Assessing Nutritional Water Productivity of Selected African Leafy Vegetables Using The Agricultural Production Systems Simulator Model

Thobeka G. Kunene (214548527)

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the University of KwaZulu-Natal, Pietermaritzburg, South Africa. The study was financially supported by the Sustainable and Healthy Food Systems (SHEFS).

The contents of this thesis have not been submitted in any form to another university except where it is acknowledged in the text. The results reported are due to an investigation by the candidate.

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Prof Albert Modi. (Supervisor)

Date: 08 December 2020

I, Thobeka Kunene, 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 additional information unless expressly acknowledged as being sourced from other persons;

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(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 and nutrition insecurities are regarded as one of the main challenges in the Sub-Saharan region. While substantial progress has been made to address food and nutrition challenges, this progress has varied across the region and over time in response to climate change hazards. Agriculture has been used as the main driver to improve food and nutrition security; however, productivity in these marginalised communities remains low. African leafy vegetables (ALVs) provide an unprecedented opportunity to ensure food security, lessen poverty and diversify farming systems while improving human health and increasing income. Crop modelling can generate information about the crop's growth, development, water, and nutritional needs. The primary objectives of this study were (i) to assess the growth and productivity of selected ALVs (amaranth (*Amaranth spp*), cowpea (*Vigna unguiculata*), sweet potato (*Ipomoea batatas*) and wild mustard (*Sinapis arvensis*)) under different management practices, and (ii) assess water productivity (WP) and nutritional water productivity (NWP) of the selected ALVs. Desktop-based research was conducted to achieve the mentioned objectives. Here, information on the studied crops' agronomy secondary data was gathered through a careful literature search. This secondary information was then used to model growth and productivity and quantify nutritional water productivity at different management practices. The Agricultural Production systems SImulator (APSIM) was used to simulate growth and productivities under different management scenarios of planting date, plant density, fertiliser application and irrigation. We used the soil and climatic data from the University of KwaZulu-Natal's research farm (Ukulinga Research Farm) situated in Pietermaritzburg, South Africa (29°37′S; 30°16′E; 775 m a.s.l.), to calibrate the model. All data analysis was done using descriptive statistical analysis (R software). All mean values were subjected to a t-test set at $p<0.05$ significance. The results showed that depending on crop species. Different management practices can be relevant to achieve optimum growth and productivity for various purposes. The investigated ALVs were found to have high nutrient content. Compared to one another, amaranth was more nutrient-dense and wild mustard the least dense crop. On the other hand, NWP was comparatively high on both amaranth and cowpea.

Keywords: African leafy vegetables, ALVs, crop modelling, APSIM, food and nutrient security

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Above all, I would like to thank God almighty for life He bestowed on me. More than anything, I would like to give thanks and acknowledge all the grace and wisdom He has blessed me with. Thank you, Lord God, for being my redeemer.

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CHAPTER 1

1.1 Thesis outline

The study's objective was addressed by assessing selected African leafy vegetables and modelling experiments for 15 years (2004 -2019). The study was then represented in a paper format that consists of interlinked chapters.

Chapter 2 is a literature review that outlines the status of underutilized crops in South Africa. This chapter addresses the first objective by tackling agronomy issues through a literature search of relevant articles and modelling. Its revises the state, distribution, and agronomic production of selected underutilized crops in South Africa. APSIM model overview as a favourable crop simulation model (CSM) was also included in the thesis.

The second objective addressed in **Chapter 3**, where the quantification of yield and water use of selected ALVs under different management options, was done through a series of modelling simulations. The assumption is that improved fertility will result in improved nutrition density, thus improved nutritional yield. Water use also plays a critical role in promoting the uptake of nutrients, thus contributing to improved yield.

Chapter 4 addresses the third objective, whereby the range of nutrient content of selected ALVs was determined using secondary data. This exercise aims to quantify nutrients. To find out what nutrients these crops are rich in and in what density (quantity). The search was done using Web of Science and Scopus as key search engines, and the results on micro-and macro-nutrients recorded in the form of a table. The measurement units were standardised to g/100 g for macronutrients and mg/ 100g for micro-grams for an accurate analysis. Units for energy and vitamin A was left as Kcal and mg RE/100 g, respectively.

Chapter 5 addresses objective number 4, where nutritional water productivity of selected ALVs under different management practices is determined using modelling outputs and through a series of calculations where water-use and water use efficiency is determined. This chapter is directly connected to chapters two and three because both chapters will use chapter 3 results to analyse and conclude the nutritional water productivity.

GENERAL INTRODUCTION AND OVERVIEW

Unacceptable slow and uneven progress of reducing hunger and malnutrition remain despite the commitments made by many African governments to end food nutrition insecurity at the International Conference on Nutrition (ICN) in 1992 (Jan van Rensburg et al., 2009). No country in sub-Saharan Africa (SSA) has met a minimum feeding of 200 kg person $^{-1}$ year^{-1} of vegetables and fruits (Nyathi et al., 2018c). South Africa is generally known as being food and nutrition secure at a national level. Still, about 30% of its population is considered food and nutrition insecure at a household level. About 4 million people residing in marginal communities suffer from malnutrition in over-nutrition and undernutrition (Govender et al., 2017). A phenomenon is known as "hidden hunger" is a state of chronic lack of micronutrients such as Fe and Zn and vitamins, A and C, mainly on the increase in rural and urban areas (Pretorius, 2014). Agriculture can improve food and nutrition security in many marginalised communities; however, productivity in many marginalised communities remains low and unsustainable (Govender et al., 2017). Apart from socio-cultural and economic factors, literature has shown several biophysical factors affecting crop productivity (Shackleton and Shackleton, 2012).

According to Snapp et al. (2010), marginal agricultural systems across SSA are characterised by low agro-biodiversity, making many cropping systems vulnerable to climate associated risks. The more significant proportion of agriculture (approximately 90%) is resource-constrained, subsistence-based and done under rainfed conditions and are susceptible to climate variability and change (Chimonyo et al., 2016). Pearce (2011) noted that many cropping systems are modelled on green revolution type systems, making them unsustainable for a resource-poor farmer. Also, Padulosi et al. (2013) state that the promotion of these systems has resulted in food and nutrition insecurity increased vulnerability to climate risks such as drought. There is a need to transform the current cropping system to address the challenges mentioned above holistically. According to Baldermann et al. (2016) and Mabhaudhi et al. (2019), to improve resilience to climate risk while increasing food and nutritional security of farming systems, incorporating neglected and underutilised crops into marginalised systems can be useful.

African leafy vegetables (ALVs) form a part of neglected and underutilised crop species (NUS). These are native to a given area in geological time (Raihana et al., 2015). They can also be crops introduced to that country and became naturalised overtime (NRC, 2006; DAFF, 2009). South Africa holds the highest diversity of underutilised crops (Senyolo et al., 2018). In general, ALVs are a vital source of genetic resources. They represent a significant part of agricultural biodiversity with a probability of subsidising climate change adaptation and food security (Chivenge et al., 2015). Research has shown that several ALVs are naturally adapted to low levels of water stress. They are drought-tolerant and can be cultivated in various climatic regions, including arid and semi-arid areas (Pretorius, 2014; Mabhaudhi et al., 2017a). DAFF (2009) also indicated that ALVs are also tolerant to common pests and diseases. These crop species are known to be nutrient-dense and have been recommended for use to improve food and nutrition security (Maseko et al., 2017). Although these crops have great potential, they are primarily under-exploited due to limited information regarding their agronomy, and the subsequent effect on nutritional value. As such, to improve their usage and utilization, there must be co-ordinated tactics on the local region to enhance the availability of information about their agronomy, and how it will affect nutritional value (Baldermann et al., 2016).

With the current climate change and diet preferences, ALVs are becoming an even more important source for climate change adaptation and ensuring food and nutrition security (Mayes et al., 2012). The limited knowledge of indigenous crops' production, mostly water and nutrient requirements, has become a significant hold-up on their promotion as choice crops (Nyadanu and Lowor, 2014) for food and nutrition security in marginal communities. There is a need to generate information or data about growth, development, and agronomic requirements (Šimůnek and Hopmans, 2009; Nyathi et al., 2018c). Classical experimentation that involves field experiments is often time-consuming and costly and confounded by risk. Crop simulation models are used to generate large amounts of information in a short period (Keating et al., 2003). Crop simulation models are a simple representation of crop's growth and developmental processes that can help solve problems related to crops by generating valid recommendations (Chakrabarti, 2013). Models combine scientific knowledge from several disciplines such as plant breeding, soil science, and plant pathology (Whisler et al., 1986; Raymundo et al., 2014). They are used to increase agricultural research and management, assimilate knowledge gained from years of experiments and improve agronomic efficiency and environmental quality for ALVs. The data generated can help provide new insights into a resource used to make recommendations to improve the productivity of ALVs and increase their contributions to food and nutrition security in marginalized rural communities (FAO, 2009; Pretorius, 2014).

Project objectives

1. Assessing relevant literature on African leafy vegetables (ALVs), modelling and agronomy
2. To quantify yield and water use of selected ALVs under different management options
3. To determine the nutrient content of selected ALVs
4. To quantify nutritional water productivity of selected ALVs under different management strategies

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The literature review outlines the status of underutilized leafy vegetables in South Africa. Their potential in contributing to food and nutrient security, especial in marginalized rural communities. The mechanism for water and nutrient uptake is revealed together with nutrient stress on plant growth and development. The distribution and agronomy of these crops are also briefly discussed. The main objective is to assess whether underutilized leafy vegetables have been modelled and, if so, to what extent. It is hypothesised that improving the information on the agronomy of ALVs can result in improved production, which will increase the availability of nutrient-dense crops for enhanced food and nutrition security. Crop modelling can be discussed briefly as a useful tool for generating information for underutilized leafy vegetables. This review focuses on amaranths (*Amaranth* spp), cowpea (*Vigna unguiculata),* sweet potato (*Ipomoea batatas*) and wild mustard (*Brassica juncea* L.) as some of the popular food plant crops for subsistence farmers in South Africa and the sub-Saharan African region. These crops' selection was credited to their short growth period, low growth input requirements, morphological structure, and similarities in their phenology.

2.2 Methodology

This chapter used a mixed-method approach that combines results from qualitative and quantitative research to review the literature on the current status of ALVs within South Africa. During the literature search, more focus was directed to South African articles. The literature was identified mainly from Scopus and Google Scholar, and peer-reviewed journal articles, reports were used as the main information sources. The key search words used were "crop modelling", "simulation", "APSIM", "water and nitrogen", "water", "nutrients", and "nitrogen", "indigenous leafy vegetables", "neglected underutilised crops", "traditional crops", "orphan crops". The literature search was limited to abstract, title, keywords, and key terms were used. We also used grey literature, such as web pages, thesis, magazine articles, reports, and briefs, deemed relevant. This was a benefit since it extended the search afar from the literature that is often not available to an audience outside research.

2.3 Results

2.3.1 State of indigenous leafy vegetable in South Africa

There are more than 100 different leafy vegetable plants known in South Africa (Rose, 1983). These include *C. olitorius* (jute mallow), *Amaranthus cruentus* (pigweed), *Citrullus lanatus* (bitter melon), *Vigna unguiculata* (cowpea), *Cleome gynandra* (spider plant), and *Cucurbita spp*. (pumpkin). Terms such as imifino (isiZulu, isiXhosa) and morogo (Sesotho, isiPedi) are common names used to describe these leafy vegetables. Already by these terms, one can tell that these are underutilized crops. African Leafy Vegetables (ALVs) used as leafy vegetables vary widely in their origin in this region. Verily their role in food consumption patterns of South African households is highly variable and may depend on factors such as time of the year, the status of poverty, distance availability of markets selling fresh produce, household income and level of urbanisation (Jansen Van Rensburg et al., 2007; Mabhaudhi et al., 2017a). Most of these leafy vegetables are grown and harvested by farmers in summer; therefore, seasonal change is another major constrains on the availability of these vegetables.

The consumption of ALVs has decreased while exotic vegetables have increased Njume et al., 2014. The utilization of ALVs is mainly in smallholder communities where local people collect them from the wild or cultivated them in farms' marginal fields. In very few cases, the seeds of selected species are broadcasted and cultivated in main fields (Maseko et al., 2018). Most popular leafy vegetables such as amaranth and spider flower grow naturally in the cultivated land. They are considered weeds by commercial farmers, where else they are an alternative source of food by smallholder farmers (Maseko et al., 2018; Njume et al., 2014). In smallholder cropping systems, women usually do most of the gathering, cultivation and harvesting. When these crops are emerging from cultivated fields, women seem to separate them from other non-edible weeds according to their usefulness.

In South Africa, ALVs in even more challenging because ALVs are mostly sold as dried products. Their selling is based on street vendors, and even though they have a well-recognized quality, they are not easily found in South African supermarkets. Their unavailability is due to a lack of sound postharvest storage systems for these crops. This, in turn, contributes to their low consumption, mostly in urban areas, as most fresh products become perishable (Jan van Rensburg et al., 2009; Maseko et al., 2018). Different amaranth species are reportedly sold in the Midlands areas of KwaZulu-Natal after being weeds from gardens and fields. However, this crop species' leading marketing was insignificant as it was mostly sold for petty cash.

Although fresh leaves produce was available at the Pietermaritzburg municipal, they were strictly sold to the public by selected greengrocers of this city (Jan van Rensburg et al., 2009).

Researchers have shown an increasing interest in indigenous leafy vegetables over the years in South Africa. For the longest time, policymakers have ignored the research of indigenous green leafy vegetables; however, this is slowly changing over the years. The Vegetables and Ornamental Plants (VOPI) and The Agricultural Research Council (ARC) are key role players in the research and training of wild vegetables in South Africa (Maseko et al., 2018). The growing interest in leafy vegetable crops, even at the policy level, has been shown to contradict their negative reputation and image, especially among young consumers in the urbanized areas of South Africa. This challenge is due to the association of their utilization with poverty and low class. There is low utilization of these crops also amongst the youth of South Africa. They do not have enough knowledge about indigenous vegetables' collection as they tend to mix them with poisonous species (Jansen Van Rensburg et al., 2007; Maseko et al., 2018).

Research on ALVs has existed in the country since the early 1990s. Since then, presentations, publications, conferences, posters, and workshops have continually created awareness in the scientific community. Many efforts are on the promotion of these crops are made continuously; for example, ARC-VOPI is currently working on the rise of different African leafy vegetables. South African universities continue to study these crops', consequently contributing to the increased capacity and knowledge of indigenous vegetables in the country (Maseko et al., 2018). However, the current funding that supports these studies is not enough to profoundly impact as the government and private sectors primarily drive the long-term partnership. Moreover, these sectors are suspected to be more favourable on major crops than these minor crop of South Africa (Maseko et al., 2018).

Having the population of South Africa likely to increase by 65.5 million in the year 2050, the proportion of people suffering from hunger and malnutrition is expected to increase. An increase of more than 50% in food production is required to alleviate this challenge. Focusing agriculture on neglected, underutilized species may be a possible solution to improve production (Mabhaudhi et al., 2017b, 2018). Because ALVs are underutilized, they create an excellent opportunity to develop new value chains supporting food security and rural agricultural development. According to Mabhaudhi et al. (2017b), the development of a new value chain may require more research, including crop improvement, plant breeding, agro-processing, production and marketing. For contribution to closing gaps within the research value chain of these crops, these must be implemented. Also, indigenous leafy vegetables could be fully recognized and enhanced by analysing both the upstream and downstream information along the value chain. Value chains are identified as undeveloped and unsustainable in the context of rural agricultural development. It is also imperative to identify actors and significant role players to translate indigenous crops to commodity crops successfully.

2.3.2 Contribution of indigenous vegetables to the human diet

The attention given to the sustainability of food and diets systems has highlighted the need for special attention to the role of biodiversity. Previous research has shown gradually increasing evidence that small changes in food cultivated on a larger scale can significantly impact dietary choices (Powell et al., 2015). According to Chadwick et al. (2013) and Powell et al. (2015), it is essential to realise that knowledge alone is not enough for the human diet. However, eating behaviour is the product of rational decision-making and conscious process and many nutritional interventions designed to improve the quality of the diet depend on education (Powell et al., 2015). Therefore, the rising promotion of ALVs will help people shift their attention towards a healthier way of living, thus improving their diets. Food choices and diet can have a massive impact on greenhouse gas emissions and the associated energy required to provide human nutrition. The shifting of peoples food choices to plant-based diets can reduce greenhouse gas emissions (Shekhawat et al., 2009).

African leafy vegetables are a good source of micronutrients such as vitamins, iron and other nutrients (Lewu and Mavengahama, 2010; Table 2.1:). Some indigenous crops, such as cowpea and sweet potato, produce nutrient-dense leaves (Suarta, 2018). However, since their intrinsic and nutritional value is often not acknowledged by development experts and researchers, the decline in their diversity of grown vegetables, production and use continue. Because most households in Africa's low regions depend mainly on these ALV, this trend can cause a negative impact on mainstreaming these crops into current diets. The small-scale farmers will also be affected as their income decreases due to decreased production.

Table 2.1: Nutritional value (based on raw 100 g) of selected neglected underutilized vegetable crops (Mabhaudhi et al., 2019).

Crop name	**Species name**	**Energy (kcal)**	**Protein (g)**	**Fat (g)**	**Fibre (g)**	**CHO (g)**	**Ca (mg)**	**P (mg)**	**Na (mg)**	**Mg (mg)**	**Cu (mg)**	**Zn (mg)**	**Fe (mg)**
Amaranthus	*Amaranthus spp*	49.00	4.00	0.20	2.87	7.86	1686.00	487.00	347.00	82.00	3.00	56.0	25.00
Nightshade	(*Solanaceae spp*)	55.00	3.00	0.60	2.42	9.03	2067.00	478.00	431.00	3.00	6.00	23.00	85.00
Blackjack	(*Bidens pilosa*)	39.00	5.00	0.60	2.92	3.72	1354.00	504.00	290.00	21.00	10.00	22.00	17.00
Mallow	(*Corchorus olitorius*)	392.00	20.90	5.20	45.61	55.50	1760.00	490.00	801.20	15.50	11.30	12.40	53.30
Wild mustard	(*Sinapis arvensis*)	26.00	2.70	0.20	1.10	4.90	0	0	0	0	0	0	0
Bottle gourd	(*Lagenaria siceraria)*	14.00	0.62	0.02	0.50	3.39	26.00	13.00	2.00	0.09	0.03	0.70	0.20
Chinese Cabbage	(*Brassica rapa subsp. Pekinensis*)	21.00	9.00	1.00	1.00	22.00	152.00	32.00	29.00	42.00	0.07	0.30	1.40
Sun–berry	(*Solanum retroflexum*)	38.00	5.80	0.80	1.40	5.00	442.00	75.00	0	0	0	0	4.20
Wild watermelon	(*Citrullus Lanatus* L.)	296.00	3.50	0.40	3.80	13.10	212.00	119.00	9.00	59.00	0.20	0.74	6.40

2.3.3 Distribution and agronomic production of underutilized crops

Indigenous leafy vegetable crops are a readily available local food source for poverty mitigation for people in rural areas. They originated in Africa or have remained in the continent for so long that they have become indigenized. Indigenous crops are one of the two subsets of crops describing traditional African vegetable crops classified based on their derivation (Jansen Van Rensburg et al., 2007). Whether they originate or introduced to the continent. However, very few leafy vegetables are utilized; thus, only ecology, distribution and local names of these major ones are documented. In South Africa, there is a high diversity of leafy vegetable species, most of which are impartially localized (Padulosi et al., 1997; Ebert, 2014). The main focus of the review looked at four ALVs, namely, amaranth, cowpea, sweet potato, and wild mustard, for this review. Research has been developed around ALVs, and through various support activities, they have been targeted for commercialization. Amaranth and wild mustard are common ALVs, while cowpea is less common and used mainly for grain and livestock forage, and sweet potato is primarily produced for the tuber. Leaves for both cowpea and sweet potato are edible and can be used as a leafy vegetable.

2.3.3.1 Amaranth (*Amaranthus spp*)

Amaranthus is from a widespread family of diverse ALV's, *Amarabhaceae. Amaranthus spp* comprises about sixty species, most of which are weeds (Njume et al., 2014). Meaning that out of the 100 identified ALVs species, 60% of them comes from this family. The cultivated amaranth species include *amaranth lividus, Amaranth viridis, Amaranth gracilis, Amaranth tricolour* and *Amaranth gangeticus* (Andini et al., 2013). Different amaranth species are used as forage, leafy vegetables, food grain, and ornamentals. They are C4 crops and grows optimally under warm conditions, and they appear as erect plants. They are short-lived perennials and can grow up to 2 m in height. Matured amaranth crop produces tiny, gleamy seeds that are dark brown. The habit of amaranth rages from spreading herbaceous plant to erect. On the leaves of some species of amaranth, there is are unique markings. The flowers may be auxiliary or terminal.

The name "amaranth' is taken from Greek and means everlasting or non-wilting, consistent at surviving in harsh environmental conditions (Njume et al., 2014). This crop can be cultivated in semi-arid and arid regions and is considered a promising crop in marginal areas as the world faces an ever-growing climate crisis (Andini et al., 2013). However, a continued dry spell will lead to flowering and reduce crop yield (Bello, 2013). Water requirement for amaranth will differ depending on soil type, the growth stage of a crop, and weather condition. Approximately 1.54 litres of water is required (Ogunlela and Isiaka, 2017).In the past few years, Amaranthus has been used as an alternative crop and served as a derivation of stabilization of ecosystems, livelihoods, and new markets without replacing mainstream crops.

The leaves of this crop are very high in vitamins, proteins and other minerals, which places Amaranthus as a potential crop grown as a source of these nutrients under vulnerable communities of sub-Saharan Africa. Amaranth leaves are very rich in vitamins, minerals and proteins. Amaranth is also a rich source of unsaturated fatty acids, dietary fibre, lipids, and several other minerals. To add, the protein content on amaranth weedy is equivalent to World Health Organisation standards.

2.3.3.2 Cowpea (*Vigna unguiculata*)

Cowpea originates from the leguminous family, *Fabaceae*, which represents the most significant family of cultivated following the grass family (*Poaceae*) from the economic perspective. In approximates, its accounts for 27% of the world's crop production (Ntatsi et al., 2018). Cowpea is an annual, herbaceous and pulse crop and can be planted during warm seasons, having a growth type of either climbing, trailing or erect (Ntatsi et al., 2018). Cowpea has tri-foliate leaves (Ntatsi et al., 2018). There are different kinds of varieties of cowpea that are either determinate or indeterminate (Ntatsi et al., 2018). The prostrate and spreading types are the ones that are mostly used as leafy vegetables(Ntatsi et al., 2018). The seeds are kidney-shaped to oblong and may differ in colour from black, dark red to white, and the seed often has a black colour, "the eye" at the hilum.

Cowpea performs best in arid and semi-arid conditions and may produce in areas with an optimum rainfall of 400 to 700 mm per year (Jan van Rensburg et al., 2009). Cowpea plants are drought tolerant and heat-loving. This is due to their long taproot that can reach a maximum rooting depth of approximately 2.4 m during eight weeks after planting. This character attests beneficial in the occurrence of nutrient mining and water stress (Chivenge et al., 2015). Seeds of cowpea are very nutritious, with a high protein and carbohydrates content, 24.8% and 63.6%, respectively. Other nutrients such as fat and fibre are reasonably high in cowpea seeds as well. Besides this valuable contribution of cowpea grains, leaves are also a significant source of nutrients for human consumption (Kabas et al., 2007). Six tonnes of fresh leaf cowpea can feed up to 800 children of 4-y years of age, providing them with 7.75 mg of iron each week for one year. Like most other legumes, cowpea has low glycemic index nutrients, which helps prevent coronary heart disease and contributes to the reduction of diabetes and inflammation. Therefore, nutrient-rich cowpea leaves can strengthen immunity and enrich the blood of human consuming it by contributing to offsetting protein-calorie deficiencies (Enyiukwu et al., 2018).

Both cowpea leaves and the seeds can be consumed in cases where utilising both grain legume and as a leafy vegetable can help address hunger in rural areas, especially during the periods before the next harvest. Therefore, this way can significantly help reduce food and nutrition security by providing proteins (grains), minerals and vitamins (leaves) (Sebetha et al., 2016). In Africa, cowpea is a common crop used for human consumption and animal feed (Ntatsi et al., 2018). In the past, studies have shown that the leaves of cowpea contain a high concentration of carbohydrates and proteins, which is more abundant in older leaves compared to the seeds (Sebetha et al., 2016).

2.3.3.3 Sweet potato (*Ipomoea batatas*)

Sweet potato is a tuber crop amongst the earliest crops domesticated by humans after the introduction of cereal crops, and it originated in East African, Central and South America. This crop remains one of the underutilized vegetables in South Africa. Together with the yams, cassava and aroids, sweet potatoes are essential crops in developing countries (Chivenge et al., 2015). These tuberous vegetable plants are believed to have been introduced by the early Portuguese explores to Africa in the 16th century and then distributed to the entire continent. It is famously known as a "poor man's crop", which may be one reason for its current status as an underutilized vegetable crop (Motsa et al., 2015). Sweet potato is grown mainly for its tuberous roots in colour ranging from white, purple, light brown, and light orange. Sweet potato is a perennial crop but primarily grown as an annual crop. The tubers produced by this plant may be extended and starchy and vary in size depending on the variety. It has adventitious roots located within the top 25 cm of the soil. The stems are thin creeping veins, approximately 4 m long. Leaves may be purple or green, heart-shaped, palmately veined and borne on elongated stalks. Flowers are pale violet or white, tubular-shaped, and withdrawn from the plant. One to four seeded pods form from the rounded fruits.

