and Coursey (1969), Purseglove (1972), Abraham and Nair (1991), Rehm and Espig (1991), Degras (1993), Onwueme and Charles (1994), Asiedu *et al.* (1997), Gamiette *et al.* (1999), Malapa *et al.* (2005), Arnau *et al.* (2009), Lebot (2009), Bradshaw (2010), Norman (2010).

Physical Appearance	Botanical Section	Dioscorea Species	Common Name	Geographic Origin	Ploidy
Have vines that twine clockwise	Enantiophyllum	*D. alata* L.	Greater yam; Water yam; Winged yam	South East Asia, Melanesia	2n=20, 30,40,50,60, 70,80
		D. rotundata Poir.	White yam; White Guinea yam	West Africa	2n=40,80
		D. cayenensis Lam.	Yellow yam; Yellow Guinea yam	West Africa	2n=36,54,60, 63,66,80,120, 140
		D. opposita Thunb.	Cinnamon yam	China	2n=40
		D. japonica Thunb.	Chinese yam; Japanese yam	China, Japan	2n=40
		D. transversa R.Br	Marou, wael	Australia, Melanesia	
		D. nummularia	Spiny yam; Wild yam	Melanesia	
Have vines that twine anticlockwise	Combilium	*D. esculenta* Burk.	Lesser yam; Asiatic yam	South-east Asia, Melanesia	2n=30,40,60, 90,100
	Opsophyton	*D. bulbifera* L.	Aerial yam; bulbil yam; bearing yam	Africa, Asia, Melanesia	2n=30,40,50, 60,70,80,100
	Macrogynodium	*D. trifida* L.	Aja, aje, cush-cush yam, Yampi	South America	2n=54,72,81
	Lasiophyton	*D. pentaphylla* L	Five-leaved yam	South-east Asia	2n=40,60
		D. dumetorum Pax	Bitter yam; cluster yam; trifoliate yam	Africa	2n=36,40,45, 54

2.3 Morphology, Cytology and Floral Ecology of Yam

2.3.1 Morphology of Yam

Yam, a monocotyledonous angiosperm, is an annual vegetative plant which has an adventitious root system (Orkwor *et al*., 1998). The yam stem is mostly climbing and usually a smooth thin twining vine. The twining leaves are petiolate, apart from some which are trifoliate with hairs on their stems (*D. dumetorum, D. hispida and D. pentaphylla*) which are alternate, opposite or both occurring on the same stem (Degras, 1993).

Most of the different cultivars are recognized when they are growing in the field by their leaf appearances (Anjorin *et al.,* 2014). For example, leaves of *D. rotundata* have a simple cordate arranged reversely on the nodes, and *D. dumetorum* has compound leaves (Coursey, 1967; Norman, 2010). Thus, it makes them distinguishable. Yam can also be identified by tuber features such as flesh texture, flesh colour, skin structure and colour, as well as the tuber size and shape (Hamon and Toure, 1990; Collins, 1997). The tuber shape can be cylindrical, oblong, pointed or round with a thick outer skin that is dark or light brown and bark-like, ranging from smooth to hairy in appearance, and the size of tuber can differ depending on the weight (IITA, 2007; Figure 2.1).

Figure 2.1: Yam tubers (IITA, 2007).

The colour of yam's flesh varies depending on the species or variety. It can be white or off-white, purple, pink or yellow. The texture differs from wet and delicate to rough, dry and mealy (Degras, 1993). Compared to other root and tuber crops, yam tubers possess a typical dormancy period of 10 to 16 weeks (Orkwor *et al*., 1998; Lebot, 2009). This dormancy period prevents sprouting during storage, enhances storability, and also conserves the quality of yam tubers.

According to recent analysis of morphological and molecular data, the *Dioscoreaceae* family has four different genera - *Dioscorea, Stenomeris, Trichopus* and *Tacca* (which was known as *Taccaceae*) (Chaddick *et al.,* 2002). The morphological features of the genus *Dioscorea* were earlier divided and classified into six different sections (Alexander and Coursey, 1969). However, lack of information on yam phylogenetic relations makes it difficult to identify species and polymorphism and morphological traits; this led to suggestions of reclassification of yam (Chair *et al.,* 2005). For example, *D. rotundata* and *D. cayenensis* were found to have debatable relationships morphologically (Burkill, 1960), suggesting that both species might have originated from the same ancestor. However, Hamon and Touré (1990) and Dansi *et al.* (2000a) found a third group when reviewing polymorphic enzyme systems in-between *D. cayenensis* and *D. rotundata* conforming inter-cluster hybrids. This was reinforced by ploidy analysis with flow cytometry (Dansi *et al.,* 2001). It was further proposed that cultivars of *D. cayenensis* be considered as a species different from *D. rotundata* (Mignouna *et al.,* 2007).

2.3.2 Cytology of Yam

Among the ten most vital cultivated *Dioscorea* species, polyploidy is dominant, with chromosome count ranging from 2n = 20 to 2n = 140 (Lebot, 2009). The cultivated and wild *Dioscorea* species is a good prototype for polyploidy analysis and chromosome development, mostly when it comes to its vegetative proliferation and domestication (Bousalem *et al.,* 2006, Arnau *et al.,* 2010). The presence of one or two chromosome base numbers, x = 9 and x = 10, was revealed in various chromosome counts of *Dioscorea* species (Zoundjihekpon *et al.,* 1990; Dansi *et al.,* 2000b). However, a chromosome base number of x = 20 was found for some species like *D. rotundata* (Scarcelli *et al.,* 2005), *D. alata* (Arnau *et al.,* 2009) and *D. trifida* (Bousalem *et al.,* 2006, 2010). The accession for *D. alata* polyploidy was reported to be 2n =40, 60 and 80 chromosomes (Abraham and Nair, 1991; Gamiette *et al.,* 1999; Malapa *et al.,* 2005; Arnau *et al.,* 2009; Norman, 2010). Therefore, these ascertain that *Dioscorea* species has different chromosome development.

2.3.3 Floral Ecology of Yam

Flowering is sensitive to photoperiod conditions (Arnolin, 1982) and therefore, sometimes yam will not flower. This limits hybridization due to less flowering in most staple yams (Egesi *et al.,* 2002). Environmental factors such as, light intensity, photoperiod, soil fertility, chromosomal factors and phenology can impact the sex ratio and flowering in yam (Degras, 1977). There is a suggestion that *Dioscorea spp.* flowers are entomophillous, which are pollinated by insects (Coursey, 1967), although this requires confirmation (Govaerts *et al.,* 2007). However, when yam plant does flower, the flowering rate amongst the genotypes differs and can be prolific. It is higher in male (staminate) plants of *D. rotundata* and *D. alata* than in their female (pistillate) plants (Bai and Ekanayake, 1998). Although, the essence of a small number of pistillate flowers and lots of staminate was indicated in *D. alata* hybrid (IITA, 1993), the same spike plants with bisexual flowers were also detected in *D. rotundata* genotype (Sadik and Okereke, 1975; Norman, 2010). However, Hahn (1988), made mention of *D. cayenensis* possessing only male flowers.

2.4 Environmental and Cultural Requirements of Yam

Climatic factors such as rainfall, temperature, light and photoperiod has both direct and indirect effects on crop production (Yengoh *et al.,* 2010). Yams are grown in various environments, from the high-rainfall forest region to the seasonally arid savannahs (Craufurd *et al.,* 2001). Therefore, effective yam cultivation involves certain awareness on the environmental conditions and cultural requirements of the crop.

Yam is propagated from seed tubers or tuber cuttings which can replicate vegetatively by transplanting the rhizomes (Onwueme and Charles, 1994). It is not advisable to propagate using vine-cuttings due to slow tuber development. The utilization of genuine seeds as propagules is limited to research stations, mostly in crop improvement platforms (Lebot, 2009). Therefore, it needs more attention. Seed tubers should be taken from vigorous tubers of healthy plants and subjected to a disinfectant treatment (IITA, 2007). The cut surfaces or sides should be coated with ash or fungicides and cured (air dried) for 24 hours (Akanbi *et al.,* 2007). This is to avoid the tubers getting infected with pathogens before planting.

According to Onwueme (1978), root and tuber crops, particularly yam, usually need loose soil for root development and this can also affect root shape. Yams require well-drained, sandy-loam or loam soils with high organic matter (Degras, 1993; Onwueme and Charles, 1994). Cultivation on clayey or stony and compacted soils should be avoided as this restricts root and tuber growth. The optimum soil pH for plant growth is 5.5 – 6.5 (Degras, 1993; Onwueme and Charles 1994).

Research by Diby *et al.* (2004) demonstrated that *D. alata* has more tolerant capacity to poor soil fertility than *D. cayenensis-rotundata*.

Diverse spacing is required for yam all over the regions where it is planted depending on the growth habit and purpose of planting. Subsequent perspectives ought to be considered when deciding the right spacing and planting density for yam; certain density relies upon projected vigour of development, and more extensive spacing has a tendency to generate bigger and many tubers (Onwueme and Charles, 1994). Generally, planting density is kept constant at approximately 10,000 plants/Ha. Spacing of 1 m between plants and 1 m between rows, and planting depth of 10-15 cm (O'Sullivan, 2010).

