EFFECTS OF WATERING REGIMES AND PLANTING DENSITY ON TARO (*COLOCASIA ESCULENTA*) GROWTH AND YIELD UNDER MOISTURE BEDS IN EMBU, KENYA

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DECLARATION

I, Joyce Wambui Njuguna, hereby declare that this thesis is my original work and has not been submitted for project research and award for degree in any other university.

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DEDICATION

To my parents, Dr. Stephen Njuguna Ngigi and Mrs. Ruth Wanjiru Muriithi for their unwavering love and financial support all through my studies. God bless you both.

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LIST OF ABBREVIATIONS

CGIAR	-	Consultative Group on International Agricultural Research
CIMMYT	-	International Maize and Wheat Improvement Centre
CL	-	Corm Length
CD	-	Corm Diameter
CM	-	Corm Mass
CY	-	Corm Yield
ET	-	Evapotranspiration
FAO	-	Food and Agriculture Organization, of the United Nations
FC	-	Field Capacity
FAOSTAT	-	Food and Agriculture Organization Statistics
HI	-	Harvest Index
KALRO	-	Kenya Agricultural and Livestock Research Organization
KEBS	-	Kenya Bureau of Standards
LAI	-	Leaf Area Index
SWC	-	Soil Water Content
UNEP	-	United Nations Environmental Programme
VGI	-	Vegetative Growth Index
WU	-	Water Use
WUE	-	Water Use Efficiency

GENERAL ABSTRACT

Taro (*Colocasia esculenta* (L.) Schott) is one of the underutilized crops and is considered an orphan crop. In the tropics, taro is an important staple food in the human diet. Taro has suffered low production in Kenya due to various factors among them its utilization. Taro is referred to as *nduma* in Kenya and is primarily grown in the riverbeds. However, the riverbeds are already a limited resource due to climate change and during periods of water scarcity. There is a need to understand the edaphic and crop management factors that affect taro production to increase its production in the country. The study was conducted at KALRO – Embu research station for three growing seasons: long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022. The main objective of the study was to determine the optimal watering regime and planting density for improved taro yields in the semi-humid areas of Kenya. Specifically, under the different watering regimes and planting densities, to determine the growth, yield, and yield components response of taro; to determine the water use efficiency (WUE) of taro; and to assess the cost and benefits of growing taro. The taro variety used in this study was *Dasheen* which is characterized by relatively large tubers. A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation watering regimes while the subfactor was the planting density, with three replications. The watering regimes were 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities were 0.5m × 0.5m (40,000 plants ha^{-1}), 1m × 0.5m (20,000 plants ha^{-1}), and 1m × 1m (10,000 plants ha^{-1}), representative of high, medium, and low plant densities respectively. The growth and yield component data collected in the field was recorded in data collection sheets and thereafter the data was entered into a Microsoft Excel spreadsheet and later imported to the GenStat statistical software for data analysis. The growth components data was subjected to repeated measures analysis of variance using the GenStat statistical software as the growth components data were observed repeatedly over time (days after planting) across each season. The yield components and water use efficiency data were subjected to split-plot analysis of variance using the GenStat statistical software. Mean separation was done using the Fisher's least significant difference (LSD) at a 5% level of probability where the ANOVA *F*-values were significant. Correlation analysis was done for the yield components data using the GenStat statistical software to determine the yield components that strongly influenced the corm yield. The results showed that the plant height and leaf area index increased with time across the three growing seasons ($P < 0.001$). The 60 % FC attained the highest plant height while the 30 % FC attained the highest leaf area index. The 0.5 m × 0.5 m planting density had the highest plant height and leaf area index. The corm length, diameter, mass, total biomass, yield, and harvest index were influenced by the seasons ($P < 0.001$). The watering regime did not influence any of the taro yield and yield components. The 60 % FC watering regime had the highest corm diameter, length, mass, and yield, the total biomass was highest under the 30 % FC while the 100 % FC attained the highest harvest index. Planting density influenced the corm length, corm diameter, total biomass, and corm yield ($P < 0.05$). The 0.5 m × 0.5 m planting density had the highest biomass, corm yield, and harvest index with the 1 m × 1 m planting density attained the highest corm length and mass.

The water use of taro was influenced by season, watering regimes, and planting density ($P < 0.001$). The 100 % FC watering regime and the 0.5m × 0.5m planting density had the highest water use values with the 30 % FC watering regime and 1m × 1m planting density having the lowest. The water use efficiency (WUE) was influenced by season and watering regime ($P < 0.001$). The WUE under 100 % FC was 23 % and 63 % lower than 60 % FC and 30 % FC respectively. The planting density did not influence the water use efficiency and the 1m × 0.5m planting density recorded the highest water use efficiency with the 1 m × 1 m recording the lowest. The total input costs were highest under the 0.5 m × 0.5 m planting density. The 0.5 m × 0.5 m under 60 % FC produced the highest net benefit while the low net benefit was obtained for the 100 % FC under 0.5 m × 0.5 m. The dominance analysis conducted showed that the 1m × 0.5m under 60 % FC and 100 % FC and 0.5m × 0.5m under 30 % and 100 % FC dominated having lower gross margins (net benefits) and were disqualified from further consideration. The 100 % FC under the 1m × 1m planting density attained the highest benefit-to-cost ratio and marginal rate of return (>100%). The highest planting density of 0.5 m × 0.5 m (40,000 plants ha^{-1}) and a 60 % FC watering regime is recommended to farmers in the area for increased vegetative growth, yields and increasing food security. To achieve the highest yield per unit of water consumed, a watering regime of 30 % FC and a planting density of 1 m × 0.5 m (20,000 plants ha^{-1}) is recommended. It is further financially viable to recommend the 100 % FC under the 1 m × 1 m planting density in Embu County, for increased financial gains in the production of taro.

CHAPTER ONE
GENERAL INTRODUCTION

1.1. Background

Taro (*Colocasia esculenta* (L.) Schott) is a herbaceous, monocotyledonous, perennial stem root crop widely grown throughout the world's tropical and subtropical areas (FAO, 2010). Its production has increased significantly over the past ten years, making it the fifth most-consumed root vegetable in the world (Macharia *et al.*, 2014). It is also the oldest crop, having been grown for over nine thousand years in Southeast Asia and India (Rao *et al.*, 2010). In Sub-Saharan Africa, it is one of the underutilized crops and an important staple food in the human diet. However, it ranks lower than other tubers such as cassava (*Manihot esculenta*), potato (*Solanum tuberosum*), and sweet potato (*Ipomoea batatas*) (Palapala and Akwee, 2016). In comparison to Africa (5.9 tons/ha) and the rest of the world (6.6 tons/ha), average taro yields in East Africa continue to be low with annual yields only occasionally exceeding one ton per hectare (Serem *et al.*, 2008; Palapala and Akwee, 2016).

Taro is a low perennial herbaceous plant with thick, fleshy, and creeping roots and white fibres. It belongs to the family *Araceae* and subfamily *Aroideae*. The leaves and corms are a rich source of carbohydrates. They aid in digestion, are gluten-free, fat-free, and low in calories. The leaves are good sources of phosphorus, potassium, copper, manganese, iron, zinc, niacin, thiamine, riboflavin, vitamin B6, and vitamin C (Enwelu *et al.*, 2014; Palapala and Akwee, 2016). On a dry weight basis, the young leaves have a high protein of about 23 % (Tumuhimbise *et al.*, 2009). Additionally, the leaves are also dried and milled into a powder that is mixed with wheat flour or used as food flavour. In East Africa, the corms have traditionally been steamed and eaten as a snack alongside tea or a beverage (Serem *et al.*, 2008; Tumuhimbise *et al.*, 2009; Akwee *et al.*, 2015; Chivenge *et al.*, 2015; Palapala and Akwee, 2016). Patients with peptic ulcers, pancreatic disease, inflammatory bowel disease, chronic liver problems, and gall bladder disease can also benefit from taro starch as well (Enwelu *et al.*, 2014; Buke and Gidago, 2016).

Taro is grown under a wide range of edaphic and environmental conditions but is commonly grown in wetlands. It grows in regions with evenly distributed rainfall and two water regimes, ranging from dryland or unflooded conditions to waterlogged or flooded conditions (Ngetich *et al.,* 2015; Ansah, 2016). Taro can be grown in swampy areas or drier places with irrigation (Yamanouchi *et al.,* 2022). In upland cultivation, taro can be grown in moisture beds that are lined with polythene to prevent the loss of water through its percolation into the soil (Oxfarm, 2021). To avoid water stress which can lead to the development of poor-quality, deformed corms, it is important to ensure constant availability of water throughout the growing season (Sibiya, 2015; Ansah, 2016). The soil's capacity to store water becomes an essential consideration in upland taro production due to the great variations and unpredictability of rainfall and the cost of irrigation (Ansah, 2016). It is best grown as a first crop after clearing and propagated vegetatively using tubers or the mature apical portion of the huge tubers (Mwenye, 2009). Thus, there is a need to understand the edaphic and crop management factors that affect taro production in Kenya.

Like many other crops, taro production is plagued by weeds, lack of improved planting material and labour, pests and diseases, post-harvest processing, marketing, limited research, and lack of extension services (Akwee *et al.,* 2015; Oduro *et al.*, 2021). Research and development organizations must create suitable taro production technologies to alleviate the current limitations. On the other hand, recent initiatives have concentrated on taro genetic diversity (Macharia *et al.,* 2014; Akwee *et al.,* 2015; Palapala and Akwee, 2016), planting density (Tsedalu *et al.,* 2014; Sibiya, 2015; Boampong *et al.*, 2020), socioeconomic constraints to production (Bammite *et al.,* 2018) and use of inorganic fertilizers (Ngetich *et al.*, 2015; Buke and Gidago, 2016).

There is a paucity of data on utilizing supplemental irrigation to increase productivity per cultivatable unit of land area. There is limited information on its production, agronomy, and contribution to food sustainability and security. However, precise water applications are necessary to comprehend taro's response to water scarcity and define the water consumption and its limitations under field conditions (El-Aal *et al.*, 2019). Efficient irrigation is critical in improving and maintaining crop productivity while preserving water and soil nutrients (Olamide *et al.,* 2022). The determination of how much water and when to irrigate to achieve the highest water use efficiency is very important in improving crop growth under irrigation (Kang'au *et al.,* 2011). Information on the correct plant spacing for improved taro growth, corm shape, and hence yields in Kenya is still scanty. Agronomic knowledge of taro is mostly derived from outside Kenya with limited studies done locally. This study aims to investigate how the taro plant responds to various water regimes and plant densities in terms of development, biomass, and corm quality.

1.2.Statement of the problem

Agriculture continues to be the primary means of addressing food and nutrition security in a region where 70 % of the population relies on agriculture. In Sub-Saharan Africa, there is a significant problem with food insecurity, which becomes exacerbated by poverty, unsustainable tillage practices, low crop production, poor soils, water deficiency, and climate change. Due to this, smallholder farmers, who account for the bulk farmers, have low production of food crops (Akwee *et al.,* 2015; Chivenge *et al.,* 2015). Climate change presents a challenge to livelihoods as recurrent droughts and variable rainfall make it difficult for smallholder farmers, who make up the majority of the population, to diversify their sources of income (FAO, 2015; Boutin and Smit, 2016).

One of Kenya's underutilized crops is taro (*Colocasia esculenta*), which subsistence farmers, largely women, grow for its nutritious leaves and fleshy corms (Ngetich *et al.,* 2015). The crop acts as a buffer crop during the shortage of other staple foods. In Kenya, it is referred to as arrowroot or *nduma* and is primarily grown in the riverbeds. The riverbeds, however, are already a finite resource in the face of climate change, particularly during times of water scarcity. Shortage of high-quality seeds and limited yields has limited its production in the semi-arid areas (Wambugu and Muthamia, 2009; Akwee *et al.*, 2015; Ngetich *et al.*, 2015). The crop can therefore be promoted to contribute to food diversity and improve livelihoods in addition to having the ability to solve food insecurity. However, little attention has been placed on Kenyan production.

By increasing plant capacity for light interception and, as a result, dry matter production, plant density is a crucial agronomic management strategy for increasing root crop production (Dessa *et al.*, 2018). Planting density is an important factor governing the corm yield of taro. However, there is limited data on the yield response of taro to population density and planting material type for different agro-ecological zones (Tsedalu *et al.,* 2014). Crops that require wetland conditions, such as arrowroot, papyrus, and rice, can benefit greatly from growth in soils lined with polythene sheets (van der Sterren, 2021) as it ensures that flooded conditions are maintained in the moisture bed.

1.3. Justification

Understanding the growth response of taro under selected watering regimes, and its water use under varied planting densities underpins this study. The taro crop has traditionally been cultivated by smallholder farmers along riverbeds, however due to climate change that has led to prolonged droughts, cultivation of this crop has been facing challenges due to the constant unavailability of water. The findings of this study are meant to inform and educate farmers on an alternative way of cultivating taro that results in constant supply of water throughout the growing season through growth on moisture beds and use of drip irrigation as a supplemental source of water during water scarcity periods. There is need to upscale the use of drip technology particularly for smallholder farmers in the cultivation of this crop because most farmers in the region rely on rainfed irrigation. In order to scale up the use of moisture beds under drip irrigation, there is need for local agricultural organizations e.g., Kenya Agricultural and Livestock Research Organization (KALRO) to work on projects that will educate and supply drip irrigation technologies to the small holder farmers so as to foster adoption of this technology.

Farmers in Kirinyaga and Murang'a Counties in Kenya have adopted the use of moisture beds for taro growing a shift from growing in riverbeds and streams. A moisture bed is constructed by digging a trench and removing 0.3 metres of topsoil which is then mixed with manure. The dimension of the bed varies in terms of width and length, with dimensions of up to 10 metres by 1.2 metres (Boland, 2005). On the bed's floor is the polythene paper, whose dimensions correspond to those of the moisture bed. The soil mixed with manure is then spread on top of the polyethylene liner that had been laid on the bed's floor to complete the moisture bed (Boland, 2005; Muchui, 2015). The polythene sheet ensures water is retained in each plot and hence available to the plants. The moisture beds make drip irrigation applicable within the plant rows (Boland, 2005). Since taro plant spacing influences taro growth, corm shape, and yield as a result of competition for soil moisture, nutrients, and light (Boampong *et al.,* 2020), it is therefore imperative to know the implications on taro growth in terms of planting density under a moisture bed.

The importance of taro in providing food security, generating money as a cash crop, and fostering rural development cannot be overstated (Temesgen and Retta, 2015). This reduces food insecurity and malnutrition among rural farmers who make their living from farming and live below the poverty line (Akwee *et al.,* 2015). Drip irrigation is a method for smallholder farmers to increase yields and harvests while taking into account the limited water resources available by substituting the traditional practice of planting taro along rivers and streams with uplands (Wainaina, 2021). To stop water seepage and lateral movement of water between plots, moisture beds trenched at a depth of 1 metre and lined with thick polyethylene sheets are used to separate the plots (Mabhaudhi, 2012).

Additionally, incorporating financial analysis improves farmers' capacity to evaluate watering regimes and planting densities, which have an impact on the viability and wide-scale adoption of this technology. The costs involved in the transition from growing in riverbeds and streams to uplands under the moisture beds and drip irrigation are critical in the adaptation of the technology to farmers. Therefore, this study seeks to increase the growth, yield, and financial benefits of taro through better management of moisture supply and optimized plant density, so as to increase its production in the country, particularly for smallholder households.

1.4. Objectives

1.4.1. General Objective

To increase the yield of taro through better management of moisture supply and optimized plant density.

1.4.2. Specific Objectives

1. To determine the growth components response of taro under varying watering regimes and planting densities.
2. To determine the yield and yield components response of taro under varying watering regimes and planting densities.
3. To determine the Water Use Efficiency (WUE) of taro under varying watering regimes and planting densities.

4. To evaluate the cost and benefits of growing taro under the different watering regimes and planting densities.

1.5. Hypotheses

1. The varying watering regimes and planting densities have no effect on taro growth components.
2. The yield and yield components of taro are not affected by the different watering regimes and planting densities.
3. The water use efficiency of taro does not vary under the different watering regimes and planting densities.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

One of Sub-Saharan Africa's neglected crops, taro (*Colocasia esculenta*) is a crucial component of the nutrition of people living in tropical regions (Akwee *et al.,* 2015). In terms of export, human consumption, industrial applications, nutritional benefits, and other health benefits, the crop is underutilized (Otekunrin *et al.*, 2021). The taro (*Colocasia esculenta* (L.) Schott) belongs to the *Aroideae* subfamily of the *Araceae* family, whose members are more commonly referred to as aroids (Lebot, 2008). When compared to other tubers like the potato (*Solanum tuberosum*), the sweet potato (*Ipomoea batatas*), and the cassava (*Manihot esculenta*), it lags (Palapala and Akwee, 2016). In the majority of African countries, taro is the third most significant root and tuber crop grown consumed, behind cassava and yam (Otekunrin *et al.*, 2021).

2.2. Importance of Taro

Taro is a low perennial herbaceous plant with thick, fleshy roots that creep and have white fibres (Figure 1). It has a wide array of economic importance and uses particularly in regions where it is widely consumed. This crop has exceptional dietary value and numerous culinary applications due to the edible stem and corm, which can be used in a variety of food preparations (Dhanraj *et al.,* 2013). The leaves and corms are rich sources of carbohydrates. Taro has a higher protein content per dry weight than cassava, yam, or sweet potato, at approximately 11% (Temesgen & Retta, 2015). Taro flour is notable for its lack of gluten, which allows it to be used in gluten-free products (Arıcı *et al.,* 2021).

Figure 1: Taro plants growing in the field and the taro root (corms), locally known as *nduma* (Teves, 2015)

The leaves are rich in thiamine, riboflavin, iron, phosphorus, zinc, vitamin B6, vitamin C, niacin, potassium, copper, and manganese, among other vitamins and minerals (Enwelu *et al.*, 2014; Palapala and Akwee, 2016). On a dry weight basis, the young leaves contain high protein of about 23 % (Tumuhimbise *et al.*, 2009). Additionally, the leaves are dried and ground into a powder that can be used with wheat flour or used as a flavouring for food. In East Africa, the corms are typically steamed and consumed with tea or a different beverage as a snack (Serem *et al.,* 2008; Tumuhimbise *et al.,* 2009; Akwee *et al.,* 2015; Chivenge *et al.,* 2015; Palapala and Akwee, 2016).