Sweet potato is adapted to sizeable environmental plasticity and low input systems, which allows it to be grown at any time of the year, especially in areas where they experience short or no frost (Chivenge et al., 2015). In the developing countries of Sub-Saharan regions, there has been an increase in the cultivation and production of sweet potato during the last decade (Raymundo et al., 2014). In South Africa, sweet potato is cultivated throughout the tropical regions, including KwaZulu-Natal, and its consumption is continuously increasing regardless of its low production. In this region, sweet potato is regarded as the most important root crop due to its flexibility (i.e. can be planted and harvested during any season of the year, mostly in frost-free areas (Oke and Workeneh, 2013).

It is assumed that the most significant contribution of sweet potato to nutrient security is derived from the potato varieties' orange flesh. These contain substantial amounts of β-carotene, a precursor for vitamin A, thus contributing to food security's nutritional dimensions (Raymundo et al., 2014). All parts of the sweet potato can be consumed, and the storage roots are eaten roasted, boiled, or baked. Some people may even prefer to eat them raw. Sweet potato leaves can also be consumed as a green leafy vegetable. Previous reports from china have regarded this crop as a highly nutritive crop. The roots of the crop provide almost a balanced diet for an average human body. Compared to other starchy crops such as maize and rice, sweet potato contains a significant amount of carbohydrates (Motsa et al., 2015). Although it might have a slightly lower protein content than potatoes, it contains almost all the micro and macronutrients such as vitamins. According to the food security perspective, the crop is an excellent crop due to its ability to triumph, where the common staple crops fail (Zhang et al., 2018).

2.3.3.4 Wild Mustard (*Sinapis arvensis*)

Wild mustard is an annual plant from the Brassicaceae (Mustard) family (Franzke et al., 2011). Different wild mustard types can be distinctly differentiated by the patch or reddish ring at the stems' junction. The upper branch consists of a cluster of flowers at the upper limb terminate, which vary from pale yellow to yellow and are similar to canola flowers. These flowers are like other flowers of plants in the mustard family, except that they are somewhat larger. They bloom from late spring, for 1-2 months, to winter. The petals fall as the flowers mature, and so showing a narrow seedpod. Seedpods are erect but do not drop downwards. Seeds are usually brown or dark brown. The plant can be spread by reseeding itself and has a taproot system.

The wild mustard seedling has cordate cotyledons, which may be with or without hairs depending on the type of mustard (yellow or brown) (Government of Saskatchewan, 2017). Adult leaves differ from light to dark green and deeply lobed. Brown mustard has the upper narrow upper leaves. The leaves of this type terminate higher up on the petiole and do not cling to the stem. While the leaves of the yellow mustard also close higher up but on the leaf stalk. The seeds produced by the brown mustard plant are smooth and hairless; they are contained in a long and conical beaked pod. They are reddish-brown to dark brown and are spherical with a diameter of about 2 mm. On the other hand, Yellow mustard type produces light creamy yellow to yellow seeds spherical with a diameter of 2 mm to 3 mm (Berglund, 2007; Government of Saskatchewan, 2017).

This plant may grow under mesic fertile loam or clay-soils under full sun or warm conditions, and it can tolerate other conditions different from this due to its adaptable characteristics as it is considered weedy. Wild mustard can be cultivated under diverse environmental regions. Wild mustard establishes very quickly, and this is a good growth characteristic that helps it avoid water stress, especially in water-scarce environments. This plant is rich in many essential elements such as iron, calcium, and other nutrients necessary for good health (Chivenge et al., 2015). Nonetheless, just like any other underutilized African leafy vegetable, information on the crop's husbandry is limited as it is locked up in the IK systems.

Figure 2.1: Selected underutilized leafy vegetables in South Africa (a. Amaranth (*Amaranthus spp.*), b. Cowpea (*Vigna unguiculata*), c. Sweet potato (*Ipomoea batatas*), and d. Wild mustard (*Sinapis arvensis*).

2.3.4 Mechanism for water and nutrients uptake in plants

2.3.4.1 Effect of water stress on crop growth and production

South Africa is considered a dry country (Donnenfeld et al., 2018).. Out of 193 countries and is ranked as the 29th driest country (Donnenfeld et al., 2018). It is expected to worsen as the country's population increases, and there is a continued increase in the number of industries. There is currently overexploitation of more than 60% of water resources in this country, and only one-third of the country's main rivers being in good condition (Donnenfeld et al., 2018). This has a negative impact because the amount of available freshwater decreased due to the industries' water pollution and increased water consumption. There is already a high demand for water than supply in many catchments (Africa, 2019). Water use efficiency (the proportion of water used for the plant's metabolism to water used by the plant through the atmosphere, transpiration) is vital in agriculture, especially since this is the largest single water user sector (Doorenbos and Pruitt, 1977).

Crop water requirement is defined as the amount of water needed to meet water lost through evapotranspiration (ET) of a disease-free crop growing under favourable environmental conditions. This is usually affected by crop characteristics, climate, and the effect of local conditions and practices in agriculture (Doorenbos and Pruitt, 1977). Associated with crop requirement or crop water use are the interaction, the root's ability to absorb water from the soil, and the leaves' capability to release the absorbed water to the atmosphere. The uptake of water from the ground depends mostly on the rooting depth distribution, soil moisture and rooting density distribution (Chimonyo et al., 2015). However, since water is the main challenge in South African agricultural production systems, there is a need to look at other efficient ways to produce food for the growing nation. This, in turn, forces farmers to shift and use marginal land for their production. For optimal growth and high yield production, irrigation is required. However, due to poor management, water wastage often occurs due to over-irrigation (Cooper et al., 2008).

2.3.4.2 Water as a limiting resource and effects

Plants are regularly exposed to a few biotic and abiotic stresses. Water stress or drought is one of the significant adverse types of stress as it can trigger a lot of other plant responses such as changes in growth rates, cellular metabolism, and yield. To understand plant-resistant mechanisms used by plants in water-limiting conditions, molecular and biochemical responses must be first understood (Ahmad et al., 2016).

Germination and stand establishment are the first processes affected during the growth stage when there is a water deficit. It has been proved in many studies that the reduction in photosynthetic activity under water limiting conditions is due to both stomatal and non-stomatal mechanisms. Stomata is an entry and exit point for exchanging gases, which includes water vapor and CO_2. As the first step, plants will respond to water stress by closing the stomata, which reduces transpiration and photosynthesis. By closing the stomata, plants prevent the absorbability of CO_2. This decreases carbon assimilation in support of photorespiration. It is also well understood that there is a good correlation between stomatal conductance and leaf water potential under water stress conditions (Ahmad et al., 2016). The root-to leaf signalling occurs due to water stress and is promoted by soil drying via the transpiration stream, provoking stomatal closure. On the other hand, the non-stomatal mechanism may include changes in the production of chlorophyll, structural and functional changes in the chloroplast and distraction in the processes of accumulation, transportation, and dispersal of assimilates (Aroca et al., 2012). As a result, the lack of water leads to a decline in yield and total biomass.

Plants may also share some physiological and biochemical responses signalling water stress condition. Crop water stress will occur due to imbalances between leaf transpiration and root water uptake. Depending on specific plant types and genotypes, some will undergo a modification of decrease in leaf expansion, root water uptake, premature leaf senescence, change in pigment structures, impaired photosynthesis, and other gas exchange parameters. Several studies have shown that stomatal or non-stomatal mechanisms mainly cause a disturbance in photosynthesis. Gas exchanges and water evaporates through the stomata. Thus, the first response to water stress and results in a decreased rate of photosynthesis. Other physiological responses such as reduced chlorophyll content, accumulation of osmolytes, rate of transpiration, and stomatal resistance can also be affected during this stage. (Aroca et al., 2012; Ahmad et al., 2016).

To manage water stress, farmers have been encouraged to adopt management practices that minimised competition for the resource. It is important to optimize planting dates and plant populations

2.3.4.3 Effect of soil nutrient stress on plant growth and productivity

Apart from the previous section's challenge, low soil fertility is also significant restrictions on plant growth, development, and yield in many warm regions. Enhancement of soil fertility by using fertilisers is usually the solution (Bengough, 2012). Sustainability of the soil can be possible if the removed nutrients are replaced by adding some more nutrients to the ground, for example, by using fertilisers. Moreover, efficient crop production is required to avoid losses, and it is attained through the optimal use of plant nutrients, nu and

The amount of nutrients needed to meet a specific yield target is known as nutrients requirement. Nitrogen is one of the essential elements needed for the plant (Jan van Rensburg et al., 2009). There are several ways in which plants use to acquire nitrogen. These approaches include nitrogen fixation, carnivory, mycorrhizal association or through roots. During unfavourable conditions, the mentioned approaches are disturbed, or they fail. In the field, different environmental conditions exist (Suarta, 2018). Factors such as run-off, erosion, leaching, and volatilization exist, and they result in the nitrogen concentration being varied and decreased dramatically. Therefore, plants must develop survival strategies during this limiting time (Kant et al., 2011).

To reduce nitrogen losses at this stage, a plant may slow down new leaves, which requires even more nitrogen. During the vegetative stage of development, leaves are the sink for nitrogen, meaning they depend on other parts of the plant, such as roots as their source. In hot, dry conditions, plants may undergo regulatory mechanisms to regulate Nitrogen (Jan van Rensburg et al., 2009; Kant et al., 2011). This remobilization of nitrogen may occur during senescence as well, and it allows plants to derive up to 80% of grain nitrogen from the leaves. Plants can use this nitrogen as an additive to the newly formed leaves. Even more efficient mechanisms have been developed by the plants where tied-up nitrogen bodies are released from source tissues via proteas activities. The plate goes through senescence during water limiting conditions. About 80% of leaf nitrogen is stored in the chloroplast, mostly in the form of protein. This nitrogen pool is significant for remobilisation and can be acquired through protein degradation.

Nitrogen remobilization and storage are vital for plants. Remobilization is mostly essential for seed nitrogen content, seed production and completion of the plant lifecycle. The content of nitrogen in the seed can be further used to predict germination efficiency and young seedlings survival. The stored nitrogen in trunks during water limiting conditions can be remobilized and used during more favourable times where there is sufficient water for crop growth (Kant et al., 2011; Ntatsi et al., 2018).

2.3.5 Nutritional Water Productivity (NWP)

The linking of crop production, water use in agriculture, and nutrient concentration results in an index known as Nutritional water productivity, NWP (Chibarabada et al., 2017; Mabhaudhi et al., 2016). An evolving concept which closely relates plants water productivity to human nutrition. Where crop production is concerned, water requirement, water use, water productivity, water use and water use efficiency are all concepts that refer to economic yield per unit of water depleted. In other words, it is the ratio of crop yield to water used. This can be represented as kg crop m^3 water (Perry et al., 2009). According to Renault and Wallender (2000) and Wenhold (2009), NWP quantifies nutrition per volume of water used (nutritional units per m^{-3}).

One of the significant challenges faced by sub-Saharan Africa includes water scarcity which if a complex issue that is often associated with climate change and variability. The population pressure also adds to this issue in terms of malnutrition and food insecurity. Resource-poor households in rural areas are most affected in South Africa, lacking micronutrients (iron and zinc and vitamin A (Nyathi et al., 2018a). Part of the research efforts to contribute to assessing this challenge, traditional leafy vegetable has been deemed as having the potential to reduce both food and nutrition security in the resource-poor households (Nyathi et al., 2018c; Nyathi, 2019).

As previously noted by Chibarabada (2017), Mabhaudhi (2016a) and Nyathi (2019), most water and nutrients agronomic research often produce higher yields with minimum irrigation as much as possible. However, crop production, nutritional and water requirements are three interlinking aspects in agriculture that cannot be assessed separately. Therefore, to successfully study food and nutrition security, an index known as nutritional water productivity (NWP) has been developed by Renault and Wallender (2000). This index accounts for water use, crop production, food access and human nutrition and can be represented in an equation as [NWP = (Yield or biomass/actual evapotranspiration) × nutritional content of a product)]. NWP = [(above ground edible biomass/ET)] × NC (Nyathi, 2019). NWP data may provide useful information regarding crop productivity, crop water use, nutritional productivity, and human nutritional requirement of ALVs. There is still a challenge in the availability of information (Maseko et al., 2018).

Most studies only focus on one part of the crop (either above-ground biomass or storage) when evaluating NWP. Nonetheless, this might not be beneficial in crops such as sweet potato and cowpea, where both parts of the crop are consumed and since the above-ground biomass can be divided into both plant parts (Nyathi, 2019). Nyathi (2019) was the first to have studied the NWP in ten selected ALVs, and it was interesting to note that these vegetable crops were more productive than alien crops in some of the lacking nutrients in South Africa, namely, Fe-NWP and Zn-NWP. However, to back up these claims, more research needs to be conducted as most recent studies still opt for subjective information to back up their conclusion (Chivenge et al., 2015; Maseko et al., 2018; Mangham et al., 2013).

Table 2.2:The potential yield for amaranth (*Amaranthus spp.*), cowpea (*Vigna unguiculata*), sweet potato (*Ipomoea batatas*) and Wild mustard (*Sinapis arvensis*) at optimum environmental conditions.

	Temperature range (°C)	**Plant density (Plants/m^2)**	**Fertiliser Requirements (kg/ha)**			**Rainfall requirement (mm)**	**Potential yield (t/ha)**	**References**
			N	**P**	**K**			
Amaranth	18 - 34	-	45 - 100	22 – 34	26	1000	40 t/ha leaves 1 t/ha grain	(DAFF, 2013), (Love, 2014), (Ojo et al., 2014), (Sullivan and Specialist, 2003)
Cowpea	20 -35	7 - 30	10 - 40	40	4	300 – 2000	1 t/ha of seed and 4 t/ha of hay	DAFF (2013), Farmers weekly (2016), (Gomez Carlos, 2004), (Ngalamu, 2015) Smith, (2017),
Sweet potato	20 - 29	0.4 – 3.33	100	90	200	450 - 2340	-	Brodie, (2018), (DAFF, 2011), (Gupta, 2011), Famers weekly, (2010)
Wild mustard	29	11 - 43	56 – 90	30 -40	-	-	112 t/ha	(Berglund, 2007), (Government of Saskatchewan, 2017), (Wysocki and Corp, 2002),

2.3.6 Brief overview of crop modelling

A model is a simplified representation of a process or system (Chakrabarti, 2013). Modelling assumes that any given system can be represented using a mathematical formula or statements (Keating et al., 2003). In agriculture, crop models are used as a simple representation of a crop to incorporate data from field experiments. They provide a structure that promotes the integration of different disciplines, uses system analysis to solve problems, and offers dynamic, quantitative tools that help analyse the complexity of cropping systems (IPGRI, 2002). Different types of crop models having a certain degree of sophistication in simulating the real world exists. These can either be explanatory or predictive models explaining the changes in the yield of a chosen crop (Chakrabarti, 2013; Gaydon et al., 2017).

These categories vary from superficial experimental relationships to complex mechanistic models (Whisler et al., 1986). Examples may include Agricultural Production Systems sIMulator (APSIM), AquaCrop, Modelling European Agriculture with Climate Change for Food Security (MACSUR), Decision Support System for Agrotechnology Transfer (DSSAT), etc. Many models such as APSIM, AquaCrop and DSSAT have been used and has allowed neglected underutilized crops but not necessarily ALVs to be calibrated for specific cultivars under different environments (Mayes et al., 2012; Bello and Walker, 2017; Gaydon et al., 2017). However, among these models, APSIM has not been a popular choice. APSIM can integrate many different models derived in fragmented research efforts. Therefore, promoting APSIM as the model of choice for underutilised crops' parameterisation is ideal (Holzworth et al., 2014). In this paper, the focus was directed to APSIM as the model of choice.

Due to a vast range of differences in the environment, field experiments on crops of interest under different climatic, soil and water availability conditions are time-consuming and tough, but it is very costly. For this reason, the development of crop models has become a very handful and an acceptable way of carrying out research based on the data collected in many different experiments carried out in that same area (Grove and Monaghan, 2018). Over the years to the present time, research has shown that the current food systems are becoming a massive threat to biodiversity, water resources availability and land use due to climate change. Previous research has proven that global warming leading to climate change alters the rainfall and temperature patterns, increasing the occurrence and gravity of extreme weather events (Erdem et al., 2010). The re-introduction and promotion of underutilized leafy vegetable crops have come across as one of the best solutions to provide nutritious foods while resulting in stable food systems in these significantly changing weather conditions. The most convenient, less costly, and quick approach to this is the use of crop models. These can be used as critical tools for generating data that will help contribute to the decision support, knowledge exchange and better understanding of crops interaction with the environment (Nyathi, 2019).

Several crop models have been established over the past few years, including the Agricultural Production System Simulator model (APSIM, the Australian crop model developed by various organisations. As much as these crop models have been testes for multiple crops such as rice, maize and wheat and growing conditions, underutilized leafy vegetables are mostly excluded. Only a few cases of these crops have been simulated. These crops play a crucial role in providing essential nutrients such as vitamins and micronutrients; thus, this gap in the research space can be concluded as lacking. Raymundo et al. (2014) showed that only two models (MADHURAM and SPOTCOMS) had been developed for sweet potato. Although there has been some modelling work done on the selected leafy vegetables, amaranth, cowpea, sweet potato and wild mustard, as mentioned before. This work usually includes other crops (intercropping) and other aspects. According to these findings, no work has focused on the management practices of these crops.

Underutilized leafy vegetables must be added to the model database to achieve sustainable-food systems that produce healthy foods (Nyathi et al., 2018c). In this study, the APSIM model was chosen to simulate nutrients and water to improve the management practice of selected underutilized leafy vegetable. This model was selected among many other models because of its ability to "Plug in" to specify any logical or required modules and "plug out" to define any modules that are no longer needed (Holzworth et al., 2014). To add, APSIM can be used to simulate more than 20 crops and forests, and the outputs can be linked with geographical information systems (GIS) and used for spatial studies. APSIM also regarded as a dynamic daily time-step model that can simulate soil water, nitrogen, carbon and phosphorus interactions and dynamics within management systems driven by climatic data, maximum and minimum soil temperature rainfall, and solar radiation (Gaydon et al., 2017). This is a huge advantage to use this model for the simulation of ALV since different factors affecting growth, such as water and nutrients, can be modelled, and outputs can be linked to make sense of plant growth.

Table 2.3: Simulations on amaranth (*Amaranhus spp.*), cowpea (*Vigna unguiculata*), sweet potato (*Ipomoea batatas*) and wild mustard (*Sinapis arvensis*).

Crop	**Model**	**Tittle/description**	**Location**	**Year**	**References**
Amaranthus	AquaCrop model	Characterization and modelling of water use by amaranthus and pearl millet	South Africa – north-west	2013	(Bello, 2013)
	AquaCrop model	Assessment of nutritional water productivity and improvement strategies for traditional vegetables in South Africa	South Africa	2019	(Nyathi, 2019)
	AquaCrop model	Evaluating the AquaCrop model for simulating the production of amaranthus (*Amaranthus cruentus*) a leafy vegetable, under irrigation and rainfed conditions	South Africa	2017	(Bello and Walker, 2017)
	AquaCrop model	Calibration and validation of the AquaCrop model for repeatedly harvested leafy vegetables grown under different irrigation regimes	South Africa	2018	(Nyathi et al., 2018c)
Cowpea	APSIM	Modelling the potential impact of climate change on sorghum and cowpea production in semi-arid areas of Kenya using the agricultural production systems simulator (APSIM)	Kenya	2010	(Onwonga, R.N., Mbuvi, J.P., Kironchi, G. & Githinji, 2010)

	CROPGRO	Simulation of growth and development of irrigated cowpea in Piauí State by CROPGRO model	Brazil	2002	
	INTERCOM	A simulation study of the competitive ability of erect, semi-erect and prostrate cowpea (*Vigna unguiculata*) genotypes	California	2007	(Wang et al., 2007)
	MACROS.CSM	Cowpea Production in Rice-Based Cropping Systems of the Philippines Extrapolation by Simulation	The Philippines and Southeast Asia	1993	(Timsina and Garrity, 1993)
	GROWIT	Simulation of Yield Distributions in Millet-Cowpea Intercropping		1991	(Lowenberg-DeBoer et al., 1991)
	APSIM	Simulating yield and water use of sorghum–cowpea intercrop using APSIM	South Africa	2016	(Chimonyo et al., 2016a)
	APSIM	Assessment of sorghum–cowpea intercrop system under water-limited conditions using a decision support tool	South Africa	2016	(Chimonyo et al., 2016b)
Sweet potato	MADHURAM	Madhuram: A Simulation Model for Sweet Potato Growth	India	2008	

	SPOTCOMS	A Model to Simulate Sweet Potato Growth	India	2008	
	AquaCrop model	Parameterizing the FAO AquaCrop Model for Rainfed and Irrigated Field-Grown Sweet Potato	South Africa	2015	(Rankine et al., 2015)
	SPOTCOMS	Evaluation of a crop growth model for sweet potato over a set of agro-climatic conditions in India	India	2019	(Sunitha et al., 2019)
	AquaCrop model	Simulating the yield response of orange-fleshed sweet potato 'isondlo' to water stress using the FAO Aquacrop model	South Africa	2013	(Beletse et al., 2013)
	MP-MAS	Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach	Uganda	2007	(Schreinemachers et al., 2007)
	Plastochron model (PLASTO) and the Wang and Wengel (WE) model	Estimating cardinal temperatures and modelling the vegetative development of sweet potato	Brazil	2013	(Erpen et al., 2013)
Wild mustard	MATLAB model	Modelling population dynamics of Sinapis arvensis in organically grown spring wheat production systems	USA	2013	(Kolb and Gallandt, 2013)

APSIM (Agricultural Production Systems sIMulator) is an agricultural modelling framework that can combine different models obtained in fractured research efforts. In this way, research from various fields can be conveyed to other areas' satisfaction or discipline. APSIM can also be used to compare different models or sub-models at a common platform, and this is a "plug-in-pull-out" approach (Le Gal et al., 2010). The user configures the model by choosing a set of sub-models from a soil, crop, and utility modules suite. The environment of APSIM is a useful tool for analysing all the farm systems, such as crop rotation, pasture sequence, and tactical planning. Using APSIM, users can improve their understanding of the impact of soil types, climate change and management of crop production (Keating et al., 2003). This is a powerful tool for investigating agronomic adaptations such as cultivar types, fertiliser/ irrigation management and changes in planting dates. Daily climatic data, soil properties, cultivar characteristics, and agronomic management are key inputs required to run the model. Advances in knowledge of soil properties and plant growth are needed for ease of use by trained agronomists.

APSIM is a more suitable and efficient tool for predicting growth and yield under diverse climatic scenarios. Therefore, it can mitigate future problems related to extreme climatic change (Ahmed and Fayyaz-Ul-Hassana, 2011). The adjusting of the model's parameters, calibration, and validation of its application for building the reliability of analytical models is very important. Therefore, it is essential to ensure that the model is calibrated and validated for the given crop.

2.3.7 Parameterizing and calibration of the APSIM model

Parameterization is a three-step process where local inputs parameters are added to the model. APSIM model requires several inputs to simulate the crop within the system: i) daily weather information (Tmax, Tmin, rainfall, and solar radiation), ii) soil information (soil type, water and nutrient status), iii) crop and genotype-specific coefficient (Gaydon et al., 2017). Soil parameters in the APSIM model are used to adequately account for and reflect all the differences among locations (Ma et al., 2011). At first, the dominant soil series can be acknowledged for each site, and data can be obtained from the literature. For each soil series, actual soil data such as texture, pH and organic carbon can be obtained from suitable soil survey sites on the internet (Ojeda et al., 2017). Some parameters may not be directly measured due to the high value of uncertainty that they may poses. Included in these parameters are some soil parameters, crop varietal coefficients. In this process of adjustment or 'calibration', the duration in which one wants to run data and treatments can be chosen by the user (Gaydon et al., 2017). This process is known as calibration.

2.3.8 Validation of APSIM model

Model validation is known as the real test of evaluating the accuracy of the model. Here, the calibrated parameters against independent factors and treatments. It is a method done to check the validity of the model following parameterization and calibration (Micheni et al., 2004). Some complex models often have issues of running unvalidated data, leading to the model generating the right answers for the wrong reasons (Gaydon et al., 2012). Therefore, resulting in misleading predictions during successive model usage. The APSIM model's testing is done using experimental data from similar studies (Micheni et al., 2004).

As mentioned before, a wide range of crop models with different levels of difficulty are currently available, and some have been used to model neglected underutilised crops. An overview of 70 models has been provided by (Di Paola et al., 2016) with a note that this list is not complete, meaning the number of available crop models is very high and still growing. For APSIM, simulation is configured by requiring different modules to be used in the simulation and data needed for that module. Typically, these are soil, crop, meteorological modules, and management module can be specified by using simple language rules to define calculations, sets of rules and messages to modules used at the simulation time.

There is very little evidence showing the application and uptake of models developed for underutilized crops in general. Although AQUACROP has seemingly been the model of choice, there is no follow-up research on model calibration for underutilized crops (Amisigo et al., 2015). The unavailability of ALVs data under its default crop folder can further testify to this. Let alone APSIM, which has never been used to model neglected underutilized vegetable crops. It is encouraged that there must be an extended focus on underutilized crops for future purposes when it comes to modelling. They have a huge potential to improve food and nutrient security (Nyathi et al., 2018c).