Despite the fact that yams are drought tolerant, they require abundant dampness all through their developing period, especially from 14-20 weeks after planting when tuber development happens quickly (Onwueme and Charles, 1994). Although yam requires annual precipitation of 1000-3000 mm, in most of its cultivating regions, its capacity to endure for long dry period (Coursey, 1967; Degras, 1993; Onwueme and Charles, 1994), can make it to survive below the required annual precipitation. It was noted that yam can be grown in areas with as little as 400-600 mm of rainfall (Onwueme and Charles, 1994). Yam requires temperature ranging from 25ºC – 30ºC for optimal growth. Temperatures below 15ºC – 20ºC limit growth (Degras, 1993; Onwueme and Charles, 1994; Lebot, 2009). Yams are photoperiod sensitive. Short days support tuber development while long days support vine development (Onwueme and Charles, 1994).

Planting season is dictated by when the farmer' past produce is harvested and seed availability in light of the fact that it gives material to the new produce (Onwuene, 1978). In West and Central Africa, growing of yam is preferably done before the rainy season. Tubers are planted between February in the tropical forest and April in the Guinea Savannah (Akanbi *et al.,* 2007). It is commonly realized that yam can't be planted constantly on the same portion of land. According to Degras (1993), yams are viewed as a challenging crop, so they come first in the rotation cycle. Therefore, they are first to profit from rebuilding of soil supplement and soil structure for good root development. Also, this is to avoid weed rivalry for supplement, dampness, and sunlight (Gigou, 1987). This is a real issue during the initial three months of yam development.

2.5 Agronomic Management

2.5.1 Intercropping, Crop rotation and Mulching

Yam is regularly intercropped with different crop groups. For example: cereals, other root and tuber crops, vegetables and legumes. Yam intercropping with grain leguminous plant is a typical practiced as a weed control strategy (Coursey, 1967; Singh *et al.,* 1986; Onwueme, 1988). Yams are frequently intercropped with maize and vegetables e.g. pumpkins, cucurbits, peppers and okra (Daisy, 1987). Intercropping with maize and cassava or sorghum is common in West Africa (Onwueme, 1988). In the ensuing year, maize and/or rice are planted and, additionally intercropped with different minor harvests while groundnut and cowpea are the primary vegetables intercropped with yam (Ibeawuchi, 2004).

Crop rotation in yam cultivation helps avert degradation of soil quality; it lessens soil erosion, diminishes the pests and diseases build-up, reduces dependence on synthetic chemicals, conserves soil fertility and helps in weed control (Daxl *et al.,* 1994). In West Africa, yam can be crop rotated with crops like groundnuts, maize, cowpea, sesame, cassava, yams, tree legumes, millet/sorghum (Pieri, 1992).

To lessen soil temperature, preserve soil dampness and stifle weed development, it is desirable to mulch the field where yams are planted (Gbadebor, 2006). Mulching helps in even sprouting and weed control. Various methods are used for mulching purposes. These include palm frond, dry coconut fronds, dry grass and other comparative materials (Gbadebor, 2006). However, dry grass is the most commonly used in West Africa. Grass mulch is known to contain some component of Nitrogen, magnesium, calcium, phosphorus and potassium (Odjugo, 2008). Furthermore, these supplements, especially N, P and K are imperative in the development and building of yam tubers, and therefore in the tuber yield (Hahn *et al.,* 1987). In general, regardless of cultivars of yam, those planted in mulched plot are fundamentally higher in tuber length, tuber size, tuber weight and yield of yam than for un-mulched plot (Lai, 1975; IITA, 1995; Odjugo, 2008).

2.5.2 Staking in Yam

Staking is a technique for lifting crawling vines over the ground level by means of supportive erections. There are several practices utilized as a part of staking developing yam plants. The likes of bamboo rods, wood, cassava stalks or any comparable materials that can bolster the yam vines for no less than seven months can be utilized as stakes. Techniques for staking are regular in yam developing zones yet the medium utilized for staking contrasts from one place to another. This is subject to location. Staking methods include: trellising, individual staking and pyramid staking. Trellising method involves each stand of the growth curved to twine with the next in the row, which also joins the next. Individual staking involves a firm stake being placed vertically and the yam crop twine on it. Pyramid staking involves each stand having a stake, but the stakes of three or four adjacent stands are slanted to each other and tied together at the top and each crop after twining its individual length, will also intertwine the other plants (Onwueme and Charles, 1994). Plants are staked immediately after emergence and before vines begin creeping on the ground. Staking is essential in cultivation for some agronomic aims, which includes the following: (i) to decrease the spread of soil-borne diseases from assaulting the developing plants parts (ii) to permit for all-out sunshine capture for plant photosynthesis, so as to get high yielding tubers (iii) and to free soil surface from prickly vines, particularly for prickly yam specie like *D. esculenta* (Lebot, 2009). Staking ought to be made available to tender shoots by coir twine attached to the artificial support and exposed to a height of about 3 m. Staking process can be set up about 20-30 cm away from the planting spot. However, spacing differs with different staking techniques. Depending on cultivar, staking generally has a positive effect on tuber yield (Ennin *et al.,* 2009).

2.5.3 Weed Management

Weeds are part of the problems in yam cultivation. In West and Central Africa, the most common weed in yam cultivation is spear-grass (*Imperata cylindrica*). It contends with yams for resources and their sharp-tipped stolons penetrate the tubers, hence exposing them to attack by pathogens in the soil (Onochie, 1974). The use of chemical control diminishes thickness spear grass, therefore prompting higher yields in yam. The types of herbicides that were discovered for the utilization of weed management in yam are: diuron, metolahar and atrazine metribuzin, ametryne, or linuron (IITA, 1972; Onwueme and Fadayomi, 1980). Mechanical weeding in yam is rare, due to their need for staking and their growth habit (Onwueme, 1978). Weeding can also be controlled with the use of hoe or by hand.

2.5.4 Fertilization

Fertilizer application improves agronomic performance and increases yam tuber yield (Akanbi *et al.,* 2007). In the regions where yams are produced, the use of chemical fertilizer is normal. The need to utilize compound fertilizer in production of yam is influenced by the higher yield typically acquired from manure plots (Ferguson *et al.,* 1970; Azih, 1987; Asadu *et al.,* 1998). The reaction of yams to fertilizer application depends on the soil fertility, species and cultivar. Yams react well to nitrogen and potassium treatment (Coursey, 1967). Further research in distinctive districts of West Africa, showed that utilization of mineral fertilizer had significant value for tuber yields (Diby *et al.,* 2004). The utilization of fertilizer could sometimes enhance leaves and stem production through consensus with the tuber for carbohydrates intake. Fertilizer application to yam is most helpful when the plants metamorphose on the tuber to autotrophy (Asiedu and Sartie, 2010). It is consequently best to apply top-dress fertilizer to yam at around one month after emergence. The root system is broad enough to retain and use the fertilizer. Fertilizer should be applied about 10 cm away from the plant (Akanbi *et al.,* 2007). The amount and mode of fertilizer application depends on the kind of land preparation.

2.5.5 Pests and pathogens

Pests and pathogens decrease yield and yield quality of yam. Yam is susceptible to infection precisely from the seedling stage through to harvesting and even after harvesting (Amusa *et al*., 2003). Pests and diseases of yam include: Insects, nematodes, fungi, bacteria and viruses. The most common insect pests that attack yam are: scale insects (*Aspidiella hartii*), mealy bugs (*Phenacoccus gossypii, Geococcus coffeae*, and *Planococcus citri*) and yam beetle (*Heteroligus spp.*). The main yam pathogen is anthracnose caused by the fungus (*Colletotrichum gloeosporioides* and *Glomerella*). It has a worldwide distribution. Among yam varieties, water yam is most susceptible (Korada *et al*., 2010; O'Sullivan, 2010). Some of the common pest and pathogen that infest yam are shown in (Tables 2.4 and 2.5).

Table 2.4: Some common insect pest of yams. Foua-Bi (1982), Brunt *et al.* (1989), Emehute *et al.* (1998), O'Hair (1990), Sherwood (2004), Lebot (2009), Ashamo (2010), Korada *et al.* (2010).

Pests	Nomenclature	Damage	Geographical Distribution
Mealybugs	*Phenacoccus gossypii*	Field pests	Worldwide
Yam moths	*Dasyses rugosella*	Storage pests	Africa, India, Asia, China, the West Indies.
Yam scale insects	*Aspidiella hartii*	Field and Storage pests, Tuber damage	Worldwide
Yam weevils	*Palaeopus costicollis*	Foliage, Storage pests	The Caribbean, Brazil.
Yam tuber beetles	*Heteroligus specie*	Field pests, Tuber damage	Tropical Africa

Table 2.5: Some common fungal and bacteria diseases of yam. Onwueme (1978), Winch *et al.* (1984), Brunt *et al.* (1989), Emehute *et al.* (1998), Lebot (2009), O'Sullivan (2010).

Diseases	Nomenclature	Damage	Geographical Distribution
Anthracnose	*Glomerella or Colletotrichum gloeosporioides*	Foliage, Small, dark brown spots or black lesions on leave	All yam producing regions worldwide
Leaf spot, neck rot	*Corticium rolfsii*	Foliage, Field disease	Worldwide
Crown gall	*Agrobacterium tumefaciens*	Field disease	West Indies
Leaf blight	*Rhizoctonia solani*	Foliage, Field disease	Worldwide
Leaf spot	*Cercospora spp.*	Tuber wilting disease, field and storage disease	Nigeria

Pests and pathogens can be managed in different ways. These include: planting of healthy materials, use of resistant cultivars (such as TDA 291, TDA 297), crop rotation and fallowing, and treating the sett or tuber with systemic fungicides or alkaline material (Opara 1999, 2003).