In Kenya, taro or traditionally known as *nduma*, has been a source of food for rural communities. The corms, which are either boiled or fried and served with various stews, are extremely nutritious. They are also high in fibre, and taro flour has been used to thicken soups and stews. Taro mixture with herbs has historically in the country been used to treat scorpion bite scars and toxins from arrows (Slow Food Foundation, 2017). Patients with pancreatic disease, peptic ulcer, chronic liver issues, inflammatory bowel disease, and gall bladder disease may all benefit from taro starch (Buke and Gidago, 2016; Enwelu *et al.,* 2014). The peels and wastes from taro have been used as animal feeds and silage produced from large quantities of taro remains after the corms have been harvested (Macharia *et al.,* 2014).

2.3. Production Status of Taro

With a production of about 12 million tonnes produced from approximately 2 million hectares at an average yield of 6.5 tonnes per hectare, taro is the fourteenth-most significant staple vegetable crop in the world (Rao *et al.,* 2010).

2.3.1. Global Taro Production

Nigeria, Cameroon, China (Mainland), and Ghana are the world's top four producers of taro, which scaled from 9.76 million tonnes in 2000 to 10.54 million tonnes in 2019 (FAOSTAT, 2020). Additionally, during the past 20 years, the amount of taro produced globally has risen significantly, increasing from 1.40 million tonnes in 2000 to 1.96 million tonnes in 2019 (FAOSTAT, 2020; Otekunrin *et al.,* 2021). The Food and Agriculture Organization (FAO) estimates that to feed an additional 2.3 billion people by 2050, raising agricultural yields and production levels on currently available croplands will be necessary (FAO, 2009). This is not the situation in the African continent, where taro cultivation requires more agricultural land, rather than greater crop yield per hectare, to improve production (Onyeka, 2014).

2.3.2. Taro Production in Africa

In Africa, especially in Sub-Saharan Africa, taro is primarily grown by small-scale, resource-constrained, and mostly female farmers (Onyeka, 2014). Africa has continuously produced more than 70 % of the world's taro output during the past two decades, accounting for almost 76 % of the worldwide share in 2000 but experiencing a little decline in production levels, accounting for 72.27 % (7.6 million tonnes) of the global total production in 2019 (Otekunrin *et al.,* 2021). The crop has received limited attention from agricultural researchers and government policymakers, although African taro production is well-known and recognized worldwide (Otekunrin *et al.,* 2021). During dry seasons, taro is a vital food supply and helps to ensure food security (Kennedy *et al.,* 2019).

2.3.3. Taro Production in Kenya

When compared to neighbouring countries that export taro such as Uganda, Rwanda, and Burundi, taro production in Kenya is low. Low-quality planting materials, a lack of value-addition and processing, and low productivity are all factors in the low output of the taro crop.

Additionally, problems including lack of planting materials, enhanced taro varieties, pest and disease control, limited research efforts, and information research on taro germplasm types in comparison to Pacific-Island communities all contribute to the nation's low taro output (Akwee *et al.,* 2015; Adhiambo, 2019).

In certain regions of Kenya, small-scale farmers grow taro near streams or riverbanks because most rural communities lack modern irrigation systems for growing upland taro (Akwee *et al.*, 2015). This might be attributed to Kenya's major agricultural stakeholders and policymakers using ineffective marketing strategies. This poses an important challenge to the nation's efforts to diversify its food crop production to meet the demands of its expanding population. Farmers that grow taro have relatively little knowledge of high-yielding cultivars from various parts of the country because of the fragmented and limited taro research (Akwee *et al.,* 2015). While much taro is grown and eaten for food, a substantial amount is grown as a cash crop. Additionally, surpluses from subsistence farming find their way to markets, contributing to poverty alleviation. However, taro research in Kenya is very limited. The actual value of taro as a food crop and its impact on the national research and conservation agenda are both modest. In comparison to the rest of Africa (5.9 tons/ha) and the rest of the world (6.6 tons/ha), taro yields in East Africa continue to be low with yields rarely topping one ton per hectare (Serem *et al.,* 2008; Talwana *et al.,* 2011; Palapala and Akwee, 2016).

2.4. Botany and Ecology

2.4.1. Morphology and Classification of Taro

Growing in the tropics and subtropics, taro is a perennial herbaceous root crop from the plant family *Araceae* and the genus *Colocasia* (Macharia *et al.,* 2014). The two types of taro that are commonly cultivated are *Colocasia esculenta var esculenta* (Dasheen type) *and Colocasia esculenta var antiquorum* (Eddoe type) (Rashmi *et al.,* 2018). The major corms and cormels of the two types differ significantly in terms of size and shape (Lebot, 2008). The Dasheen type features a single, sizeable cylindrical main corm and a few, smaller cylindrical side corms that branch off the main plant and eventually become suckers. The Eddoe type produces small corms that are round to oval in shape, with smaller corms clustered around the base of the main corm (Robin, 2008; Singh *et al.,* 2008; Sibiya, 2015). The Dasheen variety is adopted in this study.

Figure 2: A). Dasheen type and B). Eddoe type (Adapted from Deo *et al.,* 2009)

The Kalenjin and Gikuyu people of Kenya's Rift Valley and Central regions commonly refer to taro as *nduma*. Because it requires wet conditions and consumes a lot of water, it grows often in waterlogged areas and on riverbeds. Taro is typically harvested twice or three times per year, depending on the field management (Slow Food Foundation, 2017). It often grows to a height of 1-2 m, with thick lateral edible runners and a big, fleshy corm at the bottom. The plant is composed of a central corm that lies just below the soil's surface; the corm's apical bud at the top of the corm produces leaves, while the corm's lower part produces roots. The roots are shallow, adventitious, and fibrous. Massive (up to 4 kg), tubular or spherical storage stem (corm), up to 30 x 15 cm in size, typically brown, and having lateral buds above leaf scars that produce new cormels, suckers, or stolons (Lebot, 2008). Cormels, daughter corms, and runners all develop laterally (Deo *et al.*, 2009). The corms' hydration, size, colour, and chemistry have all been found to be very variable according to Sibiya, (2015). On the outside, the corm is made up of concentric circles of leaf scars and scales. Each scale or leaf base has one or more secondary cormels that develop from lateral buds. The diameter is between 15 and 18 cm, and form spans from elongated to spherical. Anatomically, the tuber consists of a thick, brown outer layer that contains the ground parenchyma, which is packed with starch (Deo *et al.,* 2009).

2.4.2. Growth Requirements

2.4.2.1. Climate

The ideal growing conditions for upland taro are warm, humid climates with regular rainfall. In dry, low-rainfall areas, supplemental irrigation is required (Elevitch, 2011; Department of Agriculture, 2017). It is adapted to moist conditions but can be grown in both rainfed or irrigated upland and flooded conditions (Miyasaka *et al.*, 2003). Taro requires consistent rainfall or irrigation throughout the growing season, moist soils, and maximum temperatures of around 25°C (CGIAR, 2021). Although there are many upland varieties with water requirements much less than 2000 mm, *Colocasia esculenta* grows best in tropical lowland areas with more than 2000 mm of annual precipitation that is evenly distributed (Lebot, 2008).

Taro grows best in warm and moist environments. Upland taro production requires rainfall that is evenly distributed. Planting upland taro in areas with distinct dry and wet seasons should be timed so that adequate rainfall is received during the first four to five months of growth. Taro responds well to applications of nitrogen, phosphorus, and potassium. It is cultivated in multi-cropping systems along with other crops such as bananas, and tree crops. It is also planted in monoculture systems. Taro prefers shade during establishment, and it is not salt-tolerant. Exposure to bright sunshine increases productivity later in the growing season (FAO, 2010).

2.4.2.2. Soils

Taro prefers slightly acidic growing conditions (pH 5.5 - 6.5) and does not compete well with weeds during emergence. It grows well in well-drained sandy, heavy (clay), and loamy soils, (Onwueme, 1999; Sofa-Kantaka, 2004; FAO, 2010). Soil texture is an important characteristic when determining the suitability for taro cultivation (Filipović *et al.*, 2016). In Malaysia, taro is said to withstand soil pH ranging from 4.2 to 7.5 (Lebot, 2008). To achieve fine tilth and proper planting depth for taro growth and development, proper land preparation is required (KEBS, 2018). Some taro varieties thrive in rich and friable loamy soil with a high-water table while others thrive in sandy and mesic soils. In the Pacific Islands, taro is commonly cultivated on raised beds made of decomposed material (histosols) and prefers flooded soils. Raised beds, organic matter, and water-filled metal or cement tanks and as a dryland crop are additional ways that taro is cultivated (Elevitch, 2011).

Taro can be grown as an upland (dryland) or a lowland (wetland) crop in a wide range of soil conditions. The term upland in this context refers to taro production in non-flooded areas and does not always imply high elevation. Deep, well-drained loam soils yield the best results in upland agriculture. When the soil is alluvial, lowland cultivation is usually done in low-lying areas with plenty of fresh water for irrigation, and it produces the best results (Department of Agriculture, 2017). Li *et al.* (2019) found that soil texture affected corm number. The study looked at how three different soil types – clay, sand, and sandy clay loam – influenced taro's growth, yield, and watering regimes. More corms were produced by sandy soil than clay and sandy clay loam soil. In comparison to other soil textures, sandy clay loam soil produced rounded corms and higher corm diameter. However, the authors suggested further investigation.

2.4.2.3. Growth and Development Stages

In the first 90 days of planting, plant height, the number of leaves, length of petiole, and leaf area index all increase, according to Tumuhimbise *et al.* (2009). After planting, growth is slow at first but accelerates after 1 to 2 months (Onwueme, 1999). Furthermore, a period of slow corm growth is observed during the first 30 days of planting, followed by a period when corm diameter and length increase substantially. Taro growth, maturity, and harvest time are all affected by cultivar. Establishment, vegetative growth, and corm initiation and bulking through maturation, are the three growth stages of taro (Mare, 2009; Sibiya, 2015) as shown in Figure 3.

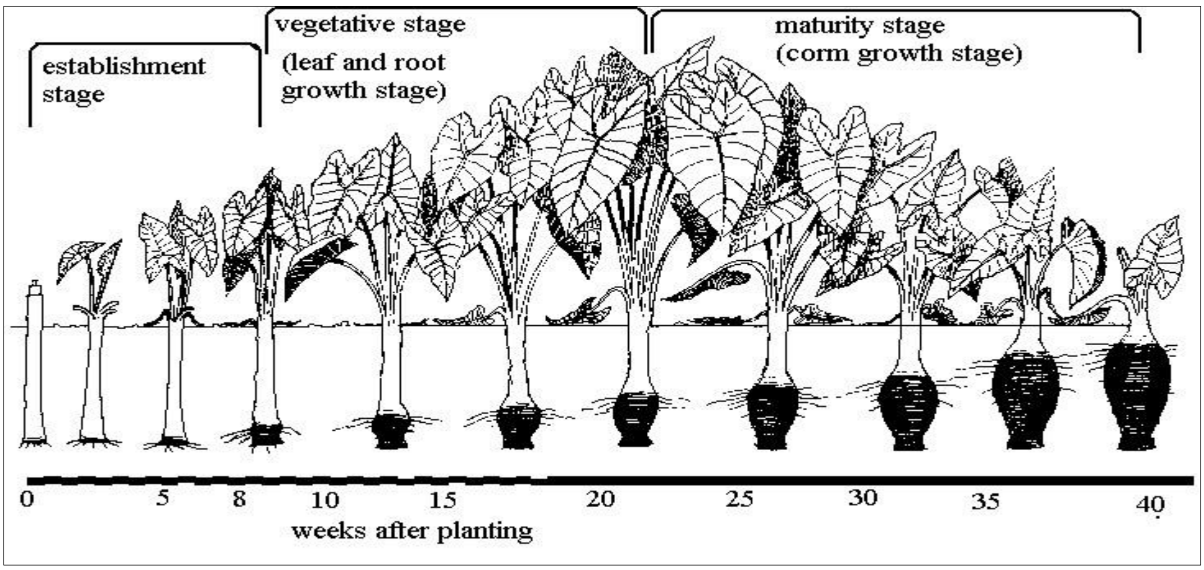

Figure 3: Diagrammatic Representation of taro growth stages (Adapted from Sibiya, 2015)

The establishment period is the first month of root formation and leaf production. This stage is distinguished by sprouting and root development. The successful establishment is a requirement for efficient crop production and is primarily determined by propagule quality (Modi, 2013). The vegetative growth and corm initiation are characterized by an increase in plant height, number of leaves, leaf area, and slow corm growth (Tumuhimbise *et al.*, 2009). Corm formation begins about three months after planting, followed by cormel formation in cultivars that produce large cormels.

When shoot growth slows in the sixth month, the corm and cormels take over as the primary sink and grow rapidly (Onwueme, 1999). Within five to six months, root and shoot growth is accompanied by an increase in corm formation, followed by a senescence period of reduced root and shoot growth with a continued increase in corm size from six to nine months (Mare, 2009). Additionally, Tumuhimbise *et al.* (2009) found that it is at this stage whereby the corm diameter and length increased rapidly throughout the 150 days after planting.

Under dryland conditions, corm development begins early, and the leaves and corm grow together until the maximum canopy is reached after about 20 weeks. During this stage, the rate of leaf production, the number of leaves, and the size of the leaves all grow increasing leaf area. When the canopy has reached its maximum size, leaf growth slows and leaf area rapidly diminishes, but rapid corm growth continues until there is very little leaf surface area. In this stage, the rate of leaf production, the number of leaves, the size of the leaves, and the durability of the leaves all decline (Mabhaudhi and Modi, 2015; Sibiya, 2015).

2.5. Cultivation of taro

Taro is traditionally propagated vegetatively mostly through suckers or stem cuttings and the best planting materials are headsets (also known as tops) or large suckers which have the apical bud, rapid growth, and a high rate of survival. In Kenya, the cormel and mother corm can both be used as planting materials. Cormels are also known as sucker corms and are used for planting. Corms should be cut into small sets of 150 - 200 grams, and cormels should be cut into whole tubers of 50 - 80 grams. Similarly, suckers are used to make setts. Larger setts are preferred since they result in larger yields. Within a week of harvesting, the setts should be planted. One should trim the plant to a new leaf inside after removing all dead leaves and petiole bases (Elevitch, 2011; KEBS, 2018).

As a result of competition for soil moisture, nutrients, and light, plant spacing within and between rows affects taro growth, corm shape, and yield (Teves, 2015; Boampong *et al.*, 2020). The taro plant can be grown in rows, ridges, furrows, or plots (Onwueme, 1999). Planting holes should be greater than the corm size, ranging from 10 to 20 cm in diameter depending on the size of the sett (Sibiya, 2015). Weed control is the most challenging task in upland taro, and it can consume a lot of time and effort. Weeds compete with taro for nutrients, light, water, and carbon dioxide, raising the cost of taro cultivation significantly (Teves, 2015; KEBS, 2018). It is recommended that weeding and earthing up be done twice in dry land production: first after 45 days of planting and again one month later. Inorganic and organic fertilizers should be applied at the recommended rates. Some weeds can provide a breeding ground for insects like aphids and mites, which can become serious taro pests (Teves, 2015).

2.6. Planting Density

Taro spacing responses vary greatly according to the species and are strongly influenced by environmental factors such as soil characteristics, site climate, and biotic components (Ogbonna *et al.,* 2015). Boampong *et al.* (2020) indicated that as plant spacing is reduced, production increases up to a point where further reduction results in only a slight increase in production. Plants grow larger and have better-developed root systems when the climate, soil, and nutrient status are all favorable for growth, which may necessitate wider spacing than usual. When conditions such as limited soil moisture are a likely limitation to the crop, a lower plant population is also justified (KZN Agriculture and Rural Development, 2016).

When taro is planted it produces several suckers that grow to become full plants. The projected plant population at planting will never equal the predicted plant population at maturity since suckers will always emerge (Ogbonna *et al.,* 2015). The authors further found that production increases with an increase in population up to a point where further increase leads to only a slight increase in production, which supports the findings by Boampong *et al.* (2020). The average cormel weight, however, falls as the plant population increases according to research done by Osundare, (2006) in Nigeria.

The findings of Ogbonna *et al.* (2015) in Nigeria, which were corroborated by the studies by Boampong *et al.* (2020) in Ghana and Tumuhimbise *et al.* (2009) in Uganda, showed a decrease in corm and cormel yield per stand at closer planting. Further, the yield components increased as plant spacing decreased. The highest corm and cormel yield per hectare was found from the planting spacing of 30 × 100 cm, which was the closest, compared to wider spacings of 50 × 100 cm and 40 × 100 cm. Furthermore, Boampong *et al.* (2020) observed that at the peak of vegetative growth (20 weeks after planting), taro plants planted at smaller spacing (1m × 0.5m and 1m × 0.75m) noted higher growth in plant height, the number of leaves/plants, and petiole length than plants spaced at 1m × 1m. Since taro grows horizontally rather than vertically may be the reason plant spacing has little or no effect on taro development. Higher corm yields per plant were observed at larger plant spacings of 1m × 1m and 1m × 0.75m, indicating taro's spacing has a significant impact on its overall performance.

Planting density has an impact on yield per area as well as individual plant size. In general, increasing density reduces corm size but increases overall yield. Traditional cultivars are better adapted to intermediate densities due to the variable genotype responses to planting density. Market demand and production objectives have a significant impact on planting density. Planting densities differ significantly between and within regions. In Hawaii, planting densities range from 7,000 to 35,000 plants per hectare, but 15,000 to 19,000 plants per hectare is recommended for New Caledonia. Usually, planting densities of 12,000 plants/ha and 26,900 plants/ha are recommended (Elevitch, 2011).

2.7. Yield and Yield Components

The number of cormels per plant, the total weight of cormels per plant, and individual corm mass are taro yield characteristics (Mare, 2009). The most desirable portions of the taro plant, from an economic standpoint, are the corms, cormels, and leaves (Ike *et al.*, 2015). The fresh corm contains approximately 2 % water and 13 - 29 % carbohydrate, the majority of which is starch (Adhiambo, 2019). The number of cormels per plant, mean cormel weight, and leaf area index (LAI) were found to be positively and significantly correlated with taro yields according to Mukherjee *et al.* (2016). Low rainfall periods contribute to poor vegetative propagule survival and corm quality due to starch loss. Further, the number of leaves was largely influenced by the environment (Mukherjee *et al.*, 2016).