2.3.9 APSIM testing

General model testing involves a comparison of simulations with observed data. Many APSIM users have done this under different conditions. In the following table are some of the crucial reports that APSIM model test results.

2.2 Conclusion

There is a wide variety of indigenous leafy vegetable crops found in South Africa. These are most popular in poor- rural communities and can be grown for health benefits as well. The remarkable potential in contributing to food security is why more attention in crop production must shift towards developing and popularising these crops, especially in these significantly changing environmental conditions. It was observed through literature that only a countable number of studies had been done in terms of modelling. There are very few models that are designed to model some of these indigenous vegetables. This is yet another gap that still needs to be addressed in crop production for improved development and production in these crops.

CHAPTER 3

Agronomic management of selected African leafy vegetables for improved Yield, Water Use and Water productivity

3.1 Introduction

Food and nutrient security remain a challenge in South Africa. At a national level, the country is regarded as food secure, but people still experience some constraints to safe, sufficient, and nutritious food at the household level. Contributing to this challenge of food and nutrient insecurities is the lack of land and resources to produce food. Often, the people that have less to access to food come from a poor community, and as much as they may have access to land for farming, they still lack resources such as water and fertilizer (Van Jaarsveld et al., 2014). On the other hand, some of those who have access to food might still fail to access nutritious foods.

South Africa is known as one of the world's driest countries (Water, 2011; Donnenfeld et al., 2018). More than 80 % (98 million ha) of South African land surface is defined as arid or semi-arid, and out of that 80 %, only 17% (16.8 million ha) is arable (Hardy et al., 2011). Out of the 22 % of land classified as having high potential for cultivation, less than 10% is irrigated, and the rest is rain-fed. Only 2.5 million ha of the arable land is rain-fed agriculture; the rest of the land is abandoned (Hardy et al., 2011). The limited amount of arable land and variable rainfall contributes largely to low crop production, thus failing to meet millions of households' food requirements. Therefore, it is crucial to implement a sustainable agricultural system given these unfavourable and water limiting conditions. One of the coping strategies for this is using African leafy vegetables (ALVs) (Hardy et al., 2011).

African leafy vegetables are best known for their high nutrition potential. Their management requires low water and fertiliser inputs (Senyolo et al., 2018). They can thrive under limiting conditions and are regarded as potential crops to contribute to food and nutrient security (Mavengahama et al., 2013). However, just like any other crop, they eventually give in to unfavourable conditions such as water stress (Mabhaudhi et al., 2018). To encourage their growth, one would have to understand what best management practices these ALVs require. However, based on the available literature on the agronomy of these ALVs, it is difficult to draw conclusions and recommend best management practices for enhanced yields, water use, and water productivity of ALVs. As part of the solution, besides long field experiments, crop modelling provides an accurate, easy, and less time-consuming solution to assess the full potential of ALVS for their best agronomic management practices for better growth and productivity. In this chapter, APSIM was used to determine best management practices for improved yields, water use, and water productivity of selected ALVs (amaranth, cowpea, sweet potato, and wild mustard). This model singled out because of its ability of "Plug in" to specify any logical or required modules and "Plug out" to define any modules that are no longer needed. This was very advantageous for the studied ALVs as they have never been calibrated for specific cultivar and under different environments.

3.2 Materials and methods

The Agricultural Production Systems Simulator (APSIM) model was calibrated using data from Ukulinga Research Farm is the University of KwaZulu-Natal’s research farm situated in Pietermaritzburg, South Africa (29°37′S; 30°16′E; 775 m a.s.l.). Ukulinga research farm has a mean annual rainfall of about 790 mm, received between October to April. During the summer, the average temperature goes up to 26.5 °C (Chimonyo et al., 2016a). According to the profile pit description, the Research Farm soils are dominantly clay-loam textures having 0.6 adequate rooting depth. Using the FAO soil classification system, Ukulinga soils can be further categorised as chromic luvisols. These are shallow brown acidic soils having low to moderate fertility.

The soil water movement and availability are affected by the soil physical properties (Chimonyo et al., 2016b; c). The initial C: N ratio calculated from the results of the soil chemical properties. On these results, carbon (%) for the top 0.2 m layer was 2.3%, while N was 0.3%. Four African Leafy Vegetables were simulated for growth and productivity. These included amaranth, cowpea, sweet potato, and wild mustard. Each crop had 15 samples for each treatment modelled for each growing season in a year (from 2014 – 2019). Yield (fresh biomass) and evapotranspiration observed as variables from the outputs of the simulation were then used to calculate water productivity for each crop. The growth of crops was also studied for different planting date, planting density, fertiliser application and irrigation scenarios.

3.2.1 Brief description of APSIM model

The Agricultural Production SIMulator (APSIM) is a point scale and daily time-step model that allows modules (sub-models) to be associated with simulating agricultural systems over a single homogenous field over a certain period (Ahmed and Fayyaz-Ul-Hassana, 2011; Chimonyo et al., 2016a). Numerous modules grouped as soil, plant, environment, and management are included in the APSIM. This model mimics the mechanistic growth of the crops, a series of management options with regards to cropping systems (e.g. mono-cropping, intercropping, and rotation), and soil processes (additions, losses, transformations (changes), and translocation or movement (Ahmed and Fayyaz-Ul-Hassana, 2011). The APSIM model simulates the growth and development of crops in a daily time-step on an area basis, per square meter, not a single plant (Robertson and Lilley, 2016). The inputs required by the APSIM module include weather, soil, crop data and management options (Ojeda et al., 2017).

The growth and development of this module respond to soil water supply, soil nitrogen, and climate. It then returns the information on the uptake of nitrogen and soil water to its SoilN and SoilWat modules each day for these systems' reset (Keating et al., 2003). Evaporation and runoff rate were calculated using the information on the soil cover provided to the SoilWat module (Ahmed and Fayyaz-Ul-Hassana, 2011). The plant modules simulate a crops' vital physiological processes with a diverse range of produce from early to focus crops such as sorghum to various crop modules available for plants such as canola, cowpea, peanut, etc. The crop species on the APSIM module currently uses the same physiological principles to capture and use growth and development resources. The main difference is the shapes and thresholds of their response functions. The SoilWater is a daily time-step cascading water balance module derived from CERES and PERFECT and is a module. The dynamics of both carbon and nitrogen in the soil are described in the SoilN module (Gaydon et al., 2017). APSIM Met provides daily weather information to all modules within the APSIM simulation (Keating et al., 2003).

3.2.2 Simulation

Model calibration included creating simulation files (soil, weather, crop, and manager folder) which was achieved using the “plug-in and plug-out” method. The simulated results validated using secondary data from different sources (Table 2.1).

3.2.2.1 Soil file

The APSIM model soil modules are classified based on the international and African format, and they include generic soil profiles for Africa. The soil properties required in this module have texture, bulk density (BD), total porosity, the drained upper limit (DUL), saturation (SAT), plant available water capacity (PAWC), pH, and crop lower limit (LL), Table 3.1, for the simulation of soil water-related processes and yields. The following table describes the shallow layers of the farm according to their physical characteristics.

Table 3.1: Soil physical characteristics (Chimonyo et al., 2016a).

Depth (cm)	**Texture**	**BD[1] (g/cm3)**	**Airdry[2] (mm/mm)**	**LL15[3] (mm/mm)**	**DUL[4] (mm/mm)**	**SAT[5] (mm/mm)**	**KS[6] (mm/day)**
0 - 10	Clay loam	1.20	0.20	0.21	0.39	0.44	20.90
10 - 30	clay loam	1.20	0.23	0.23	0.41	0.467	18.18
30 - 60	clay	1.20	0.26	0.26	0.43	0.467	13.92

[1]BD - Bulk density; [2]Airdry – Hydroscopic water content; [3]LL15 – Permanent wilting point; [4]DUL – Field capacity; [5]SAT – Saturation; [6]KS – Hydraulic conductivity

Table 3.2: The soil water module description.

Parameter	**Value**
Summer Cona	3.5
Summer U	5
Summer date	1 Nov
Winter Cona	2
Winter U	2
Winter date	1 April
Diffusivity constant	40
Diffusivity slope	16
Soil albedo	0.12
Bare soil runoff curve number	73

The maximum reduction curve number due to cover for the current study cover for maximum curve reduction, slope, discharge width, catchment area, and the maximum pond will be left on default. Each soil depth, soil water condition (SWCON) was given as a fraction at planting. The portion of water that moves to the next layer (above DUL) was set as 0.3

3.2.2.1.1 Soil organic matter

The soil chemical and physical parameters were obtained from the Ukulinga soil results published by (Chimonyo et al., 2016a). After analysing the soil, Soil organic matter was inputted into the model as a percentage of carbon, C and nitrogen, N, which was then used to calculate the C: N ratio. The root C: N ratio was set to 40, root mass as 1000 kg/ha and the soil C: N ratio as 12. The initial nitrogen was measured as 56 kg/ha for both NO3 and NH4 before planting. The initial water was also measured and set before the beginning of the simulation. Where absent, it was interpolated by running the model for two seasons before the actual planting date.

3.2.2.2 MET file (appendix)

The daily weather data to create the Met file was obtained from the Automatic Weather Station (AWS) situated less than 1 km within Ukulinga Research Farm. The AWS is a division of the Agricultural Research Council − Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations. For the MET file, daily weather data comprising maximum (Tmax), minimum (Tmin) air temperature (◦C), solar radiation (Rad, MJ m^{-2}), rainfall (mm) was used. The same data was used by Chimonyo et al. (2016a) was extracted from the period between 27 January 2004 and appended to 20 October 2019. It was then converted to XML format. The values of average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP) were calculated and input into the MET files via "tav amp.

3.2.2.3 Crop file

The crop files found in APSIM do not include leafy vegetable crops except cowpea. Therefore, The APSIM model was adapted for canola, cowpea, and potato varieties. For amaranth and wild mustard, the canola file was used. The potato was adjusted for sweet potato, and the brown mix variety of cowpea was used since it is the most drought-tolerant variety. To achieve this step, describing the growth phenology of these crops using growth degree days (GDD °C) and time of growth (days) is essential (Table 3.3 - Table 3.6).

Table 3.3: The phenological growth stages of amaranth (*Amaranthus spp*).

APSIM stage name (code) - Canola	**Amaranth Phenological growth stages**	**Days**	**GDD °C**
Sowing (1)	-	-	-
Germination (2)	Germination[1,3]	3 – 4[1,3]	13 – 16[2,3]
Emergence (3)	Germination[1,3]		
End_of_juveline (4)	Opening of cotyledons[1,3]	4 – 5[1,3]	16 – 20[2,3]
End_of_juveline (4)	True leaves (2 leaves) [3]	8 -10[1,3]	26 – 24[3]
-	5 -6 Leaves[3]	21 – 32[1,3]	63 – 115[3]
Floral_initiation (5)	Apical inflorescence[3]	40 – 57[1,3]	130 – 218[3]
Flowering (6)	Anthesis and axillary inflorescence[1,3]	69-79[1,3]	299-377[3]
Start_grain_fill (7)	Seed development and ripening[1,3]	85-113[1-3]	410 – 644[2,3]
End_grain_fill (8)	-	-	-
Maturity (9)	Ripening[1,3]	120 -153[1,3]	709 – 731[3]
Harvest_ripe (10)	Ripening – Senescence[1,3]	-	-
End_crop (11)	-	-	-

[1]Bello (2013), [2]VeggieHarvest. (2019), [3]Martínez-Núñez et al. (2019)

Table 3.4: The phenological growth stages of cowpea (*Vigna unguiculata*).

APSIM stage name (code) - Canola	**Cowpea phenological Growth stages**	**Days**	**GDD °C**
Sowing (1)	-	-	-
Germination (2)	-	-	-
Emergence (3)	Emergence[2,3]	16[1,2,4]	242[3,4]
End_of_juveline (4)	End of the juvenile stage[2,3]	33[1,4]	514[3,4]
Floral_initiation (5)	Floral initiation[2,3]	52[1,2,4]	787[3,4]
Flowering (6)	Flowering[2,3]	64[1,2,4]	933[3,4]
Start_grain_fill (7)	Start of grain filling[2,3]	83[1,2,4]	1190[3,4]
End_grain_fill (8)	End of grain filling[2,3]	107[1,2,4]	1453[3,4]
Maturity (9)	Maturity[2,3]	125[1,2,4]	1660[3,4]
Harvest_ripe (10)	Harvest[2,3]	125[1,2,4]	1660[3,4]
End_crop (11)	Senescence[2,3]	-	-

[1]Shiringani (2007), [2]Ntombela (2012), [3]International Insitute of Tropical Agriculture (2012), [4]Schwartz (2010)

Table 3.5: The phenological growth stages of sweet potato (*Ipomoea batatas*).

APSIM stage name (code) - Potato	**Sweet potato phenological growth stages**	**Days**
Sowing (1)	-	-
Germination (2)	Initial phase[1,3]	28[2,3]
Emergence (3)	Initial phase[1,3]	
Floral (4)	Intermediate phase[1,3]	49[2,3]
Tuberin (5)	Intermediate phase[1,3]	-
Flowering (6)	Final phase[1,3]	-
Fullsenescence (7)	Final phase[1,3]	
Maturity (8)	Final phase[1,3]	

[1]van de Fliert, E. and Braun (1999), [2]Francesco (2005), [3]Kharzhevska (2019)

Table 3.6: The Phenological growth stages of wild mustard (*Brassica juncea L.)*.

APSIM stage name (code) - Canola	**Wild mustard phenological Growth stages**	**Days**	**GDD °C**
Sowing (1)	-	-	-
Germination (2)	Germination[1,2]	0 – 35[2]	3 – 4[2]
Emergence (3)	Emergence[1,2]		108 – 136[2]
End_of_juveline (4)	Leaf stages - two leaf unfolded[1,2]	30 – 90[2]	214 – 251[2]
	Four leaves unfolded[1,2]		320 – 365[2]
Floral_initiation (5)	Flowering – at least one open floret on 50% or more plants[1,2]	90 – 100[2]	506 – 567[2]
Flowering (6)	Flowering- flowering 50% complete[1,2]	95 - 125[2]	679 – 747[2]
Start_grain_fill (7)	Seed fill – seed filling begins. 10% of seed have reached a final size[1,2]	120 - 150[2]	886 – 962[2]
End_grain_fill (8)	Maturity - Seeds begins to mature. 10p% of the seeds has changed the colour[1,2]		1232 – 1322[2]
Maturity (9)	Maturity -70% of the seeds on the main stem has changed the colour[12]	145 - 1502	1440 – 1538[2]
Harvest_ripe (10)	Maturity complete - 90% of seeds has changed colour (ripe) [1,2]		1509 - 1610[2]
End_crop (11)	Senescence[1,2]		

[1]Kullabas (2019), [2]Canola Council of Canada (2017)

3.2.2.4 Manager Folder

The APSIM manager module is used to request any action available to any other module. Here this module was used for the following steps: the resetting of individual modules, sowing, application of fertilisers, irrigation or tilling of the soil, harvesting, or killing off crops, calculating of additional variables, to track the system state, and for the reporting of the system in response to events. The sowing variable rules were adjusted as shown in (Table 3.7).

3.2.3 Scenario analysis

The major factors affecting plant growth, planting date, plant density, fertilizer application rate and irrigation were used to develop scenarios for modelling the best management practice of the studied ALVs. These growth factors were chosen because of the vital role they play in the growth and productivity. since they are major growth factors in APSIM

3.2.3.1 Planting dates

The selected African leafy vegetables (amaranth, cowpea, sweet potato, and wild mustard) are known as warm-season crops. Therefore, the selection of planting date began in spring until the end of summer. That is from 1-Septemeber, 1-October, 1-November, 1-December, 1-January, 1-February, 1-March (Table 3.8).

3.2.3.2 Plant density

Simulations were performed at less or more than 50% of the recommended plant population to determine the optimum plant density (or plant population) for each leafy vegetable crop. For amaranth, an optimum plant density of 17.4 plants m^2 was used. For cowpea, 17.4 plants m2, for sweet potato five plants m^2, and wild mustard, 27 plants m^2. Simulations were done by maintaining the recommended plant population of one component and changing the other, resulting in 8 simulations (Table 3.8).

3.2.3.3 Fertiliser application rate

Amaranth requires a minimum of 100 kg ha^{-1} N to produce 40 tons ha^{-1} of leaves and 1 ton ha^{-1} of grain (Sullivan and Specialist, 2003). Cowpea requires 40 kg ha^{1} N to make 1 ton ha^{-1} of seed and ton ha^{-1} of hay (DAFF, 2013). Sweet potato 100 kg ha^{-1} N (Gupta, 2011), and wild mustards requires 90 kg ha^{-1} N to produce 112 tons ha^{-1} (Government of Saskatchewan, 2017) (Table 3.8). Accurate fertiliser recommendations can help farmers correctly apply fertilisers for better yields that meet or exceed food demands. Therefore, improving yields by addressing fertiliser application as one of the limiting factors is desirable.

To model this scenario analysis based on the recommendations made by Sullivan and Specialist (2003), DAFF (2013), Gupta (2011) and Government of Saskatchewan (2017) for amaranth, cowpea, sweet potato and wild mustard, respectively, were used with fertiliser representatives of 0%, 25%, and 50% of the recommended rates (Table 3.8). This range represents a scenario whereby the farmer does not have access to fertiliser (0%), somewhat have access (25%) and (50%) only have access to half the fertiliser of the recommended rate (Table 3.8).

3.2.3.4 Irrigation

Depending on texture and structure, different soils may differ in water-holding capacity. As one of the management options to improve growth and yield gaps, irrigation can be introduced to growing plants. Irrigation is defined as applying controlled amounts of water to plants at set intervals (Hirota and Satoh, 1988; Zotarelli et al., 2010). However, to be more precise about irrigation and intervals, farmers often develop a schedule using the irrigation calendar based on the crop's previous seasons' water requirements. This is irrigation scheduling, which is merely applying water at the right time and at the correct time (Zotarelli et al., 2010). Irrigation is affected by numerous factors such as root distribution, and soil characteristics and evaporative plant demand. Thus, to establish proper irrigation, these are essential factors to look into. In the present experiment, a drip irrigation method was used to simulate the growth and yields of amaranth, cowpea, sweet potato, and wild mustard at three different Field Capacity (FC) water levels (Table 3.8). Here, the idea is to use the irrigation scheduling with crop water requirement by considering the most critical growth stages where the plant requires water and use guidelines for irrigation.

Table 3.7: Sowing using the variable rule.

Description	**Value**			
Crop properties				
Name of crop	Canola	Cowpea	Potato	Canola
Enter cultivar	Mustard	banjo	Sweet potato	Wild mustard
Method of cropping	Sole	Sole	Sole	Sole
Exclude from rotation sequence	no	no	no	no
Sowing criteria				
Enter sowing window START date (dd-mm)	1 – Sep	1-Sep	1 – Sep	1-Sep
Enter sowing window END (dd-mm)	1-Apr	1-Apr	1-Apr	1-Apr
Must sow	Yes	Yes	Yes	Yes
Enter amount of cumulative rainfall (mm)	20	20	20	20
Enter number of days to acumulate rainfall (days)	5	5	5	5
Enter amount of soil water (mm)	100	100	200	100
Enter opportunity number to sow on	2	2	2	2
Enter upper limit of soil water in top layer (0-2) (mm esw/mm soil)	2	2	2	2
Enter upper limit of soil water in top layer (0-2) (mm esw/mm soil)	0	0	0	0
Sowing parameter				
Enter name of crop to sow	canola	cowpea	potato	canola
Enter sowing density (plant/m2)	174	25	1.87	27
Enter sowing depth (mm)	20	20	300	15
Enter cultivar	Amaranth	banjo	russet	Wild_mustard
Enter crop growth class	Plant	plant	plant	plant
Enter row spacing (mm)	300	300	900	100

Harvesting rule				
Harvesting rule				
Enter the name of crop ti harvest when ripe	canola	cowpea	potato	canola
Fertiliser at sowing				
Amount of starter fertiliser at sowing (kg/ha)	72.5	44	100	101
Sowing fertiliser type	urea_N	urea_N	urea_N	urea_N
Fertiliser on days after sowing – top-up				
Aount of N required in top 3 layers (kg/ha)	200	100	0	200
Fertiliser application details				
The module used to apply fertiliser	Fertiliser	Fertiliser	Fertiliser	Fertiliser
Fertiliser type	NO3_N	NO3_N	broadcast_p	urea_N

The manager folder was modified for each leafy vegetable, and the sowing variable was set. The above table does not show variables where default settings were used.

Table 3.8: A scenario analysis of selected African leafy vegetables.

Scenarios	**Amaranth**	**Cowpea**	**Sweet potato**	**Wild mustard**
1. Nitrogen fertiliser application (kg/ha) (0, 50, 100% of recommended)	72.50	44.00	100.00	73.00
2. Irrigation (mm) 0, 45, 90 of PAW	1000.00	1150.00	1395.00	1000.00
3. Planting dates (trigger season climate method, modelling and fixed date approaches)	For all crops, the planting dates for the sowing of crops began from 1-Septemeber, 1-October, 1-November, 1-December, 1-January, 1-February, 1-March, 1-April			
4. Planting density (plants/m^2) high (-50%) or low (+50%) of the recommended	17.40	18.50	1.85	27.00

3.2.5 Data analysis and visualisation

The simulation output obtained on growth and productivity were subjected to descriptive statistics, t-test analysis and generalized linear mixed analysis (GLMM) on R statistical software (version 1.3.959). The generalized linear mixed and t-test analysis was used at a confidence interval level of 95%. For the output analysis, descriptive values such as means, standard deviations, box and whiskers plots, and graphs were used. The box and whiskers plot were used to show the general trend and steadiness of data. In contrast, the t-test was used to determine any difference among the means of leaf number, leaf mass, leaf area index and water productivity.

3.3 Results

3.3.1 Amaranth

3.3.1.1 Planting date

Different planting date resulted in different responses to leaf number, leaf mass, leaf area index (LAI) and water productivity (WP) (Figure 3.1). Early planting 01-September (1) favoured a high number of leaves (123). Contrary to this, late plantings (01-March) resulted in a low leaf number (89). Results for leaf mass, LAI and WP showed an inverse relationship with leaf mass. The general observation was that late planting date gave the highest leaf mass, LAI and WP compared to early planting dates. Planting date 01-March (7) and 01-December (4) gave the highest (1 324 g plant^{-1}) and lowest (1 089 g plant^{-1}) leaf mass, respectively. Planting in March resulted in the highest LAI (2.53) and WP (0.41 g m^{-3}) and while November planting had the lowest simulated values (1.90, 0.21 g m^{-3}, respectively).

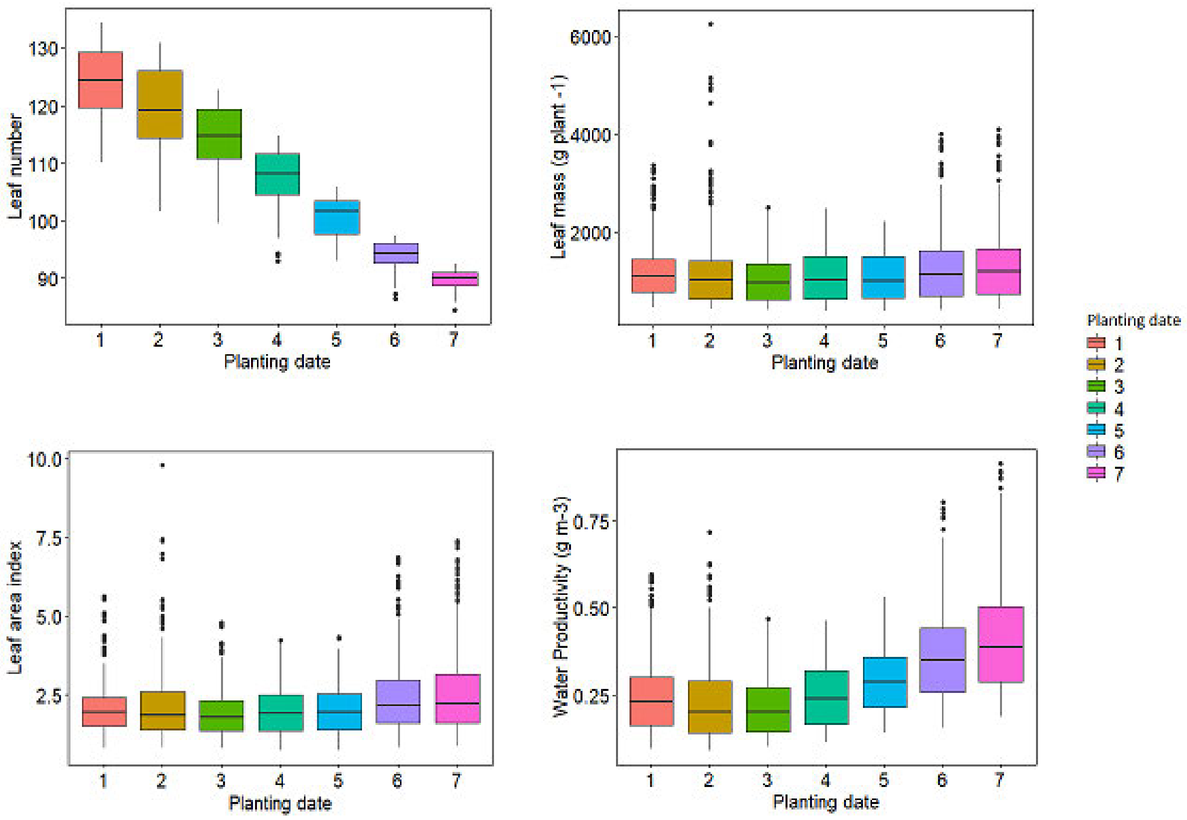

Figure 3.1: The effect of planting dates on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-3}) on growth and development of amaranth. Planting date 1 through 7 correspond to the 1st of September (1), October (2), November (3), December (4), January (5), February (6) and March (7) respectively.