2.6 Socio-economical and Nutritional Importance of Yam

Yam is the second most important tuber crop under cultivation in Africa and has high socio-economic value (FAOSTAT, 2013). In some parts of West Africa, yam is included as part of the dowry (bride price) and it also serves as important food source in ceremonies like weddings (O'Sullivan, 2008). Furthermore, it is celebrated as a festival in some parts of West Africa (Osunde and Orhevba, 2009). Yam serves as raw materials for starch in pharmaceutical and industrial companies (Amanze *et al.,* 2011). Apart from being a food source, yam serves as medicinal treatment of arthritis and several allergies (Higdon *et al.,* 2001).

Yam serves as an essential source of income to more than 150 million people in West Africa (Reuben and Barau, 2012). It is also a great source of foreign exchange rate in West Africa (Amanze *et al.,* 2011). Nutritionally, yam is better in terms of Ca, Mg and P content, compared to some roots and tuber crops in sub-Saharan Africa (Table 2.6). Yam is a source of carbohydrate (Etim *et al.,* 2013). The high starch content which is the main storage of polysaccharides makes the edible yam an essential food source in many tropical countries (Chien-Chen *et al.,* 2005). It adds more than 200 dietary calories per capita daily (Reuben and Barau, 2012). According to Splittstoesser *et al.* (1973); and Bhandari *et al.* (2003), the vital amino acids in yam are more than those found in sweet potato, because the amino acid structure of yam protein is suboptimal in cysteine and methionine (sulphur-containing amino acids). Nutrient composition and nutritional value of yam is shown in (Table 2.7).

Yam can be commonly prepared in different methods such as; boiling, baking, or roasting and eaten with vegetable sauce or oil. Boiled yam can be pounded or mashed with mortar and pestle, and eaten as dough or be processed into several food products such as; instant pounded yam and yam flour (Omonigho and Ikenebomeh, 2000; Ferede *et al.,* 2010).

Table 2.6: Some vital nutritional quality of sweet potatoes, potatoes, taro and yam USDA (2014).

	Sweet Potatoes	Potatoes	Taro	Yam
	Content per 100g			
Energy (KJ)	360	322	112	494
Carbohydrate (g)	20	17	26.46	27.9
Protein (g)	2.0	1.6	1.50	1.5
Fats (g)	0.09	0.05	0.20	0.17
A (IU)	2	14187	76	138
C (mg)	19.7	2.4	4.5	17.1
E (mg)	0.01	0.26	2.38	0.39
K (µg)	1.9	1.8	1	2.6
Calcium (mg)	12	30	43	17
Iron (mg)	0.78	0.61	0.55	0.54
Copper (mg)	0.11	0.15	0.172	0.18

2.7 Other constraints to yam production

Other than abovementioned production factors, a few more exist that hinder productivity of yam. These include: availability of labour, level of education, shortage of farm inputs, insufficient of funds, inadequate of material inputs like fertilizer, and insufficient storage amenities (Ike and Inoni, 2006; Shehu *et al.*, 2010; Etim *et al.*, 2013; Maikasuwa and Ala, 2013; Zaknayiba and Tanko, 2013).

Maroya (2014) confirmed these findings further, stating that constraint in production and after production in yam regions emerged from the high rate of damaging yam pests and diseases, both at pre-harvest and postharvest stages. Hard work input such as land preparation, planting, staking, weeding, and harvesting; and the increasing scarcity of virgin acreage fit for yam production thus add to the constraint.

IITA (2013) reported a way to minimize the constraints in yam production is by producing healthy (clean) planting materials and infringement of pest and pathogen progressions through alternations with non-host produces and other agronomic methods. That study recommended the utilization of disease-resistant selections with great receptiveness to high nutrients, the use of effective and suitable organic and inorganic fertilizers and creating more awareness to farmers that are into other root and tuber crops worldwide.

Table 2.7: Nutrient composition and nutritional value of yam in raw harvested method. The National Agricultural Library (USDA), (2014) Note: *µg = micrograms, mg = milligrams

Nutrient composition	Amount per 100 g	% per daily value
Water (g)	70 g	-
Energy (KJ)	494 KJ	-
Protein (g)	1.5 g	-
Fat (g)	0.17 g	-
Carbohydrate (g)	28 g	9
Fibre (g)	4.1 g	16
Sugar (g)	0.5 g	
Calcium (mg)	17 mg	2
Iron(mg)	0.54 mg	4
Magnesium (mg)	21 mg	6
Phosphorus (mg)	55 mg	8
Potassium (mg)	816 mg	17
Sodium (mg)	9 mg	0
Zinc (mg)	0.24 mg	3
Copper (mg)	0.18 mg	
Manganese (mg)	0.40 mg	19
Selenium (µg)	0.7 µg	
Vitamin C (mg)	17.1 mg	21
Thiamine (mg)	0.11 mg	10
Riboflavin (mg)	0.03 mg	3
Niacin (mg)	0.55 mg	4
Pantothenic acid (mg)	0.31 mg	6
Vitamin B6 (mg)	0.29 mg	23
Folate (µg)	23 µg	6
Vitamin A (µg)	7 µg	1
Vitamin E (mg)	0.35 mg	2
Vitamin K1(µg)	2.6 µg	2
Beta-carotene (µg)	83 µg	-

2.8 Harvesting

Harvesting is also referred to as topping, beheading, and milking (Onwueme and Charles, 1994). In West Africa, harvesting of yam is occasionally done in August in tropical forest agro ecological region (180 days after planting). In Guinea Savannah, harvesting is done October and November (about 180 – 270 days) mostly when leaves have dried up (Akanbi *et al*., 2007). Harvesting of yam involves two practices which are single-harvesting and double-harvesting. Single-harvesting is done mostly one month before the dried up till two months after they have dried while Double-harvesting involves first-harvest which is done mostly four–five months of development (Onwueme and Charles, 1994). Yams are set for harvesting when their vine discontinues developing and their leaves is already yellowing or withering up. The tubers are dug out by the use of a 2 m long wooden stick, shovel, hoe or cutlass. They should be placed 10 cm away from the plants so as to avoid any damages to the tuber. Consideration is expected to unearth yams from underneath the soil with least harm to evade extreme wounding that will give entrance for pests and pathogens (Onwueme and Charles, 1994).

2.9 Post-Harvest Handling, Curing and Storage

Post-harvest handling is vital in sustaining the worth of harvested farm yield and lessens the level of damage within the storage and marketing confines. Healthy tubers and diseased tubers are advised to be packed in separate containers to avoid transmission of post-harvest pests and pathogens (Dumet *et al.,* 2008).

Curing aids yam tuber skin to solidify by forming of new flesh underneath the surface of harmed part in the tuber (Bautista, 1990; Jochen, 1993). Clean and smooth tubers recuperate better when cured immediately after harvesting (Booth, 1978). Therefore, all injuries, compressed spaces and different wounds on tuber ought to be neatly removed with alkaline substance, such as lime, chalk or wood ashes to minimise re-infection (Coursey, 1982). The best high temperature for curing newly harvested tuber before storage is between 29ºC–30ºC (Onwueme and Charles, 1994).

Yams can be stored for several months in suitable aerated, non-refrigerated shielded storage buildings (Onwueme and Charles, 1994). Yams should be store under temperature of 12ºC–15ºC. The most common storage for yam is barn in all yam producing regions. Barns are mostly kept below the shade to shield the tuber from extreme temperature and insect infestation (Igbeka, 1985; Ijabo and Jirgba, 1989; Opera, 1999; and Osunde and Yisa, 2000). Yam can also be stored in silos or trench, but this method makes tuber susceptible to pests and rodents attacks (Nwankiti and Makurdi, 1989).

2.10 Conclusion

Yam remains one of the most nutritional crops among root and tuber crops and it occupies an important part in food and farming systems across Africa. Despite limited research and many production constraints, yam has potential as a food security crop. In comparison to West Africa, yam in South Africa is not well known as a tuber crop. The current review of literature provided no indication that the crop cannot be grown in South Africa. Hence, it is necessary to determine yam productivity, yield quality and nutritional value under South African conditions which are typical to those suited to yam production. In this regard, KwaZulu-Natal offers one such environment and there is already significant cultivation of taro in the province. Thus, yam could be another alternative crop for the cropping systems in this province.

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CHAPTER 3

Materials and Methods

3.1 Plant Material

Three different cultivars of yam (*Dioscorea spp*) were obtained from commercial farmers in Gambari, Ilorin, Kwara State, North Central Nigeria (8°16'S, 4°20'E) during 2014. The three cultivars were: white yam (*Dioscorea rotundata*), yellow yam (*Dioscorea cayanensis*) and water yam (*Dioscorea alata*). Seed yams weighing 50-100 g were utilized for the current study. Seed yams used in this study were whole, small tubers (International Institute of Tropical Agriculture, 2012). The three yam cultivars differ in leaf and tuber shape as well as growing period. White yam has narrow ovate leaves. Tubers are cylindrical in appearance with smooth skin and inner flesh and a growing period ranging from 7-10 months. Yellow yam is almost similar to white yam in appearance and tuber shape. However, yellow yam can be distinguished by its broadly ovate leaves and spiny stem. Its tuber inner flesh is yellow and the growing period is 9-12 months. Water yam has ovate to cordate leaves. Tubers have hairs and are oblong or cylindrical in shape while the flesh can be white, purple or pinkish in colour. The growing period ranges from 6-10 months (Figure 3.1).