2.8. Water Use (WU) and Water Use Efficiency (WUE) of a taro crop

Crop water use has two parts: evaporation from the soil surface, and transpiration from the plant leaves. Since it is challenging to distinguish between transpiration and evaporation, the two are typically measured or calculated as a single quantity known as evapotranspiration, or ET. ET and agricultural water use are usually used interchangeably (Irmak, 2017). Water use by a crop in a single field is difficult to determine without soil water content data. Therefore, crop water use can be estimated through crop ET calculations based on estimated ET for a reference crop (Allen *et al.,* 1998; Irmak *et al.,* 2011). Evapotranspiration has two concepts that are utilized in its estimation, namely: reference evapotranspiration (ETo) and crop ET under standard conditions (ETc). The ETo is the rate of evapotranspiration from a reference surface, not short of water. It is determined through the FAO Penman-Monteith method (Allen *et al.,* 1998). The ETc is the evapotranspiration from disease-free, well-fertilized crops grown in broad fields under ideal soil conditions and producing fully under certain climatic conditions (Djaman *et al.,* 2018). Evapotranspiration/water use is not easy to measure and can be determined through several methods including: the soil water balance method that is utilized in this study, ET computation from meteorological data, and ET estimated from pan evaporation (Allen *et al.,* 1998).

Water Use efficiency (WUE) is determined from water use/ET values. Crop physiologists define water use efficiency as the amount of biomass or marketable yield per unit of evapotranspiration. Irrigation scientists further define it as how effectively water is delivered to crops (Heffer *et al.,* 2015), as well as the plant productivity per amount of irrigation water supplied (Pereira *et al.,* 2002). WUE is measured by agronomists in terms of the amount of biomass that is produced (harvested yield) per cubic meter of water applied throughout the day, growth stage, or growth season (de Pascale *et al.,* 2011).

WUE takes into account the number of plants produced per unit volume of water used across a specific land area as well as the number of plants produced per unit of water lost through evapotranspiration during growth (Caviglia and Sadras, 2001; Koech *et al.,* 2015). WUE is an important determinant of crop yield under stress and has been used to imply that rainfed crop production per unit of water used can be increased (Blum, 2009). Optimizing water use efficiency for agriculture has necessitated a change in emphasis from maximizing productivity per unit of land area to maximizing productivity per unit of water consumed. Therefore, to maximize WUE, water must be conserved, and crop growth must be maximized (de Pascale *et al.,* 2011).

Taro (*Colocasia esculenta*) is mainly grown in the riverbeds; however, the riverbeds are already a limited resource with climate change and especially during water scarcity periods. Therefore, maximizing WUE in upland taro production will ensure water, which is already a scarce resource, is utilized efficiently for optimum production. The ability of taro to withstand water stress is not well understood (Li *et al.*, 2019). Working in India, Sahoo *et al.* (2006) discovered a considerable decline in leaf number and leaf area as water stress increased; nevertheless, the author also reported a slight reduction in yield. In Brazil, Li *et al.* (2019) found that limited water availability (20 % and 60 % ETc) decreased the number of taro leaves and area of leaves. On the contrary, overirrigation (180 % ETc) negatively influenced leaf number, although it was beneficial in increasing leaf area.

Using three water regimes based on crop water requirements (ETc), Mabhaudhi *et al.* (2013) evaluated taro growth, yield, and WUE in South Africa. They found that the leaf area and the number of leaves decreased by 5 % and 19 % respectively, at 60 % and 30 % ETc. Additionally, taro yield increased by 15 % and 46 % at the most optimum irrigation regime, 100 % ETc, compared to 60 % ETc and 30 % ETc, respectively, but WUE remained similar across all water regimes. Working in Hawaii, Uyeda, (2011) investigated how different taro cultivars responded to irrigation rates of 50 %, 100 %, 150 %, 200 %, and 250 % ETo (reference evapotranspiration) and found that 150 % ETo produced the highest yields of taro. Thus, there is a need to understand the WUE under the sub-humid environment of Kenya, to ensure crop growth is maximized alongside with conservation of already dwindling water resources.

2.9. Partial budgeting analysis

The process of organizing experimental data and information on the costs and benefits of different treatment alternatives is called partial budgeting (CIMMYT, 1988). The analysis of the partial budget compares the expenses and benefits of various treatments. In an on-farm experiment, it is a method of determining the overall expenses that vary and the net benefits of each treatment. It encompasses the adjusted yields, the gross field benefit (based on the field price of the crop), and the average yields for each treatment. Crop yields are adjusted to account for field and post-harvest losses (CIMMYT, 1988; Karuma *et al.*, 2020). This budgeting approach is known as partial because it only accounts for production costs that differ or change from the farmer's current and proposed methods of production (Soha, 2014; Tigner, 2018; Karuma *et al.*, 2020).

Farm owners and managers can assess the financial implications of gradual adjustments with the use of a partial budget. Only resources that will change are included. The resources that remain constant are not taken into account. Only the proposed change is evaluated for its ability to increase or decrease farm income (Tigner, 2018). When determining the expenses of each treatment, farmers are only concerned with the costs that vary or differ between treatments. Costs that do not differ between treatments (such as ploughing and planting) are incurred regardless of which treatment is used (CIMMYT, 1988). Therefore, it is necessary to carry out a cost-benefit analysis on watering regimes and planting densities in this study to determine the appropriate treatment combinations to recommend to the farmers in this study area.

CHAPTER THREE

EFFECTS OF WATERING REGIMES AND PLANTING DENSITY ON TARO (*COLOCASIA ESCULENTA)* GROWTH COMPONENTS IN EMBU, KENYA

3.1. Abstract

Taro (*Colocasia esculenta* (L.) Schott) is one of the underutilized crops in Sub-Saharan Africa and an important staple food in the tropics. Determining its growth response under selected watering regimes and planting densities underpins this research. A study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre, for three seasons, during the long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022. A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation watering regimes while the sub-factor was the planting density, with three replications. The irrigation watering regimes were at 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5 m × 0.5 m (40,000 plants ha^{-1}), 1 m × 0.5 m (20,000 plants ha^{-1}), and 1 m × 1 m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. The growth components data collected in the field was recorded in data collection sheets and thereafter the data was entered into a Microsoft Excel spreadsheet and later imported to the GenStat statistical software for data analysis. The data was subjected to repeated measures analysis of variance using the GenStat statistical software as the growth components data was observed repeatedly over time (days after planting) across each season. Mean separation was carried out using the least significant difference (LSD) at a 5% level of probability where the ANOVA F-values were significant. The data analysed was pooled across the three seasons. Time and season, and their interaction ($P < 0.001$) significantly influenced taro height and leaf area index. The watering regime did not affect taro growth components. The plant height (60.01 cm) was tallest in the 60% FC and the high planting density (0.5m × 0.5m) (59.51 cm). It is recommended that farmers use the 0.5m × 0.5m planting density and 60% FC watering regime for increased taro growth.

3.2. Introduction

Taro (*Colocasia esculenta* (L.) Schott) is a herbaceous, monocotyledonous, perennial stem root crop widely grown throughout the world's tropical and subtropical areas (FAO, 2010). In Kenya, taro is mainly cultivated by subsistence farmers for its fleshy corms and nutritious leaves (Ngetich *et al.,* 2015). It is referred to as arrowroot or *nduma* and is primarily grown in the riverbeds. However, the riverbeds are already a limited resource due to climate change and during periods of water scarcity (Wambugu and Muthamia, 2009; Akwee *et al.,* 2015; Ngetich *et al.,* 2015). Along the riverbeds farmers do not have specific standards for taro plant density and moisture regimes (Oxfarm, 2021), therefore, this research is aimed to inform farmers of the soil moisture regimes and plant densities they can use for planting taro in order to realize increased growth and yields.

Farmers in Kirinyaga, Embu, and Murang'a Counties in Kenya have adopted moisture beds in the uplands for growing taro, a shift from growing in riverbeds and streams, however, there is no scientifically informed data on taro's growth requirements under the moisture beds in Kenya, therefore this research provides a basis/starting point in terms upscaling the use of moisture beds upland. A moisture bed is constructed by digging a trench and removing 0.3 metres of topsoil, laying a polythene paper on the floor to ensure water is retained in each plot and hence available to the plants, and finally mixing the removed soil with manure and returning it to the bed (Boland, 2005; Muchui, 2015). The moisture beds make drip irrigation applicable within the plant rows (Boland, 2005). Since spacing influences taro growth as a result of competition for soil moisture, nutrients, and light (Boampong *et al.,* 2020) it is therefore important to determine its growth components in terms of planting density under a moisture bed. The use of drip irrigation for taro production provides an alternative to planting taro in the uplands and acts as a way for smallholder farmers to increase harvests (Wainaina, 2021). The objective of this study to determine the growth components response of taro under varying watering regimes and planting densities.

3.3. Materials and Methods

3.3.1. Site Description

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre (Figure 4). Embu County is located between latitude 0^0 8' and 0^0 50' South and longitude 37^0 3' and 37^0 9' East (Kangai *et al.*, 2021). The Research Centre receives 1250 mm of annual rainfall in two rainy seasons (Figure 5), namely, March to May (long rainy season - LR) and October to December (short rainy season - SR). The temperature ranges from 12°C in July to 30°C in March and September, with a mean temperature of 21° C. (Kisaka *et al.*, 2015).

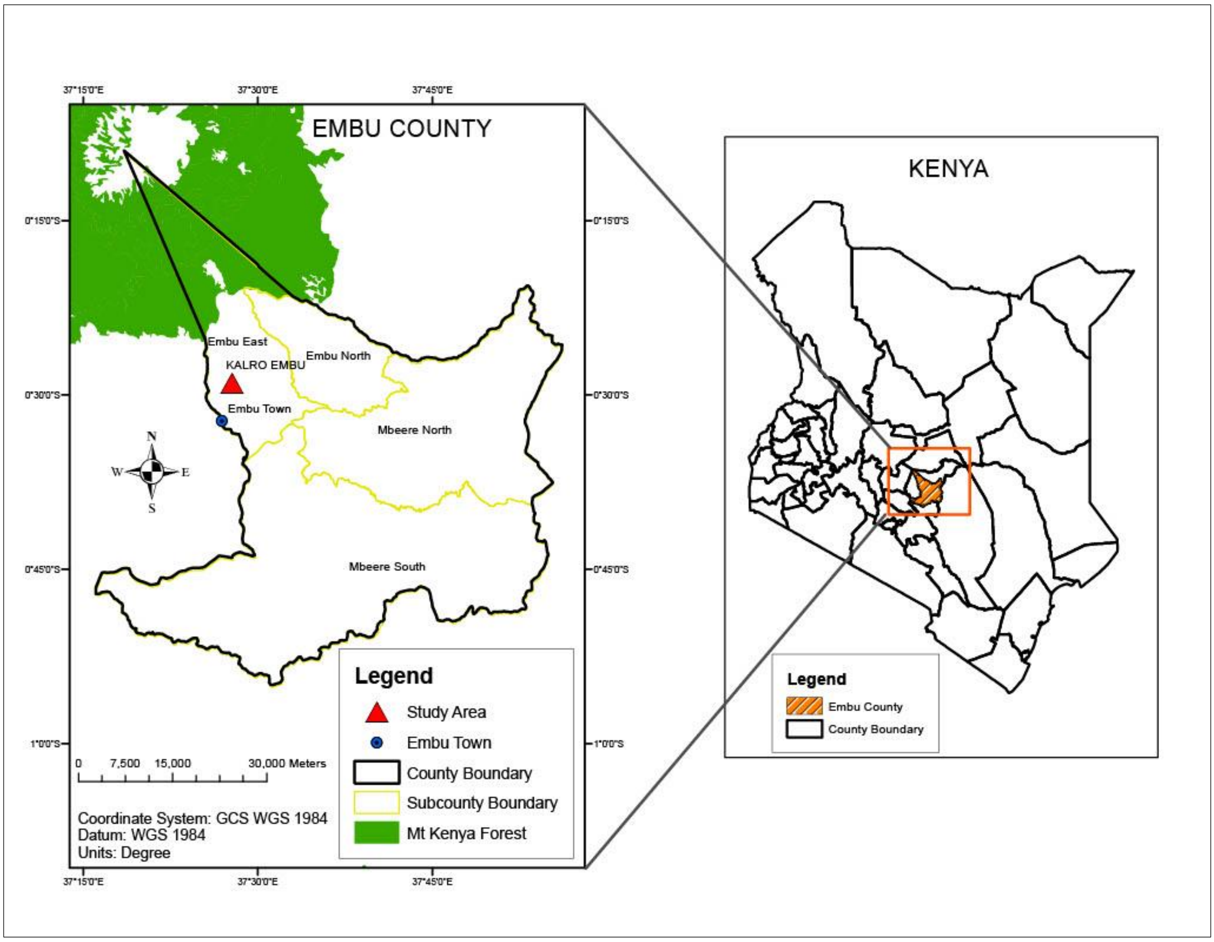

Figure 4: Location of the Study Site, KALRO – Embu, Kenya (Generated from ArcGIS)

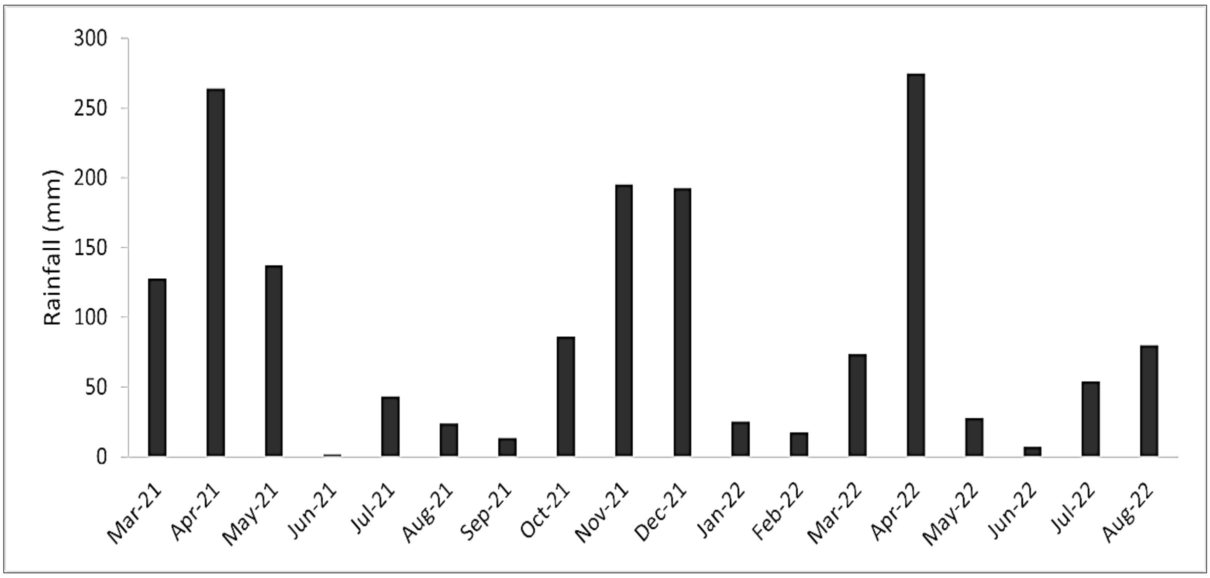

Figure 5: Monthly rainfall averages during three growing seasons - LR 2021 (March to August 2021), SR 2021/2022 (September 2021 to March 2022), and LR 2022 (March to August 2022) of taro (*Colocasia esculenta*) at KALRO, Embu

The soils are well-drained, very deep with strong structure, and predominantly clay in the study area (Embu County Government, 2019). According to the IUSS Working Group WRB, (2015), classification the soils are classified as *Eutric Nitisols*. Table 1 displays the physical and chemical characteristics of the soil. The composite soil samples were analyzed using standard methods as described in Okalebo *et al.* (2002). Total nitrogen is very low (0.09 %), phosphorous is moderate (50.75 mg kg^{-1}) and potassium is high (624 mg kg^{-1}), all of which are important for crop growth (Lebot, 2008; Msanya *et al.,* 2001). The soil has a pH of 5.12, slightly acidic and the ideal pH for the growth of taro (Onwueme, 1999).

Table 1: Baseline physical and chemical soil properties of the experimental site (0 - 30cm) at KALRO Embu

Soil Property	Value	Soil Property	Value
Chemical properties			
pH	5.12	Manganese (mg kg^{-1})	143.50
Organic Carbon (%)	2.10	Physical Properties	
Total Nitrogen (%)	0.09	Bulk Density (g cm^{-3})	1.06
Phosphorous (mg kg^{-1})	50.75	Sand (%)	42.0
Potassium (mg kg^{-1})	624.0	Silt (%)	16.0
Calcium (mg kg^{-1})	700.0	Clay (%)	42.0
Zinc (mg kg^{-1})	51.70	Textural Class	Clay
Sodium (mg kg^{-1})	26.45	Saturated Hydraulic Conductivity (Ksat) (cm hr^{-1})	13.36
Iron (mg kg^{-1})	32.15	Permanent Wilting Point (PWP) (% volume)	16.0
Magnesium (mg kg^{-1})	154.80	Field Capacity (FC) (% volume)	37.8

3.3.2. Experimental Layout

The experiment was carried out for three cropping seasons during the long rains (LR) (March – August 2021), short rains (SR) (September 2021 – March 2022), and long rains (LR) (March – August 2022) i.e., LR 2021, SR 2021/2022, and LR 2022. A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation watering regimes while the sub-factor was the planting density, with three replications. The three irrigation regimes were at 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5m × 0.5m (40,000 plants ha^{-1}), 1m × 0.5m (20,000 plants ha^{-1}), and 1m × 1m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. Time in days after planting (DAP), and season were experimental factors to test the changes within and across the growing seasons.