3.3.1.2 Plant density

There was a significant difference ($P<0.05$) in leaf number and LAI of the amaranth plants (Figure 3.2). However, plant density did not affect leaf mass and WP. Overall, the leaf mass, LAI and WP were all optimum under medium plant density, 17.4 plants m^2. On the other hand, leaf number decreased with an increase in plant density. The leaf number results were highly distributed along with the mean, mostly where density was low, suggesting less competition for growth resources under low plant densities. Leaf mass was the highest (1193 kg ha^{-1}) at medium plant density (17.4 plants m^2) and the lowest (1165 g $plant^{-1}$) at low (8.7 plants m^2) plant density. At plant density, 26.1 plants m^2, the mean leaf mass was 1173 g $plant^{-1}$. The leaf area index was 2.32, 2.21, and 1.87 at 26.1, 17.4 and 8.7 plants m^2. There were no significant differences for WP across the simulated plant density. There was no significant difference in WP across the different plant densities. Overall, WP was 0.29 g m^{-3} with a standard deviation of 0.13. There were more outliers for the simulated WP under high plant density than under low plant density (Figure 3.2).

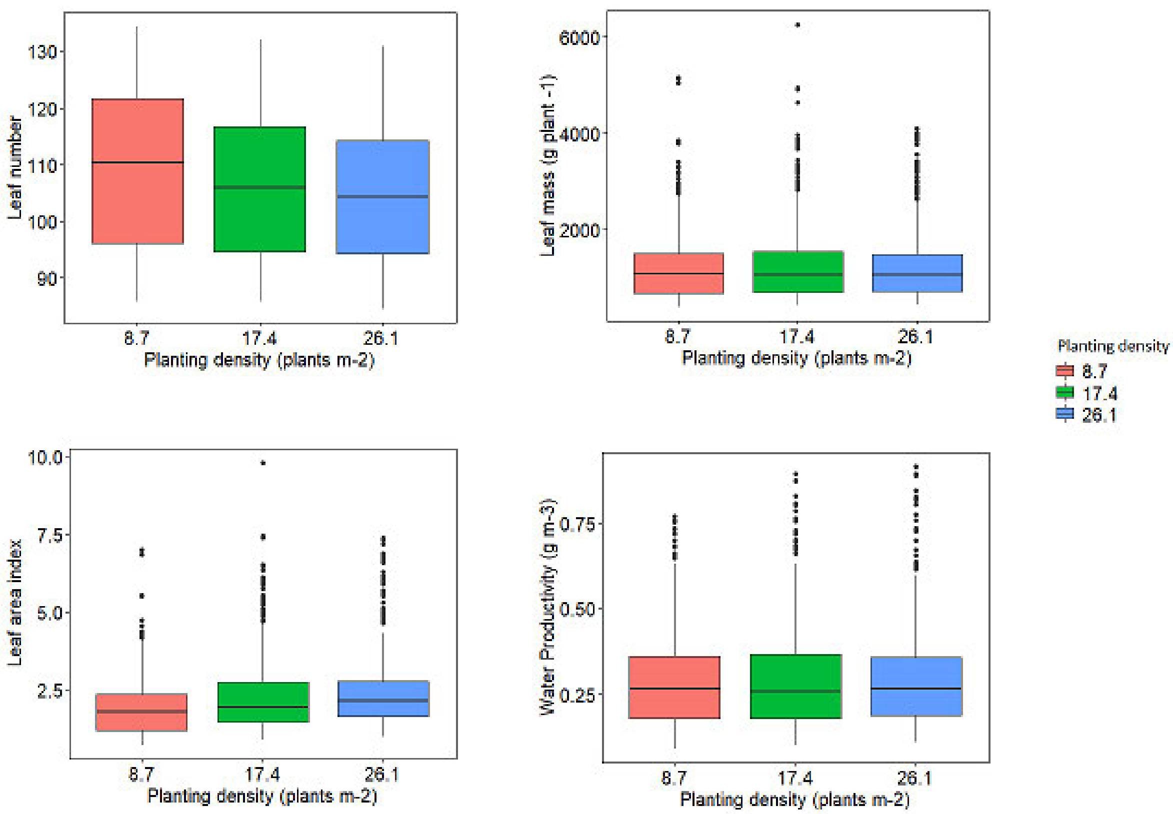

Figure 3.2: The effect of plant density (plants m^2) on leaf number, leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth and development of amaranth.

3.3.1.3 Fertiliser application

In terms of leaf number and leaf mass, the simulated results at different fertiliser application showed no significant differences. The simulated leaf number was the same (106) at different fertiliser rates, respectively. An average leaf mass of 1188, 1173 and 1170 g $plant^{-1}$ was obtained at 71, 35.5, and 0 kg ha-1 of fertiliser application. The plants simulated with 71 kg ha^{-1} fertiliser had the highest (2.17) LAI, and the ones simulated with 0 and 35.5 kg ha^{-1} gave the lowest (2.14). Water productivity also showed a similar trend with LAI. The highest WP means value (0.29 g m^{-3}) was at 71 kg ha^{-1} and 0 and 35.5 kg ha^{-1} fertiliser application giving the lowest (0.28 g m^{-3}). Several outliers were observed across the measure variables, and this could have been attributed to different climatic conditions observed.

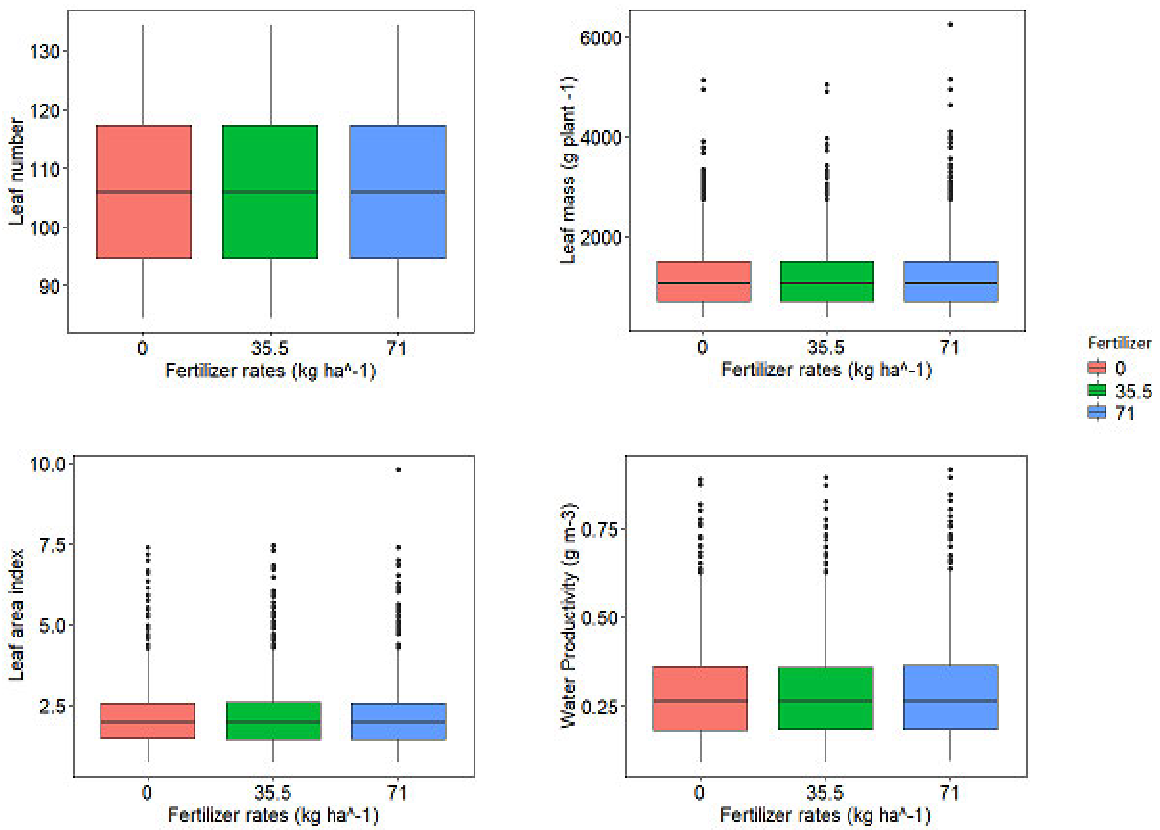

Figure 3.3: The effect of Fertiliser (kg ha^{-1}) on leaf number, leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth and development of amaranth.

3.3.1.4 Irrigation

The different irrigation levels resulted in significant differences ($P<0.05$) in leaf number, leaf mass, LAI, and WP. Increasing water availability through irrigation increased simulated leaf mass. There were no irrigation, leaf number, leaf mass, LAI, and WP values. Adding 40 mm of water resulted in an increase in leaf number, leaf mass, LAI, and WP by 4.8, 119.2, 89.3, and 85.0%, respectively.

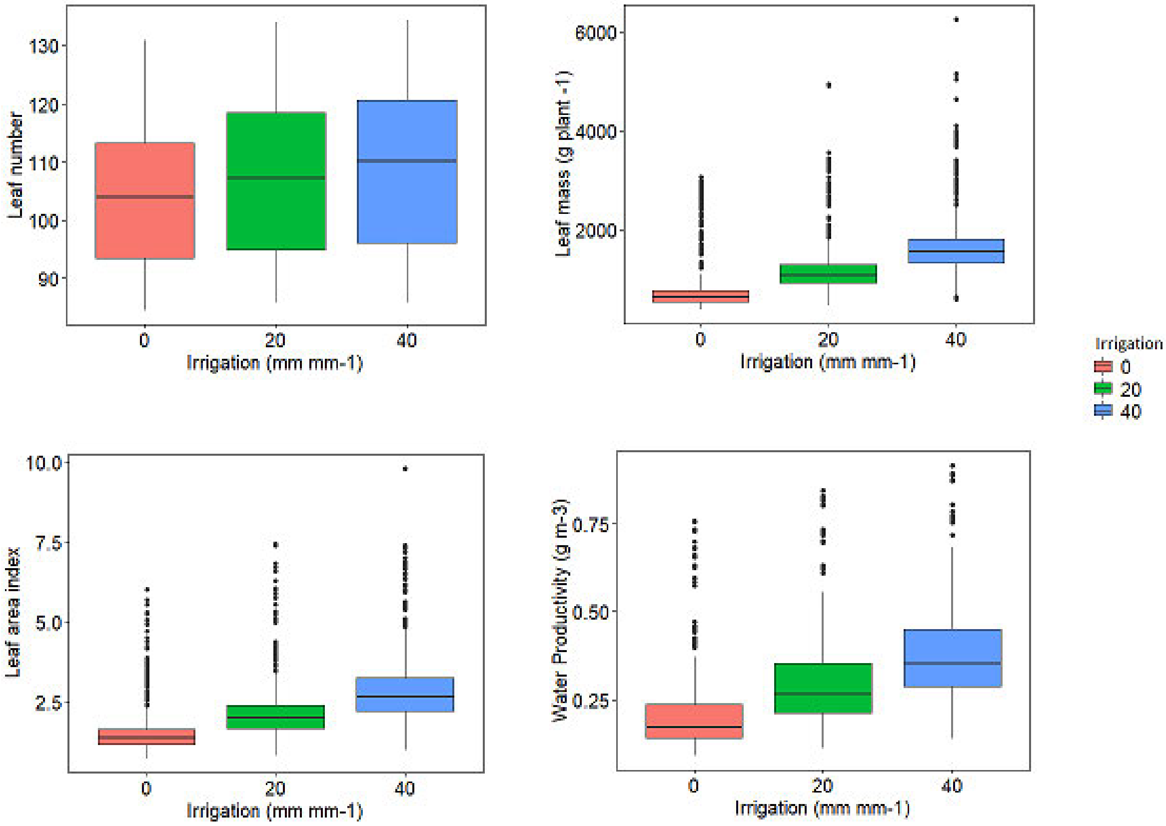

Figure 3.4: The effect of irrigation (mm mm^{-1}) on leaf number, leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth and development of amaranth.

3.3.1.5 Management Practice Combinations

The best management combination for high leaf number (130) was no fertiliser, 17.4 plants m^2, 40 mm mm^{-1}, planting date 1 (01-September). Leaf mass was the highest (2130 g $plant^{-1}$) at the combination 71 kg ha^{-1}, 17.4 plants m^2, 40 mm mm^{-1}, 01-October. The planting date 01-March (7), high irrigation (40 mm) and fertilization (71 kg ha^{-1}), and plant density (26.1 plants m^2) resulted in a high leaf area (3.84). Lastly, WP was the highest at the combination of high fertilization (71 kg ha^{-1}) and irrigation (40 mm), plant density (17.4 plants m^2) and when amaranth was sown in March (7). Different management strategies can be applied to promote growth and productivity depending on the overall production objective,

3.3.2 Cowpea

3.3.2.1 Planting date

The effect of planting dates on leaf number, leaf mass, LAI and WP were observed to be pronouncedly different (P<0.05) for each planting date scenario (Figure 3.5). They were planting early increased in leaf number, leaf mass, and LAI, while late planting resulted in a decrease in these variables. To add, simulated growth and productivity decreased on plants simulated in 01-March. 01-October (2) had the highest (53) and 01-March (7) the lowest (24) leaf number. The leaf mass also differed according to planting dates. Observed simulated results showed that plants sown on 01-October (2) had the highest leaf mass (2309 g plant^{-1}), compared to those planted on 01-March (7), which had the lowest mean leaf mass of 998.32 kg ha^{-1}. The LAI was the highest (6.05), and the lowest (2.91) for the planting dates 01-October and 01-March. There was a slight increase in WP from early to late planting. Plants simulated in 01-March, which had the lowest (0.52 g m^{-3}) WP while 01-February (2) had the highest (0.64 g m^{-3}) mean WP (Figure 3.5).

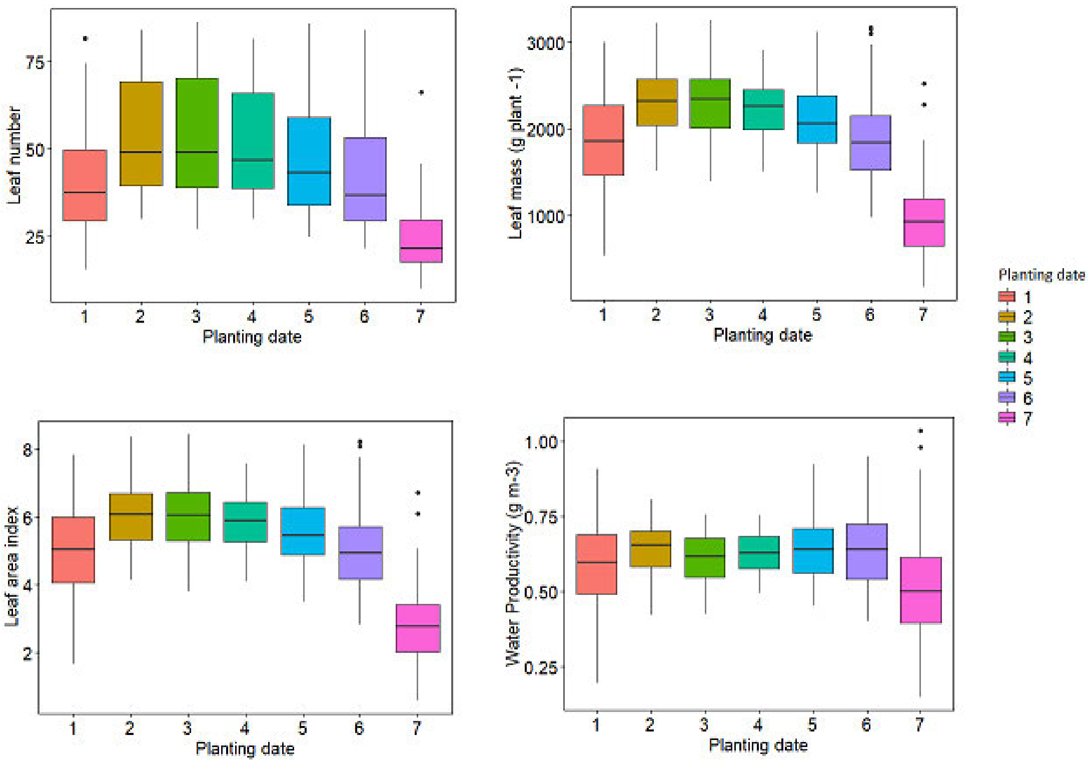

Figure 3.5: The effect of planting dates on leaf number, leaf mass (g plant^{-1}), leaf area index

and water productivity (g m^{-3}) on growth and development of cowpea. Planting date 1 through to 7 correspond to the 1st of September (1), October (2), November (3), December (4), January (5), February (6) and March (7), respectively.

3.3.2.2 Plant density

Different plant densities resulted in significantly different ($P<0.05$ leaf number, leaf mass, LAI and WP. While other growth parameters increased with an increase in plant density, leaf number decreased (Figure 3.6), which may have been due to the high competition of resources such as sunlight and nutrients that resulted from the in-between spaces being too small. The mean number was 62 at low plant density (8.7 plants m^2), 40, and 31 at 17.4 plants m^2, the mean number of leaves was 40, and it was lowest (31) at 26.1 plants m^2. Leaf mass, LIA, and WP increased with an increase in plant density. These were the highest at 26.1 plants m^2, (2163 g $plant^{-1}$, 5.75, and 0.66 g m^{-3}), moderate at medium plant density, 17.4 plants m^2, (1993 g $plant^{-1}$, 5.32, and 0.62 g m^{-3}) and lower at low plant density, 8.7 plants m^2 (1673 g $plant^{-1}$, 4.47, and 0.54 g m^{-3}) respectively. Moreover, the plant leaf mass data was fairy legally distributed away around the mean (Figure 3.6).

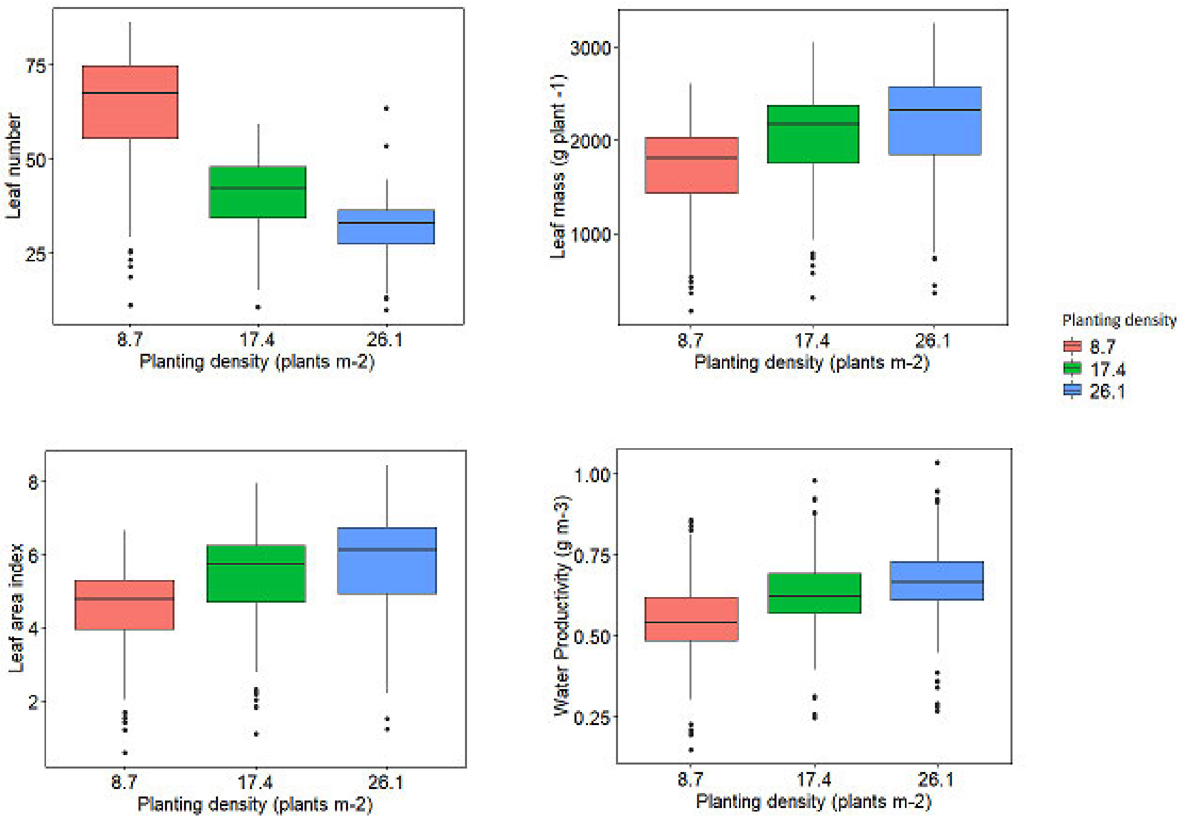

Figure 3.6: The effect of planting density (plants m^2) on leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth, development, and productivity of cowpea.

3.3.2.3 Fertiliser application

There was a significant difference ($P<0.05$) in leaf number across different fertiliser application rates. However, the simulated results showed no change in the cowpea plant's growth and productivity (Figure 3.7). The mean leaf number was 44 across different fertiliser applications (0, 30, 60 kg ha^{-1}). Leaf mass, LAI and WP were also the same across all fertiliser application rates (0, 30, and 60 kg ha^{-1}). These were 1948 g $plant^{-1}$, 5.19, and 0.61 g m^3, respectively (Figure 3.7). These findings were not expected as fertiliser is generally known to affect the growth and development, thus productivity of plants. The cause of cowpea not responding to the applied fertiliser maybe that cowpea can fix its nitrogen and supply it to the soil, thus leaving the inputted fertiliser with no role to play as the soils were already sufficient in nitrogen for the growth of the cowpea plants. The type of fertiliser used on these plants and the time of application may also cause these similarities.

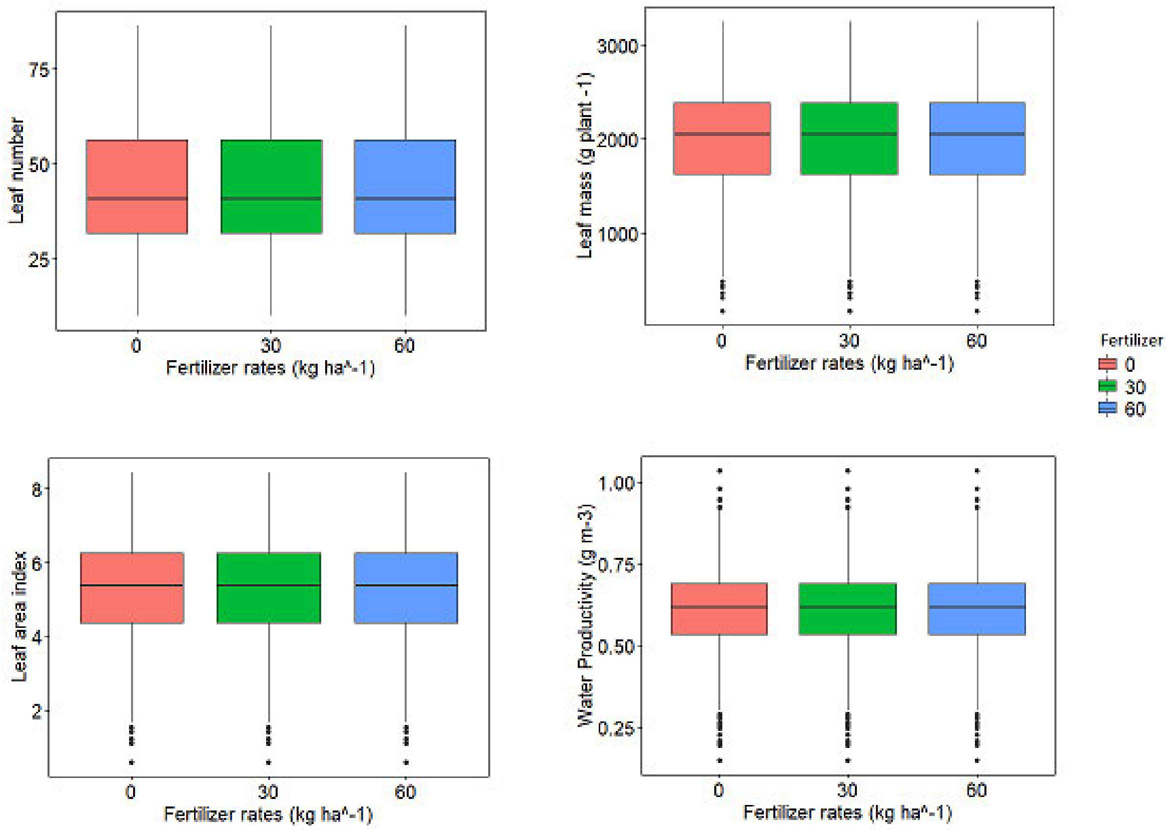

Figure 3.7: The effect of Fertiliser (kg ha^{-1}) on leaf number, leaf mass (g $plant^1$), leaf area index and water productivity (g m^3) on growth, development, and productivity of cowpea.