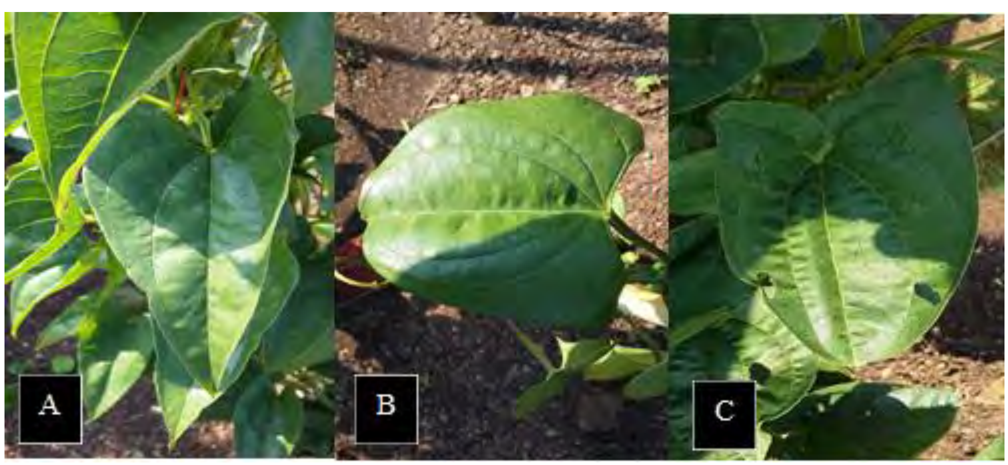

Figure 3.1: White (A), Yellow (B) and (C) Water yam. Cultivars used in the study. Photo taken at the research site for the current study during vegetative growth.

3.2 Description of Experimental Site

A field trial experiment was conducted at the University of KwaZulu-Natal's Controlled Environment Facility (CEF), Pietermaritzburg, South Africa (29°37'12"S; 30°23'49"E) during the 2014/2015 growing season. The environmental conditions were 35/10ºC (day/night) temperatures, altitude of 850 – 950 m, winters are mild with no frost. Soil texture was coarse sand – loam.

3.3 Experimental Design and Field Layout

The experimental design was arranged as a completely randomized design with three species (white yam, yellow yam and water yam) as factor and replicated three times. The plots were 6.5 m long and 3.5 m wide. The ridges were 25 cm high and interplant spacing was 0.5 m with 0.25 m lagging between the last plant on each row and the end of the row. Inter-row spacing was also 1 m, with 1 m spacing between replicates.

3.4 Crop Management

Land preparation for the yam cultivation experiment involved making of ridges by hand-hoe. Prior to planting, soil samples were taken and submitted for soil textural and fertility analyses. Results of soil fertility analysis revealed that there was need for fertiliser application to meet the crop requirements for macro and micro-nutrients (Table 3.1). Fertilizer [NPK 2:3:2 (22)] was applied at 400 kg/ha, broadcast before planting according to soil analysis recommendations. The seed yam was planted by hand. The trial was irrigated using overhead sprinklers daily from 9 – 10 am for 91 days (13 weeks) to achieve crop establishment in all cultivars. The trial received 5 mm irrigated water per day. Weeding was done by hand-hoeing regularly after emergence, to avoid competition of resources with the crops. Staking was done upon emergence to provide support for vine twining (Figure 3.2). Harvesting of yam was done manually eight months after planting. Each of the harvested tubers was cleaned of soil adhered to it and weighed immediately.

Table 3.1: Results of physical and chemical characteristics of soil used for field trial.

ID sample	P mg/L	K mg/L	Ca mg/L	Mg mg/L	pH (KCl)	Zn mg/L	Mn mg/L	Cu mg/L	org. C %	N %	Clay %
CEF	74	472	1522	376	4.91	12.0	34	9.4	3.0	0.35	36

Figure 3.2: Staking of yam at the experimental site.

3.5 Data Collection

3.5.1 Growth and Physiology

Data were collected weekly for tuber emergence, number of leaves, and number of vine by visual counting. Emergence was taken until at least 90% of the plants had emerged (protrusion of the hypocotyl 2 mm above the soil surface). Number of leaves was counted visually as number of fully unfolded, fully expanded leaves. Number of vine was weekly counted as number of hypocotyls protruding above 2 mm of soil surface per yam seed. Chlorophyll content index (CCI) was measured weekly using the SPAD-502 *Plus* Chlorophyll Meter (Konica Minolta, USA) on the second youngest fully expanded, fully exposed and photosynthetically active (at least 50% green leaf area) leaves from establishment (Igamberdieva *et al.,* 2011; Mabhaudhi and Modi, 2013) (Figure 3.3A).

Stomatal conductance (SC) was measured weekly from the 63 DAP using (Leaf Porometer, Model SC-1, Decagon Devices, USA) on the adaxial surface of the second youngest, fully expanded and fully exposed leaves (Figure 3.3C). Chlorophyll fluorescence (CF) was measured on weekly basis on the adaxial surface of second youngest, fully expanded, fully exposed green leaves using a Pocket PEA-Chlorophyll fluorescence system (Hansatech Instruments, United Kingdom). Chlorophyll fluorescence was measured so as to determine plant photosynthetic effectiveness, and before measuring a section area of the leaf to be measured was covered with a lightweight leaf clip (Hansatech Instruments, UK) for 10 minutes to exclude external light sources. (Figure 3.3B).

Figure 3.3: Collection of chlorophyll content index (A), chlorophyll fluorescence (B) and stomatal conductance (C) measurements using non-destructive methods.

3.5.2 Phenology

Time taken to reach a phenological stage was observed as time taken for 50% of experimental plant population to show signs of that stage. Phenological stages that were observed were: crop establishment, end of vegetative state, and physiological maturity. Crop establishment was recorded when 90% of plants had emerged for a given cultivar. End of vegetative growth was marked by end of leaf formation. Physiological maturity was marked as time taken for 50% of tuber with full bark formation.

3.5.3 Yield and yield components

At harvest yield and yield components were measured which included tuber size (length, width circumference, diameter and volume), number of tubers per plant, and tuber above ground biomass. Number of tubers was taken as an average of tuber number per plant. Tuber size was measured as average length, volume, circumference and diameter of tuber per cultivar. Tuber mass was measured as average mass of total tubers.

3.6 Starch Content Determination

Starch was determined using the enzymatic method by Weinmann (1947) with modifications. Freeze-dried, ground material (0.10 g DM) was mixed with 10 ml 80% (v/v) ethanol and homogenized for 60 seconds. Thereafter, the mixture was incubated in a water bath set at 80°C for 60 minutes. Supernatant was suctioned off. These steps were repeated twice then cooled before samples were dried in a Savant Vacuum Concentrator (SpeedVac, Savant, NY, USA). Warm (40 – 50°C) acetate buffer (10 ml) and 200 µl of hexakinase were added to each sample then incubated at 90°C for 30 minutes. Samples were allowed to cool at room temperature before adding 200 µl of G6P-dehydrogenase (G6P-DH) then incubated at 60°C for 20 hrs. Thereafter, samples were vortexed and diluted to 200 ml with distilled water and filtered through Whatman filter paper No. 541. An aliquot (200 µl) of the filtered sample was then taken and diluted further to 3 ml with distilled water. Copper reagent (5 ml) was then added to each sample, vortexed and placed in a boiling water bath for 20 min. Arsenomolybdate (5 ml) was then added to each sample after cooling, vortexed and left to stand at room temperature for one and a half hours. Samples were diluted (with distilled water) to 200 ml, agitated and read at 750 nm.

3.7 Statistical Analysis

Data collected were subjected to analysis of variance (ANOVA) using GenStat® Version 16 (VSN International Ltd, UK) at the 5% level of significance (Appendix). Significant differences between means were determined using Duncan's multiple range tests at $P \leq 0.05$.

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CHAPTER 4

Agronomy and eco–physiology of three yam (*Dioscorea rotundata, Dioscorea cayanensis and Dioscorea alata*) varieties

4.1 Introduction

Crop production is affected by environmental factors (Obiokoro, 2005) such as rainfall, temperature, solar radiation and photoperiodism. Environmental factors often have direct and indirect effects on crop production (Eruola *et al.,* 2011). Root and tuber crops seldom survive during adverse climatic conditions; their growth becomes favourable when environmental conditions are optimal (Leopold, 2015). Their adaptation to a range of environmental conditions and contribution to household food security makes them important to the welfare of small–scale farmers living in rural areas (Scott *et al.,* 2000). In several parts of Africa, in particular East and West Africa (Orkwor and Ekanayake, 1998), the majority of food insecure households depend on root and tuber crops as a source of food, nutrient, income and employment.

The situation is different in Southern Africa where the majority of poor rural households rely mainly on maize for their livelihoods. This is the case for South Africa which is classified as food secure at national level (Food and Agriculture Organization, 2008). However, it still faces food insecurity at the household level (De Klerk *et al.,* 2004), especially in rural and peri–urban areas (Wenhold *et al*., 2012). Reasons given for this include a narrow food basket in poor rural and peri-urban households (Wenhold *et al*., 2007, 2012). In this regard, South Africa has a limited and narrow scope of root and tuber crops [Irish potato (*Solanum tuberosum*), sweet potato (*Ipomoea batatas*) and taro (*Colocasia esculenta*)]. There is a need to include other drought tolerant and nutritious tuber crops to diversify the food basket and improve resilience of food production.

Yam, as a multi–species crop, is important for food, income, and socio–cultural activities in Africa (Ekanayake and Asiedu, 2003). It represents a large pool of agro–biodiversity which also confers them wide environmental plasticity. Growth and development of yam is well–documented under different agro–ecologies in East and West Africa (Orkwor and Ekanayake, 1998). However, growth and development of yam under South African environmental conditions is not yet known. There is need to evaluate the agronomy and eco-physiology of yam varieties under South African conditions. Information generated would be useful in promoting its inclusion in rural cropping systems.