Table 2: Experimental layout showing the watering regime and planting density treatments

100 - 1m x 1m **(21)**	30 - 0.5m x 0.5m **(22)**	60 -1m x 0.5m **(27)**
100 - 1m x 0.5m **(20)**	30 - 1m x 1m **(23)**	60 - 0.5m x 0.5m **(26)**
100 - 0.5m x 0.5m **(19)**	30 - 1m x 0.5m **(24)**	60 - 1m x 1m **(25)**
60 - 1m x 1m **(18)**	100 - 1m x 0.5m **(13)**	30 - 0.5m x 0.5m **(12)**
60 - 0.5m x 0.5m **(17)**	100 - 1m x 1m **(14)**	30 - 1m x 0.5m **(11)**
60 - 1m x 0.5m **(16)**	100 - 0.5m x 0.5m **(15)**	30 -1m x 1m **(10)**
30 - 0.5m x 0.5m **(3)**	60 - 1m x 0.5m **(4)**	100 - 1m x 0.5m **(9)**
30 - 1mx 0.5m **(2)**	60 - 0.5m x 0.5m **(5)**	100 - 1m x 1m **(8)**
30 - 1m x 1m **(1)**	60 - 1m x 1m **(6)**	100 - 0.5m x 0.5m **(7)**

Key: (x) - Plot no; 30/60/100 – watering regime; planting density – 1 m × 1 m, 1 m × 0.5 m, 0.5 m ×0.5 m

3.3.3. Planting Material

Taro basal stems were sourced from farmers' fields in Kirinyaga County. The planting materials were collected as apical 1-2 cm of the corm with basal 15-20 cm of the petioles attached. Farmers in the region prefer the *Dasheen* variety of taro.

3.3.4. Moisture bed Preparation and Irrigation

Each plot was 4 m × 4 m separated by 2 m wide spacing and dug to a 50 cm depth and lined with a 1000-gauge double-folded black polythene sheet to create a moisture bed. The polythene sheet prevented lateral water movement between plots and seepage. Manure was added to the dug-out soil from each plot in a ratio of 2:1 ratio before being added back to each plot (the moisture bed) with a 10 cm depression. The drip system consisted of a 5000 litres tank, a water filter, a water metre, a ball valve, nine valves, nine T-joins, button drippers, start connectors, PVC pipes, L-bows, drips lines, end lines, and end caps. The tank was raised to 1.5 meters and supplied water to the crop. The system also consisted of a disk filter of one-inch diameter. This filter is effective for water laden with debris, and it does not allow any particles or debris to pass through. Water was then supplied to the crop through a one-inch diameter mainline which was connected to a sub-main line, which was further connected to the drip lines within the plots. Button drippers/emitters on the drip lines supplied water to the individual plants. The end caps were fixed to terminate the water flow. The drip line spacing was dependent on the different plant spacings in each plot. The emitter discharge was 5.6 l/hr.

Crop coefficient (Kc) values for taro are described by Fares, (2008) whereby Kc initial is 1.05 (2 months), Kc mid-season is 1.15 (4 months) and Kc late season is 1.1 (1 month). An average Kc value of 1.2 was used. The reference crop evapotranspiration (ETo) was obtained from Embu's automatic weather station (AWS). Using the values of Kc and ETo, the crop water requirement (ETc) was calculated as described by Allen *et al.* (1998):

$$ETc = ETo \times Kc$$

Where ETc is crop water requirement, ETo is reference evapotranspiration, and Kc is crop factor/coefficient.

3.3.5. Irrigation Scheduling

Irrigation scheduling was determined using the soil moisture depletion technique (AgriInfo, 2018; Dong, 2023). This technique is more site-specific than the climatic parameter technique which is generalized and widely variable. For the first two months of the trial, all treatments were irrigated to field capacity (Table 1) to ensure good taro crop establishment. Thereafter, the watering regime treatments were applied. To ensure water availability during the day's peak demand periods, irrigation was carried out three times every week, during the mornings.

The irrigation schedule was determined as shown below.

$$\text{Irrigation schedule} = \frac{Daily\ Water\ Requirement\ (l/day)}{Emitter\ Discharge\ (l/hr)}$$

When it rained, moisture regimes were imposed only when the maximum allowable depletion (MAD) was below 26.8 % volume, which was determined through soil moisture measurements. The irrigation schedule for the 100 % FC, 60 % FC, and 30 % FC watering regimes were 22 minutes, 13 minutes, and 6 minutes respectively. After 24 hours, skipping a day, the irrigation water was applied. With the use of a water metre, the average total amount of water used for each irrigation regime was 2000 litres (30 % FC), 4000 litres (60 % FC), and 8000 litres (100 % FC).

3.3.6. Soil moisture measurements

A digital handheld moisture sensor meter–HSM50 was used to monitor soil moisture content weekly, two months after the planting when the crop has been established until when the taro reaches the physiological tuber maturity. Moisture readings (percent water by volume) were taken from between and within the crop rows. The meter readings (% v) were converted to mm as follows:

Soil moisture content (mm) = % v × SD

Where: % v is the percent soil water by volume and SD is the rooting soil depth (mm)

3.3.7. Measurements of taro growth components

Canopy characteristics (plant height and leaf area index (LAI)) were determined weekly. Five plants were tagged on each plot for data collection and monitored throughout the growing seasons. Plant height (cm) was measured from the ground up to the base of the plant's second-youngest fully unfolded leaf. The LAI was determined by dividing the total leaf area of a taro plant by the total land area occupied by a single plant.

The vegetative growth index was also measured (Lebot, 2008; Mabhaudhi and Modi, 2015).

$VGI = [\,(\text{Leaf width} \times \text{leaf length}) \times \text{leaf number}) \times H/100] - (\text{suckers} + \text{stolons})^2$ Where: VGI = vegetative growth index and H = plant height

3.3.8. Statistical Analysis

Data was collected on the taro growth components and subjected to repeated measures analysis of variance using the GenStat statistical software. ANOVA with repeated measures was used since the growth components data was observed repeatedly over time (days after planting) across each season. Mean separation was carried out using the least significant difference (LSD) at a 5% level of probability where the ANOVA *F*-values were significant.

3.4. Results

3.4.1. Plant growth as influenced by watering regimes and planting density

3.4.1.1. Taro height

The plant height increased with time within the three growing seasons, with the LR 2021 season having the tallest plants (66.89 cm), compared with the SR 2021/2022 (64.19 cm), and LR 2022 (45.05 cm) seasons (Table 3). The planting density influenced the plant height over time within a growing season ($P < 0.001$). The watering regime did not affect the plant height in the three seasons (Table 3). The three-season mean values indicate that the 60 % FC (60.01 cm) and 0.5 m × 0.5 m planting density (59.51 cm) attained the tallest plants while 30 % FC (59.33 cm) and 1m × 0.5 m planting density (57.56 cm) had the lowest.

3.4.1.2. Taro leaf area index (LAI)

The LAI increased on the different days after planting within and across the growing season at the different planting densities (Table 3). The growing seasons influenced the LAI ($P < 0.001$) with the LR 2021 season attaining the largest LAI (0.241) and the LR 2022 season the lowest (0.116) (Table 3). The watering regime did not affect the leaf area index (Table 3). The LAI was highest in the 30 % FC (0.194) and 0.5 m × 0.5 m (0.294). A 3-season mean shows the watering regime trend of 30 % FC > 100 % FC > 60 % FC and a planting density trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m was observed for leaf area index.

3.4.1.3. Vegetative Growth Index (VGI)

In the first season (LR 2021), the suckers and stolons did not appear in the tagged plants but, in the other plants hence VGI could not be determined. In the SR 2021/2022 and LR 2022 seasons, where VGI was recorded, there was an increase in the VGI with time in the seasons ($P < 0.001$) and was influenced by the watering regime at the different time intervals *($P < 0.001$)*. The watering regime was not significant ($P = 0.748$) (Table 3). The 60 % FC watering regime and the 1 m × 1 m planting density had the highest VGI values with 2172 and 2195, respectively.

Table 3: Plant height, leaf area index (LAI), and vegetative growth index (VGI) as influenced by the watering regimes and planting densities in Embu, Kenya.

	Plant Height (cm)	Leaf Area Index (LAI)	Vegetative Growth Index (VGI)
Season			
LR 2021	66.89	0.241	-
SR 2021/2022	64.19	0.192	2772
LR 2022	45.05	0.116	1177
Watering Regime			
100 % FC	56.79	0.181	1814
60 % FC	60.01	0.173	2172
30 % FC	59.33	0.194	1938
Planting Density			
1m × 1m	59.05	0.091	2195
1m × 0.5m	57.56	0.162	1831
0.5m × 0.5m	59.51	0.294	1899
Significant Levels			
Season	< 0.001	< 0.001	< 0.001
Time	< 0.001	< 0.001	< 0.001
WR	0.443	0.358	0.748
PD	0.743	< 0.001	0.719
WR × PD	0.171	0.131	0.516
Season × WR	0.897	0.821	0.719
Season × PD	0.607	0.095	0.824
Season × WR × PD	0.522	0.232	0.486
Time × Season	< 0.001	< 0.001	< 0.001
Time × WR	0.737	0.932	< 0.001
Time × PD	< 0.001	< 0.001	0.956
Time × WR × PD	0.224	0.320	0.590
Time × Season × WR	0.891	0.592	0.827
Time × Season × PD	0.781	0.005	0.804
Time × Season × WR × PD	0.174	0.006	0.171

Where, FC = Field Capacity, PD = Planting Density, WR = Watering Regime.

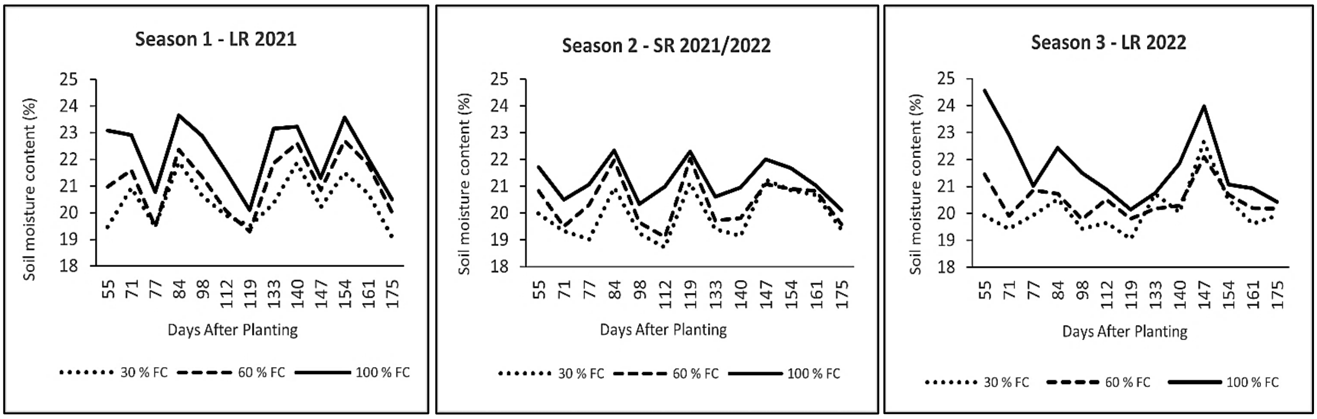

Figure 6: Soil moisture content (%) across the three seasons - LR 2021 (March to August 2021), SR 2021/2022 (September 2021 to March 2022), and LR 2022 (March to August 2022) of taro (*Colocasia esculenta*) at KALRO, Embu

3.5. Discussion

3.5.1. Taro height

The lower plant height observed under 100 % FC (59.79 cm) showed excess water conditions did not favour taro plant height. High soil moisture content was recorded across the three seasons (Figure 6) for the 100 % FC watering regime. The clay soils may explain the low plant height observed under waterlogged conditions. Clay soils are subject to compaction during moist and wet conditions and infiltration is impeded reducing water availability to the root zone (FAO, 2015a). Soil compaction has been reported to affect plant emergence and development, particularly reducing plant height (Wolkowoski and Loweri, 2008). Soils with a clay texture are most susceptible to compaction because their particles hold more water longer than sandy or loamy soils. The degree of compaction in nitisols, like those in the study site, is measured through determination of bulk density, and has been found to be high due to human and wheel traffic during cultivation (Mahdi, 2007). When soil moisture exceeds field capacity there is a potential for soil compaction, particularly at topsoil depths due to reduction in soil porosity (Viciedo *et al.,* 2018). Therefore, the type of the soil in the study area coupled with irrigation to field capacity (100 % FC) lowered the taro growth components due to compaction of the soil. Lower plant height under limited water conditions was also observed by studies in South Africa and Brazil working with sandy clay loam soil (Mabhaudhi, 2012; Li *et al.,* 2019).

Since taro develops laterally by creating new shoots, planting density did not affect the height of the plants. The highest planting density (0.5m × 0.5m) (40, 000 plants ha^{-1}) had the tallest plants, while the 1 m × 1 m planting density had the lowest plant height. These results corroborate with other studies in Ghana, where it was observed on well-drained silty loam soils, that taro spaced at a higher spacing of 1m × 1m attained lower plant height at the peak of vegetative growth as opposed to plants spaced at a closer spacing (Boampong *et al.,* 2020). The plant height of taro increased as planting density increased, and this was attributed to an increase in linear growth due to higher plant density per unit area in a study in Southern Ethiopia (Dessa *et al.*, 2018). Tall taro plants have longer petioles, and this is significant in areas where the petioles are consumed. Taro leaf stems (petioles) are eaten in many places, particularly in Asian countries, and are high in calcium and fibre while being low in calories (Rao *et al.,* 2010).

3.5.2. Taro leaf area index (LAI)

Limited water availability (30 % FC) favoured LAI while excess water availability (100 % FC) lowered the LAI. This was consistent with lower plant height observed under 100 % FC. The leaf area index reduced by 11 % and 7 % at 60 % FC and 100 % FC, respectively, compared with that 30 % FC. This may be attributed to clay soils having smaller pores and higher water retention under lower water availability, unlike sandy soils whose water retention is lower because of their large pores (Rout and Arulmozhiselvan, 2019). These findings contrast those Mabhaudhi *et al*. (2013) in South Africa who found a 5 % and 12 % reduction in LAI at 30 % FC and 60 % FC, respectively, compared with that of 100 % FC.

The highest LAI was recorded from the highest planting density of 0.5 m × 0.5 m (40,000 ha^{-1}) and this can be ascribed to the high leaf number contribution from many plants per unit area. Maximum LAI has also been observed in high plant density in Ethiopia (Tsedalu *et al.,* 2014) and in wetland-grown taro plant populations in Uganda (Tumuhimbise *et al.*, 2009). Taro leaves are consumed as leafy vegetables in various parts of the world and are a rich source of protein, dietary fibre, and nutrients including minerals and vitamins. Additionally, the leaves are dried and milled into powder and used as flour, which is a healthy alternative to wheat flour notably due to its lack of gluten (Dhanraj *et al.,* 2013; Arıcı *et al.,* 2021). Therefore, to produce taro plants with the largest size of leaves, farmers must plant at 30 % FC and higher spacing or lower densities.

3.5.3. Vegetative Growth Index (VGI)

The VGI was low under 100 % FC, in the two seasons (SR 2021/2022 and LR 2022) where it was recorded. The reduction in VGI is attributed to low and lack of sucker and stolon formation throughout the growing seasons. The plant height, leaf area, suckers and stolons, highly affected the VGI, and high values of VGI were observed where these parameters were highest. The tallest plants were in the 60 % FC which had the highest VGI (2172), this means that tall plants produced more suckers and stolons due to the higher VGI values (Soulard *et al.,* 2016). The 1 m × 1 m planting density (2195) had the highest VGI, and the 1 m × 0.5 m planting density (1831) had the lowest. This can be attributed to the fact that the number of suckers per plant increases as the plant spacing increases. The increase in the number of suckers with lower planting densities may be due to the availability of more nutrients, moisture, and low competition for light (Boampong *et al.,* 2020).

The VGI is a unique specific index in taro plants that considers all the aspects of taro morphology which includes plant height, number of leaves, leaf area, and also the number of suckers and stolons (Lebot, 2008; Mabhaudhi, 2012). Soulard *et al.* (2016) in Vanuatu, South Pacific found similar results to this study where tall taro plants produced more and bigger leaves, and more suckers and hence high VGI values. In contrast, smaller plants, in terms of height and number of leaves, had low VGI values and produced a low number of suckers.

3.6. Conclusion

The 0.5 m × 0.5 m planting density (40,000 plants ha^{-1}) produced the highest plant height, and leaf area index, while the low planting density, 1 m × 1 m (10,000 plants ha^{-1}) had the highest VGI. The 60 % FC watering regime produced the tallest plants and highest VGI, across the three seasons, while the 30 % FC had the highest leaf area index. Therefore, a high planting density of 0.5m × 0.5m, and a 60 % FC watering regime is recommended to farmers for increased vegetative growth.

CHAPTER FOUR

THE INFLUENCE OF WATERING REGIMES AND PLANTING DENSITY ON UPLAND TARO (*COLOCASIA ESCULENTA* (L.) SCHOTT) YIELD AND YIELD COMPONENTS IN EMBU, KENYA

4.1. Abstract

Taro (*Colocasia esculenta* (L.) Schott) is one of the underutilized crops in Sub-Saharan Africa and an important staple food in the tropics. Understanding its growth response under selected watering regimes and planting densities is the basis of this research. A study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre, during the long rains (LR) 2021, short rains (SR) 2021/2022), and long rains (LR 2022). A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation watering regimes while the sub-factor was the planting density, with three replications. The three irrigation watering regimes were 100 %, 60 %, and 30 % based on the field capacities (FC). The planting densities used were 0.5m × 0.5m (40,000 plants ha^{-1}), 1m × 0.5m (20,000 plants ha^{-1}), and 1m × 1m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. The yield and yield components data collected in the field was recorded in data collection sheets and thereafter the data was entered into a Microsoft excel spreadsheet and later imported to the GenStat statistical software for data analysis. The data was subjected to split-plot analysis of variance using the GenStat statistical software. Mean separation was done using the Fisher's least significant difference (LSD) at a 5% level of probability where the ANOVA *F*-values were significant. Correlation analysis was done using the GenStat statistical software to determine the yield components that strongly influenced the corm yield. Season significantly ($P < 0.001$) influenced the yield and yield components. Corm mass (0.57 kg) and yield (12.76 t/ha) were all highest in the 60 % FC. The 1 m × 1 m spacing produced the highest corm length (11.09 cm), corm diameter (9.36 cm) and corm mass (0.56 kg). The high planting density (0.5 m × 0.5 m) resulted in the highest total biomass (63.53 t/ha), yield (20.14 t/ha), and harvest index (32.64 %). As a result, the 0.5 m × 0.5 m planting density and 60 % FC watering regime is recommended to farmers in the area for increased yields, and food security.