3.3.2.4. Irrigation

There was no significant difference in leaf number upon different irrigation levels results. (0, 20 and 40 mm) (Figure 3.8). Across all water application levels, the leaf number was 44. Leaf mass was higher (1963, g plant^{-1}) where no there was no irrigation (0 mm) and lower (1922 g plant^{-1}) at 20 mm. At high water application (40 mm), leaf mass was moderate (1960 g plant^{-1}). LAI was higher (5.23) at no water application and lower (5.13) at 20 mm. High irrigation 40 mm resulted in a moderate (5.22) leaf area index. On the other hand, WP was (0.61 g m^{-3}) at both 0- and 40-mm and lower (0.60 g m^{-3}) at medium irrigation 20 mm mm^{-1} (Figure 3.8).

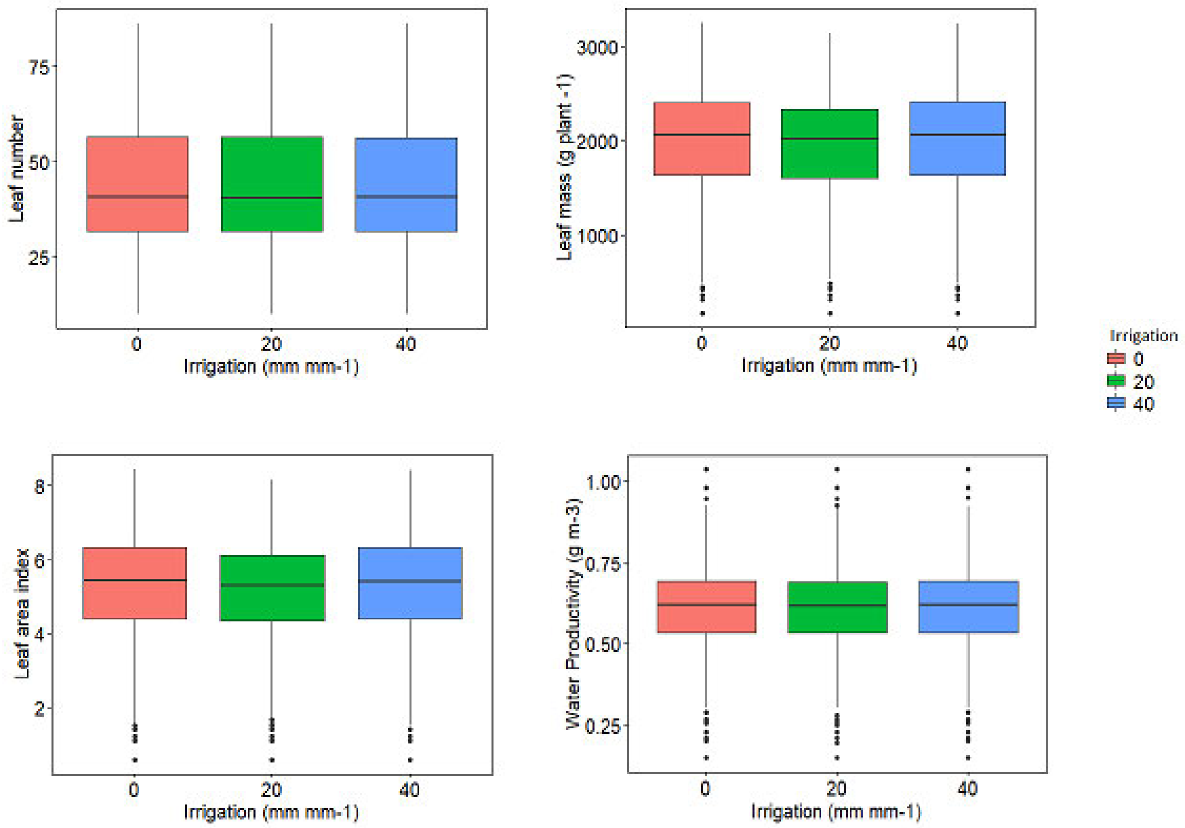

Figure 3.8: The effect of irrigation (mm mm-1) on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-3}) on growth and development of cowpea.

3.3.2.5 Management Practice Combinations

The interaction of plant density and planting date was significantly different ($P<0.05$) in leaf number. Leaf number was the highest (74) for plants sown on the 1st of October (2) at 8.7 plants m^{2} for all fertiliser levels (0, 30, 60 kg ha^{-1}) with high (40 mm) or no (0 mm mm^{-1}) water application. The combination (0 mm, 26.1 plant m^{-2} across all fertiliser application levels and planting date 2 (01-October) resulted in high leaf mass, 2587 g plant^{-1}. These results were the same for LAI, which was 6.78. A high mean WP of 0.69 g m^{-3} was observed when there was no water applied on cowpea plants, at a plant density of 26.1 plant m^{-2}, in all fertiliser application rates (0, 30, and 60 kg ha^{-1}) on plants simulated on planting date 5 (01-January).

3.3.3 Sweet potato

3.3.3.1 Planting date

Different planting date resulted in varied responses to leaf number, leaf mass, LAI, and WP for sweet potato. The LAI, leaf mass and WP were significantly ($P<0.05$) affected by planting date. Simulated leaf number differed slightly across different planting dates. Overall, the leaf number was 43 regardless of the planting date. The planting date 01-November (3) and 01-March (7) had the highest (931 g $plant^{-1}$) and lowest (767 g $plant^{-1}$) leaf mass, respectively. There was a general increase in LAI and WP with later planting. Interestingly, planting February (6) and December (4) gave the highest (0.04) and the lowest (0.03) LAI. Growing in March (7) gave the highest (0.35 g m^{-3}), and planting in October (2) gave the lowest (0.21 g m^{-3}) WP, respectively, Figure 3.9. Results suggest that late planting gives optimum results in leaf number, leaf mass, LAI, and WP.

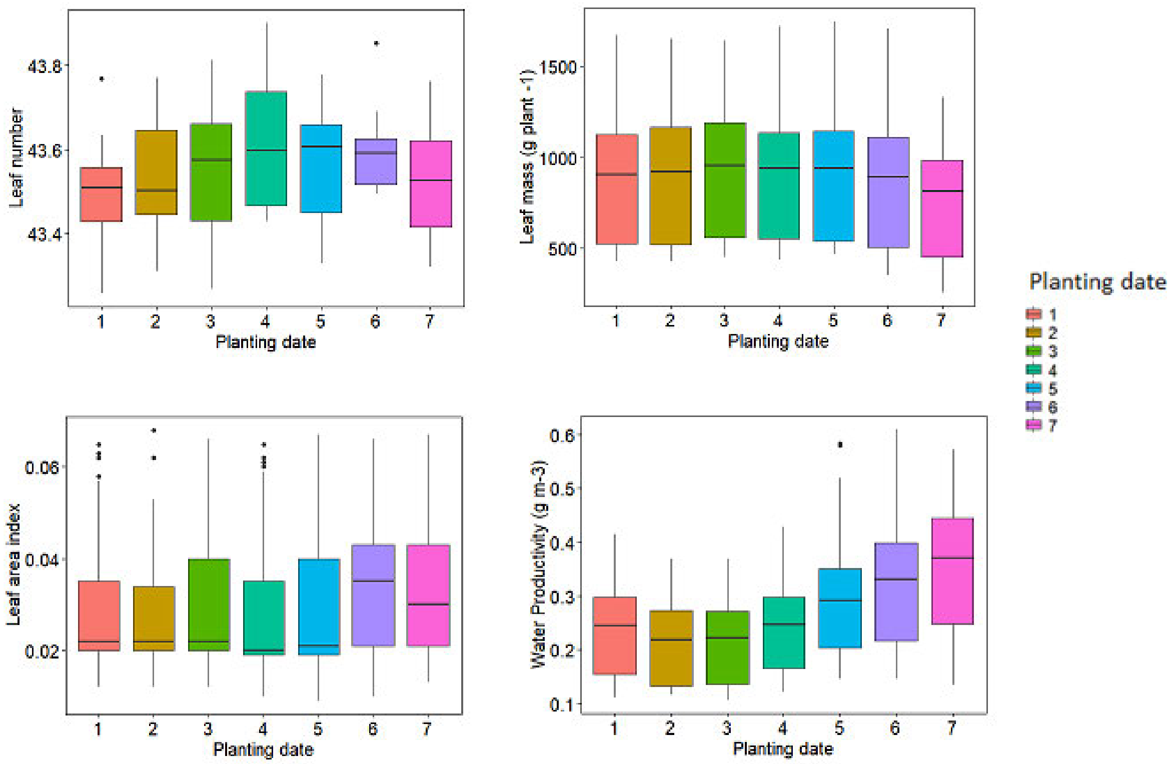

Figure 3.9: The effect of planting dates on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-3}) of sweet potato. Planting date 1 through to 7 correspond to the 1st of September (1), October (2), November (3), December (4), January (5), February (6) and March (7), respectively.

3.3.3.2 Plant density

There was no change in leaf number of sweet potato plants observed across different plant density. However, a significant ($P<0.05$) increases in leaf mass, LAI, and WP, with an increase in plant density (Figure 3.10). At high plant density (2.5 plants m^2), leaf mass was 491 g plant^{-1}, at 5.0 plants m2, 907g plant$^{-1,}$ and at a high planting date of 7.5 plants m^2, leaf mass was the highest (1234 g plant^{-1}). LAI and WP were high (0.04 and 0.36 g m^{-3}) at high plant density (7.5 plants m^2), medium plant density (0.32 and 0.28 g m^{-3}) and at low plant density (2.5 plants m^2) was (0.20 and 0.17 g m^{-3}), respectively. The simulated LAI results showed a wider distribution around the mean for sweet potato planted at higher plant density. The reasoning behind this might be that LAI is less stable under tall plant density owing to increased competition for resources such as light and other growth factors.

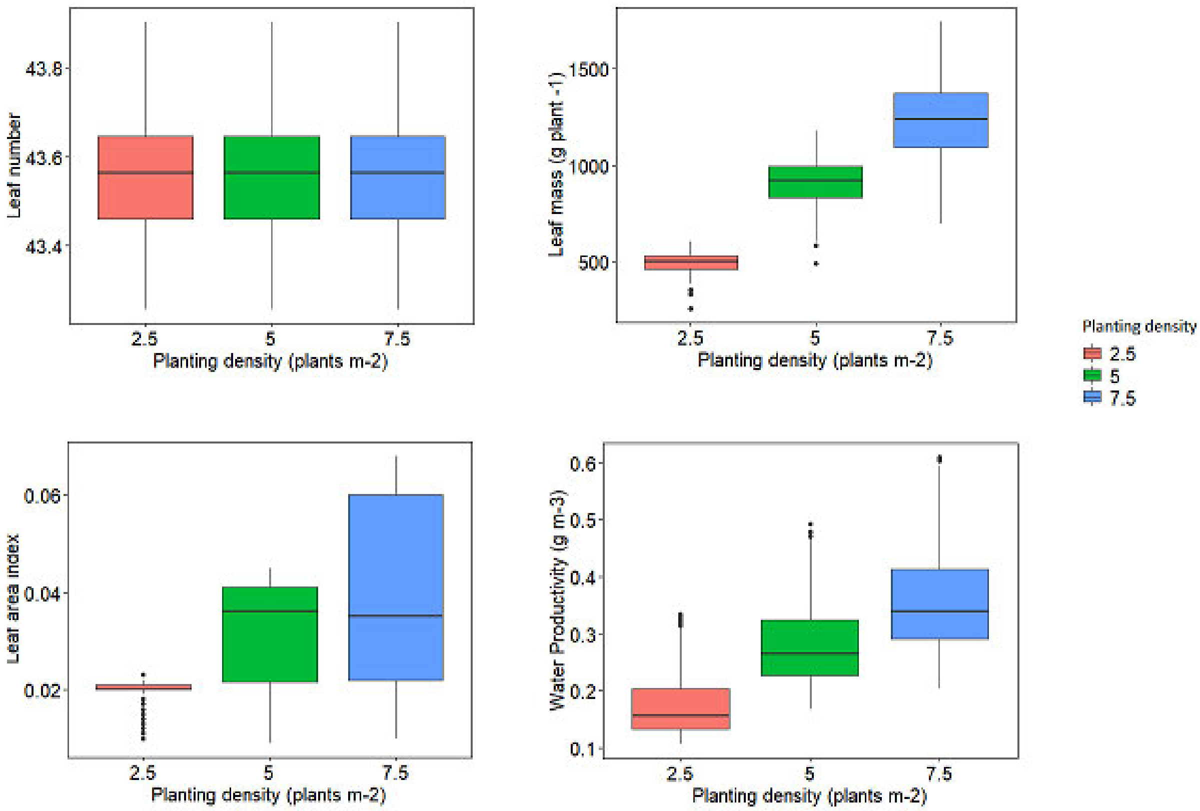

Figure 3.10: The effect of plant density (plants m^2) on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-3}) on growth and development of sweet potato.

3.3.3.3 Fertiliser application

Fertiliser application rate did not affect leaf number. However, a pronounced effect on leaf mass, LAI and WP was observed. There was a significant increase ($P<0.05$) in leaf mass, LAI, and WP, increasing fertiliser rates. At high fertiliser application, 60 kg ha^{-1}, the average leaf mass was 933 g $plant^{-1}$ and medium fertiliser application (30 kg ha^{-1}), 901 g $plant^{-1}$ at no fertiliser application, 797 g $plant^{-1}$. The LAI was 0.04, 0.03, and 0.02 at high, medium and no fertiliser application, respectively. Lastly, at high fertiliser application, the average WP was 0.27 g m^{-3} (Figure 3.11). Generally, adding fertiliser improves growth. However, as observed from the simulated results, this was not the case for leaf number. To add, although these results varied (outliers), fertiliser application at a higher (60 kg ha^{-1}) rate resulted in optimum growth and development of sweet potato.

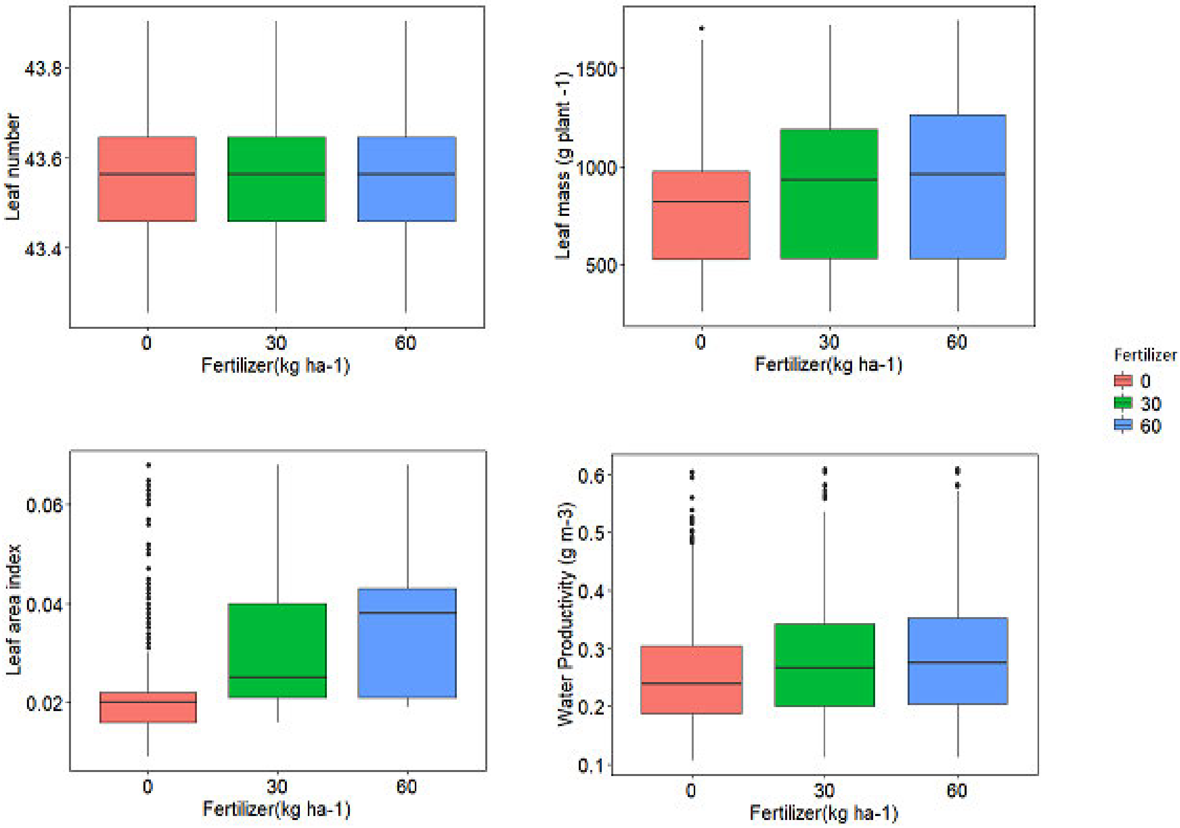

Figure 3.11: The effect of Fertiliser (kg ha^{-1}) on leaf number, leaf mass (kg ha^{-1}), leaf area index and water productivity (g m^{-3}) on growth and development of sweet potato.

3.3.3.4 Irrigation

There was no significant difference ($P>0.05$) across different leaf number, leaf mass, LAI and WP simulated mean results. No change in leaf number observed upon changing the amount of water applied to the sweet potato plants (Figure 3.12). However, a slight change was observed for leaf mass, LAI, and WP. Leaf mass was 875 g plant^{-1} at no water application, 882 g plant^{-1} at 40 mm, and 874 g plant^{-1} and 60 mm of irrigation. Overall, the mean LAI was 0.03, and WP was 0.27 g m^{-3} regardless of water applied. It was interesting to note that the simulated results varied widely across the mean. There were outliers in the results for water productivity (Figure 3.12).

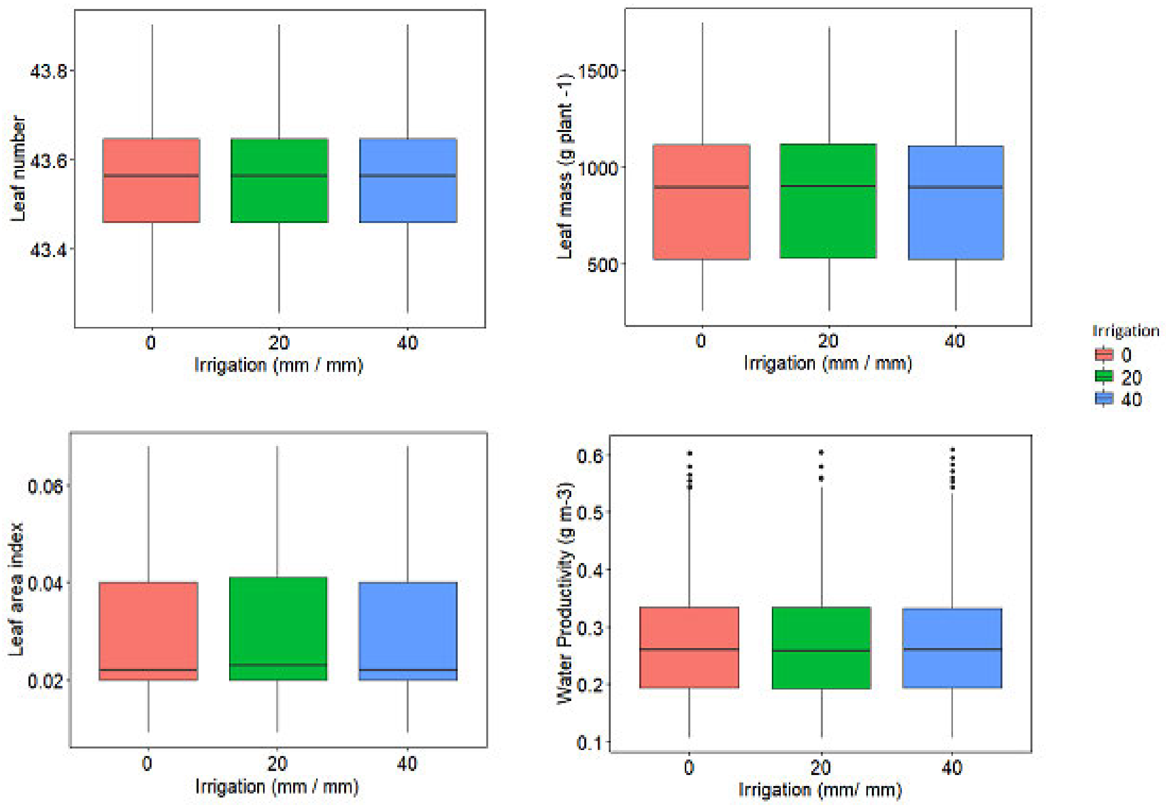

Figure 3.12: The effect of irrigation (mm mm^{-1}) on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-3}) on growth and development of sweet potato.

3.3.3.5 Management Practice Combinations

The interaction of plant density, fertiliser and planting date was found to be significantly different on leaf mass. The WP results were also significantly different ($P<0.05$) under plant density and fertiliser interaction. The interaction of fertiliser and planting date was also considerably different in terms of leaf mass. A significant difference was observed on LAI where plant density, fertiliser and planting date interacted. In terms of leaf number, there was no significant difference. All combinations of management practices resulted in an average of 43 leaves.

The planting date 4 (01-December) was found to ideal for different plant densities, fertiliser application and irrigation levels. Across all different management practice combinations, leaf number was the same, 43. On the other hand, leaf mass, LAI and WP showed a substantial difference when subjected to different managerial practices changes. The best management practice for leaf mass (1458 g plant^{-1}) was at planting date 4 (01- December), high plant density (7.5 plants m^{2}), 60 kg ha^{-1} of fertiliser and 20 mm water application. Planting in March, at high density, 30 kg ha^{-1} fertiliser application and high irrigation of 40 mm were the best management practice combination to give a high LAI of 0.06. Lastly, WP was the highest (0.47) in plants sown on 01-March, at 7.5 plants m^{2}, 30 kg ha^{-1} fertiliser application and irrigation of 40 mm.

3.3.4 Wild mustard

3.3.4.1 Planting date

Different planting dates gave varied results in leaf number, leaf mass, LAI, and WP, and these simulated results were significantly different ($P<0.05$). A general decrease in leaf number, leaf mass, and LAI was observed to progress from early to late planting (Figure 3.13). However, planting in 01-November (3) gave more leaves (39) per plant. The mean leaf number was lower (23) on plants sown 01-March (3). Leaf mass, on the other hand, was high (1491 g plant^{-1}) and low (903 g plant^{-1}) on wild mustard sown on (01-October) and 7 (01-March). Interestingly, LAI was higher, 3.84 and more down, 2.35, on plants sown in 01-October (2) and 01-March (7), respectively. Early planting (01-September) resulted in high (0.33 g m^{-3}) WP and low WP (0.29 g m^{-3}) on wild mustard sown in 01-March (7) (Figure 3.13). Given the results, they were planting early resulted in higher yields compared to planting late.

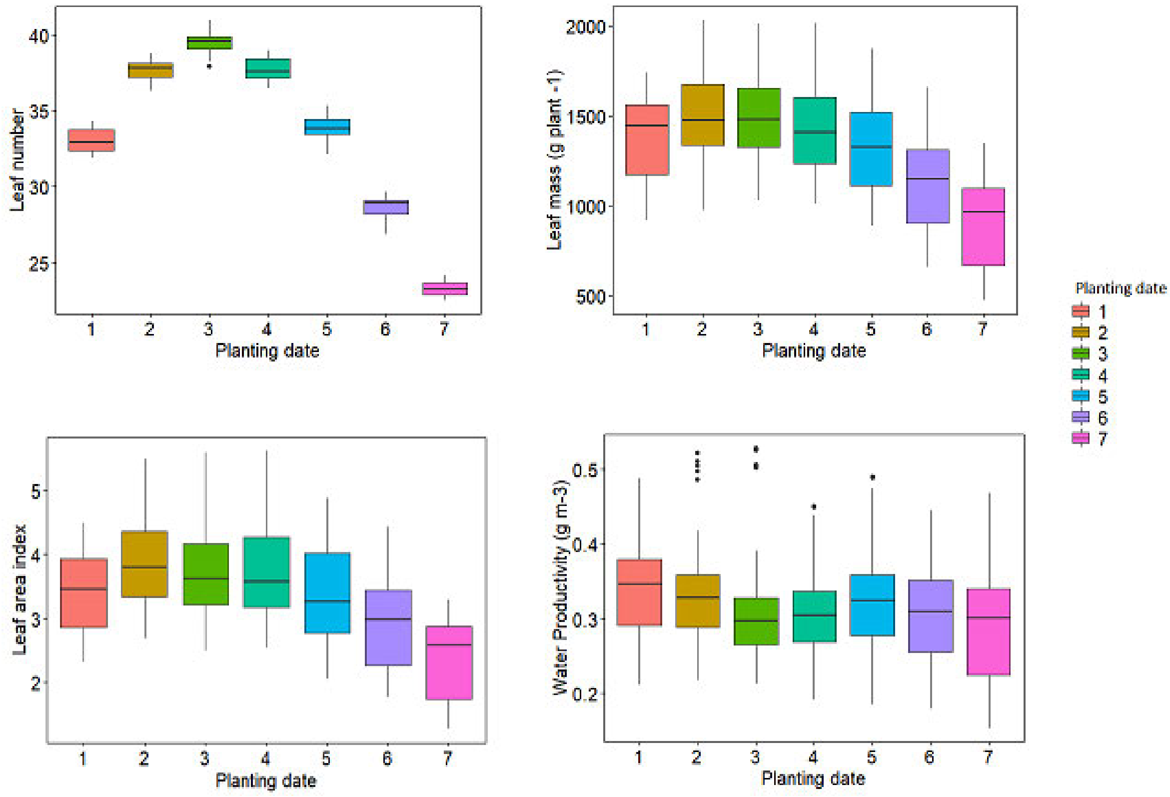

Figure 3.13: The effect of planting dates on leaf number, leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth and development of wild mustard. Planting date 1 through to 7 correspond to the 1st of September (1), October (2), November (3), December (4), January (5), February (6) and March (7), respectively.