The aim of this study was to evaluate the agronomy and eco–physiology of three different yam species white yam (*Dioscorea rotundata),* yellow yam *(Dioscorea cayanensis),* and water yam *(Dioscorea alata*) under local environmental conditions in Kwazulu-Natal, South Africa. The province already cultivates and utilises root and tuber crops such as sweet potato (Motsa *et al.,* 2015) and taro (Mabhaudhi and Modi, 2015).

4.2 Results

4.2.1 Meteorological Data and Yam Growth

Daily rainfall (mm) was constant from sowing until 45 DAP (Figure 4.1). Afterwards, rainfall was low and irregular. A hailstorm occurred at 11 DAP; however, no damage was observed since yam varieties had not emerged. For this study, rainfall variability did not affect growth and development of yam since the trials were under irrigation. The total amount of daily rainfall received during the trial was 312 mm. However, 599 mm of supplementary irrigation was applied for the duration of the trial.

During the planting season, minimum temperature was below 10°C while maximum temperature ranged between 15°C and 40°C. Maximum temperature became low for growth of yam at 107 DAP. This signified onset of cold stress on growth of yam. However, no frost effect was observed on yam. At 59 DAP; minimum temperature went below 10°C; this may have retarded the growth of yam (Figure 4.1).

The relative humidity value ranged from 35 to 90% throughout the growing season. Relative humidity dropped at 107 DAP, just as much as minimum temperature became low for growth of yam. Afterwards, relative humidity was fluctuating (Figure 4.1).

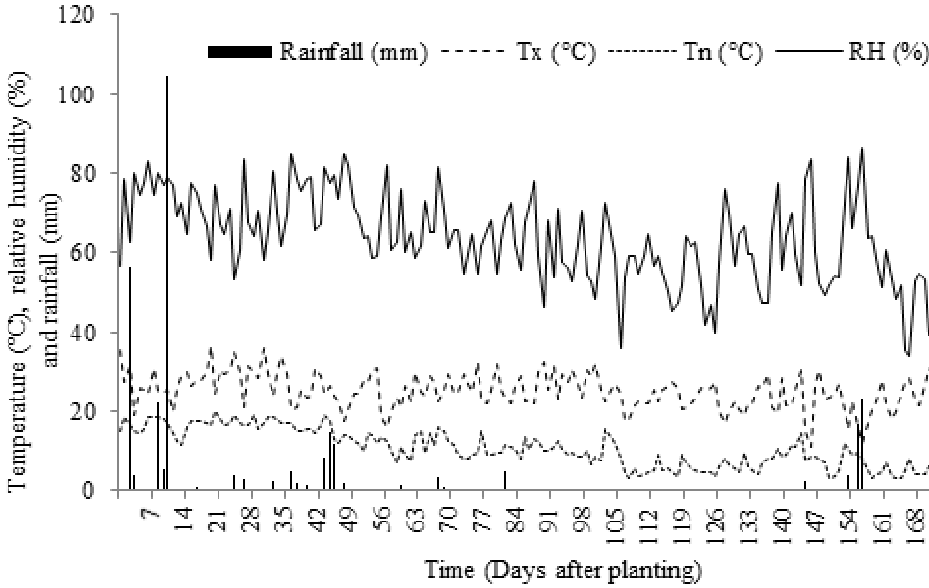

Figure 4.1: Daily meteorological data [rainfall, maximum temperature (Tx), minimum temperature (Tn), and relative humidity (RH)] at the study site during the yam growing seasons.

4.2.2 Emergence

There were significant differences (P<0.001) among the species with respect to emergence. Yellow yam had lower emergence (83.3%) compared to water and white yam (94.4%), respectively (Figure 4.2). Emergence occurred earlier in water yam (56 DAP) relative to white and yellow yam (91 DAP). Yam species showed no uniformity, with zero emergence observed during the first 21 days after planting.

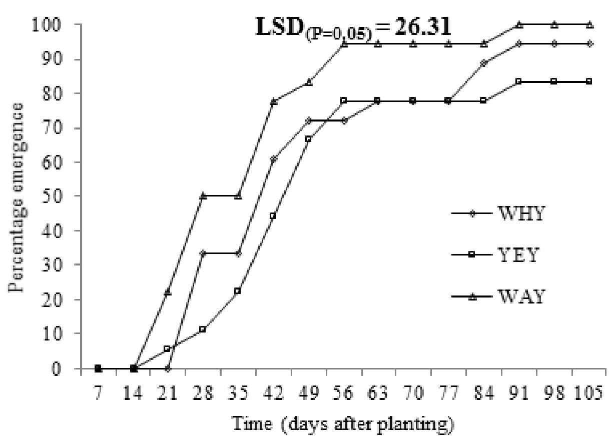

Figure 4.2: Emergence of yam species [White yam (WHY), Yellow yam (YEY) and Water yam (WAY)] measured weekly. The LSD value is for means of species.

4.2.3 Crop Morphology

Number of vine differed highly significantly ($P<0.001$) among yam species. Water yam had the highest vine number (4.3) compared to white (1.8) and yellow yam (1.5), respectively (Figure 4.3A). Vine number for yellow yam reached a peak at 105 DAP while that of water and white yam peaked at 98 DAP. Differences in vine number between species were attributed to genotypic variations and time to crop establishment. Early establishing varieties tended to produce more vines compared to late establishing varieties. Vines provide nodes for leaf growth, and high vine numbers were linked to significantly high leaf numbers in yam varieties. There was a linear correlation between vine number and leaf number from 63 DAP to 98 DAP for all varieties ($r = 0.8$). There were significant differences ($P<0.001$) in number of leaves of the different yam species. Consequently, water yam had the highest leaf numbers (51) compared to white (32) and yellow yam (27), respectively (Figure 4.3B). There were varietal differences in time from onset of cold stress to when senescence occurred. Leaf senescence was delayed in water yam at (112 DAP) compared to white and yellow yam at (119 DAP) in response to cold stress.

4.2.4 Crop Physiology

Stomatal conductance (SC) varied highly significantly ($P<0.001$) among yam species (Figure 4.4). Based on mean value of species over time, white yam (190 mmol m^{-2} s^{-1}) had the highest SC compared to water (169 mmol m^{-2} s^{-1}) and yellow yam (131 mmol m^{-2} s^{-1}), respectively. The SC for all varieties fluctuated throughout the growing period and showed a declining trend over time.

There were no significant differences ($P>0.05$) in chlorophyll content index (CCI) among the different yam species (Figure 4.5). Over time, based on mean values of species, water yam (54) had the highest CCI compared to white (51) and yellow yam (48). All species showed stability (58) at 98 DAP for CCI. Chlorophyll content index for all species fluctuated throughout the growing period. The photosynthetic capacity for all species was similar since there were no differences between species.

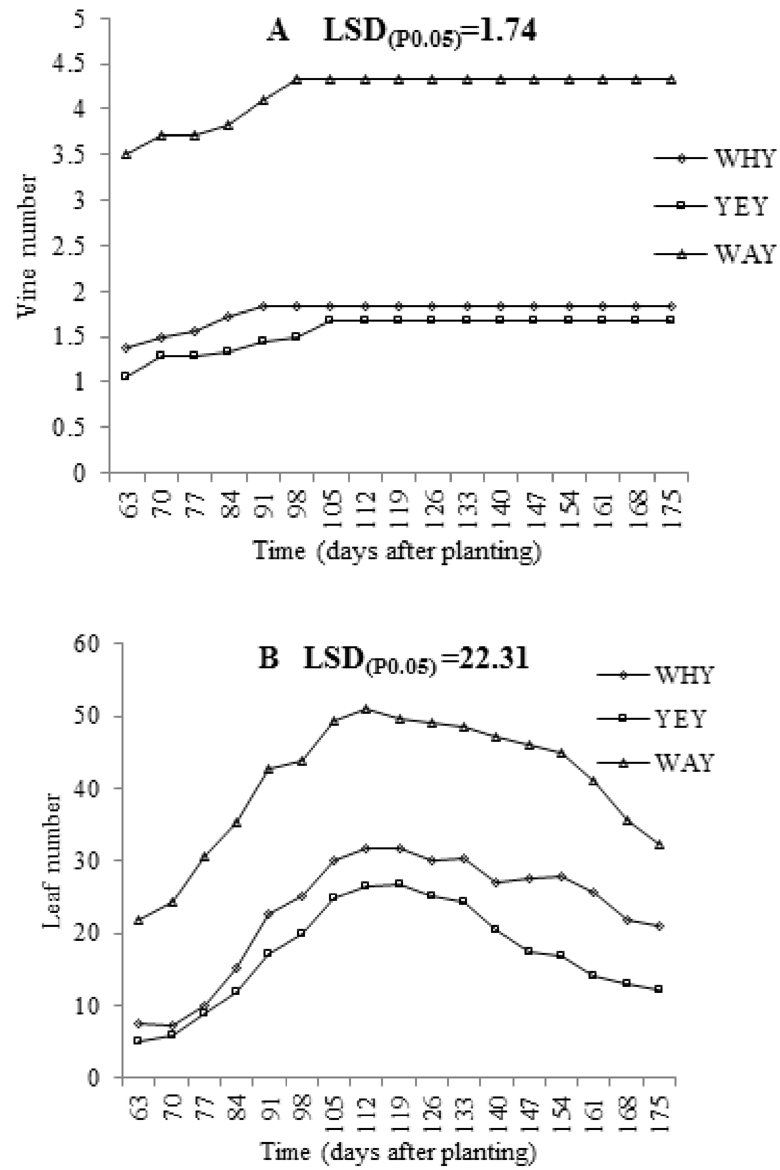

Figure 4.3: Vine and leaf number yam species [White yam (WHY), Yellow yam (YEY) and Water yam (WAY)] measured weekly. LSD values are for means of species.