4.2. Introduction

Taro (*Colocasia esculenta* (L.) Schott) is a herbaceous, monocotyledonous, perennial stem root crop widely grown throughout the world's tropical and subtropical areas (FAO, 2010). However, it is one of the underutilized crops in Sub-Saharan Africa (Palapala and Akwee, 2016), grown for its fleshy corms and nutritious leaves. In comparison to Africa (5.9 tons ha^{-1}) and the rest of the world (6.6 tons ha^{-1}) (Palapala and Akwee, 2016), taro annual yields in East Africa rarely exceed one ton ha^{-1} (Serem *et al.*, 2008). Taro has a wide range of economic value and applications, particularly in areas where it is commonly consumed. Because of the edible stem and corm, which may be utilized in a variety of food dishes, this crop offers high dietary value and diverse culinary applications (Dhanraj *et al.*, 2013).

Paddy field areas are mostly used to cultivate taro in locations where water is abundant or in upland settings where rainfall or supplemented irrigation water is used for irrigation (Sharma *et al.*, 2020). Taro acts as a buffer crop during the shortage of other staple foods. In Kenya, it is referred to as arrowroot or *nduma* and is primarily grown in the riverbeds. However, the riverbeds are already a limited resource in the face of climate change and especially during water scarcity (Wambugu and Muthamia, 2009; Akwee *et al.*, 2015; Ngetich *et al.*, 2015). Therefore, the crop has the potential to reduce food insecurity, and it can also be promoted to contribute to food diversity and improve livelihoods. However, little attention has been given to its production in Kenya. Plant population, plant spacing, planting materials, and moisture requirements are among the elements of Kenyan taro that have not been extensively studied. The challenges described above in Kenya's taro sector can be addressed and, if possible, solved through research.

Farmers in Kirinyaga, Embu, and Murang’a Counties in Kenya have adopted moisture beds in the uplands for taro growing, a shift from growing in riverbeds and streams. A moisture bed is constructed by digging a trench and removing 0.3 metres of topsoil, laying a polythene paper on the floor to ensure water is retained in each plot and hence available to the plants, and finally mixing the removed soil with manure and returning it to the bed (Boland, 2005; Muchui, 2015). The moisture beds make drip irrigation applicable within the plant rows (Boland, 2005). Since taro plant spacing influences taro corm shape and yield as a result of competition for soil moisture, nutrients, and light (Boampong *et al.*, 2020), it is, therefore, imperative to know the implications on taro growth in terms of planting density under a moisture bed. The use of drip irrigation for taro production provides an alternative to planting taro in the uplands as opposed to traditionally along rivers and streams and acts as a way for smallholder farmers to improve yields (Wainaina, 2021).

A study by Boampong *et al.* (2020) found that plant spacing was an important factor in influencing taro's overall production. Individual taro plant corm yield (corm mass) increased as spacing increased however total taro corm production per unit area increased as spacing decreased. Other crops have seen similar increases in production with decreased plant spacing (Ogbonna and Obi, 2000). However, a study by Abd- Ellatif *et al.* (2010) found that increasing the distance between taro plants significantly boosted the plant yield, and a study by (Osundare, 2006) noted that average corm mass decreased with a decrease in plant spacing. Many taro production techniques in Kenya still rely on the traditional production methods, mainly cultivating taro along riverbeds with no standard plant densities, necessitating research into various agronomic strategies in order to improve taro production in Kenya. The objective of this study was to investigate upland taro yield, and yield components to varying watering regimes and planting densities.

4.3. Materials and Methods

The study site description, experimental layout, planting material, moisture bed preparation and irrigation, soil moisture determination, and irrigation scheduling are outlined in chapter 3; sections 3.3.1., 3.3.2., 3.3.3., 3.3.4., 3.3.5., and 3.3.6. respectively.

4.3.1. Yield and yield components measurements

Yield and yield components (total biomass, corm mass per plant, corm length, and corm diameter) were measured at harvest (180 days after planting) after each season. Biomass was determined by weighing the shoots together with roots which are corms in taro, and corm mass was determined by weighing the corms only. Corm length is the distance from the tip of the corm to a point where the outer leaf petiole is attached to the corm. The diameter of the cross-section of the corm at the point where the outer leaf petiole is attached to the corm was taken as the corm diameter. The corm yield was calculated based on the mean experimental plot area and later adjusted to metric tonnes per hectare (tonnes ha^{-1}). The harvest index (HI) is the proportion of corm yield [Y] to the total biomass [B] and was determined as follows:

$$HI = \frac{Corm\ Yield\ [Y](\frac{t}{ha})}{Total\ Biomass\ [B]\ (\frac{t}{ha})}$$

4.3.2. Statistical Analysis

Taro yield and yield components data collected were subjected to analysis of variance using the GenStat statistical software. Mean separation was done using Fisher's least significant difference (LSD) at a 5% level of probability where the ANOVA *F*-values were significant. Correlation analysis was done using the GenStat statistical software to determine the yield components that strongly influenced the corm yield.

4.4. Results

4.4.1. Taro yield components as influenced by the growing seasons

The corm length, diameter, mass, total biomass, yield, and harvest index (HI) were influenced by the seasons ($P < 0.001$) (Table 4). The LR 2021 season (12.57 cm) had the highest corm length compared to the SR 2021/2022 (10.75 cm) and LR 2022 (8.62 cm) seasons. Total biomass was also highest in the LR 2021 season (53.2 t ha^{-1}) than in the SR 2021/2022 (42.6 t ha^{-1}) and LR 2022 (29 t ha^{-1}).

4.4.2. Taro yield components as influenced by the watering regimes

The watering regime did not influence any of the taro yield and yield components in the 3 seasons (Table 4). However, the 60 % FC watering regime had the highest corm mass (0.57 kg) and the lowest (0.51 kg) noted under the 100 % FC. The 60 % FC attained the highest corm yield (12.76 t/ha), compared to the other watering regimes that had < 12.1 t/ha, though not significant. Additionally, the corm length was significantly ($P = 0.028$) influenced by the watering regime and planting density and there was also a significant interaction between the growing season and planting density ($P = 0.043$).

4.4.3. Taro yield components as influenced by the planting densities

Planting density significantly ($P = 0.030$) influenced the corm length, corm diameter ($P = 0.019$), total biomass ($P < 0.001$), and corm yield ($P < 0.001$) but not the corm mass and harvest index (Table 4). Notably, the planting density influenced the corm yield within the growing seasons ($P = 0.002$). The 1 m × 1 m planting density attained the highest corm length (11.09 cm) and mass (0.56 kg) with a 3-season average trend of 1 m × 1 m (10,000 plants ha^{-1}) > 1 m

× 0.5 m (20,000 plants ha^{-1}) > 0.5 m × 0.5 m (40,000 plants ha^{-1}). On average, the 0.5 m × 0.5 m (40,000 plants ha^{-1}) had the highest biomass (63.53 t ha^{-1}), corm yield (20.14 t ha^{-1}), and harvest index (32.64 %) (Table 4).

Table 4: Taro yield and yield components (corm length, corm diameter, corm mass, total biomass, and harvest index) as affected by the season, watering regime, and planting density in Embu, Kenya

	Corm Length (cm)	Corm Diameter (cm)	Corm Mass (kg)	Total Biomass (t ha $^{-1}$)	Corm Yield (t ha $^{-1}$)	Harvest Index (%)
Season						
LR 2021	12.57^{c}	10.20^{c}	0.37^{a}	53.20^{c}	7.76^{a}	13.92^{a}
SR 2021/2022	10.75^{b}	8.94^{b}	0.79^{b}	42.64^{b}	18.29^{b}	43.74^{c}
LR 2022	8.62^{a}	7.76^{a}	0.46^{a}	29.00^{a}	10.59^{a}	35.40^{b}
Watering Regime						
100 % FC	10.57	8.75	0.51	40.56	12.09	33.10
60 % FC	10.79	9.14	0.57	40.96	12.76	31.63
30 % FC	10.58	9.02	0.53	43.33	11.79	28.33
Planting Density						
1m * 1m	11.09^{b}	9.36^{b}	0.56	22.61^{a}	5.56^{a}	29.19
1m * 0.5m	10.66^{ab}	8.89^{ab}	0.55	38.71^{b}	10.95^{b}	31.22
0.5m * 0.5m	10.20^{a}	8.65^{a}	0.50	63.53^{c}	20.14^{c}	32.64
Significant Levels						
Season	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
WR	0.973	0.835	0.863	0.935	0.929	0.116
PD	0.030	0.019	0.383	< 0.001	< 0.001	0.162
WR×PD	0.028	0.055	0.103	0.065	0.396	0.407
Season × WR	0.984	0.478	0.847	0.482	0.643	0.317
Season × PD	0.043	0.068	0.572	0.668	0.002	0.999
Season × WR × PD	0.428	0.289	0.600	0.298	0.337	0.246

Where, FC = Field Capacity, PD = Planting Density, WR = Watering Regime, Different letters within columns indicate significant differences at a 5 % probability level

4.4.4. Correlation analysis of the yield components

The correlation analysis of the yield components is represented in Table 5. The results shows that the corm yield had strong positive and significant correlations (*$P < 0.001$*) with corm mass (r = 0.6282), total biomass (r = 0.6683), and harvest index (r = 0.4921), and no significant correlations with corm length (r = 0.1202) and diameter (r = 0.1442). The harvest index had significantly (*$P < 0.001$*) negative correlations with the corm diameter (r = -0.3735) and corm length (r = -0.3500) and a nonsignificant negative correlation with the total biomass (r = -0.1904), indicating that high values of harvest index were linked to low values of these parameters. The strongest positive correlation of corm mass, harvest index, and total biomass with the yield, shows their strong influence on the determination of the corm yield.

Table 5: Correlation matrix of taro yield components (corm length, corm diameter, corm mass, corm yield, total biomass, and harvest index) based on LR 2021, SR 2021/2022, and LR 2022 seasonal averages.

	CL	CD	CM	TB	CY	HI
CL	-					
CD	0.8440**	-				
CM	0.3505*	0.4186**	-			
TB	0.4421**	0.4858**	0.2412*	-		
CY	0.1202	0.1442	0.6282**	0.6683**	-	
HI	-0.3500*	-0.3735**	0.5513**	-0.1904	0.4921**	-

Where CL = Corm Length, CD = Corm Diameter, CM = Corm Mass, TB = Total Biomass, CY = Corm Yield, HI = Harvest Index. * = *$P < 0.05$*, ** = *$P < 0.001$*

4.5. Discussion

The high values in corm length, diameter, and total biomass in the LR 2021 season can be attributed to the higher average rainfall received in the long rains (LR) 2021 season (99.9 mm) than the short rains (SR) 2021/2022 (88.3 mm), and LR 2022 (86.5 mm) (Figure 5). This was paired with high soil moisture content recorded in the season (Figure 6). The corm length, corm diameter, and corm mass exhibited a similar trend based on planting density with the highest planting density, 0.5 m × 0.5 m (40000 ha $^{-1}$) having lower values. This was attributed to the higher competition for light, moisture, and nutrients at closer spacing. The 100 % FC had the lowest corm diameter, this means that high water availability affected corm diameter by reducing its size. Li *et al.,* (2019) in Brazil however found contradictory results that corm diameter increased with an increase in water availability. Saturated conditions (100 % FC) also attained the lowest corm length, mass and total biomass signifying that high moisture availability reduced these parameters. Mabhaudhi, (2012) in South Africa found contradictory results where the total biomass was highest under the 100 % FC watering regime.

Though not significant, the 60 % FC watering regime attained the highest corm mass (0.57 kg). The low spacing of 0.5 m × 0.5 m (40,000 plants ha^{-1}) attained the lowest corm mass and this is attributed to higher competition due to higher plants per unit area for below-ground resources such as moisture, nutrients, and solar radiation. Sibiya, (2015) working in South Africa found similar results. Shelembe, (2020), in South Africa, however, found that the 30 % FC watering regime attained the lowest corm mass with the Eddoe taro variety. The 0.5 m × 0.5 m (40,000 plants ha^{-1}) planting density had the highest total biomass, and this can be attributed to more plants per unit area at lower plant spacing.

The corm yield was higher in the SR 2021/2022 season which was characterized by lower rainfall than the LR 2021 and LR 2022 season (Figure 5). This means that on a seasonal basis, lower rainfall amounts, and hence lower moisture availability favoured corm yield. The 60 % FC watering regime produced the highest corm yield similar to the corm mass. The 0.5 m × 0.5 m (40,000 plants ha^{-1}) planting density had the highest yield (20.14 t/ha), and 1 m × 1 m (10,000 plants ha^{-1}) had the lowest yield (5.56 t/ha). It is further notable that the yields observed in this study were equal to or greater than the East African, the African, and the world average of ≤ 1 t ha^{-1}, 5.6 t ha^{-1}, and 6.6 t ha^{-1} respectively (Serem *et al.,* 2008; Palapala and Akwee, 2016). With closer spacing, there are more plants per area, promoting photosynthesis and ensuring sufficient ground cover (Scheffer *et al.,* 2005; Tumuhimbise *et al.,* 2009; Youssef, 2010; Boampong *et al.,* 2020). In taro, the total yield is determined by the number of corms produced per unit area rather than the size of each corm or mass of corms. Due to the high number of taro plants per unit area, higher planting densities produce more corms, which in turn leads to better yields. Abd- Ellatif *et al.* (2010) in Egypt found that increasing the distance between taro plants from 20 cm to 50 cm significantly boosted the plant yield.

The harvest index was influenced by the season with the SR 2021/2022 season having a higher value (43.74 %) than the LR 2021 season (13.92 %) and LR 2022 season (35.40 %). This was due to the lower biomass and higher yield obtained in the seasons. The low biomass and higher yield obtained mean that there was more corm growth as opposed to vegetative growth in the seasons. A negative effect on moisture stress was noted under water-limited conditions (30 % FC) with a positive effect noted in the high moisture availability (100 % FC) where the harvest index was highest. The higher harvest index under conditions of high-water availability illustrates taro's capacity to convert biomass to economic yield more efficiently than in those of low water availability. These findings contradict those by Mabhaudhi, (2012) in South Africa working with *Dasheen* and *Eddoe* varieties, who found the harvest index to be higher in conditions of limited water availability. Taro plants with a high harvest index had the highest corm yield similar to studies by Lu *et al.* (2001) and Shelembe, (2020) in Taiwan and South Africa, respectively.

The results of the correlation analysis suggested that there was no significant link between the corm yield and corm diameter and length, but there was a positive and significant correlation between the corm yield and the total biomass, harvest index, and corm mass. This means higher yields were associated with higher values of corm mass, total biomass, and harvest index. Eze and Nwofia, (2016) in Nigeria reported that corm mass had a positive effect on taro yield, implying that larger corm sizes resulted in higher yields. Boampong *et al.* (2020) in Ghana on the contrary found that corm yield had a significant correlation with corm length and diameter. Positive and significant effects of the corm mass, total biomass, and harvest index show their importance in the determination of yield and indicates that an increase in these components will increase the taro yields.

4.6. Conclusion

Planting density significantly affected the corm length, diameter, total biomass, and corm yield. The yield and its components were not significantly affected by the watering regime. The long rains 2021 season received higher rainfall and favoured higher values of corm length, corm diameter, and total biomass, but lower values for corm mass, corm yield, and harvest index. Limited water conditions (30 % FC) produced the highest total biomass, while intermediate conditions (60 % FC) had the highest corm length, diameter, corm mass, and corm yield. Based on the results from this study, planting at a high density of 0.5m × 0.5m (40,000 plants ha^{-1}) produced the highest harvest index, total biomass, and corm yield per hectare. Therefore, the highest planting density of 0.5 m × 0.5 m (40,000 plants ha^{-1}) and a 60 % FC watering regime is recommended to farmers in the area for increased yields and increasing food security.

CHAPTER FIVE

WATER USE EFFICIENCY OF TARO (*COLOCASIA ESCULENTA*) UNDER VARYING WATERING REGIMES AND PLANTING DENSITIES IN EMBU, KENYA

5.1. Abstract

Taro (*Colocasia esculenta*) can be grown in a variety of environmental and edaphic conditions, but it is most typically grown in wetlands. The optimal conditions for its growth are two water regimes i.e., waterlogged or flooded conditions to dryland or unflooded conditions. An important criterion in crop yield is water use efficiency (WUE), and it has been suggested that crop production per unit of water used can be increased. A study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre, during the long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022. A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation watering regimes while the sub-factor was the planting density, with three replications. The three irrigation watering regimes were at 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5 m × 0.5 m (40,000 plants ha^{-1}), 1 m × 0.5 m (20,000 plants ha^{-1}), and 1 m × 1 m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. The biomass (kg) was determined by weighing the shoots together with roots which are corms in taro. The biomass in terms of unit area (kg/ha) was then calculated based on the mean experimental plot area and later adjusted to metric tonnes per hectare (tonnes ha^{-1}). The water use was determined through the soil water balance method. The water use efficiency was later determined by dividing biomass (kg/ha) with the water use (mm). Yield, water use, and water use efficiency data collected were subjected to split - plot analysis of variance using the GenStat statistical software. Mean separation was done using the Fisher's least significant difference (LSD) at a 5 % level of probability where the ANOVA *F*-values were significant. The WUE was influenced by season and watering regime ($P < 0.05$). The 30 % FC had the highest WUE with the 100 % FC having the lowest. The high WUE under 30 % FC (19.40 kg $ha^{-1}mm^{-1}$) was associated with the high biomass (1.97 kg) and low water use (2269.41 mm) recorded under limited water conditions.

The intermediate (1 m × 0.5 m) planting density attained the highest WUE (12.16 kg $ha^{-1}mm^{-1}$) with the high planting density (0.5 m × 0.5 m) having the lowest (10.65 kg $ha^{-1}mm^{-1}$), though no significant differences were recorded. Planting at an intermediate density and low watering regime, produced the highest WUE. Therefore, to achieve the highest yield per unit of water consumed, a watering regime of 30 % FC and a planting density of 1 m × 0.5 m (20,000 plants ha^{-1}) is recommended.