3.3.4.2 Plant density

Different planting densities did not affect leaf number. Leaf mass, LAI and WP increased with an increase in plant, $P<0.05$ (Figure 3.14). At high plant density (30.5 plants m^2) leaf mass, LAI and WP were (1443 g $plant^{-1}$, 3.67, 0.34 g m^{-3}), at medium plant density (27 plants m^2) it was (1395 g $plant^{-1}$, 3.58, and 0.33 g m^{-3}) and at low planting (13.5 plants m^2) density it was (1056 g $plant^{-1}$, 2.72, 0,25 g m^{-3}), respectively. It suggested that planting in high densities is ideal for the growth and development of wild mustard. However, as observed from the simulated results (Figure 3.14), the growth parameters' responses were highly distributed and had outliers. This could mean that plants' growth was not even, and resources are more likely to be received by some plants and not others.

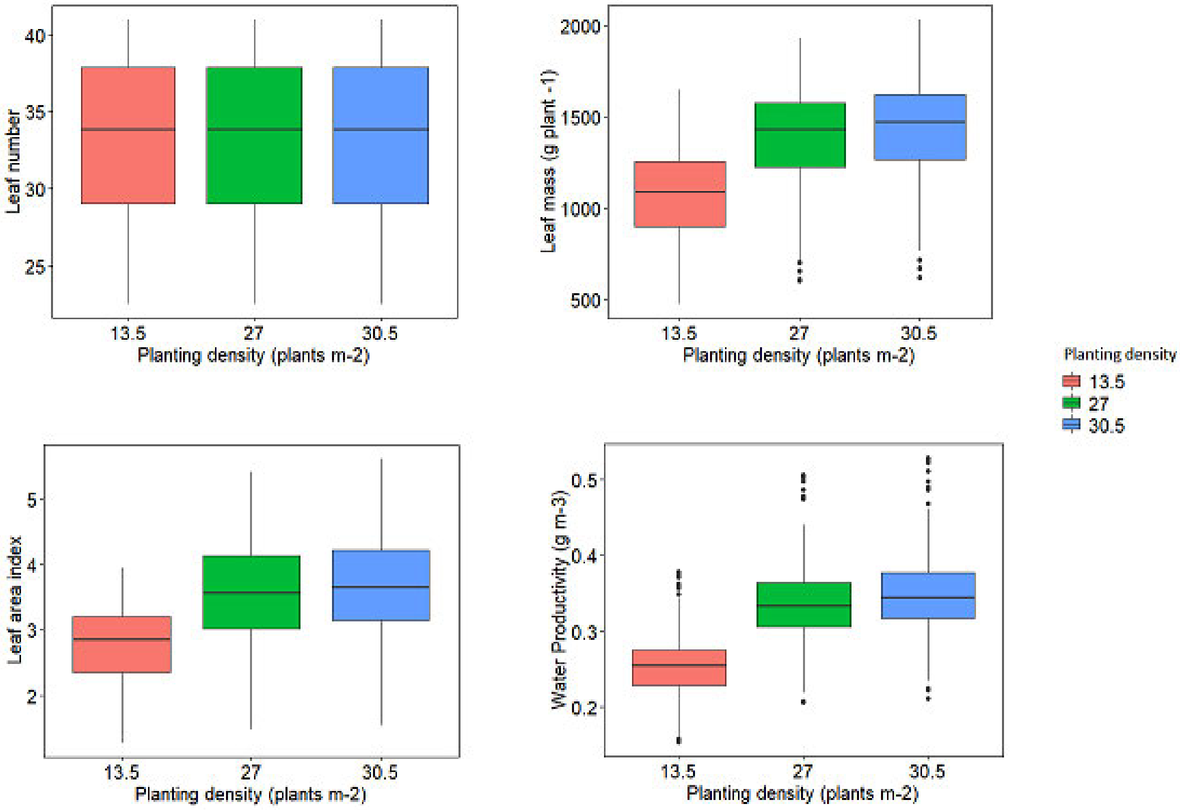

Figure 3.14: The effect of plant density (plants m^2) on leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^{-3}) on growth and development of wild mustard.

3.3.4.3 Fertiliser application

Different fertiliser applications did not affect leaf number. The leaf mass results, LAI and WP, were significantly different ($P<0.05$) (Figure 3.15). Across all fertiliser application rates (0, 35.5, 71 kg ha^{-1}), the mean number of leaves was 33. The leaf mass and LAI were higher 1319 g $plant^{-1}$ and 3.38 at medium fertiliser application (35.5 kg ha^{-1}) and lower (1287 g $plant^{-1}$ and 3.27) at 71 kg ha^{-1} fertiliser application. At no fertiliser application, leaf mass was 1288 g $plant^{-1}$, and LAI was 3.32, respectively. On the other, WP did not follow this trend. It increased with an increase in fertiliser application. The crops were more productive (0.33 g m^{-3}) where there 0.30g m^{-3}, respectively (Figure 3.15).

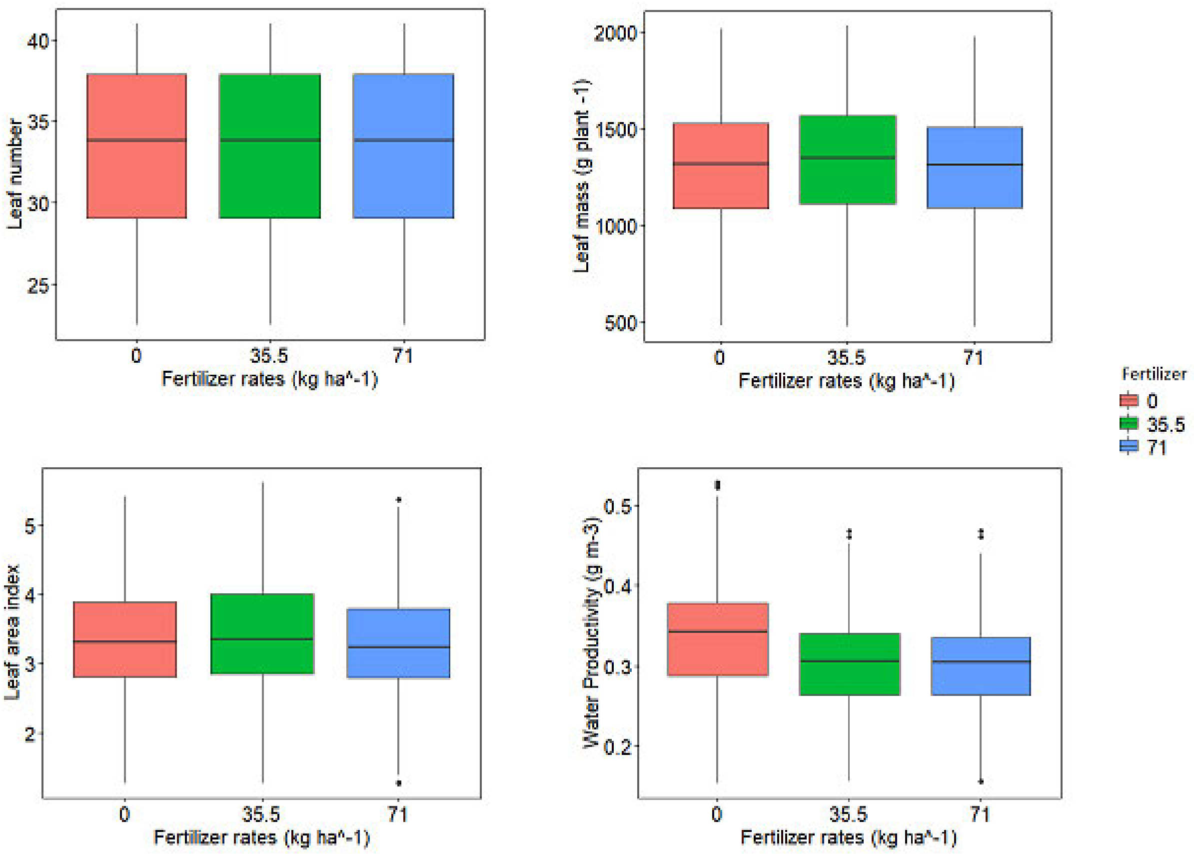

Figure 3.15: The effect of Fertiliser (kg ha^{-1}) on leaf number, leaf mass (g $plant^{-1}$), leaf area index and water productivity (g m^3) on growth and development of wild mustard.

3.3.4.4 Irrigation

The simulates results on leaf number, leaf mass, LAI and WP were significantly different ($P<0.05$) across different irrigation treatments. However, there was no change in leaf number across different irrigation levels 0,40,60 mm, (Figure 3.16). The mean number of leaves was 33. On the other hand, leaf mass, LAI and WP had varied results upon increasing water application to crops. At different irrigation levels 0, 40,60 mm, leaf mass and LAI was 1263, 1299 and 1331g $plant^{-1}$, and 3.21, 3.33, and 3.34, respectively. Water productivity was 0.30 g m^{-3} at 0 mm, and for both levels 40, 60 mm, it was 0.31 g m^{-3} which was a small difference between different irrigation levels (Figure 3.16). The simulated growth and productivity response values were observed to be fairly distributed around the mean and LAI, and WP had outliers.

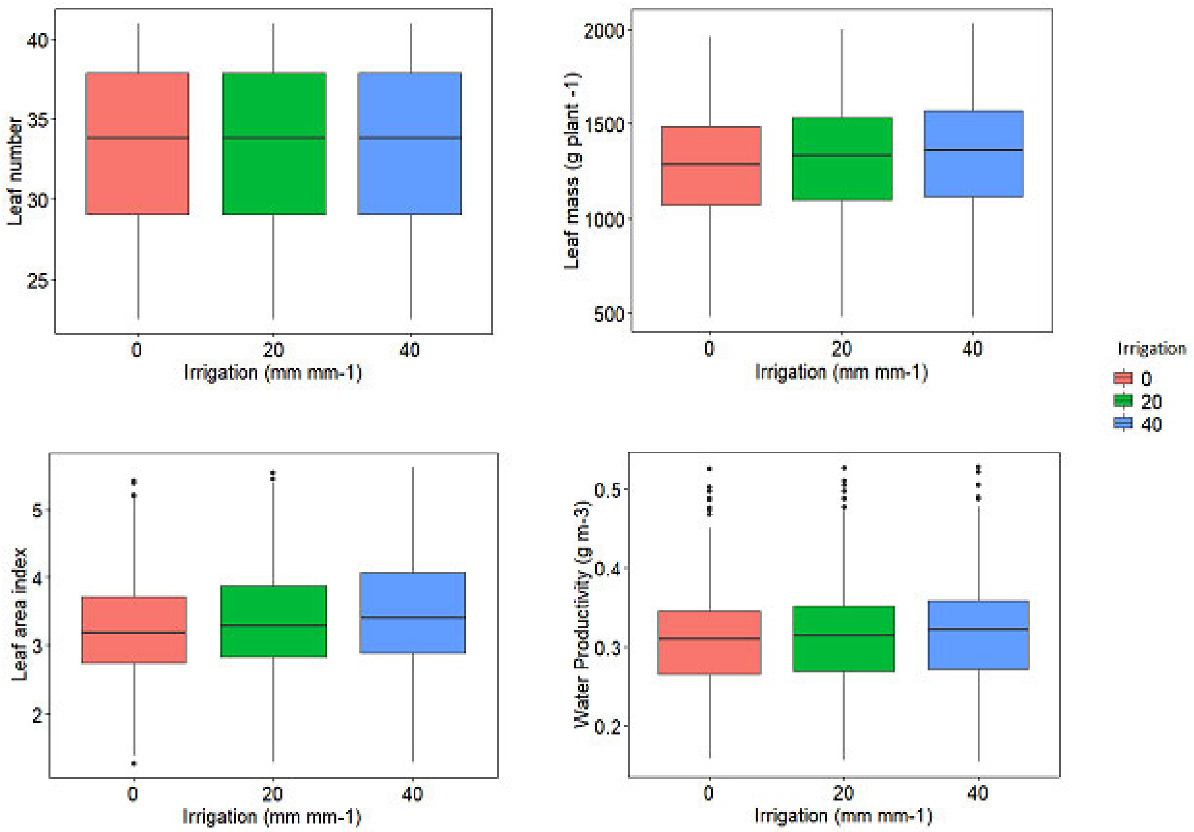

Figure 3.16: The effect of irrigation (mm mm^{-1}) on leaf number, leaf mass (g plant^{-1}), leaf area index and water productivity (g m^{-1}) on growth and development of wild mustard.

3.3.5 Management Practice Combinations

Planting date 3 (01-November) at all fertiliser applications, irrigation, and plant density combinations for high leaf number (39) was the best management practice. A high mean leaf mass of 1724 g plant^{-1} was obtained under best management practice combinations of 35.5 kg ha^{-1} of fertiliser, irrigation at 40 mm, increased plant density (30.5 plants m^{2}), and plants' sown planting date (01-October). This was the same for the LAI, which was 4.51. However, for high WP (0.39 g m^{-3}), the ideal management combinations were no fertiliser application, plant density at 30.5 plants m^{2}, 40 mm mm^{-1} of water and at planting date 01-January (5).

3.4 Discussion

3.4.1 Planting date effect on growth and productivity of ALVs

The optimum planting date gives the highest yields and shows less variation over time (Kucharik, 2008). Overall, and across all the studied crop species, planting late (December to February) results in high leaf mass, LAI, and water productivity. Except for cowpea, planting late resulted in an improvement in growth and productivity for simulated crops. The simulated trend could be because, during February and March, it is assumed that soil has increased water content that supports the early establishment of crops. Also, air temperatures are high, creating a conducive environment for successful establishment. The simulated crops are sub-tropical and thrive in warm-cool climates (Chivenge et al., 2015). With late planting, the vegetative pick period occurs during colder months. Less water was lost through evaporation, meaning more was available for crop uptake and use.

The low temperatures experienced during the vegetative phase also allows for the slow accumulation of heat units, extending the growth duration and time spent accumulating assimilates (Evans and Sadler, 2008). Simulations at the beginning of the summer season may have resulted in less low leaf mass, resulting in low LAI and WP because plants grow more rapidly due to higher temperatures. This also corresponds to higher evaporative demand and overall evapotranspiration resulting in lower WP. Water productivity can be defined as the obtained yield per given water unit (Morison et al., 2008). Therefore, any strategy aimed at improving yield while using the same amount of water or decreasing the amount of water with the same or increasing yield will improve water productivity (Molden et al., 2010).

3.4.2 Plant density effect on growth and productivity of ALVs

Overall, the increase in plant density resulted in leaf number reduction for all simulated crops. However, simulated results showed that increasing plant density resulted in a general rise in leaf mass, LAI, and WP for the crops under investigation. These results are contrary to many studies that have observed a decrease in plant growth and productivity, increasing plant density. For instance, Walp et al. (2010) observed that increasing plant density decreased LAI in cowpea plants. When plant density increases, resource competition among plants arises, resulting in uneven growth or death of some plants (Maseko et al., 2015). With each additional plant, a reduction in individual plants' mass was offset by an increase in plant density.

Another reason may be the development of fewer branches per plant at a high density, leading to high leaf mass (Maseko et al., 2015). To add, an increase in LAI resulted in a reduction in evaporation, which improved water availability, leading to increased transpiration, thus increasing leaf mass. Overall, this was the same amount of water received by the system, but there was an increase in leaf mass, increasing water productivity. A note must be taken that increasing plant density above a certain threshold can result in yield penalties. It was observed on these results that more plants per square metre can still be sown above-recommended planting density, and this may be at the expense of other growth parameters. Different growth variables favoured by different plant densities across all crops. For optimal leaf number, plants must be sown under low plant density and at high plant density for ideal leaf area index. Leaf mass and water productivity differed depending on a crop species type, and these were higher under high or medium plant densities. Therefore, no matter what plant density is used, one or more growth aspects may be compromised.

3.4.3 Fertiliser application effect on growth and productivity of ALVs

Crop growth nutrients are essential for crops as it improves the photosynthetic capacity of crops by enhancing carbon dioxide assimilation and improving enzymic function (Deng et al., 2006). Depending on a crop species, increasing fertiliser application either showed some or no effect on growth and productivity for selected ALVs. Amaranth and cowpea did not respond to the application of fertiliser at different levels. Also, cowpea can fix nitrogen, producing nitrogen that can be useful for its growth and development, suggesting no need for fertiliser addition (DAFF, 2013). Results also suggest that the Ukulinga farm soils are sufficiently fertile to provide optimum growth for these crops. However, sweet potato followed a different trend as the increase in fertiliser application resulted in an improved leaf canopy, thus leaf area index (LAI) and consequently water productivity. These results suggest that sweet potato is a heavy N feeder and requires relatively high N fertiliser amounts. According to Kuzhivilayil et al. (2016), tuber crops that grow under warm to hot summers and cool to mild winters are high nutrient demanding, and proper integrated management helps achieve yield potential. Leaf mass, LAI, and WP decreased with more fertiliser application. Under different fertiliser application rates, no change in leaf number was observed across all crop species.

3.4.4 Irrigation effect on growth and productivity of ALVs

Increasing water application increased the WP of these selected leafy vegetables. Irrigation had no effect on leaf number across all plants. The Ukulinga soils are clay-loam and therefore are suitable for irrigation since they can retain water for more extended periods, attributed to their excellent water-holding, aeration and drainage properties (Chimonyo et al., 2016a). Generally, under semi-arid conditions, irrigation often improves crops' growth by enhancing water availability for transpiration. Depending on the crop's growth stage, one of these processes is more vital than the other. For example, in the early stages of growth, evaporation is more important than transpiration (Brouwer and Heibloem1986). Therefore, it is imperative that irrigation increases during critical growth stages and where water is limited to improve WP.

Water productivity increment is achieved where most transpiration result in yield gain (Rockström and Barron, 2007). However, for all crops expect amaranth, there was no change in leaf mass upon increasing irrigation. This might have been because the soil in the system already had water from the rainfall, which was above a certain threshold where irrigation could not be initiated.

3.4.5 Effect of factor/treatment combinations on growth and productivity of ALVs

The different treatment combinations resulting in optimum yields for each leafy vegetable was evidence that these crops can be grown under other conditions on different management strategies. It was also evident that multiple planting can is possible when these optimal management practices are observed. The growth in terms of leaf number being not affected for some crops such as amaranth may have been since conditions were already favourable. Thus, changing any managerial practice could not be effective. This was not expected as it disagrees with Kanda et al. (2020), who found irrigation to significantly affect the cowpea plant's growth and development. Different crops species with different architecture require different management practices. Therefore, they utilize and share resources differently.

3.5 Conclusion

ALVs are generally grown under dry environments where they experience water stress, so correct management of these crops may improve productivity. The studied leafy vegetables establish in a short period (4 – 5 weeks) and are mostly favoured by early planting. Nonetheless, this may compromise their water productivity. As noticed, plant density plays a vital role in the growth and productivity of ALVs; increasing it to a certain threshold may result in growth, yield and productivity are compromised. The unresponsiveness of fertiliser to leaf number was not expected as fertiliser application is thought to improve vegetative growth. In this study, irrigation was shown to have disagreed with some of the previous studies. Therefore, it might be of interest that future studies revisit these sections for validation and correction.

CHAPTER 4

Nutrition composition of African leafy vegetables

4.1 Introduction

A big challenge is faced by South African communities where at a household level, people experience food insecurities and nutrient deficiencies such as iron, zinc, and vitamins (Maseko et al., 2017). More than 70% of the people living in semi-arid/ arid rural areas are heavily dependent on growing crops for their livelihoods. Here, crop production is dominated by starchy crops (Graeub et al., 2016; Chibarabada et al., 2017a). Although this may ensure enough calories, the need for diet diversity is indirectly neglected (Chibarabada et al., 2017a). Some of the contributors to this challenge include water scarcity and population growth. Therefore, there is a need to introduce and improve nutrients food for human health benefit (Maseko et al., 2017). Vegetables are a substantial part of the diet, especially for individuals that do not have access to rich protein sources (Ebert, 2014). Their nutrient composition may vary mainly depending on the part of the plant used. African leafy vegetables (ALVs) are primarily known for their dense nutrient content (Li et al., 2009). Compared to other vegetables, they provide magnificent amounts of minerals, vitamins and b-carotene and are a good source of antioxidants and dietary fibre (Kala and Prakash, 2007a). Essential minerals such as proteins are in high contents in some ALVs ranging between 1 and 7 g/100g more of edibles than exotic leaf vegetables (Nangula et al., 2010). Information regarding nutritional composition is not always readily available and, if it is known, defers depending on the source. There is a need to improve understanding of the nutritional value of ALV. This will help in mainstreaming these crops into existing cropping systems and diets.

Nonetheless, as much as ALVs are significant in contributing to food and nutrition security, profiling them for nutrient content is still challenging. In food production, nutrition or nutrient composition in crops grown for utilization is very important. According to their contribution to a balanced diet, a nutrient analysis that includes nutrient profiling must take place (Azaı¨s-Braesco et al., 2006). Although some work has been done on profiling some of the ALVs (Almazan et al., 1997; Ahenkora et al., 1998; Shukla, 2013; Sun et al., 2014; Van Jaarsveld et al., 2014; Obidiegwu et al., 2015), it is not enough to draw coherent profiling on nutrient composition of these crops. Preferably, a nutrient-dense crop is ideal as it can act as a superfood, thus providing an array of nutrients in small quantities. Nutrient density is the concentration of nutrients per 100 g (Drewnowski et al., 2019).

The nutritional content of raw leafy vegetables is very diverse and may differ from one cultivar to another. It also depends on the climate or geological site of production, storage, part of the cultivar consumed, and harvesting and post-harvest handling conditions. Therefore comparing the nutrient content from leaves is challenging (Pennington and Fisher, 2010). According to Kala and Prakash (2007b), minerals or macronutrients are not lost when using different cooking methods. In this chapter, secondary data on mineral, macronutrient, vitamin composition of amaranth, cowpea, sweet potato, and wild mustard analysed from different source types (i.e. fresh, dried, cooked, blanched etc.) will be used. The main aim was to determine the nutrient content of the former mentioned ALVs based on secondary data to make recommendations on which vegetable is nutritious. This will be more beneficial to the people living in rural areas of arid to semi-arid regions dependent on agriculture.

4.2 Materials and methods

4.2.1 Literature search

In this study, a mixed-methods approach was applied where qualitative and quantitative data was used. The literature search focused on the nutritional value of amaranth, cowpea, sweet potato, and wild mustard as leafy vegetables. The leading search engines used were Scopus and Web of Science. The following key terms were used, nutrient composition, nutrient density, nutritional value, nutrient content, proximate analysis, and leaves. And the following words were used for crops Amaranthus, amaranth, pigweed, cowpea, black-eyed pea, southern pea, sweet potato, wild mustard, mustard (Table 4.*1*). To add, other sources of information such as the U.S Department of Agriculture (https://ndb.nal. usda.gov/ndb/) and the Food and Agricultural Composition/In Foods (http://www.fao.org/infoods/infoods/tables-and-databases/ faoinfoods-databases/en/) were also used. The literature search was not sorted according to article type. However, it was limited to language, English. The number of total hits obtained for all crops was 6288. For each search, the articles were arranged according to relevance. Scopus achieve this by first finding papers related to the topic and then sort them by date from most recent to old. Whereas, in Web of Science, sorting by relevance considers the fields, title, abstract, and keywords. The results record was sorted in a descending order based on a recording system that considers how many of the search terms are found in each history. Records with the highest-ranking appeared first and vice versa. The first 100 articles were selected and then combined to develop a database on each search results. Duplicates were removed, and the papers were further sorted by screening their abstract, where the relevance of the article was obtained using the keywords.

Each crop's findings were then separated according to the author, source, location, sample type, digestion type, and treatments. The total number of articles found after screaming each crop were 23, 5, 15, and 3 for amaranth, cowpea, sweet potato, and wild mustard, respectively. The obtained results were then used to create proximate and nutrient composition tables for the mentioned selected leafy vegetables. The focus was directed to essential nutrients and minerals, some of which are regarded as interest in public health. These were Fe, Zn, Ca, total fibre, fats, proteins, carotenoids, ash, carbohydrates, ascorbic acid, vitamin A, and E. The nutrient content of these crops reported in %, and values were expressed as $x10^2$.

Table 4.1: Scopus and Web of Science literature search record on African leafy vegetables.