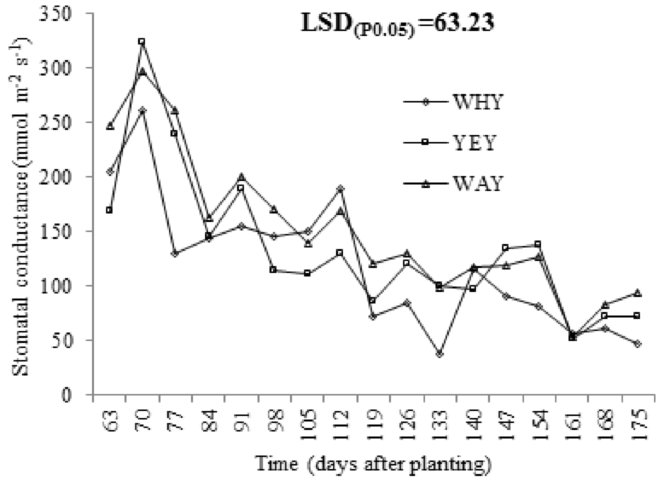

Figure 4.4: Stomatal conductance of yam species [White yam (WHY), Yellow yam (YEY) and Water yam (WAY)] measured weekly. LSD values are for means of species

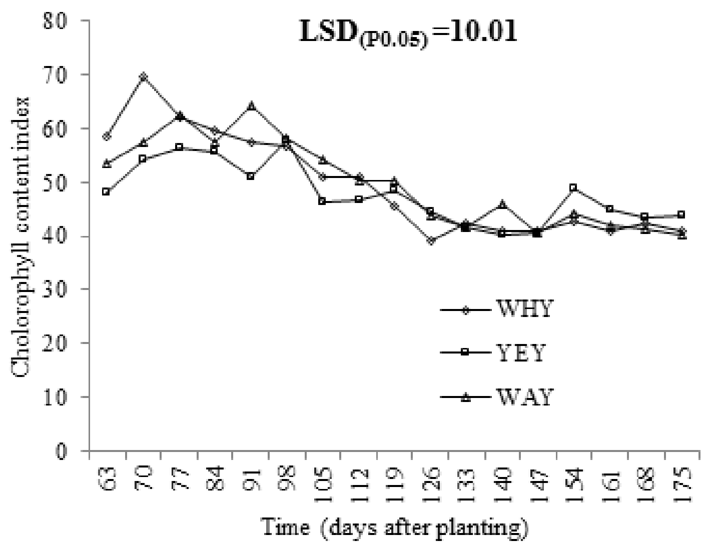

Figure 4.5: Chlorophyll content index of yam species [White yam (WHY), Yellow yam (YEY) and Water yam (WAY)] measured weekly. LSD values are for means of species.

There were no significant differences (P>0.05) in chlorophyll fluorescence among the yam species (Figure 4.6). White and yellow yam species had similar (0.49) chlorophyll fluorescence compared to water yam (0.63). All species showed fluctuating trends around a stable margin (0.7) at 112 DAP. Afterwards, chlorophyll fluorescence declined at 119 DAP for all species.

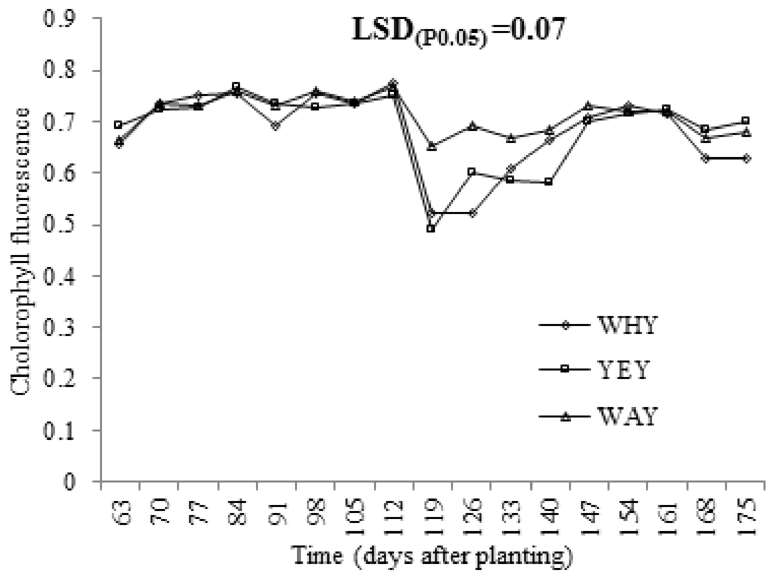

Figure 4.6: Chlorophyll fluorescence of yam species [White yam (WHY), Yellow yam (YEY) and Water yam (WAY)] measured weekly. LSD values are for means of species.

4.2.5 Crop Phenology

There were highly significant differences ($P<0.001$) among yam species with respect to time taken to crop establishment. Time to crop establishment was defined as when 90% emergence was achieved. Water yam established early at (56 DAP), whilst crop establishment was delayed in white and yellow yam at (91 DAP) (Table 4.1). However, time to crop establishment for yellow yam was recorded as time taken for cultivar to reach maximum percentage emergence, since 90% emergence was not achieved. End of vegetative state among the different yam species showed no significant differences. End of vegetative growth was marked by end of leaf formation. Vegetative stage ended earlier for yellow yam (117 DAP) than water (119 DAP) and white (131 DAP) yams, respectively (Table 4.1). There were significant differences ($P<0.001$) among yam species with respect to physiological maturity. Water yam reached physiological maturity earlier than white and yellow yam respectively.

Table 4.1: Phenological development of three yam cultivars at the experimental site.

Cultivar	Crop establishment	End of vegetative state	Physiological maturity
		(days)	
White yam	91b	131a	116b
Yellow yam	91b*	117a	119b
Water yam	56a	119a	109a
LSD(0.05)	27.48	27.99	5.3
%cv	30.4	10.1	2.0

* Time to crop establishment was recorded as time taken for cultivar to reach maximum percentage emergence, since 90% emergence was not achieved.

4.3 Discussion

Temperature thresholds describing upper and lower thresholds for yam cultivation were lacking in the literature. However, sprouting studies (Adesuyi, 1982; Mozie, 1984; Elsie, 2011) gave an indication that sprouting was inhibited at temperatures below 10°C (Mozie, 1984), suggesting that this may be the lower temperature threshold. Sprouting significantly reduces above 35°C; however, metabolic activity and growth does not cease (Passam, 1977). Upper threshold temperature can therefore be hypothesized to be ≥40°C for yam (Elsie, 2011). The variations in weather parameters, mainly temperature and relative humidity, formed diverse situations, with cold stress and heat stress occurring at different stages of crop growth. In relation to the cited lower and upper temperature thresholds, minimum temperature became low for growths of yam at 107 DAP. Exposure of crops to higher or lower temperatures than those optimal for growth can result in both physical and biological damage (Lyons 1973; Grace *et al.,* 1998; Rivero *et al.,* 2001).

Uneven emergence of yam consequently leads to reduction in yield (Cornet *et al.,* 2014). Emergence of yam species in the study was uneven, with yellow yam failing to reach 90% emergence. However, it is worth noting that yellow yam percentage emergence was above the acceptable threshold of 80% (Elsie, 2011). Craufurd *et al.* (2001) reported that duration to emergence of yam was typically early between 30 to 50 DAP, but could take longer if environmental conditions were unfavourable, such as low temperature. The effect of temperature ≤10°C exposes yam varieties to cold stress, which in turn stops the growth of yam (Mozie, 1984). This suggests that yellow yam may be more sensitive to low temperatures than the other two varieties. Early emergence in yam has previously been associated with corresponding early tuber formation and high yield (Cornet *et al.,* 2014). In this regard, it would be advisable to grow water yam as it had early and high emergence.

Cold stress or low temperature has been reported to result in reduced plant growth and crop productivity due to inhibition of cell division and photosynthesis (Hasanuzzaman *et al.,* 2013). The trend observed showing reduction in number of leaves under low temperature was consistent with reports by Onwueme and Charles (1994) and Lebot (2009) who observed reduced growth in yam species subjected to cold stress. Common yam species are known to differ morphologically (Tamuri *et al.,* 2008). High vine and leaf numbers confer photosynthetic and yield advantage in yam varieties. Therefore, water yam had the advantage of giving more yields due to its high vine and leaf number. Plants, when exposed to temperatures below a specific threshold, are prone to cold stress (Hong-Bo *et al.,* 2010). The effect on crop morphology was due to prolonged cold stress after minimum temperature went below 10°C. This prompted early senescence of leaves and decline in leaf number across all yam varieties.

Environmental conditions are not always favourable for crop growth. Effective tolerance of plant species to unfavourable weather condition relies on their ability to acclimatise (Hong-Bo *et al.,* 2010; Mabhaudhi *et al.*, 2013). Stomatal regulation (opening and closing) is influenced by relative humidity which facilitates water loss from the plant through transpiration as well as photosynthesis (Bareja, 2011). The decrease in stomatal conductance over time was attributed to decrease in temperatures, prolonged cold stress at temperature below 10°C, and decreasing relative humidity over time. Reduction in stomatal conductance confines limits the ability of plants to assimilate carbon dioxide (Ocheltree *et al.,* 2013); this has e negative effect on biomass accumulation. Differences among yam varieties can be attributed to genotypic differences. Genotypic differences in stomatal regulation have been reported elsewhere in other root and tuber crops (Dwelle *et al.,* 1981). In this regard, white yam indicated high maintenance of stomatal conductance under unfavourable conditions as demonstrated by its greater display of stomatal control making it more suitable for production.