5.2. Introduction

One of Kenya's underutilized crops is taro (*Colocasia esculenta*), which is primarily cultivated by women subsistence farmers for its fleshy corms and nutritious leaves. Taro also serves as a buffer crop when other staple foods are in low supply (Ngetich *et al.*, 2015). It is mainly grown in riverbeds and is referred to as arrowroot or *nduma*. The riverbeds, however, are already a finite resource due to climate change, particularly during periods of water scarcity (Wambugu and Muthamia, 2009; Akwee *et al.,* 2015; Ngetich *et al.,* 2015). Farmers in the country utilize traditional taro farming systems that involve cultivation along riverbeds with no scientific data on the appropriate plant spacing and moisture requirements. This study therefore aims to provide information on cultivating taro upland in moisture beds coupled with drip irrigation as a supplemental water source. Taro can be cultivated on moisture beds that are lined with a polyethylene sheet in upland farming to prevent water loss through its percolation into the soil (Oxfarm, 2021). Water must be consistently available throughout the growing season to prevent water stress, which can lead to the development of poor-quality, malformed corms (Sibiya, 2015; Ansah, 2016).

There is little data on using supplemental irrigation to increase taro productivity per amount of land being cultivated. The agronomy of taro and its contribution to food security and sustainability are also little understood. To define water use and its limits under field conditions and to understand how taro responds to water shortages, precise water applications are crucial (Odubanjo *et al.,* 2011). To improve crop growth under irrigation, it is essential to figure out how much water to use and when to irrigate to obtain the best water use efficiency (Kang'au *et al.,* 2011). As a result, efficient irrigation will aid in enhancing and maintaining crop productivity while preserving water and soil nutrients (Olamide *et al.,* 2022).

When used over a time scale of days, development stages, or growth seasons, water use efficiency (WUE) is described as the kilograms of biomass generated per applied cubic meter of water (de Pascale *et al.,* 2011). The WUE takes into account the quantity of plant yields per unit volume of water consumed across a given land area as well as the quantity of plant yields per unit of water lost through evapotranspiration during growth (Koech *et al.*, 2015). WUE has been used to suggest that rainfed crop production per unit of water consumed can be increased because it is a key factor in determining crop yield under stress (Blum, 2009). Agriculture should prioritize improving water use efficiency, shifting the emphasis from increasing production per unit of land area to increasing productivity per unit of water consumed. Water must be conserved, and crop growth must be maximized, to maximize WUE (de Pascale *et al.,* 2011).

Kenya has experienced severe water shortages for many years, primarily as a result of years of repeated droughts, poor water supply management, and pollution of scarce water resources (Marshall, 2011). Moreover, Kenya is one of the world's water-scarce nations, which has led to a decline in crop productivity over time (Mulwa *et al.*, 2021). By supplying the needed water resources directly to the plant, drip irrigation reduces water demand and decreases water evaporation losses during times of drought and water scarcity (UNEP, 2013). This has a favourable impact on WUE in irrigated crop areas, demonstrating the need to increase the WUE in the management of irrigation water (Hatfield and Dold, 2019). Additionally, the irrigation efficiency is as high as 95 % under drip while it is 30-50 % under surface irrigation, making drip irrigation an effective strategy for increased irrigation and water use efficiency (Ngigi, 2009; Khan *et al.*, 2019). Early in the growing season, the adoption of a micro-irrigation system reduces soil water evaporation from between plant rows and limits almost all canopy evaporation. These changes demonstrate that WUE can be changed through system water management by improving WUE in irrigated crop areas (Hatfield and Dold, 2019).

Several methods can help decide when to irrigate or the irrigation schedule. The soil moisture depletion approach is most relevant to this study as it involves the determination of the amount of moisture present in the root zone (AgriInfo, 2018). Soil moisture sensors are useful in the determination of soil moisture as the measurements are in real-time (Subir *et al.,* 2011). It is crucial to periodically measure soil moisture where irrigation is used to know the soil moisture status and determine how much water to apply. Water management has become crucial with the evolution of irrigation-based farming, emphasizing the requirement to evaluate soil water content and plants' consumption of water (Onoja *et al.*, 2014). Using water use efficiency in irrigation planning and decision-making will facilitate efficient water management that will improve yields (Vieira *et al.*, 2018). As such, it is crucial to understand the WUE of taro in Kenya's sub-humid environment under different watering regimes and planting densities.

5.3. Materials and Methods

5.3.1. Study Site Description

The site description, experimental layout, planting material, moisture bed preparation and irrigation, irrigation scheduling, and soil moisture determination are outlined in Chapter 3; sections 3.3.1., 3.3.2., 3.3.3., 3.3.4., 3.3.5., and 3.3.6. respectively.

For use in watering taro, the irrigation water's quality was evaluated (Table 6). The irrigation water was analyzed for pH, electrical conductivity (EC), chlorides, sulphates, fluorides, sodium (Na^+), magnesium (Mg^{2+}) and potassium (K^+), calcium (Ca^{2+}), and alkalinity (Katerji *et al.*, 2003). The quality of the irrigation water meets the standards for irrigation water (FAO, 1994; Republic of Kenya, 2006).

Table 6: Irrigation water chemical analysis in the experimental site at KALRO Embu

Parameter	**Value**	**Parameter**	**Value**
pH	6.8	Chlorides (Mgl^{-1})	30.96
EC (uS/cm)	400	Sulphates (Mgl^{-1})	6.15
Potassium (Mgl^{-1})	4.52	Magnesium (Mgl^{-1})	2.3
Sodium (Mgl^{-1})	14.7	Fluoride (Mgl^{-1})	0.40
Calcium (Mgl^{-1})	0.89	Alkalinity (Mgl^{-1})	13

5.3.2. Christiansen's Coefficient of Uniformity

The coefficient of uniformity (CU) is described as the ratio of the absolute difference of each value from the mean and the mean of means (Christiansen, 1942). The Christiansen's Coefficient of Uniformity (CU) can be expressed as shown below.

$$CU = 100\left(1 - \frac{\sum_{i=1}^{n}|xi - \mu|}{\sum_{i=1}^{n} xi}\right)$$

Where, n – Number of the depth measurements of the water applied, representing an equal irrigated area. Xi – measured application depth in litres (L). µ – mean application depths in litres (L). CU – coefficient of uniformity (%).

This test was conducted to determine the efficiency of the drip irrigation system. Using graduated beakers, the system was opened, and water samples were collected for 90 seconds, and thereafter the uniformity was determined to be 89 %, indicating a high efficiency in water application (Veeranna *et al.,* 2017; Darimani *et al.,* 2021).

5.3.3. Taro biomass measurements

Six months after planting, the biomass (kg) was determined by weighing the shoots together with roots which are corms in taro. The biomass in terms of unit area (kg/ha) was then calculated based on the mean experimental plot area and later adjusted to metric tonnes per hectare (tonnes ha^{-1}).

5.3.4. Determination of water use

The residual of a soil water balance as described by Allen *et al.* (1998) was used to compute the water use (WU) for each treatment. The water use was determined as follows:

$$WU = P + I - D - R - \Delta SWC$$

Where: WU = water use /evapotranspiration (mm), P = precipitation (mm), I = irrigation (mm), D = drainage (mm), R = Runoff (mm), and ∆SWC = changes in soil water content (mm).

Drainage was considered to be negligible since the moisture beds were lined with polythene paper, which prevents water from seeping beyond the root zone. The gradient in the study area was flat (< 5 %), and runoff was negligible. The change in soil water content (∆SWC) was measured using moisture meter readings to give volumetric water change. The soil water balance was then simplified to:

$$WU = P + I - \Delta SWC$$

Where: WU = water use = evapotranspiration (mm), P = Precipitation (mm), I = irrigation (mm), and ∆SWC = changes in soil water content (mm).

5.3.5. Determination of water use efficiency (WUE)

The water use efficiency was calculated as:

$$WUE = Biomass/ WU$$

Where: WUE = water use efficiency in kg $ha^{-1}mm^{-1}$, Biomass = above-ground biomass plus below-ground portion in kg/ha, and WU = water use/ crop evapotranspiration (mm).

5.3.6. Statistical Analysis

Yield, biomass, water use, and water use efficiency data collected were subjected to split- plot analysis of variance using the GenStat statistical software. Mean separation was done using the Fisher's least significant difference (LSD) at a 5 % level of probability where the ANOVA *F*-values were significant.

5.4. Results

5.4.1. Weather data

Figure 7 represents the monthly average temperature and rainfall received at the study site for the Long Rains 2021, Short Rains 2021/2022, and Long Rains 2022 growing seasons. The months of April 2021, November 2021, and April 2022 received the highest rainfall average for the first, second, and third seasons respectively. This is the second month after planting for the three seasons which is characterized by vegetative growth and corm initiation (Tumuhimbise *et al.,* 2009). Temperatures were highest in March 2021 for the first season, February 2022 for the second season, and March 2022 for the third season, and significantly cooler in July 2021, August 2021, and August 2022. A trend can be seen whereby the months of April received the highest rainfall, March the highest temperatures, and August the lowest temperatures during the three seasons of the study. Warmer temperatures (from the second to the fourth month after planting) coincided with vegetative development and corm initiation stages for the three seasons, providing optimum temperatures for taro growth.

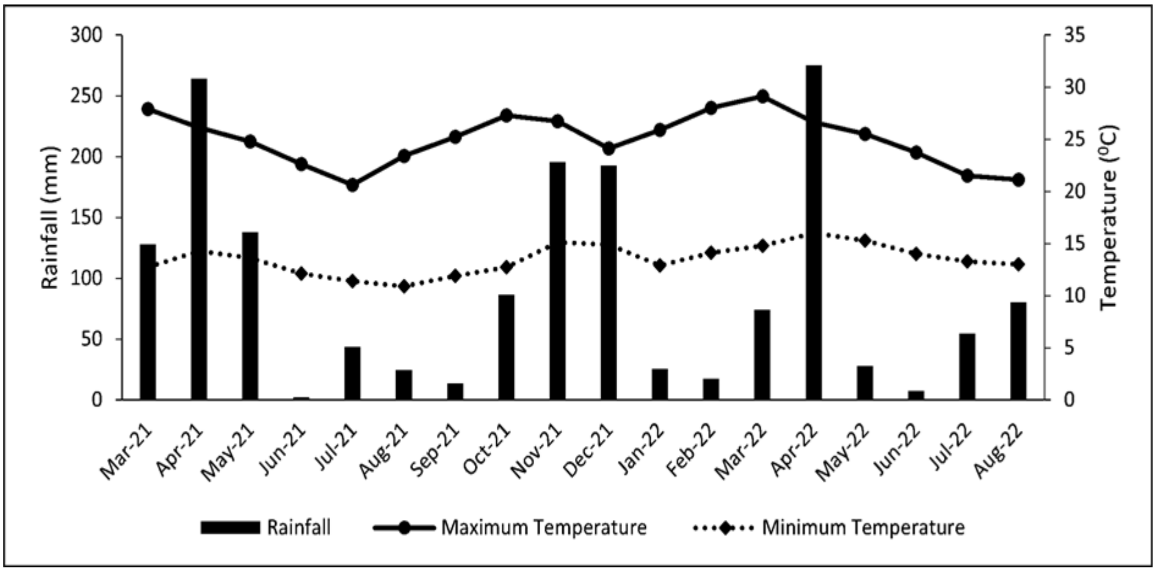

Figure 7: Monthly averages for the rainfall and temperature during the three growing seasons (LR 2021, SR 2021/2022, and LR 2022) of taro (*Colocasia esculenta*) at KALRO, Embu

5.4.2. Total Biomass and Yield of taro as influenced by watering regimes and planting density

The total biomass and yield were influenced by season and planting density ($P < 0.05$) (Table 7). The 30 % FC had the highest biomass per plant (1.97 kg) and the lowest yield (11.79 t/ha) across the three seasons. Intermediate moisture conditions (60 % FC) had the highest corm yield (12.76 t/ha). The low planting density (1 m × 1 m) recorded the highest biomass per plant (2.12 kg), with a decreasing trend of 1 m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m. The high planting density (0.5 m × 0.5 m) increased the corm yield (20.14 t/ha), with a trend of 0.5m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m. Additionally, there was a significant interaction between season and planting density for the total biomass and the yield ($P < 0.05$) (Table 7).

5.4.3. Water Use of taro as influenced by watering regimes and planting density

The water use was influenced by season, watering regimes, and planting density ($P < 0.001$) and there was a significant interaction between the watering regime and the planting density ($P < 0.001$) (Table 7). The second season had the highest water use (5097.43 mm) compared with the first (4874.35 mm) and third (4837.40 mm) seasons. The 100 % FC watering regime (8269.95 mm) and the 0. 5m × 0.5 m (40,000 plants ha^{-1}) planting density (7646.09 mm) had the highest water use values with the 30 % FC watering regime (2269.41 mm) and 1 m × 1 m (10,000 plants ha^{-1}) planting density (2678.30 mm) having the lowest (Table 7), with a trend of 100 % FC > 60 % FC > 30 % FC for the watering regime and of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m for the planting density.

5.4.4. Water Use Efficiency (WUE) of taro as influenced by watering regimes and planting density

Growing season and watering regime influenced the WUE ($P < 0.05$) with the first season (15.11 kg ha^{-1} mm^{-1}) having a higher value compared to the second season (10.86 kg ha^{-1} mm^{-1}) and the third season (7.92 kg ha^{-1} mm^{-1}) (Table 7). The high WUE observed in the LR 2021 season coincided with the high biomass per plant (2.29 kg) recorded in the season. The WUE under 100 % FC (4.75 kg ha^{-1} mm^{-1}) was 51 % and 75 % lower than in 60 % FC (9.74 kg ha^{-1} mm^{-1}) and 30 % FC (19.40 kg ha^{-1} mm^{-1}) respectively, with a trend of 30 % FC > 60 % FC > 100 % FC. The planting density did not influence the water use efficiency ($P = 0.390$) and the 1 m × 0.5 m planting density recorded the highest water use efficiency (12.16 kg ha^{-1} mm^{-1}) with the 0.5 m × 0.5 m recording the lowest (10.65 kg ha^{-1} mm^{-1}). The high WUE under 30 % FC was associated with high biomass (1.97 kg) and low water use (2269.41 mm) under limited water conditions (30 % FC) (Table 7). Additionally, the growing seasons were significantly influenced by the planting density ($P = 0.005$) and watering regime ($P = 0.018$) (Table 7).

Table 7: Total Biomass, Corm Yield, Water Use, and Water Use Efficiency of taro under varying watering regimes and planting density for the LR 2021, SR 2021/2022, and LR 2022 planting seasons

Season	Total Biomass plant^{-1} (kg)	Yield (t/ha)	Water Use (mm)	WUE (kg ha^{-1} mm^{-1})
LR 2021	2.29^{c}	7.76^{a}	4874.35^{b}	15.11^{c}
SR 2021/2022	1.90^{b}	18.29^{b}	5097.43^{c}	10.86^{b}
LR 2022	1.26^{a}	10.59^{a}	4837.40^{a}	7.92^{a}
Watering Regime				
100 % FC	1.66	12.09	8269.95^{c}	4.75^{a}
60 % FC	1.83	12.76	4269.82^{b}	9.74^{a}
30 % FC	1.97	11.79	2269.41^{a}	19.40^{b}
Planting Density				
1m × 1m	2.12^{b}	5.56^{a}	2678.30^{a}	11.08
1m × 0.5m	1.8^{ab}	10.95^{b}	4484.78^{b}	12.16
0.5m × 0.5m	1.53^{a}	20.14^{c}	7646.09^{c}	10.65
Significant Levels				
Season	< 0.001	< 0.001	< 0.001	< 0.001
WR	0.742	0.929	< 0.001	0.003
PD	0.007	< 0.001	< 0.001	0.390
WR × PD	0.140	0.396	< 0.001	0.101
Season × WR	0.753	0.643	0.687	0.018
Season × PD	0.012	0.002	0.985	0.005
Season × WR × PD	0.726	0.337	0.834	0.179

Where, FC = Field Capacity, PD = Planting Density, WR = Watering Regime, Different letters within columns indicate significant differences at a 5% probability level

5.5. Discussion

The 100 % FC watering regime had the least biomass, indicating that high water availability reduced biomass size, contradicting a study by Mabhaudhi *et al.* (2013) working on *Eddoe* and *Dasheen* taro cultivars in South Africa, who found that high moisture availability favoured biomass production. The 0.5 m × 0.5 m planting density (40000 plants ha^{-1}) had the lowest biomass, and this can be attributed to competition for light, moisture, and nutrients at closer spacing. The corm yield was higher in the SR 2021/2022 season which was characterized by lower rainfall than the LR 2021 and LR 2022 season. This means that on a seasonal basis, lower rainfall amounts, and hence lower moisture availability favoured corm yield. The highest crop yield was obtained at the planting density of 0.5 m × 0.5 m (40,000 plants ha $^{-1}$) because a high number of plants per area increases photosynthesis while ensuring sufficient ground cover (Scheffer *et al.,* 2005; Tumuhimbise *et al.,* 2009; Youssef, 2010; Boampong *et al.,* 2020). The yields observed in this study were comparable to or higher than the averages for East Africa, Africa, and the world, which are 1 t/ha, 5.6 t/ha, and 6.6 t/ha, respectively (Serem *et al.,* 2008; Palapala and Akwee, 2016).

The low watering regime (30 % FC) and the low (1 m × 1 m) planting density had the lowest water use and in turn the lowest yield. This means that the reduction in water use (water applied) reduced the corm yield, similar to a study by Mabhaudhi *et al.* (2013). The seasons played a significant role in the determination of WUE (Table 7), where reductions in rainfall reduced the WUE, with rainfall seasonal averages of 99.9mm (LR 2021), 88.4 mm (SR 2021/2022), and 86.5 mm (SR 2022) (Figure 7). The increase in WUE with limited water availability (30 % FC) is associated with an increase in biomass and a decrease in water use (Table 7) due to the lower amount of irrigation applied. This was similarly reported by Mabhaudhi *et al.* (2013) working with South African *Dasheen* and *Eddoe* taro landraces planted under a rainshelter and Li *et al.* (2019) working with the Chinese taro variety in Brazil.

Similar studies have shown that the WUE will be higher in water-limited conditions due to an increase in biomass or a decrease in the amount of irrigation water supplied to the crop (Pandey *et al.,* 2000; Shelembe, 2020). With the São Bento taro variety, Vieira *et al.* (2018) found a decrease in WUE at higher watering regimes of 100 % and 125 % ETc. They also found that an increase in the depth of water application increased the WUE. Contradictory to Bussell and Bonin's (1998) study with traditional and drought-tolerant taro varieties, they reported that WUE was typically higher at high watering-level treatments than at low water-level treatments. Uyeda *et al.* (2011) found that upland taro varieties use water more efficiently than varieties that are better suited to flooded conditions.