Crop Species	Search engine				
	SCOPUS	**Number of hits**	**WOS**	**Number of hits**	**Articles used**
Amaranth (*Amaranthus spp*.)	ALL ((“nutrient composition” OR “nutrient density” OR “nutritional value” OR "nutrient content" OR "proximate analysis") AND " amaranth" OR “amaranthus” OR “pigweed” leaves)	139	ALL ((“nutrient composition” OR “nutrient density” OR “nutritional value” OR "nutrient content" OR "proximate analysis") AND ""amaranth” OR “amaranthus” OR “pigweed” leaves)	6	23
Cowpea (*Vigna unguiculate*)	ALL ((“nutrient compos*" OR "nutrient density" OR "nutrit* value" OR "nutrient content" OR "proximate analysis”) AND "cowpea" OR "black-eyed pea" OR "southern pea" leaves)	2055	(ALL= ((“nutrient compos*" OR "nutrient density" OR "nutrit* value" OR "nutrient content" OR "proximate analysis”) AND "cowpea" OR "black-eyed pea" OR "southern pea" leaves))	221	5
Sweet potato (*Ipomoea batatas*)	ALL ((“nutrient compos*" OR "nutrient density" OR "nutrit* value" OR "nutrient content" OR "proximate analysis”) AND "sweet potato leaves”)	112	((ALL= ((“nutrient composition" OR "nutrient density" OR "nutritional value" OR "nutrient content" OR "proximate analysis”) AND "sweet potato leaves")))	4	13
Wild mustard (*Brassica juncea L*.)	ALL ((“nutrient compos*” OR “nutrient density” OR “nutrit* value" OR "nutrient content" OR "proximate analysis") AND "wild mustard" OR "mustard" leaves)	2049	((ALL= ((“nutrient composition" OR "nutrient density" OR "nutritional value" OR "nutrient content" OR "proximate analysis”) AND "wild mustard" OR "mustard" leaves)))	1702	3

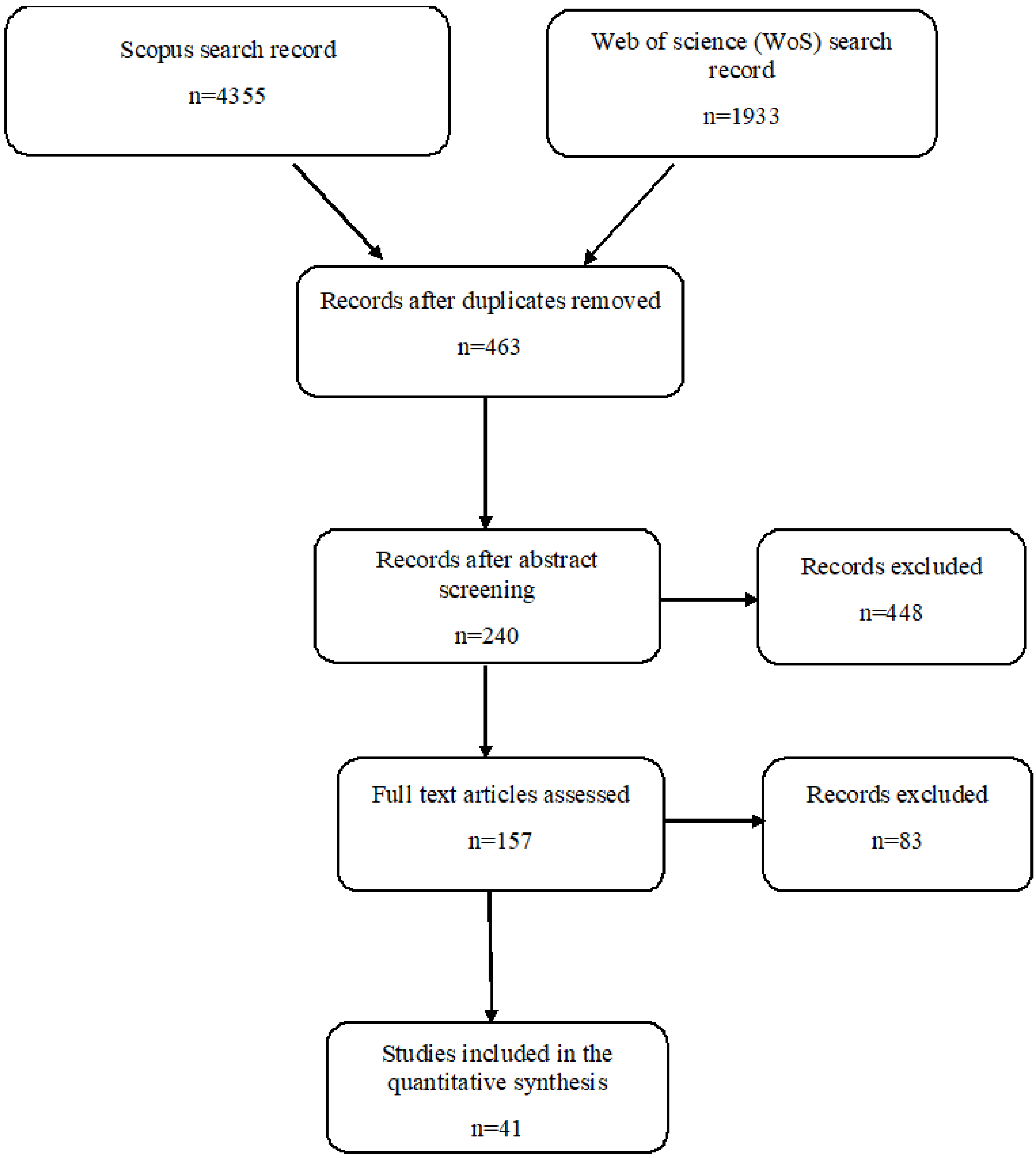

Figure 4.1: PRISMA flow chart for screening process of eligible articles included in the nutritional database.

4.2.3 Data visualisation and Statistical analyses

The secondary data on the nutritional composition was subjected to descriptive statistics, t-test analysis and generalized linear mixed analysis (GLMM) on R statistical software (version 1.3.959). The generalized linear mixed and t-test analysis was used at a confidence interval level of 95%. Results considered significant where $p<0.05$. Here, the minimum, maximum and maximum values in these crops' nutritional content were identified to investigate the density or quantity of nutrients and find out which one of these crops has a high or low content of nutrients.

4.3 Results

4.3.1 Literature review results

There were 23 articles from 14 different locations in countries: Niger, Nigeria, Taiwan, India, Argentina, Tuskegee, Kenya, South Mali, South Africa, Czech Republic, Turkey, and Nairobi. The source (or environment) where the study was done ranged from the field, market and undefined. 47% of these studies were done on the field, and the rest 26. 5% each were conducted under undefined locations and markets. Sample type on these studies was mostly (30- 42 %) fresh or dry material, 5% boiled, and the rest was undefined. Treatments of these studies were mainly processed and ranged from ground, oven-dried, blanched, fresh, cooking, sun-dried, shade dried, drained, refrigerated) Only 26% was agronomic (cultivar type, fertiliser (nitrogen) application level, age at harvest, and storage type). Most of the digestion processes on these were not defined; however, only two authors described the digestion method they used. This was the method described by Speek et al. (1986) in Vitro digestion/Caco-2 cell model.

The database on cowpea's nutrient composition had only five publications, and the studies were done in countries Ghana, East Africa, Tuskegee, and South Africa. Fifty per cent (50%) of the studies were mostly conducted under field conditions using fresh material (61 %), only 7% was boiled, and the rest of the sample type was undefined. The sample material was either used raw(fresh) or dry. Duodu et al. (2010) used the method described by (Speek et al., 1986) for digestion and treatment type ranged from agronomic to processed. Processed treatments types were about 75% ranging from fresh and dry mass (raw), blanched, cooked, dried, and fermented.

On the other hand, the sweet potato database was obtained from 13 articles conducted from countries such as Ghana, Los Angeles, Taiwan, Japan, Tanzania, Tuskegee, Kwara State, George Washington, Sri Lanka, China, India. This was a good representation; however, some of the authors did not mention their studies' location. About 77% of these were conducted under field conditions, 15% not defined, and the rest was done under controlled environments (greenhouse). In terms of the digestions method, there was quite a range, from in vitro digestion/Caco-2 cell model, HPLC analysis, AOAC analysis and Automatic Absorption Spectrometer, the technique described by Speek et al. (1986), Atomic Absorption Spectrometer, Tecator block digestor, and α-amylase, amyloglucosidase, and protease. Only two authors did not describe their method, and in one study conducted by Essack et al. (2017), they used different digestion procedures. Treatment types range from agronomic to processing. Under agronomic, the main factors used included cultivar, the season of planting. Under processing, the crops were either blanched, cooked, dried, or raw.

Compared to all the other three mentioned crops, wild mustard was less studied in terms of nutrition, as only three articles were obtained. The studies were conducted from three different Brazil, China, and Taiwan, and the experiments were conducted under the field, green-house, and undefined locations, respectively. The sample preparation was variable since all the three studies had their samples dry, fresh, and boiled. However, only Kant et al. (2011) from China described their digestion method as HNO_3–$HClO_4$, and treatment, which were only separated using numbers.

4.3.2 Nutritional content of selected ALVs

These selected ALVs have a very dense content of vitamins, carotenoids and total polyphenols, **Error! Reference source not found.**, and Table 4.3, and Table 4.4. Although in the literature, some nutrients were not assessed for some crops. This was pointed out as a gap for future research.

4.3.2.1 Proximate analysis

Proximate composition accounts for moisture, crude protein, crude fibre, ash, lipids, carbohydrates, and other nitrogen-free extracts expressed in terms of percentage (%) as content in the sample (Table 4.2). Wild mustard had the highest moisture content (91.0%), and sweet potato had the lowest (89.0%). The total fibre was the highest (53.1%) for amaranth and the lowest (3.2%) for wild mustard. Lipids/fats were high (12.9%) in cowpea and low (0.9%) in wild mustard. Cowpea had the highest (42%) total protein content than the other three crops, and wild mustard had the lowest (1.9%). Amaranth and wild mustard had the highest (22.8%) and the lowest (0.9%) ash content. Sweet potato, on the other hand, had the highest total carbohydrates (68.8%), followed by amaranth (67.7%), while wild mustard had the lowest (2.8%). In terms of energy, raw sweet potato leaves had the highest (438.5), followed by amaranth (406.3) and cowpea (390.2) and wild mustard leaves (26.5 Kcal 100 g^{-1}), which was substantially lower.

4.3.2.2 Mineral content

The nutritional composition of these crops also includes a wide range of elements, most of which are regarded as the primary dietary source. These are significant elements such as calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), phosphorus (P), manganese (Mn), nitrogen (N), chlorine (Cl), and trace minerals such as iron (Fe), copper (Cu), and selenium (Se). Amaranth had the highest Ca and K content, while both these minerals were the lowest in wild mustard. Calcium (Ca) content was the highest (2.3%) and the lowest (0.1%). Sweet potato had the highest Mg, P, and Fe content while wild mustard had the lowest range of these minerals. Amaranth had the highest (0.08%) content of Mn, and wild mustard had the lowest (<0.01%). Copper (Cu) content was <0.01%, and zinc (Zn) content was the highest (0.32 %) and the in sweet potato and wild mustard, respectively. Cowpea also had the lowest Cu content together with wild mustard. Na content was the highest (2.22%) for cowpea, and for wild mustard, it was less than 0.01%. There were trace amounts (<0.001%) of selenium in wild mustard, and cowpea had the highest (0.028%) of selenium.

4.3.2.3 Vitamin content

The data on vitamin content, total carotenoids, and polyphenols were found to have some gaps for most crops (amaranth, cowpea, and wild mustard). Nonetheless, amaranth showed to have the highest content (0.66%) of vitamin A, and in sweet potato, it was lower than 0.02%, respectively. This was true for the ascorbic acid, which was the highest (0.63%) for amaranth and the lowest (0.121%) for sweet potato. Again, amaranth had the highest total carotenoids (131.00 %), while wild mustard showed the lowest (0.003%). The total carotenoids content was the highest in amaranth (13.1%) and the lowest (0.003%) in wild mustard. For the rest of the vitamins and polyphenols, characterisation was not done. And this was taken as a gap for future studies.

Table 4.2: Proximate composition (%) of edible raw leaves in selected African leafy vegetables (Values are expressed as $\times 10^2$).

	Amaranth	**Cowpea**	**Sweet potato**	**Wild mustard**
Moisture/water content	7850.0 - 9100.0 (8542.0)[1-7]	0.0 – 9060.0 (43.613)[15-17]	3515.0 – 8900.0 (8593.0)[4,21-25]	9168.0[30]
Total fibre	100.0 - 5381.0 (1167.1)[5-13]	0.0 – 2948.0 (1533.6)[16-18]	149.0 – 1167.0 (822.6)[4,22-27]	320.0[30]
Lipids/ fats	200.0 – 1100.0 (346.2)[1,2,4,7,12-17]	0.3 - 1291.0 (418.8)[16-18]	20.0 – 650.0 (352.4)[4,22-28]	085.0[30]
Total protein	2.4 – 3230.0 (1517.4)[2-4,7,14,16,14]	320. – 4200.0 (2175.0)[12-17]	142.0 – 3108.0 (2194.0)[4,21-29]	197.0[30]
Ash	181.0 – 2280.0 (1319.0)[3-7,8,9,12,13,14,17]	480.0 – 1480.0 (1162.0)[16-19]	149.0 – 1167.0 (822.6)[23,24,27-29]	098.0[30]
Total carbohydrates	430.0 – 6778.0 (3212.0)[4,5,7,8,11,14]	178.0 – 3911.0 (814.5)[18-23]	100.0 – 6860.0 (5453.0)[4,22,25-29]	275.0[30]
Energy (Kcal)	326.7 – 40631.0 (18935.8)[4,7,10,12]	109.0 – 39026.0 (5117.6)[16,18,20]	3500.0 – 43850.0 (40420.0)[4,21,25,27,29]	2657.0[30]

[1]Awoyinka et al., (1995), [2]Mziray et al., (2001), [3]Onyango et al., (2008), [4]Vishwakarma and Dubey, (2011), [5]Escudero et al., (1999), [6]Kala and Prakash, (2004), [7]Odhav et al., (2007), [8]Mziray et al., (2001), [9]Aletor et al., (2002), [10] Mithra and Somasundaram, (2008), [11]Devi et al., (2007), **[12]**Pisarikova et al., (2006)**,** **[13]**SekeroÅlu et al., (2006), [14]Nordeide et al., (1996), [15]Ahenkora et al., (1998) [16] Owade et al., (2019), [17]Imungi and Potter, (1983), [18]Chikwendu et al., (2014), [19] Enyiukwu et al., (2018), [20]Madodé et al., (2012), [21]Amagloh et al., (2017), [22]Mohanraj and Sivasankar, (2014), [23]Paranama et al (2015), [24]Suárez et al., (2020), [25]Sun et al., (2014), [26]Olayiwola et al., (2009), [27]Mosha and Gaga, (1999), [28]Almazan et al., (1997), [29]Pace et al., (1988), [30]Filho et al., (2018)

Table 4.3: Mineral content (%) of edible raw leaves in selected African Leafy vegetables. (Values are expressed as $\times10^2$).

	Amaranth	**Cowpea**	**Sweet potato**	**Wild mustard**
K	0.0 – 650.0 (3 12.5)[1,2,4,8-10,13]	120.0 – 1344.5 (531.6)[15,19,20]	24.2 – 428.0 (162.2)[22,23,26,28-30]	0.0 – 43.6 (4.0)[31-32]
Ca	0.0 – 741.0 (2.286)[1,6-11,13]	0.1 – 175.0 (87.0)[17-21]	2.0 – 195.8 (82.0)[24,26-30]	0.0 – 12.3 (1.2)[31-32]
Mg	0.0 - 147.0 (0.842)[1-4,8,10,13]	26.4 – 165.9 (69.4)[19,20]	3.2 – 91.1 (41.1)[26,28-29]	0.0 – 2.7 (0.2)[31-32]
P	0.0 - 70.0 (29.8)[2-5,8-11,13]	0.9 – 81.8 (25.6)[16,18-20]	10.0 – 264.0 (114.7)[23,28-29]	<0.1[31]
Fe	0.1 - 14.0 (5.5)[1,3-14]	0.0 – 1717.0 (684.4)[17-21]	0.1 - 3.5 (1.0)1[24,2,24,26-30]	0.6 – 1.5 (1.1)[31-32]
Mn	0.3 – 8.2 (1.1)[4,8,12-13]	0.0 – 5.5 (3.1)[19]	0.2 - 1.1 (0.4)[28-29]	0.0 – 0.3 (0.2)[31-32]
Cu	0.1 -0.3 (0.2)[4,8,10 ,12-13]	0.1[19]	0.1 – 0.5 (0.1)[28-30]	0.0 – 0.1 (0.1)[31-32]
Zn	0.0 – 5.6 (1.1)[4,6-10,12-13]	0.0 - 14.5 (4.1)[17-21]	0.0 – 31.5 (5.5)[22,24,26-30]	0.0 – 0.7 (0.5)[31-32]
Na	0.0 – 5.2 (3.5)[1, 2,4,8-10,13]	0.9 – 222.0 (56.3)[19,20]	0.3 – 83.2 (15.7)[23,25-26,28-29]	0.3[32]
Se	0.1 - 0.2 (0.1)[8,13]	0.4 – 2.8 (1.3)[19]	0.8 - 0.9 (0.9)[28]	<0.1[32]
Pb	0.1 - 0.2 (0.1)[7]	0.1[19,20]	<0.1[28]	N/A

[1]Devi et al., (2007), [2]Fadupi et al., (2017) [3]Kala and Prakash, (2007a), [4]Odhav et al., (2007), [5]Mziray et al., (2001), [6]Nordeide et al., (1996), [7]Singh et al., (2001), [8]Freiberger et al., (1998), [9]Escudero et al., (1999), [10]Taylor, B.L.Fetuga, (1982), [11]Awoyinka et al., (1995), [12]SekeroÅlu et al., (2006), [13]Sena et al., (1998), [14]Vishwakarma and Dubey, (2011), [15]Mduma et al., (2012),[16]Ahenkora et al., (1998) [17]Owade et al., (2020), [18]Chikwendu et al., (2014), [19]Imungi and Potter, (1983), [20]Enyiukwu et al., (2018), [21]Madodé et al., (2012), [22]Pace et al., (1988), [23]Paranamana and Bulugahapitiya, (2014), [24]Amagloh et al., (2017), [25]Kurata et al., (2017), [26]Mosha and Gaga, (1999), [27]Olayiwola et al., (2009), [28]Suárez et al., (2020), [29]Sun et al., (2014), [30]Ranathunga et al., (2019) [31]Jiao et al., (2012)

Table 4.4: Vitamin content (%) of edible raw leaves in selected African leafy vegetables (Values are expressed as $\times 10^2$).

	Amaranth	**Cowpea**	**Sweet potato**	**Wild mustard**
Vitamin A	0.0 – 54.8 (5.2)[1,5]	0.0 - 0.6 (0.3)[1]	0.0 – 0.2 (0.1)[1]	0.3[21]
Vitamin B1	<0.1[13]	N/A	0.0 – 0.1 (0.1)[19]	0.3[21]
Vitamin B2	N/A	318.0 – 1480.0 (469.5)[12,14-15]	0.4 – 0.6(0.6)[19]	N/A
Vitamin B3	N/A	3039.0 – 3111.0 (3075.0)[12,14]	0.5[19]	N/A
Vitamin C	0.8 - 9.9 (5.4)[2,8,11]	0.1 – 20.3 (8.2)[12]	2.2 – 10.4 (6.0)[19]	N/A
Vitamin E	N/A	N/A	0.3 – 0.6 (0.4)[19]	<0.1[21]
Vitamin K	N/A	N/A	<0.1[9]	<0.1[9]
Ascorbic acid	0.8 – 62.9 (32.2)[3,4,6]	0.9 – 41.0 (6.6)[10,13]	0.0 – 12.1 (3.3)[16-18,20]	N/A
Total carotenoids	0.6 – 13100.0 (898.0)[1,2,5,7]	4.2 - 4.5 (4.3)[1]	0.7 – 2.7 (2.5)[18]	0.3[21]
Carotene	N/A	0.2 – 9.1 (5.3)[12,13]	0.4 – 1.0 (0.8)[16]	N/A
Total polyphenols	N/A	1.0 – 3.3 (2.1)[12]	23.1 – 164.7 (61.6)[16]	N/A

[1]Mosha et al., (1997), [2]Devi et al., (2007), [3]Kala and Prakash, (2007b), [4] Mziray et al., (2001), [5] Nordeide et al., (1996), [6] Yadav and Sehgal, (1995)[7] Sena et al., (1998), [8] SekeroÅlu et al., (2006), [9]Paula et al., (2013), [10]Ahenkora et al., (1998), [11] Owade et al., (2019), [12] Chikwendu et al., (2014), [13]Mziray et al., (2001), [14]Enyiukwu et al., (2018), [15]Madodé et al., (2012), [16]Amagloh et al., (2017), [17]Barrera and Picha, (2014), [18]Suárez et al., (2020), [20]Ranathunga et al., (2019), [21]Paula et al., (2013)

4.4 Discussion

The nutrient composition of selected African leafy vegetables (ALVs) showed to be high depending on the crop species. Comparing these vegetables to other commercialized crops such as spinach, cabbage, and dry beans remain superior in their nutrient density (Shukla, 2013; Grain SA, 2020; Van Jaarsveld et al.). Information is rarely available. The high moisture content of ≥89.0 × 10% shows that these ALVs may be prone to deterioration and need proper preservation and storage post-harvest. It is also a good indication that these crops are easily digestible when eaten raw, which is a health benefit since less energy would be used by the body for digestion, thus improving the speed at which the nutrients will be assimilated (Lussier, 2010). The differences in values recorded for total fibre, lipids/fats, total proteins, ash, total carbohydrates, and energy may have been attributed to the difference in analytical sample preparation and digestion method. However, wild mustard had the lowest percentage composition across all minerals. The results from different studies suggest that sweet potato can be a good source of energy and carbohydrates.

A wide variety in mineral content of ALVs is due to differences in sample preparation, variety or cultivar of the crop species used, climate, production site (i.e. field, green-house or hydroponic), harvest-handling materials, post-harvest handling, method of digestion. The general trend observed in the mineral content was that cowpea was more nutrient-dense than the other three ALVs. According to the health organisation of South Africa, Cowpea has a high range of some of the essential micro-nutrients (K, Mg, Fe, Cu, Na and Se). Therefore, this crop is an excellent source of nutrients and can is ideal for human health benefits. Given the obtained results (Table 4.2, Table 4.3, and Table 4.4), cowpea, together with amaranth, have the potential to become superfoods due to their noticeably high nutrient content across most nutrients. The unexpectedly low nutrient content in wild mustard might have been influenced by the number of published articles on this crop's nutrient composition. However, wild mustard can still be an excellent crop for intercrop with crops such as amaranth. Because both these crops have similar physiology, growing them as an intercrop might benefit yield and productivity.

Vitamins, carotenoids, and polyphenols content of ALVs showed missing data; in other words, few studies have been conducted to evaluate them. This can be, therefore, regarded as gaps for future studies. Table 4.4 showed that sweet potato is the only vegetable among the studied to have been analysed for vitamins, carotenoids, and polyphenols. Although this might not be good for comparison, it is still a great sign that at least there are some efforts to understand the nutritional value of some of ALVs.

4.5 Conclusion

African leafy vegetables (ALVs) are nutritious and versatile (can be consumed in different ways); they also have many potentials in the marginal communities since they can contribute to their food and nutrition security. Thus, they can contribute extensively to the improvement of human health. However, data unavailability creates a considerable gap in understanding African leafy vegetables' nutritional characteristics or content (ALVs). The former studied ALVs are underutilized crops, and the information on their agronomy is limited. Given this challenge of insubstantial data on the nutrient composition of these selected African leafy vegetables (amaranth, cowpea, sweet potato, and wild mustard), the main aim of this chapter of determining the nutrient content of former mentioned ALVs based on secondary data could not be fully achieved for all nutrients. Nonetheless, for all essential nutrients and minerals such as carbohydrates, moisture content, zinc (Zn), iron (Fe), vitamin A. The main aim was fully achieved. Therefore, upscaling nutrient profiling of these crops by adding more nutrients and doing more research on the ones characterized would be essential for the understanding and development of these crops.

This chapter also confirmed a few nutrients found in the studied crops and the density at which they are found. The studied crops, amaranth, cowpea, sweet potato, and wild mustard, contain all essential nutrients necessary for growth and development in humans, and these nutrients are found in relatively high amounts. Therefore, it is suggested that for a proper understanding of these crops' contribution, nutritionally, more characterization or in-depth analysis of "essential nutrients" must be conducted in future for a coherent conclusion. It is for the currently studied crops and other African vegetables, which may be regarded as underutilized.

CHAPTER 5

Nutrition water productivity of selected African leafy vegetables (ALVs)

5.1 Introduction

To date, water scarcity remains a challenge in this country and many other parts of the world (Mabhaudhi et al., 2016). Metrics such as water productivity have been assessed for increased sustainable food production under water-scarce environments (Gaydon et al., 2012). Meanwhile, different foodstuffs have been quantified for their nutritional content to recommend healthy diets for an improved human nutritional status (Renault and Wallender, 2000). Chibarabada et al. (2017b) suggested merging these similar efforts to produce adequate nutritious foods under water scarcity. South Africa falls under semi-arid to arid tropics, where water shortages are a big challenge, especially in the agricultural sector (Bello and Walker, 2017). An increase in water productivity would be an essential strategy to contribute to coping strategies with additional food and nutrients requirement under water scarcity in the coming era. This might also introduce a much-needed turn from yield per unit of land to nutritional yield per unit of water, nutritional water productivity (Renault and Wallender, 2000).