Chlorophyll content is an indicator of photosynthetic capacity of plant tissue (Nayyar and Gupta, 2006). Chlorophyll content is an important index used in estimating plant nutrition condition (Zhao *et al.,* 2011). Temperature is involved in the chlorophyll effectiveness of yam (Onwueme, 1978); with low temperature being detrimental to yam physiology (Ramakrishna and Ravishankar, 2011). The results obtained in the current study showed reduction in the chlorophyll content of yam due to declining temperatures below the lower threshold. Oyetunji and Afolayan (2007) reported similar findings of declining chlorophyll content in yam varieties subjected to cold stress. It was reported that low temperature caused reduction or stopped chlorophyll synthesis in yam. Decreasing chlorophyll content index in response to cold stress was linked to leaf senescence and loss of canopy cover. This would have impaired biomass accumulation possibly leading to low yields.

A lot of environmental factors alter chlorophyll capacity in pants (Hakan *et al.,* 2012). The light use effectiveness for photosynthesis is determined by chlorophyll fluorescence (Oyetunji and Afolayan, 2007); with PSII being prone to damage under low temperature (Hasanuzzaman *et al.,* 2013). Values of chlorophyll fluorescence less than 0.73 observed for all yam varieties in the current study confirm that the photosynthetic apparatus had incurred some damage due to low temperatures. Similar findings were reported by Yorda-nova and Popova (2007) and Silva *et al.* (2004) in exposure of wheat to low temperature at 3°C which resulted in decreased chlorophyll with intense reduction in photosynthetic performance. The observed decrease in chlorophyll content index can also be linked with chlorophyll fluorescence and overall impairment of plant photosynthetic capacity.

The time to crop establishment is of economic importance in managing yam growth and development by farmers. Effectiveness, time and degree of stress have an important role in crop establishment. The trend in time to crop establishment was observed to be affected by declining temperatures, especially white and yellow yam. Craufurd *et al.* (2001) reported that time to maximum establishment of yam was typically 60 to 90 days after planting. It was further emphasized that any biotic or abiotic stress during this stage could cause severe distress to the growth and development of plants, and consequently tuber yield. Temperature declined after 59 DAP and this might have prolonged dormancy in yam due to cold stress; this would explain the observed slow establishment, especially in yellow yam. The time to end of vegetative state and physiological maturity observed in the current study concur with reports by Craufurd *et al.* (2001) that it takes 80 to 150 days for yam to attain canopy senescence and tuber maturity. However, the ability of yam, notably water yam, to adapt to the low temperatures experienced during the study suggests that it may be suited for off-season production in KwaZulu-Natal.

4.4 Conclusion

The results obtained suggest that there is potential for growing the three varieties of yam during winter in KwaZulu-Natal. An understanding of the environmental conditions that control the production of yam varieties is necessary for maximising productivity. The performance of water yam in terms of establishment, growth and physiology suggests that it may have better adaptation relative to white and yellow yam. While this study was conducted during the winter season to assess possibility for off-season production, it would be imperative to conduct a similar study during summer. This would allow for a complete evaluation of the yam varieties.

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CHAPTER 5

Yield and nutrient of three yam (*Dioscorea rotundata, Dioscorea cayenensis, and Dioscorea alata*) varieties

5.1 Introduction

Out of the crops that provide food and energy to people, tuber crops (5.4% energy) are the second main crop after cereals (49%) (Nayyar, 2014). According to Nayyar (2014), yam ranks among the top 15 crops in the world in terms of area cultivated. They are a good substitute source of food to lessen hunger and malnutrition. South Africa is one of the countries that are affected by malnutrition, most especially the rural poor areas (Wenhold *et al.,* 2012). The addition of other root and tuber crops to the food basket, especially ones with high energy supplement, will help alleviate hunger and malnutrition in rural areas.

Apart from providing basic food security and income, yam has high nutritional content compared to other root and tuber crops (Rakotobe *et al.,* 2010). They serve as a major source of energy, carbohydrate, vitamins and dietary supplement for most subsistence farmers in West and East Africa (Wanasundera and Ravindran, 1994; Adeleye *et al.,* 2010). According to Knoth (1993), and Osunde (2008), yam can supply 100% of the energy and protein, 13% of calcium and 80% of iron requirement in human diets. Carbohydrate content in yam is categorized as starch, polysaccharides and sugar (Osunde, 2008). The importance of starch cannot be overemphasized in both food and non-food industries such as pharmaceutical and textile industries (Alinnor and Akalezi, 2010).

Several authors (Osunde and Orhevba, 2009; Akanbi *et al.,* 2007; Aseidu and Sartie, 2010) have reported on the nutritional composition for cultivated yam in West Africa. However, to the best of our knowledge, there were no published studies on nutritional composition of yam tubers in South Africa. This can be attributed to the fact that yam is not part of South Africa's root and tuber crops. The aim of the chapter was to evaluate the starch content of three different yam varieties white yam (*Dioscorea rotundata*), yellow yam (*Dioscorea cayenensis*), and water yam (*Dioscorea alata*) in Kwazulu-Natal.

5.2 Results

5.2.1 Yield and yield components

There were no significant differences (P>0.05) among the different yam species with respect to all measured variables (Table 5.1). However, based on mean values, yellow yam (419 g) had the highest biomass compared to white (374 g) and water yam (347 g), respectively (Table 5.1). Consequently, it had the highest in volume (545 mm^3) compared to water (501 mm^3) and white yam (334 mm^3), respectively. Water yam had the highest tuber of yield (24 t ha^{-1}) compared to white (18 t ha^{-1}) and yellow yam (11 t ha^{-1}), respectively (Table 5.1). For all the other yield components (tuber number per plant, length, circumference and diameter), water yam was superior to yellow and white yam, respectively (Figure 5.1).

Figure 5.1: Some of the harvested yam at the experimental site.

Table 5.1: Tuber mass, number of tuber, length, volume, circumference and diameter of fresh yam tubers of harvest 2015.

Yam Varieties	Tuber No. plant^{-1}	Biomass plant^{-1} (g)	Length plant^{-1} (cm)	Volume plant^{-1} (mm^3)	Circumference plant^{-1} (cm)	Diameter plant^{-1} (cm)	Tuber yield (kg m^{-2})
White yam	1.30a	374a	13.78a	334a	26.1a	8.31a	1.18a
Yellow yam	1.80a	419a	14.17a	545a	26.6a	8.46a	1.80a
Water yam	2.90a	347a	15.22a	501a	30.7a	9.78a	2.00a
LSD$_{(P=0.05)}$	1.910	329.6	6.132	359.3	12.44	3.958	1.467
%cv	42.1	38.3	18.8	34.5	19.7	19.7	39.0

5.2.2 Moisture and Starch content

There were significant differences (P<0.001) among yam species with respect to moisture content. Moisture content was observed to be high in water yam (19.65%) compared to yellow (15.74%) and white yam (9.16%), respectively (Table 5.2). There were no significant differences (P>0.05) among yam species with respect to starch content (Table 5.2). However, water yam had the highest (66.17%) starch content compared to yellow (64.24%) and white yam (58.74%), respectively (Table 5.2).

Table 5.2: Moisture and Starch Content on 100% dry matter basis of yam tubers of harvest 2015.

Yam Varieties	Moisture Content (%)	Starch Content (%)
White yam	9.16a	58.74a
Yellow yam	15.74b	64.24a
Water yam	19.65c	66.17a
LSD$_{(P=0.05)}$	3.381	7.41
%cv	10.0	5.2

5.3 Discussion

Higher yield in yam tuber relates to early emergence (Cornet *et al.,* 2014). Although all the variables between the yam species did not significantly differ, high tuber number per plant for water yam may be attributed to early emergence and high vine and leaf number. This may also explain water yam having the highest tuber of yield. Climatic conditions such as temperature, solar radiation, and drought influence yam yields (Carsky *et al.,* 2010). In relation to the observed weather data during the growth season of the three yam varieties, low temperature might have affected the yields of yam. Low temperature lowers crop yield (Hasanuzzaman *et al.,* 2013). The average mean for the result of number of tuber per plant showed the range from 1.30 to 2.90 for all yam varieties. This was contrary to earlier reports by Asadu and Dixon (2013) that the number of tuber per plant range from 1.5 to 1.8 in Eastern Nigeria, West Africa. However, the length of the tuber in the report was 25.20 cm, which was greater than the highest tuber length (15.22 cm) observed in this study.

The tuber yield per hectare for the three species was observed to be between 11 t ha^{-1} and 24 t ha^{-1}. This was despite the low temperature regimes experienced during the season and observed stunted growth (Chapter 4, Fig 4.1). This was contrary to reports by Verter and Becvarova (2014) of low yam yields (10 t ha^{-1}) under sub-optimum environmental conditions. However, under optimum environmental conditions the yield potential of yam ranges from 20 to 50t/ha. Given that the current study was conducted during the winter season, the results obtained confirm the wide environmental plasticity of yam. Currently cultivated root and tuber crops such as sweet potato are sensitive to low temperatures often resulting in crop failure (Motsa *et al.,* 2015). This implies that in such environments yam could be considered as an alternative.