The low WUE under closer plant spacing (0.5 m × 0.5 m) signifies that with more plants per unit area, more water is used by the plants for growth and development and similarly lost through evapotranspiration, hence lower WUE. However, due to the partitioning of the soil water evaporation and the transpiration of the canopy, Hatfield and Dold, (2019) concluded that plants in narrow rows would decrease the time the soil is not covered and, in theory, increase WUE. Reducing plant row spacing could be a climate adaptation strategy for increasing WUE in water-stressed environments or rain-fed environments with increasing variability in rainfall during the growing season (Hatfield and Dold, 2019).

5.6. Conclusion

The results demonstrate that different watering regimes and planting densities have various capacities to utilize the supplied water. Corm production was decreased and the total biomass per plant was increased due to the decrease in water use (water applied). The WUE was considerably influenced by the watering regime, and the lowest watering regime resulted in both an increase in biomass and a decrease in water use because less irrigation water was used. The WUE was greatly influenced by the seasons, and the seasonal WUE increased as rainfall averages increased. Considering the findings of the study, the highest WUE was obtained from planting at a medium density and a low watering regime. To achieve the highest yield per unit of water consumed, a watering regime of 30 % FC and a planting density of 1 m × 0.5 m (20,000 plants ha^{-1}) is recommended.

CHAPTER SIX

FINANCIAL RETURNS OF GROWING TARO (*COLOCASIA ESCULENTA*) UNDER VARYING WATERING REGIMES AND PLANTING DENSITIES IN EMBU, KENYA

6.1. Abstract

An on-farm experiment was conducted to evaluate the financial returns of growing taro (*Colocasia esculenta*) under varying watering regimes and planting densities over three cropping seasons in the year 2021/2022. The watering regime treatments were 100 %, 60 %, and 30 % based on the field capacity (FC). The planting densities used were 0.5 m × 0.5 m (40,000 plants ha^{-1}), 1 m × 0.5 m (20,000 plants ha^{-1}), and 1 m × 1 m (10,000 plants ha^{-1}), representative of high, medium, and low planting densities respectively. This was investigated in a factorial experiment with a split-plot layout arranged in a completely randomized block design with three replications. To calculate the financial returns, local market prices for the inputs and outputs were obtained. The net benefits realized under the 100 % FC for each planting density were 1 m × 1 m (KES 912,284), 1 m × 0.5 m (KES 432,723), and 0.5 m × 0.5 m (KES 144,496). The net benefits from the 60 % FC were 1 m × 1 m (KES 260,056), 1 m × 0.5 m (KES 413,808), and 0.5 m × 0.5 m (KES 915,657) and those attained under the 30 % FC were 1m × 1m (KES 210,443), 1 m × 0.5 m (498,877), and 0.5 m × 0.5 m (KES 755,640). Based on marginal analysis, it is financially viable to recommend the 100 % FC watering regime under the 1 m × 1 m planting density to farmers in Embu County as it had a high net benefit (KES 912,284) coupled with the highest benefit-cost ratio (22.11), and a marginal rate of return of above 100 %.

6.2. Introduction

In the tropical and subtropical regions of the world, taro (*Colocasia esculenta* (L.) Schott) is a perennial herbaceous stem root crop (FAO, 2010). Its production has more than doubled in the last decade, making it the fifth most-consumed root vegetable in the world (Macharia *et al.*, 2014) and the oldest crop having been utilized in Southeast Asia and India for over 9000 years (Rao *et al.*, 2010). Taro is a crucial staple food in the human diet in the tropics and an underutilized crop in Sub-Saharan (Mabhaudhi *et al.*, 2019). It is known as arrowroot or *nduma* in Kenya. In comparison to tubers like cassava (*Manihot esculenta*), sweet potato (*Ipomoea* *batatas*), and potato (*Solanum tuberosum*), taro is ranked lower (Palapala and Akwee, 2016). In comparison to Africa (5.9 tons/ha) and the rest of the world (6.6 tons/ha), average taro yields in East Africa continue to be low, with annual yields only occasionally exceeding one ton per hectare (Serem *et al.,* 2008; Palapala and Akwee, 2016).

The taro plant has a variety of economic uses, especially in areas where it is widely consumed. The edible stem and corm which can be used in a variety of food preparations, give an exceptional dietary value and a wide range of culinary applications (Dhanraj *et al.,* 2013). To ensure food security, generate income as a cash crop, and advance rural development, taro is essential (Temesgen and Retta, 2015) in aiding rural farmers who are below the poverty line in reducing food insecurity and malnutrition in their households (Akwee *et al.,* 2015). Taro can be grown in upland agriculture in moisture beds that are covered in polythene sheets to prevent seepage and lateral movement of water through percolation into the soil (Mabhaudhi, 2012; Oxfarm, 2021). With drip irrigation, smallholder farmers can increase yields and harvests while still considering the limited water resources available by planting taro uplands rather than the customary locations along rivers and streams (Wainaina, 2021).

Recent research has concentrated on planting density (Tumuhimbise *et al.,* 2009; Tsedalu *et al.,* 2014; Sibiya, 2015; Boampong *et al.,* 2020), taro genetic diversity (Macharia *et al.,* 2014; Akwee *et al.,* 2015; Palapala and Akwee, 2016), and socioeconomic production constraints (Bammite *et al.,* 2018). The study of the taro value chain must consider agricultural accounting and financial analysis because these topics have recently not received attention in Kenyan studies (Onsay *et al.*, 2022). Integrating financial analysis enhances farmers' ability to evaluate watering schedules and planting densities, which has an impact on the viability and wide adoption of this technology. Farmers' adoption of the technology depends heavily on the costs associated with the transition from growing in riverbeds and streams to uplands under the moisture beds and drip irrigation. This study aimed to assess the financial returns of taro production in the sub-humid regions of Embu, Kenya, under varied watering regimes and planting densities.

6.3. Materials and Methods

The site description, experimental layout, planting material, moisture bed preparation and irrigation, irrigation scheduling, and soil moisture determination are outlined in Chapter 3; sections 3.3.1., 3.3.2., 3.3.3., 3.3.4., 3.3.5., and 3.3.6. respectively.

6.3.1. Taro Yield Measurements

Six months after planting, the corm yield was assessed. The average experimental plot area served as a basis for the corm yield calculation which was then converted to metric tonnes per hectare (tonnes/ha).

6.3.2. Financial Analysis

The financial benefits of growing taro under different watering regimes and planting densities were calculated using a partial budget analysis (CIMMYT, 1988). The partial budget analysis was aimed to evaluate the benefits and drawbacks of the varying watering regimes and planting densities. For the three seasons of taro production, the total input and output data were used. The taro yields were adjusted by 10 % to account for field and post-harvest losses, according to CIMMYT, (1988). The adjusted taro yield was multiplied by the market price at harvest to determine the crop's gross income. Taro's average market price of 50 KES per kilogram was used.

$$Total\ Gross\ Income\ (KES) = Adjusted\ yield\ \times Prevailing\ market\ price$$

The costs of taro basal stems, labour, irrigation water, weeding, and harvesting were summed up to calculate the total variable costs. The total variable costs of production were then subtracted from the gross income to determine the gross margins.

$$Gross\ Margins\ or\ Net\ benefits\ \ (KES) = Total\ variable\ costs - Total\ Gross\ Income$$

The benefit-cost ratio (returns on investment per shilling) was later calculated by dividing total gross income by total variable costs (CIMMYT, 1988).

$$Benefit\ to\ cost\ ratio = \frac{Total\ Gross\ Income}{Total\ Variable\ Costs}$$

Marginal analysis was later done to determine how the costs differed from the net benefits. The marginal analysis entails determining the dominance and calculating the marginal rate of return (MRR) for the non-dominated treatments. Dominance analysis involves ranking treatments in terms of rising total costs that vary and is usually used to select potentially profitable treatments (CIMMYT, 1988; Fadipe *et al.*, 2015; Tesfaye *et al.*, 2015). Watering regimes and planting densities combinations were arranged in order of increasing variable costs. Treatment dominance was determined by comparing treatments with lower gross margins (and higher total variable costs) to treatments with higher gross margins (and lower total variable costs). The former practices are typically considered dominated by the latter in dominance analysis

(CIMMYT, 1988). As the dominated options are generally not the best to recommend to farmers, they are excluded from further consideration, such as the MRR calculation. The MRR is required to fine-tune farmer recommendations and to focus on non-dominant alternatives. The MRR was calculated as the ratio of the extra benefit gained to the extra cost incurred by switching from one non-dominated option to another (CIMMYT, 1988; Melese *et al.*, 2018; Karuma *et al.,* 2020). Based on this analysis, the recommendation was made by arranging the treatments in increasing cost order and then taking the MRR between each pair of treatments into account. Farmers were advised to adopt the treatment with the highest net benefits and an MRR greater than 100 %.

6.4. Results and Discussion

6.4.1. Taro corm yield

The 0.5 m × 0.5 m planting density attained the highest yield under the 60 % FC (21.40 t/ha) and 30 % FC (17.79 t/ha) watering regime while the 1m × 1m planting density attained the highest yield for the 100 % FC watering regime (21.23 t/ha) (Table 4). A different trend was further observed in the lowest yield attained whereby the 1 m × 1 m planting density had the lowest yield for 60 % FC (6.70 t/ha) and 30 % FC (5.58 t/ha) watering regimes as opposed to 100 % FC where the lowest yield was from the 0.5m × 0.5m (4.39 t/ha) planting density. There was a 219 % increase in yields from 1 m × 1 m to 0.5 m × 0.5 m planting density for both the 60 % FC and 30 % FC watering regimes, and a 79 % decrease in yield for the 100 % FC. The 1 m × 0.5 m planting density had intermediate yields in the different watering regimes and across the three seasons.

The high corm yield attained from the high planting density can be attributed to more plants per unit area at lower plant spacing. The high plant density per area increases photosynthesis and solar radiation absorption while ensuring sufficient ground cover (Scheffer *et al.,* 2005; Tumuhimbise *et al.,* 2009; Boampong *et al.,* 2020). The yields observed in this study were greater than the averages for East Africa, Africa, and the world, which were 1 t/ha, 5.6 t/ha, and 6.6 t/ha, respectively (Serem *et al.,* 2008; Palapala and Akwee, 2016). Saturated conditions (100 % FC) reduced the corm yield at low spacing while increasing the yield at high spacing (low planting density). The intermediate watering regime (60 % FC) under the high planting density (0.5 m × 0.5 m) produced the highest corm yield meaning that farmers can adopt this treatment combination for increasing yields.

6.4.2. Partial budget analysis

Table 9 shows the findings of the partial budget analysis for the different watering regimes and planting densities. The high planting density (0.5 m × 0.5 m) had the highest drip installation costs (Table 8) across the three watering regimes because of the high number of plants in the plots, which required more drip lines, button drippers, and valves. The total input costs were highest under the 0.5 m × 0.5 m planting density due to more taro planting material and high costs of water as a result of more emitters on the drip lines. The total variable costs under the different planting densities within the watering regimes had a trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m, ranging from KES 40,557 to KES 53,004 (Tables 8 and 9). The high planting density (0.5 m × 0.5 m) had the highest total variable costs due to high drip installation costs, and inputs cost particularly in terms of water costs and taro basal stems. More emitters along the drip lines and more taro plants in the plots result in higher water and basal stem costs for taro.

The average net benefit/gross margins for the 100 % FC followed a trend of 1 m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m, while the 60 % FC and 30 % FC watering regime followed a decreasing trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m with values ranging from KES 144,496 to KES 915,657 (Table 9). The 0.5 m × 0.5 m under 60 % FC produced the highest corm yield (21.40 t/ha) and the highest net benefit (KES 915,657) (Table 9). The low net benefit obtained for the 100 % FC under 0.5 m × 0.5 m is attributed to the treatment combination's low yield combined with high cost, similar to a study by Melese *et al.* (2018), on partial budget analysis of pepper in Ethiopia. The benefit-to-cost ratio (BCR) was within the acceptable range (> 1) (Tafa *et al.,* 2021) under the different treatments with values ranging from (3.73 to 22.11). This means that the costs of taro production under the various treatment combinations of watering regimes and planting densities were recovered from the benefits realized, similar to a study by Karuma *et al.* (2020) on the financial returns of maize and bean production in Kenya. A trend of 1 m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m was noted for the 100 % FC, while the 60 % FC and 30 % FC watering regime followed a trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m. Higher BCR indicates higher net returns generated from the treatments while lower BCR signifies increasing production costs (Aurangzeb *et al.,* 2007; Karuma *et al.,* 2020). Based on this study, the 100 % FC under the 1 m × 1 m planting density treatment combination with the highest BCR value would be recommended for farmers in the study area.

Table 8: Average seasonal cost of production for taro under varying watering regimes and planting densities in Embu, Kenya (n = 3 cropping seasons)

Variable Costs (KES)	100 % FC Watering Regime			60 % FC Watering Regime			30 % FC Watering Regime		
	1 m × 1 m	1 m × 0.5 m	0.5 m × 0.5 m	1 m × 1 m	1 m × 0.5 m	0.5 m × 0.5 m	1 m × 1 m	1 m × 0.5 m	0.5 m × 0.5 m
Drip Installation/ Conveyance Costs									
Drip Irrigation Materials (drip lines, button drippers, valves, 5000 litre tank and tank stand, filter, elbows, tees, endcaps, PVC pipes)	21,348	21,889	22,833	21,348	21,889	22,833	21,348	21,889	22,833
Drip Irrigation Installation	6,111	6,111	6,111	6,111	6,111	6,111	6,111	6,111	6,111
Transport	1,111	1,111	1,111	1,111	1,111	1,111	1,111	1,111	1,111
Total Drip Installation Costs	28,570	29,111	30,055	28,570	29,111	30,055	28,570	29,111	30,055
Labour Costs (Field)									
Land clearing and levelling	555	555	555	555	555	555	555	555	555
Moisture bed preparation	2,333	2,333	2,333	2,333	2,333	2,333	2,333	2,333	2,333
Polythene layering and Planting	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600
Weeding	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400
Harvesting	400	400	400	400	400	400	400	400	400
Total labour costs	7,288	7,288	7,288	7,288	7,288	7,288	7,288	7,288	7,288
Inputs									
Polythene rolls	3,333	3,333	3,333	3,333	3,333	3,333	3,333	3,333	3,333
Taro basal stems	480	840	1470	480	840	1470	480	840	1470
Water costs	3,545	6,205	10,858	1,773	3,120	5,197	886	1,551	2,714
Total input costs	7,358	10,378	15,661	5,586	7,293	10,000	4,699	5,724	7,517
Total variable costs (drip + labour + input costs)	43,216	46,777	53,004	41,444	43,692	47,343	40,557	42,123	44,860

Table 9: Partial budget analysis of taro production under varying watering regimes and planting densities in Embu, Kenya (n = 3 cropping seasons)

Variable Costs (KES)	100 % FC Watering Regime			60 % FC Watering Regime			30 % FC Watering Regime		
	1 m × 1 m	1 m × 0.5 m	0.5 m × 0.5 m	1 m × 1m	1 m × 0.5 m	0.5 m × 0.5 m	1 m × 1 m	1 m × 0.5 m	0.5 m × 0.5 m
Taro corm Yield (t/ha)	21.23	10.65	4.39	6.70	10.17	21.40	5.58	12.02	17.79
Adjusted Yields (t/ha)	19.11	9.59	3.95	6.03	9.15	19.26	5.02	10.82	16.01
TGI (KES)	955,500	479,500	197,500	301,500	457,500	963,000	251,000	541,000	800,500
TVC (KES)	43,216	46,777	53,004	41,444	43,692	47,343	40,557	42,123	44,860
NB/Gross Margins (KES)	912,284	432,723	144,496	260,056	413,808	915,657	210,443	498,877	755,640
BCR	22.11	10.25	3.73	7.27	10.47	20.34	6.18	12.84	17.84

Where, TGI = Total Gross Income, TVC = Total Variable Costs, NB = Net Benefits, BCR = Benefit-Cost Ratio, KES = Kenya Shillings

6.4.3. Marginal Analysis

6.4.3.1. Dominance Analysis

Table 10 displays the dominance analysis findings. Treatments with lower variable costs have lower or comparable benefits than dominated treatments (CIMMYT, 1988). According to the results of the dominance analysis, 1 m × 0.5 m under 60 % FC and 100 % FC and 0.5 m × 0.5 m under 30 % and 100 % FC dominated having lower gross margins (net benefits) and were therefore disqualified from further consideration. High total costs and little gain in net benefits explain the dominance of the high planting density for the 30 % FC and 100 % FC watering regimes (Tables 9 and 10).

6.4.3.2. Marginal Rate of Return (MRR)

The marginal rate of return (MRR) is characterized by switching from one course of treatment to another. Due to the marginal analysis' exclusion of the dominated treatments, the MRR is always positive (CIMMYT, 1988; Soha, 2014). The marginal rate of return range of the non-dominated treatments was 0.82 - 379.99 % (Table 11). For crops with cycles of four to five months, farmers generally accept MRR ranges between 50 and 100 %. Nevertheless, crops with longer cycles, like the taro crop in this study, have correspondingly higher minimum rates of return acceptable to farmers (CIMMYT, 1988; Arebu *et al.*, 2019).

Farmers would gain by shifting from 30 % FC to 60 % FC under the 1 m × 1 m planting density and would gain even more by shifting from the latter to 30 % FC under 1 m × 0.5 m. Additionally, switching from 30 % FC under 1 m × 0.5 m to 100 % FC under 1 m × 1 m would provide farmers with the highest marginal net benefit (KES 413,407) and MRR (378.23 %). Farmers are not recommended to switch from the latter to 60 % FC under 0.5 m × 0.5 m due to the low marginal net benefit (KES 3,373) and MRR recorded (0.82 %) (Table 11).

The treatment with the highest net benefit along with an acceptable MRR becomes the preferred recommendation for treatments subject to the marginal rate of return. The best recommendation is based on the minimum acceptable marginal rate of return rather than the highest marginal rate of return (CIMMYT, 1988). Therefore, to maximize their profitability, farmers in the study area can adopt the 100 % FC under the 1m × 1m planting density, which has a high net benefit and an MRR of < 100 %.