Nutritional water productivity (NWP) is a measure of nutrition yield outcome given the water consumed unit (Morison et al., 2016). It associates the information about crop productivity with their dietary requirements and water use, resulting in a valuable index used to assess food and nutrient security, especially under water limiting conditions (Molden et al., 2010). The linkage between water use, crop production, food and nutrient security plays a vital role in agriculture. Especially in water limiting areas, it can introduce a simple way of understanding the complexities in agriculture (Nyathi, 2019)

As stated in previous chapters, food and nutritional security continue to be a concern in South Africa. Consuming foods that lack proteins and essential minerals (i.e. iron, zinc, vitamins, carotenoids etc.) but rich in carbohydrates is one of the contributors to this challenge. Statistics have shown that in South Africa, given two households, one suffers from some deficiencies in micro-nutrients, and only a fifth of the population is food-secure (Schönfeldt and Pretorius, 2011). Often, the people living in marginal resource-poor areas are most affected. This might be because most people from these areas already have limited access to nutritious foods; their livelihood depends on small-scale farming. However, with an additional challenge of accessing water, food production remains low. Therefore, it is vital to integrate strategies that will allow producing low-cost nutritious foods, and ALVs come as promising crops for the future to contribute to food and nutrient security. In this chapter, the aim was to quantify the NWP of selected leafy vegetables under different management strategies to improve production and for better diet recommendations for human health benefit.

5.2 Materials and methods

The modelling output on biomass and transpiration from ***Chapter 3*** and nutritional data from ***Chapter 4*** were used to calculate nutrient content for the harvested yield (nutritional yield), then nutritional water productivity (NWP), and for quantifying nutrients present in these crops as well as their density. Data was analysed using a statistical analysis known as R statistical software (version 1.3.959), and the t-test analysis was used at a confidence interval level of 95%. The formula used for nutrient content of harvested yield and NWP were as follows:

NY = $\frac{nutrient\ (g\ 100g)}{harvested\ yield\ (kg\ ha{-}1)} \times 100$, and NWP= $\frac{NY\ (kg)}{Water\ productivity\ (g\ m3)}$

here only the averages were used to understand further the NWP of selected leafy vegetables (amaranth, cowpea, sweet potato, and wild mustard)

5.3 Results

5.3.1 Nutritional water productivity in response to changing planting dates.

Nutritional Water Productivity (NWP) of all nutrient components (total fibre, lipids/fats, total carbohydrates, total proteins, energy, calcium (Ca), potassium (K), iron (Fe), zinc (Zn), vitamin A, and total carotenoids) varied for all crops across different planting dates. To add, amaranth had the highest NWP content for all nutrient's components compared to other crops, and wild mustard had to have the lowest. For amaranth, planting date 2 (1st of October) resulted in the highest NWP for all nutrients (total fibre, lipids/fats, total carbohydrates, total proteins, K, Ca, Fe, Zn, vitamin A, total carotenoids and energy), which was 60.87, 18.05, 167.51, 79.14, 16.30, 11.92, 0.297, 0.06, 0.27,46.83 kg m^{-3} and 987.53 kcal/100g, respectively. Nutritional water productivity across all nutrients for cowpea, sweet potato and wild mustard was the highest at planting date 7 (01-March), 3 (01-November), and 1 (01-September), respectively. Although amaranth had the highest average NWP in most nutrients, cowpea had to have the highest water productivity for Ca, Fe, and Zn. The specific NWP averages for nutrients Ca, Fe, and Zn) was (2.82, and 22.15, and 0.13). Wild mustard had the lowest NWP compared to all other ALVs (Table 5.1). It is also essential to note that although amaranth had the highest nutrient content, sweet potato had the highest range of total energy (Table 5.*1*). This might have been caused by the initial low or high harvested nutritional yield, high content of profiled nutrient or the combination of both.

Table 5.1: Average nutritional water productivity average of total fibre, lipids/fats, total carbohydrates, total proteins, energy, potassium (K), calcium (Ca), iron (Fe), zinc (Zn), vitamin A, and total carotenoids of selected ALVs (amaranth, cowpea, sweet potato and wild mustard) under different planting dates (1-7).

Row Labels	**Total fibre (kg m^{-3})**	**Total Protein (kg m^{-3})**	**Total carbohydrates (kg m^{-3})**	**Lipids/Fats (kg m^{3})**	**Energy (Kcal 100 g^{-1})**	**K (kg m^{3})**	**Ca (kg m^{-3})**	**Fe (kg m^{-3})**	**Zn (kg m^{-3})**	**Vitamin A (kg m^{-3})**	**Total carotenoids (kg m^{3})**
Amaranth	**47.73**	**62.05**	**131.35**	**14.16**	**774.32**	**12.78**	**9.36**	**0.23**	**0.05**	**0.21**	**36.72**
1	52.80	68.69	145.40	15.67	857.19	14.15	10.35	0.25	0.05	0.24	40.65
2	60.87	79.14	167.51	18.06	987.53	16.30	11.92	0.29	0.06	0.27	46.83
3	54.64	71.04	150.37	16.21	886.48	14.63	10.70	0.26	0.05	0.24	42.04
4	50.34	65.45	138.53	14.93	816.70	13.48	9.86	0.24	0.05	0.22	38.73
5	42.84	55.70	117.90	12.71	695.08	11.47	8.39	0.20	0.04	0.19	32.96
6	39.04	50.76	107.45	11.58	633.46	10.45	7.65	0.187	0.04	0.17	30.04
7	34.95	45.44	96.18	10.37	567.03	9.36	6.85	0.15	0.033	0.16	26.89
Cowpea	**48.60**	**68.92**	**25.81**	**13.27**	**162.17**	**16.85**	**2.76**	**21.69**	**0.13**	**0.01**	**0.14**
1	47.94	67.99	25.46	13.09	159.97	16.62	2.72	21.39	0.13	0.01	0.13
2	47.76	67.73	25.37	13.04	159.37	16.56	2.71	21.31	0.13	0.01	0.13
3	48.66	69.02	25.85	13.29	162.39	16.87	2.76	21.72	0.13	0.01	0.14
4	48.42	68.68	25.72	13.22	161.59	16.79	2.75	21.61	0.13	0.01	0.134
5	48.82	69.24	25.93	13.33	162.91	16.92	2.77	21.79	0.13	0.01	0.14
6	48.90	69.35	25.97	13.35	163.18	16.95	2.77	21.82	0.13	0.01	0.14
7	49.63	70.39	26.36	13.55	165.61	17.20	2.82	22.15	0.13	0.01	0.14
Sweet potato	**26.71**	**71.23**	**177.04**	**11.44**	**1312.28**	**5.27**	**2.64**	**0.03**	**0.18**	<0.01	**0.09**
1	26.88	71.68	178.16	11.51	1320.59	5.30	2.68	0.03	0.18	<0.01	0.09
2	26.88	71.70	178.20	11.52	1320.91	5.30	2.68	0.03	0.18	<0.01	0.09
3	27.45	73.20	181.93	11.76	1348.57	5.41	2.76	0.03	0.18	<0.01	0.09

4	25.71	68.55	170.37	11.01	1262.88	5.07	2.56	0.03	0.17	<0.01	0.08
5	26.753	71.34	177.32	11.46	1314.33	5.27	2.67	0.03	0.13	<0.01	0.09
6	26.68	71.15	176.83	11.43	1310.74	5.26	2.66	0.03	0.18	<0.01	0.09
7	26.63	71.02	176.50	11.41	1308.32	5.25	2.65	0.03	0.18	<0.01	0.09
Wild mustard	**13.33**	**8.20**	**11.45**	**3.54**	**110.64**	**0.16**	**0.05**	**0.05**	**0.02**	**0.01**	**0.01**
1	13.46	8.27	11.54	3.57	111.48	0.17	0.05	0.05	0.02	0.01	0.01
2	13.42	8.26	11.53	3.56	111.39	0.17	0.05	0.05	0.02	0.01	0.01
3	13.39	8.24	11.51	3.56	111.16	0.17	0.05	0.05	0.02	0.01	0.01
4	13.25	8.16	11.39	3.52	110.01	0.17	0.05	0.05	0.02	0.01	0.01
5	13.29	8.18	11.42	3.53	110.33	0.17	0.05	0.05	0.02	0.01	0.01
6	13.24	8.15	11.38	3.52	109.91	0.17	0.05	0.05	0.02	0.01	0.01
7	13.29	8.18	11.42	3.53	110.31	0.17	0.05	0.05	0.02	0.01	0.01
Grand Total	**33.99**	**52.49**	**86.84**	**10.58**	**592.87**	**8.71**	**3.71**	**5.38**	**0.09**	**0.06**	**9.30**

5.3.2 Nutritional water productivity in response to changing plant density

Generally, nutrient water productivity (NWP) results varied across different plant densities for each crop. The general trend observed was that crops had the highest NWP for all nutrients at high plant density. However, wild mustard was the exception as the highest NWP was noted under low plant density across all nutrients. Changing plant density in wild mustard did not always result in an increase in leaf mass. The general trend observed was that high plant density resulted in high NWP for both amaranth and cowpea. Overall, amaranth had higher average NWP_{energy}, 758.86 Kcal/100g. Cowepa had the highest NWP value for K and Fe (16.54 and 21.34 kg m^{-3}, respectively) but had the lowest NWP for Vitamins low in (0.02). Vitamin A and total carotenoids content were the highest (0.23 and 36.51 kg m^{-3}) in amaranth, and sweet potato had the lowest (<0.01 and 0.09 kg m^{-3}), respectively. Comparing these ALVs, the NWP of selected nutrients varied largely. However, between different plant density, the difference in NWP was not as much for each crop.

Table 5.2: Average nutritional water productivity (NWP) of total fibre, lipids/fats, total carbohydrates, total proteins, energy, potassium (K), calcium (Ca), iron (Fe), zinc (Zn), vitamin A, and total carotenoids of selected ALVs (amaranth, cowpea, sweet potato and wild mustard) under different plant densities (plant m^{-2}).

Row Labels	**Total fibre (kg m^{-3})**	**Total Protein (kg m^{-3})**	**Total carbohydrates (kg m^{-3})**	**Lipids/Fats (kg m^3)**	**Energy (Kcal/100 g)**	**K (kg m^{-3})**	**Ca (kg m^{-3})**	**Fe (kg m^{-3})**	**Zn (kg m^{-3})**	**Vitamin A (kg m^{-3})**	**Total carotenoids (kg m^{-3})**
Amaranth	**46.77**	**13.87**	**60.81**	**128.72**	**758.86**	**12.52**	**9.16**	**0.22**	**0.04**	**0.21**	**35.98**
8.7	47.35	14.45	61.56	130.31	768.23	12.68	9.24	0.22	0.05	0.21	36.43
17.4	45.52	13.50	59.18	125.27	738.51	12.19	8.92	0.22	0.04	0.20	35.02
26.1	47.45	14.08	61.70	130.57	769.85	12.71	9.29	0.22	0.05	0.23	36.51
Cowpea	**48.30**	**13.19**	**68.50**	**25.65**	**161.18**	**16.74**	**2.74**	**21.56**	**0.13**	**0.01**	**0.14**
8.7	48.64	13.28	68.99	25.84	162.33	16.86	2.76	21.71	0.13	0.01	0.14
17.4	47.57	12.99	67.47	25.26	158.74	16.49	2.70	21.23	0.13	0.01	0.13
26.1	48.67	13.30	69.05	25.86	162.46	16.88	2.76	21.73	0.13	0.01	0.14
Sweet potato	**26.70**	**11.48**	**71.22**	**176.99**	**1311.98**	**5.27**	**2.66**	**0.03**	**0.18**	<0.01	**0.09**
2.5	26.70	11.44	71.21	176.99	1311.89	5.26	2.66	0.03	0.18	<0.01	0.09
5	26.70	11.44	71.21	176.99	1311.90	5.26	2.66	0.03	0.18	<0.01	0.09
7.5	26.70	11.44	71.22	177.02	1312.16	5.27	2.66	0.03	0.18	<0.01	0.09
Wild mustard	**13.29**	**3.53**	**8.18**	**11.42**	**110.36**	**0.17**	**0.05**	**0.05**	**0.02**	**0.012**	**0.01**
13.5	13.29	3.53	8.18	11.42	110.37	0.17	0.05	0.05	0.02	0.01	0.01
27	13.29	3.53	8.18	11.42	110.37	0.17	0.05	0.05	0.02	0.01	0.01

30.5	13.29	3.53	8.18	11.42	110.34	0.17	0.050	0.05	0.02	0.01	0.01
Grand Total	**33.77**	**10.51**	**52.18**	**85.70**	**585.60**	**8.67**	**3.65**	**5.46**	**0.09**	**0.06**	**9.06**

5.3.3 Nutritional water productivity in response to changing fertiliser

The average total protein, lipid/fats, energy, Ca, vitamin A, and total carotenoids water productivity was the highest in amaranth, while total fibre, total carbohydrates, K, Fe and Zn water productivity was the highest in cowpea (Table 5. 3). The highest nutritious yield was produced for both amaranth and cowpea at different fertilizer applications upon each addition of water unit. However, wild mustard had significantly lower NWP across all fertilizer applications compared to the other studied ALVs. The NWP in energy was considerably higher than that of cowpea, sweet potato, and wild mustard.

Table 5. 3: Average nutritional water productivity (NWP) of average total fibre, lipids/fats, total carbohydrates, total proteins, energy, potassium (K), calcium (Ca), iron (Fe), zinc (Zn), vitamin A, and total carotenoids of selected ALVs (amaranth, cowpea, sweet potato and wild mustard) under different fertiliser application rates (kg ha^{-1}).

Row Labels	**Total fibre (kg m^3)**	**Total Protein (kg m^3)**	**Total carbohydrates (kg m^3)**	**Lipids/Fats (kg m^3)**	**Energy (Kcal/100 g)**	**K (kg m^3)**	**Ca (kg m^3)**	**Fe (kg m^3)**	**Zn (kg m^3)**	**Vitamin A (kg m^3)**	**Total carotenoids (kg m^3)**
Amaranth	**47.45**	**14.07**	**61.69**	**130.58**	**769.79**	**12.70**	**9.29**	**0.22**	**0.05**	**0.21**	**36.52**
0	47.46	14.08	61.71	130.62	770.07	12.71	9.30	0.22	0.05	0.21	36.52
35.5	47.45	14.07	61.69	130.57	769.77	12.70	9.29	0.22	0.05	0.21	36.51
71	47.43	14.07	61.67	130.53	769.53	12.70	9.29	0.22	0.05	0.21	36.50
Cowpea	**48.72**	**13.30**	**69.09**	**25.87**	**162.56**	**16.89**	**2.76**	**21.74**	**0.13**	**0.01**	**0.14**
0	48.712	13.30	69.09	25.87	162.56	16.89	2.76	21.74	0.13	0.01	0.14
30	48.72	13.30	69.09	25.87	162.56	16.89	2.76	21.74	0.13	0.01	0.14
60	48.72	13.30	69.09	25.87	162.56	16.89	2.76	21.74	0.13	0.01	0.14
Sweet potato	**26.64**	**11.41**	**71.04**	**176.57**	**1308.83**	**5.25**	**2.66**	**0.03**	**0.18**	<0.01	**0.09**
0	25.99	11.14	69.33	172.31	1277.2	5.13	2.59	0.03	0.17	<0.01	0.09
30	26.79	11.48	71.45	177.58	1316.28	5.28	2.67	0.03	0.18	<0.01	0.09
60	27.13	11.62	72.36	179.83	1332.99	5.35	2.70	0.03	0.18	<0.01	0.09
Wild mustard	**13.28**	**3.53**	**8.173**	**11.41**	**110.23**	**0.17**	**0.05**	**0.05**	**0.02**	**0.01**	**0.01**
0	13.08	3.48	8.05	11.24	108.62	0.16	0.05	0.05	0.02	0.01	0.01
35.5	13.36	3.54	8.22	11.48	110.89	0.17	0.05	0.05	0.02	0.01	0.01

71	13.39	3.56	8.24	11.51	111.17	0.17	0.05	0.05	0.02	0.01	0.01
Grand Total	**34.02**	**10.58**	**52.50**	**86.11**	**587.85**	**8.75**	**3.69**	**5.51**	**0.09**	**0.06**	**9.19**

5.3.4 Nutritional water productivity in response to irrigation

There was a small/ no difference observed in the nutritional water productivity of nutrients (NWP) across all crops, which meant that subjecting crops to different water treatments did not affect the NWP of the crops. Nonetheless, amaranth and cowpea had the highest average NWP across all nutrients, and wild mustard had the lowest. Sweet potato had the highest energy with a mean average of 1313.961 kcal/100 g, and wild mustard the lowest (110.316 Kcal/100 g).

Table 5. 4: Nutritional water productivity of total fibre, lipids/fats, total carbohydrates, total proteins, energy, potassium (K), calcium (Ca), iron (Fe), zinc (Zn), vitamin A, and total carotenoids of selected ALVs (amaranth, cowpea, sweet potato and wild mustard) under different irrigation (mm mm^{-1}) levels.

Row Labels	**Total fibre (kg m^3)**	**Total Protein (kg m^3)**	**Total carbohydrates (kg m^3)**	**Lipids/Fats (kg m^3)**	**Energy (Kcal/100 g)**	**K (kg m^3)**	**Ca (kg m^3)**	**Fe (kg m^3)**	**Zn (kg m^3)**	**Vitamin A (kg m^3)**	**Total carotenoids (kg m^3)**
Amaranth	**47.45**	**14.07**	**61.69**	**130.58**	**769.78**	**12.70**	**9.29**	**0.22**	**0.05**	**0.21**	**36.51**
0	47.55	14.10	61.80	130.82	771.24	12.73	9.31	0.22	0.05	0.21	36.58
20	47.43	14.07	61.67	130.54	769.60	12.70	9.29	0.22	0.05	0.21	36.50
40	47.37	14.05	61.58	130.36	768.51	12.68	9.28	0.22	0.05	0.21	36.45
Cowpea	**48.70**	**13.30**	**69.07**	**25.87**	**162.52**	**16.88**	**2.76**	**21.74**	**0.13**	**0.01**	**0.14**
0	48.73	13.31	69.11	25.88	162.61	16.89	2.76	21.75	0.13	0.01	0.14
20	48.66	13.29	69.02	25.85	162.39	16.87	2.76	21.79	0.13	0.01	0.14
40	48.72	13.30	69.09	25.87	162.57	16.89	2.76	21.74	0.13	0.01	0.14
Sweet potato	**26.74**	**11.46**	**71.32**	**177.23**	**1313.96**	**5.27**	**2.67**	**0.03**	**0.18**	<0.01	**0.09**
0	26.56	11.38	70.83	176.03	1304.83	5.24	2.65	0.03	0.18	<0.01	0.09
20	26.78	11.47	71.42	177.50	1315.70	5.28	2.67	0.03	0.18	<0.01	0.09
40	26.89	11.52	71.72	178.26	1321.35	5.30	2.68	0.03	0.18	<0.01	0.09
Wild mustard	**13.29**	**3.53**	**8.18**	**11.42**	**110.32**	**0.17**	**0.05**	**0.05**	**0.02**	**0.01**	**0.01**
0	13.12	3.49	8.08	11.27	108.92	0.16	0.05	0.05	0.02	0.01	0.01
20	13.27	3.53	8.17	11.41	110.21	0.17	0.05	0.05	0.02	0.01	0.01
40	13.47	3.58	8.29	11.57	111.82	0.17	0.05	0.05	0.02	0.01	0.01
Grand Total	**34.04**	**10.59**	**52.57**	**86.28**	**589.15**	**8.76**	**3.69**	**5.509**	**0.09**	**0.06**	**9.19**

5.4 Discussion

This section's objective was to quantify the nutritional water productivity of selected ALVs (amaranth, cowpea, sweet potato, and wild mustard) under different management strategies (planting date, plant density, fertiliser application and irrigation). Crops differed in their nutritional content, which resulted in a varied NWP. Overall, cowpea was more nutrient-dense compared to the other three crops. Different planting date resulting in high NWP for different crop species meant that these ALVs could be planted either early or late during the season. Table 5.1 shows that amaranth had high NWP across all nutrients, contrary to nutrient composition findings. Since cowpea had to be more nutrient-dense than other crops in the previous chapter, one might expect it to have high NWP, which was not the case. Amaranth's was favoured by early planting, while cowpea does better when planted late, and this was attributed to nutrient content and water availability. Because planting date 2 (01-September) is the beginning of rainfall season at Ukulinga farm and yield production starts to increase slowly. The NWP ratio was increased for all crops.

Low to medium plant density resulted in high NWP across ALVs. However, Cowpea did not follow this trend as its NWP showed an increase under high plant density. An increase in plant density promotes vertical growth. Resource competition under this condition results in plants developing small leaves and weak stems to speed up growth and development. However, this may mean less nitrogen content which reduces total protein. Table 5.2 shows that cowpea demonstrated a copying strategy where there was a trade-off among different nutrients given different plant density. An increase in total carbohydrates, energy, and total fibre compensated for the decrease in protein. These results agreed with the results obtained by (Kanda et al., 2020)

This novel concept, nutrient concentration, water use, and production can be linked together to understand better crops growth and productivity (Nyathi et al., 2018b). The similarities observed under NWP response to fertiliser application and irrigation may have been due to a carried over error from the modelling chapter (chapter 3). Here a similar issue was observed in a modelling output and carried over when estimating harvestable nutritional yield. However, according to Chibarabada et al. (2017) and Nyathi et al. (2018b), different water regimes had an accountable effect on the NWP of crops, including one of the studied vegetable amaranth. Another challenge that may have resulted in the results showing no treatment effects under mentioned management practices may be the number of published papers on the nutrient content of ALVs. The number of published articles available for each crop's nutrient composition might have potentially caused bias and gave the wrong impression on crops' nutrient concentration. For example, wild mustard was the least nutrient-dense leafy vegetable amongst the other three. This limited availability of published information might have truly cased biases in the results obtained. Nonetheless, we cannot fully conclude that there is little literature on this crop's nutrient composition than other crops.

5.5. Conclusions

This section presented new insight that there is still room for improvement when speaking of African leafy vegetables (ALVs). To improve our understanding of ALVs, it is essential to design more research or projects that will focus on the growth and production of these crops. It is also of equal essence to understand agronomy and publish more papers on that aspect so that it is easier to calibrate and model these ALVs. According to what we have, it might be safe to conclude that these selected ALVs (amaranth, cowpea, sweet potato, and wild mustard) have higher NWP for most nutrients than famous vegetable cabbage. However, more work still needs to be done to give evidence or support that statement strongly.

CHAPTER 6

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1 General discussion

The present study assessed the impact of different agronomic management (planting date, plant density, fertiliser application, and irrigation) on nutrient composition and nutritional water productivity (NWP) of African leafy vegetable (ALVs). Each chapter served as fulfilment for each objective mentioned above. Key findings were that the leaves of amaranth, cowpea, sweet potato, and wild mustard are very nutrient-dense. However, their nutritional concentration or density may vary with change in agronomic practices. The combination of agronomic management practices also differs from one crop to another, and this was important to note to understand best management practices for each crop. The major challenge was the availability of published papers on the agronomy and nutrient composition of ALVs, which might have resulted.

6.1.1 Agronomic management of selected African leafy vegetables for improved Yield, Water Use and Water productivity

There was a significant effect on growth and productivity observed in ALVs (amaranth, cowpea, sweet potato, and wild mustard) upon changing agronomic management practices, with irrigation as the exception. The reason might have been that during modelling, the soil was field into capacity, so adding any amount of water resulted in no change in terms of growth and development of these ALV. For future research, it is ideal that this aspect must is looked at again.

6.1.2 Nutrition composition of African leafy vegetables

The results revealed that the leaves of amaranth, cowpea, sweet potato and wild mustard have good nutritional attributes. They agree with the study done by Enyiukwu et al. (2018), who suggested that consumption of such vegetables may account for a good source of nutrients that could be beneficial, health-wise, to both children and adults. The superior nutrient attribute of amaranth as a vegetable crop is to be commanded and may serve as a reasonable explanation of why this is a slowly emerging food choice in many feeding schemes, especially during warm seasons. The non-uniformity in published papers for nutrient composition of ALVs off-limits accurate and fair conclusions on nutrient concentration.

6.1.3 Nutrition water productivity of selected African leafy vegetables (ALVs)

Nutritional water productivity varied among the crops. Nutritional yield (harvested) had a considerable impact on the nutritional water productivity of different nutrients across all crops. The nutritional yield was not affected by water application, resulting in different water treatments not affect NWP. Chibarabada et al. (2017) made a similar observation on cowpea and other legume crops where there was no significant difference in NWP across various water regimes. These findings raise some question as there is still no proof if this occurrence is caused by cowpea being drought tolerant of an undefined error.

6.2 Conclusions

More research must focus on modelling indigenous crops. And to achieve this, researchers must develop a better understanding of these crops' agronomy is required for future modelling studies. Future research still needs to do more nutrient profiling studies of many ALVs and other indigenous crops, more especial to assess the NWP of crops. It is also important to consider conducting tasks that will investigate NWP under different management practices for a different location, including more rural communities where substantial farming is still relevant.

6.3 Recommendations

It is necessary to study factors affecting the growth and productivity of ALVs to provide new bases for modelling. Analysing these factors will also help in understanding the concentration of nutrients in different environments. For example, protein content tends to decrease where there is less water available for growth due to less nitrogen in dry leaves—in this way, minimizing challenges faced when modelling NWP. Lastly, Nutrient concentration and nutritional water productivity must be assessed under various sample treatments (cooked, raw, blanched, etc.), requiring efforts from different disciplines

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