Yam nutritive value is related to its high moisture and starch content. The moisture content in this study for white and yellow yam conforms to reports by Moorthy (2008) that moisture content for white and yellow yam ranges from 8 to 18.6%. On the other hand, the result for water yam was contrary to the same report. It was reported that moisture content for water yam ranged from 13.6 to 18.2% (Moorthy, 2008); the moisture content observed in the current study was higher than that. Starch is the main determinant of yam's physical and chemical properties (Osagie, 1992; Baah, 2009). The result of the starch content observed in the study, particularly for water yam, was within the range reported by Oli (2006) which was from 65.2 to 76.6%. However, it was contrary to reports by Wanasundera and Ravindran (1994) of range of 75.6 to 84.3% starch content. The fairly high starch content achieved during winter implies that yam production can be considered to meet the gap in nutrition that usually occurs during the time between planting and the next harvest.

5.4 Conclusion

Yam moisture and starch content was within accepted and reported values found in the literature. Low yam yields were attributed to low temperatures during the growing season. Water yam performed well relative to yellow and white yam. The ability of yam to produce reasonable yields even when planted off-season confirms its wide environmental adaptation and suitability for consideration as an alternative food security crop. Future studies should consider conducting a complete nutritional profile of yam species as this would be more meaningful to informing on its value for addressing malnutrition.

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CHAPTER 6

General Conclusion and Recommendations

6.1 General Discussion

In sub-Saharan Africa (SSA), food security remains a critical challenge as the population continues to increase (Ekanayake and Asiedu, 2003). Growing population and limited resources are placing pressure on the capacity of agriculture, especially smallholder agriculture, to deliver food security. In this regard, there is growing food insecurity, even in countries like South Africa that are generally considered as food secure. Foods that can alleviate food insecurity, both now and in the intermediate future, are required to lessen the impacts of growing food insecurity (Canadian International Development Agency, 2010). Diversification of crop species has been suggested as a means to addressing food insecurity by broadening the food basket (Modi and Mabhaudhi, 2013). South Africa being one of the countries affected by malnutrition (Wenhold *et al.,* 2012), depends more on staples like cereals and grain legumes and a narrow range of root and tuber crops [Irish potato (*Solanum tuberosum*), sweet potato (*Ipomoea batatas*) and taro (*Colocasia esculenta*)], respectively (Allermann *et al*., 2004). There is a need to embrace other alternative tuber crops to broaden the food basket and improve resilience of food production. It was on the basis of this hypothesis that this study was conducted to assess the agronomic performance of popular yam cultivars under Kwazulu-Natal conditions.

Root and tuber crops are one of the essential staples after cereals and grain legumes for over 20% world's populace (Orkwor and Ekanayake, 1998). Yam remains one of the staple foods that plays an important part in food security and livelihood systems of the populace (Maroya *et al.,* 2014). It has high nutritional value (energy, carbohydrate, vitamins and dietary supplement) (Wanasundera and Ravindran, 1994; Adeleye *et al.,* 2010).

Chapter 4 evaluated growth and development of the three yam species. The results showed that cold stress impacted negatively on plant growth. This was observed by slow and uneven emergence, stunted growth and suppressed physiology. Water yam performed better than the other species under these conditions. It managed to maintain a relatively larger canopy size with longer duration. This was associated with its stomatal regulation and ability to maintain relatively high chlorophyll content index and chlorophyll fluorescence relative to the other two species. This allowed it to perform better than yellow and white yam; with yellow yam being shown to be susceptible to cold temperature stress especially during establishment.

The results of yield and yield components (Chapter 5) were consistent with the observations of growth and development (Chapter 4). The results showed that there were no statistical differences for all yield components measured. Although yellow yam was observed to have the higher biomass compared to white and water yam, water yam produced the highest tuber yield. The superior performance of water yam relative to white and yellow yam was linked to its growth and development characteristics which allowed for longer yield formation and availability of assimilates for tuber filling. In addition, water yam was also shown to have higher moisture and starch content compared to white and yellow yam. High starch content was associated with the ability to maintain photosynthetic capacity and thus assimilate production under sub-optimum conditions.

While the current study was conducted during the winter season, it is noteworthy that yam was able to produce reasonable yields under such sub-optimum conditions. This suggests that yam can be produced in areas where temperatures may be too low during the winter for sweet potato and taro production. In such cases, producing yam would address the shortages in food supply that are normally experienced by farmers during the time between planting and the next harvest. In addition, the results confirmed that yam has wide environmental adaptation, especially water yam and should be considered for inclusion in rural cropping systems in South Africa. However, the results obtained in this study are of a preliminary nature and would require further field trials, preferably multi-site trials to fully establish its suitability to a range of agro–ecologies.

6.2 Future Teaching, Learning and Research Possibilities

The following recommendations may be made as regards the observations made during the study in order to enhance to promotion of the crop;

- Selecting the right planting time for crop growth is important, hence further study to investigate and determine the range of time period of planting is necessary. Early planting is encouraged i.e. September/October.
- Planting in a different (site) environment within or outside the province needs to be put into consideration.
- The investigation of intercropping with other crops such as cereals, legumes and vegetables should be explored.
- Research on the use of cover crops, organic matter to improve growth, development and yield of yam should be considered.

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APPENDICES

Appendix 1: List of tables of ANOVAs for Chapter 4

Variate: EMERGENCE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	527.0	263.5	0.92	
REP.*Units* stratum					
DAS	12	135303.1	11275.3	39.50	<.001
VAR	2	6667.0	3333.5	11.68	<.001
DAS.VAR	24	3024.9	126.0	0.44	0.987
Residual	76	21695.9	285.5		
Total	116	167218.0			

Variate: NUMBER OF VINE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	5.432	2.716	2.35	
REP.*Units* stratum					
DAS	15	5.782	0.385	0.33	0.990
VAR	2	203.336	101.668	88.10	<.001
DAS.VAR	30	0.678	0.023	0.02	1.000
Residual	94	108.480	1.154		
Total	143	323.708			

Variate: NUMBER OF LEAVES

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
REP stratum	2		4298.0	2149.0	11.35	
REP.*Units* stratum						
DAS	15		9068.8	604.6	3.19	<.001
VAR	2		14969.5	7484.7	39.54	<.001
DAS.VAR	30		372.8	12.4	0.07	1.000
Residual	93	(1)	17606.4	189.3		
Total	142	(1)	45726.2			

Variate: SC

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
REP stratum	2		15293.	7647.	5.03	
REP.*Units* stratum						
DAS	15		508354.	33890.	22.28	<.001
VAR	2		24889.	12445.	8.18	<.001
DAS.VAR	30		60751.	2025.	1.33	0.151
Residual	93	(1)	141446.	1521.		

Total 142 (1) 747647

Variate: CCI

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
REP stratum	2		41.38	20.69	0.54	
REP.*Units* stratum						
DAS	15		7242.52	482.83	12.66	<.001
VAR	2		166.60	83.30	2.18	0.118
DAS.VAR	30		1138.08	37.94	1.00	0.486
Residual	93	(1)	3545.70	38.13		

Total 142 (1) 12041.46

Variate: CF

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
REP stratum	2		0.021046	0.010523	4.95	
REP.*Units* stratum						
DAS	15		0.506515	0.033768	15.90	<.001
VAR	2		0.029030	0.014515	6.83	0.002
DAS.VAR	30		0.105953	0.003532	1.66	0.034
Residual	93	(1)	0.197561	0.002124		

Total 142 (1) 0.857136

Variate: DAYS TO END OF VEGETATIVE STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	337.6	168.8	1.11	
REP.*Units* stratum					

VAR	2	337.6	168.8	1.11	0.414
Residual	4	609.8	152.4		

Total 8 1284.9

Variate: PHYSIOLOGICAL MATURITY

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	43.556	21.778	4.00	
REP.*Units* stratum					
VAR	2	141.556	70.778	13.00	0.018
Residual	4	21.778	5.444		

Total 8 206.889

Appendix 2: List of tables of ANOVAs for Chapter 5

Variate: TUBER NO PER PLANT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	1.2800	0.6400	0.90	
REP.*Units* stratum					
VAR	2	4.0200	2.0100	2.83	0.171
Residual	4	2.8400	0.7100		

Total 8 8.1400

Variate: MASS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	67729.	33865.	1.60	
REP.*Units* stratum					
VAR	2	7748.	3874.	0.18	0.839
Residual	4	84547.	21137.		

Total 8 160024.

Variate: LENGTH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	20.146	10.073	1.38	
REP.*Units* stratum					
VAR	2	3.307	1.654	0.23	0.807
Residual	4	29.265	7.316		

Total 8 52.718

Variate: VOLUME

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	87301.	43650.	1.74	
REP.*Units* stratum					
VAR	2	73794.	36897.	1.47	0.332
Residual	4	100482.	25121.		

Total 8 261577.

Variate: CIRCUMFERENCE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	92.41	46.20	1.53	
REP.*Units* stratum					
VAR	2	38.98	19.49	0.65	0.571
Residual	4	120.46	30.11		

Total 8 251.84

Variate: DIAMETER

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	9.369	4.685	1.54	
REP.*Units* stratum					
VAR	2	3.947	1.974	0.65	0.571
Residual	4	12.196	3.049		

Total 8 25.513

Variate: TUBER_kg_m2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	0.8870	0.4435	1.06	
REP.*Units* stratum					
VAR	2	1.1191	0.5595	1.34	0.359
Residual	4	1.6749	0.4187		
Total	8	3.6809			

Variate: MOISTURE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	6.510	3.255	1.46	
REP.*Units* stratum					
VAR	2	168.625	84.312	37.89	0.003
Residual	4	8.901	2.225		
Total	8	184.035			

Variate: STARCH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	5.27	2.63	0.25	
REP.*Units* stratum					
VAR	2	89.27	44.64	4.17	0.105
Residual	4	42.79	10.70		
Total	8	137.33			