Table 10: Dominance analysis of costs and returns in taro production under different watering regimes and planting densities in Embu, Kenya

Watering Regime	Planting Density	TVC (KES)	NB (KES)
30 % FC	1 m × 1 m	40,557	210,443
60 % FC	1 m × 1 m	41,444	260,056
30 % FC	1 m × 0.5 m	42,123	498,877
100 % FC	1 m × 1 m	43,216	912,284
60 % FC	1 m × 0.5 m	43,692	413,808**D**
30 % FC	0.5 m× 0.5 m	44,860	755,640**D**
100 % FC	1 m × 0.5 m	46,777	432,723**D**
60 % FC	0.5 m × 0.5 m	47,343	915,657
100 % FC	0.5 m × 0.5 m	53,004	144,496**D**

Where, TVC = Total Variable Cost, NB = Net Benefit, D = Dominated treatment

Table 11: Financial returns of the non-dominated watering regimes and planting densities in Embu, Kenya

Watering Regime	Planting Density	Taro Yields (t/ha)	Adjusted Yields (t/ha)	TGI (Ksh.)	TVC (KES)	Net Benefit (KES)	MAC	MNB (KES)	MRR	BCR
30 % FC	1 m × 1 m	5.58	5.02	251,000	40,557	210,443				6.19
60 % FC	1 m × 1 m	6.70	6.03	301,500	41,444	260,056	887	49,613	55.93	7.27
30 % FC	1 m × 0.5 m	12.02	10.82	541,000	42,123	498,877	679	238,821	351.72	12.84
100 % FC	1 m × 1 m	21.23	19.11	955,500	43,216	912,284	1093	413,407	378.23	22.11
60 % FC	0.5 m × 0.5 m	21.40	19.26	963,000	47,343	915,657	4127	3373	0.82	20.34

Where, TGI = Total Gross Income, MAC = Marginal Cost (USD /ha), MNB = Marginal Net Benefits (USD /ha), MRR = Marginal Rate of Return, BCR = Benefit Cost Ratio

6.5. Conclusion

Under the various combinations of watering regimes and planting densities used in this study, the total costs incurred, and net benefit realized showed significant variations. There is a need to integrate financial analysis into the taro watering regime and planting density studies to better understand the costs involved and benefits realized in its production and then to make appropriate farmer recommendations. Studies on partial budget analysis for the taro crop are widely understudied in Kenya and around the world. The 1 m × 0.5 m planting density under 60 % FC and 100 % FC and 0.5 m × 0.5 m under 30 % and 100 % FC dominated having higher total costs and lower net benefits, and hence eliminated from further consideration of MRR. The 60 % FC under the 0.5 m × 0.5 m produced the highest net benefit however its MRR was below the threshold value, and therefore not acceptable. The 100 % FC under the 1 m × 1 m planting density had an MRR above 100 %, the highest BCR, and a high net benefit and is favourable for adoption. It is therefore financially viable to recommend the 100 % FC under the 1 m × 1 m planting density in Embu County, for increased financial gains in the production of taro.

CHAPTER SEVEN

GENERAL DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

7.1. Discussion

7.1.1. Taro growth components as influenced by varying watering regimes and planting densities

Taro growth components, namely, plant height, leaf area index (LAI), and vegetative growth index (VGI) were computed to evaluate taro's response under the varied water treatments and plant densities (Chapter 3). Taro height and leaf area index were highest under the 0.5 m × 0.5 m planting density, meaning that at this close spacing, there was a large photosynthetic area subject to transpiration (Boampong *et al.,* 2020). Plant height and LAI of taro increased as planting density increased, and this was attributed to an increase in linear growth due to higher plant density per unit area. The 1 m × 1 m density recorded high values for the vegetative growth index. The VGI is especially useful because it includes all aspects of taro vegetative growth, such as leaf number and area, plant height, and stolons and/or suckers (Lebot, 2008). The 60 % FC recorded high values for VGI and plant height while 30 % FC had high values for leaf area index. The 100 % FC recorded low values for the growth components, and this was attributed to the clay soils in the study area. Clay soils have small pores and are subject to compaction during moist and wet conditions therefore, infiltration is impeded reducing water availability to the root zone (FAO, 2015a; Rout and Arulmozhiselvan, 2019). Soil compaction has been reported to affect plant emergence and development, particularly reducing plant height (Wolkowoski and Loweri, 2008). Soils with a clay texture are most susceptible to compaction because their particles hold more water longer than sandy or loamy soils. The degree of compaction in nitisols, similar to soils in this study site, is measured through determination of bulk density, and has been found to be high due to human and wheel traffic during cultivation (Mahdi, 2007). When soil moisture exceeds field capacity there is a potential for soil compaction, particularly at topsoil depths due to reduction in soil porosity (Viciedo *et al.,* 2018). Therefore, the type of soil in the study area coupled with irrigation to field capacity (100 % FC) lowered the taro growth components due to compaction of the soil.

7.1.2. Taro yield and yield components as influenced by varying watering regimes and planting densities

Planting density is one of the key factors affecting yield. This was affirmed by this study's findings, which showed that taro yields increased with plant density (Chapter 4). Planting taro at 0.5 m x 0.5 m spacing significantly increased corm yield per unit area. Similar to findings by Sibiya, (2015) in South Africa and Boampong *et al.* (2020) in Ghana. The 1 m × 1 m plant spacing increased the yield components determined per individual taro plant while the 0.5 m × 0.5 m density increased the yield components per unit area (t ha^{-1}). Wide spacing increased the corm yield of individual taro plants (corm mass) whereas narrow spacing increased the total corm yield of taro per unit area. It is important to note that the total yield in taro is a function of the number of corms produced per unit area rather than the size of the individual corm or corm mass (Boampong *et al.,* 2020). High moisture availability (100 % FC) negatively influenced the corm length, diameter, corm mass, and total biomass while low moisture availability lowered the corm yield and harvest index. The intermediate moisture conditions (60 % FC) increased all the taro yield components. This is interesting as the taro crop is known to grow under high moisture conditions (Uyeda *et al.,* 2011).

7.1.3. Taro's water use efficiency under varied water regimes and plant densities

Chapter 5 discusses the water use efficiency (WUE) of taro under different water treatments and plant densities. Drip irrigation is known to reduce soil water evaporation from between plant rows and limits almost all canopy evaporation (Mabhaudhi, 2012; Hatfield and Dold, 2019), and it was used as a supplemental source of irrigation in this study. The use of a micro-irrigation system early in the growing season reduces soil water evaporation from between plant rows and virtually reduces all canopy evaporation. These changes show how system water management can alter WUE by increasing WUE in irrigated crop areas (Hatfield and Dold, 2019). The 30 % FC and 1 m × 0.5 m planting density resulted in the highest WUE. This means that the water treatment with the lowest amount of water applied (30 % FC) achieved the highest yield per unit of water consumed.

7.1.4. Costs and benefits of growing taro under varied watering regimes and planting densities

A partial budget analysis was used to compute the financial benefits of growing taro under different watering regimes and planting densities (CIMMYT, 1988) (Chapter 6). There is a need to integrate financial analysis into the taro watering regime and planting density studies to better understand the costs involved and benefits realized in its production and then to make appropriate farmer recommendations. The total input costs were highest under the 0.5m × 0.5m planting density due to more taro planting material and high costs of water as a result of more emitters on the drip lines. The 0.5 m × 0.5 m under 60 % FC produced the highest net benefit. The low net benefit obtained for the 100 % FC under 0.5 m × 0.5 m was attributed to the treatment combination's low yield combined with high cost, similar to a study by Melese *et al.* (2018). The benefit-to-cost ratio (BCR) was within the acceptable range (> 1) (Tafa *et al.,* 2021) under the different treatments. This means that the costs of taro production under the various treatment combinations of watering regimes and planting densities were recovered from the benefits realized. Dominance analysis was determined and then the treatments that dominated having lower gross margins (net benefits) were excluded from the determination of the marginal rate of return (MRR). The MRR was determined from the nondominated treatments. The treatment with the highest net benefit along with an acceptable MRR (> 100 %) became the preferred recommendation. The 100 % FC under the 1 m × 1 m planting density had an MRR above 100 %, the highest BCR, and a high net benefit.

7.2. Conclusion

This study aimed to determine the best watering regime and plant density for increasing taro growth and yield. It was found that the intermediate conditions (60 % FC) had the highest plant height, corm length, diameter, corm mass, and corm yield while the high planting density of 0.5 m × 0.5 m (40,000 plants ha $^{-1}$) had the highest plant height, harvest index, total biomass, and corm yield per hectare. The results for the water use efficiency show that different watering regimes and planting densities have different capacities to utilize the water applied. The reduction in the water use (water applied) reduced the corm yield and increased the total biomass. The watering regime significantly ($P < 0.05$) affected the water use efficiency (WUE). The 30 % FC watering regime had an increase in biomass and a decrease in water use due to the lower amount of irrigation applied. The WUE was significantly influenced by the seasons, and the seasonal WUE increased as seasonal rainfall averages increased. It was concluded that planting at an intermediate density (1 m × 0.5 m) and a low watering regime

(30 % FC), produced the highest WUE. Under the various combinations of watering regimes and planting densities used in this study, the total costs incurred, and net benefit realized showed significant variations. The 100 % FC under the 1 m × 1 m planting density had an MRR above 100 %, the highest BCR, and a high net benefit.

7.3. Recommendations

1. The highest planting density of 0.5 m × 0.5 m (40,000 plants ha^{-1}) and a 60 % FC watering regime is recommended to farmers in the area for increased vegetative growth, yields, and increasing food security. This recommendation is based on the premise that agricultural research organizations and non-governmental organizations work with the local communities through projects to educate them on this technology and to provide drip irrigation systems and polythene sheets for the moisture beds to enable them to cultivate taro and upscale the use of this innovation.
2. The 100 % FC under the 1 m × 1 m planting density in Embu County is financially viable and therefore recommended for increased financial gains in the production of taro in Embu County. This recommendation will ensure taro farmers realize higher profits while improving their livelihoods and overall economic wellbeing.
3. More studies need to be conducted in other agro-ecological zones in the country to better understand taro’s growth response under different environmental conditions.
4. On-farm upland taro studies need to be done and contrasted with local farmers’ practices.

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APPENDICES

Analysis of Variance (ANOVA)

Appendix 1: ANOVA for plant height (cm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	14533.81	7266.90	4.56	
Block.Subject stratum					
Season	2	130138.24	65069.12	40.84	<.001
Watering_Regime	2	2633.23	1316.61	0.83	0.443
Planting_density	2	952.76	476.38	0.30	0.743
Season.Watering_Regime	4	1708.32	427.08	0.27	0.897
Season.Planting_density	4	4350.06	1087.52	0.68	0.607
Watering_Regime.Planting_density	4	10642.14	2660.54	1.67	0.171
Season.Watering_Regime.Planting_density	8	11493.18	1436.65	0.90	0.522
Residual	52	82858.54	1593.43	102.24	
Block.Subject.Time stratum					
d.f. correction factor 0.1297					
Time	16	12865.65	804.10	51.59	<.001
Time.Season	32	37678.26	1177.45	75.55	<.001
Time.Watering_Regime	32	252.94	7.90	0.51	0.737
Time.Planting_density	32	4451.96	139.12	8.93	<.001
Time.Season.Watering_Regime	64	453.12	7.08	0.45	0.891
Time.Season.Planting_density	64	599.68	9.37	0.60	0.781
Time.Watering_Regime.Planting_density	64	1346.98	21.05	1.35	0.224
Time.Season.Watering_Regime.Planting_density	128	2704.47	21.13	1.36	0.174
Residual	864	13465.38	15.58		
Total	1376	333128.73			

Appendix 2: ANOVA for leaf area index (LAI)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Block stratum	2	0.1755852	0.0877926	1.87	
Block.Subject stratum					
Season	2	3.6447819	1.8223909	38.77	<.001
Watering_Regime	2	0.0984161	0.0492081	1.05	0.358
Planting_density	2	9.7258697	4.8629348	103.46	<.001
Season.Watering_Regime	4	0.0717829	0.0179457	0.38	0.821
Season.Planting_density	4	0.3936398	0.0984099	2.09	0.095
Watering_Regime.Planting_density	4	0.3500497	0.0875124	1.86	0.131
Season.Watering_Regime.Planting_density	8	0.5146045	0.0643256	1.37	0.232
Residual	52	2.4440655	0.0470013	74.65	
Block.Subject.Time stratum					
d.f. correction factor 0.1492					
Time	16	0.4056193	0.0253512	40.27	<.001
Time.Season	32	1.0809331	0.0337792	53.65	<.001
Time.Watering_Regime	32	0.0050756	0.0001586	0.25	0.932
Time.Planting_density	32	0.2392605	0.0074769	11.88	<.001
Time.Season.Watering_Regime	64	0.0336147	0.0005252	0.83	0.592
Time.Season.Planting_density	64	0.1114795	0.0017419	2.77	0.005
Time.Watering_Regime.Planting_density	64	0.0470399	0.0007350	1.17	0.320
Time.Season.Watering_Regime.Planting_density	128	0.1728970	0.0013508	2.15	0.006
Residual	864	0.5439721	0.0006296		
Total	1376	20.0586871			

Appendix 3: ANOVA for vegetative growth index (VGI)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.438E+06	2.219E+06	0.07	
Block.Subject stratum					
Season	1	5.150E+08	5.150E+08	16.94	<.001
Watering_Regime	2	1.784E+07	8.922E+06	0.29	0.748
Planting_density	2	2.027E+07	1.013E+07	0.33	0.719
Season.Watering_Regime	2	1.184E+07	5.920E+06	0.19	0.824
Season.Planting_density	2	7.772E+06	3.886E+06	0.13	0.880
Watering_Regime.Planting_density	4	1.007E+08	2.518E+07	0.83	0.516
Season.Watering_Regime.Planting_density	4	1.070E+08	2.675E+07	0.88	0.486
Residual	34	1.033E+09	3.040E+07	75.27	

Block.Subject.Time stratum					
d.f. correction factor 0.1742					
Time	14	1.279E+08	9.134E+06	22.62	<.001
Time.Season	14	1.410E+08	1.007E+07	24.94	<.001
Time.Watering_Regime	28	2.346E+06	8.378E+04	0.21	0.956
Time.Planting_density	28	2.295E+07	8.198E+05	2.03	0.084
Time.Season.Watering_Regime					
	28	4.786E+06	1.709E+05	0.42	0.827
Time.Season.Planting_density					
	28	5.150E+06	1.839E+05	0.46	0.804
Time.Watering_Regime.Planting_density					
	56	1.897E+07	3.388E+05	0.84	0.590
Time.Season.Watering_Regime.Planting_density					
	56	3.297E+07	5.887E+05	1.46	0.171
Residual	504	2.035E+08	4.038E+05		
Total	809	2.378E+09			

Appendix 4: ANOVA for corm length (cm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	6.185	3.093	0.21	
Block.Watering_Regime stratum					
Watering_Regime	2	0.809	0.404	0.03	0.973
Residual	4	58.345	14.586	12.87	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	10.833	5.416	4.78	0.030
Watering_Regime.Planting_density					
	4	18.072	4.518	3.99	0.028
Residual	12	13.599	1.133	0.66	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	211.679	105.839	61.24	<.001
Watering_Regime.Season	4	0.645	0.161	0.09	0.984
Planting_density.Season	4	19.023	4.756	2.75	0.043
Watering_Regime.Planting_density.Season					
	8	14.316	1.789	1.04	0.428
Residual	36	62.214	1.728		
Total	80	415.720			

Appendix 5: ANOVA for corm diameter (cm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	14.057	7.029	1.24	

Block.Watering_Regime stratum					
Watering_Regime	2	2.141	1.070	0.19	0.835
Residual	4	22.610	5.653	9.14	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	6.901	3.450	5.58	0.019
Watering_Regime.Planting_density					
	4	7.774	1.944	3.14	0.055
Residual	12	7.424	0.619	0.50	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	80.445	40.222	32.32	<.001
Watering_Regime.Season	4	4.445	1.111	0.89	0.478
Planting_density.Season	4	11.966	2.991	2.40	0.068
Watering_Regime.Planting_density.Season					
	8	12.644	1.580	1.27	0.289
Residual	36	44.795	1.244		
Total	80	215.202			

Appendix 6: ANOVA for corm mass (kg)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.28127	0.14063	0.76	
Block.Watering_Regime stratum					
Watering_Regime	2	0.05621	0.02811	0.15	0.863
Residual	4	0.73590	0.18398	7.65	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	0.05000	0.02500	1.04	0.383
Watering_Regime.Planting_density					
	4	0.23511	0.05878	2.45	0.103
Residual	12	0.28845	0.02404	0.43	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	2.63888	1.31944	23.50	<.001
Watering_Regime.Season	4	0.07697	0.01924	0.34	0.847
Planting_density.Season	4	0.16595	0.04149	0.74	0.572
Watering_Regime.Planting_density.Season					
	8	0.36280	0.04535	0.81	0.600
Residual	36	2.02120	0.05614		
Total	80	6.91276			

Appendix 7: ANOVA for corm yield (t/ha)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	96.66	48.33	0.55	
Block.Watering_Regime stratum					
Watering_Regime	2	13.21	6.61	0.07	0.929
Residual	4	354.28	88.57	3.85	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	2935.85	1467.93	63.77	<.001
Watering_Regime.Planting_density	4	102.26	25.57	1.11	0.396
Residual	12	276.25	23.02	0.84	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	1604.16	802.08	29.18	<.001
Watering_Regime.Season	4	69.53	17.38	0.63	0.643
Planting_density.Season	4	588.31	147.08	5.35	0.002
Watering_Regime.Planting_density.Season	8	259.88	32.49	1.18	0.337
Residual	36	989.53	27.49		
Total	80	7289.92			

Appendix 8: ANOVA for total biomass (t/ha)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	837.3	418.6	0.48	
Block.Watering_Regime stratum					
Watering_Regime	2	120.8	60.4	0.07	0.935
Residual	4	3509.0	877.2	6.65	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	22944.9	11472.4	87.02	<.001
Watering_Regime.Planting_density	4	1555.9	389.0	2.95	0.065
Residual	12	1582.1	131.8	0.63	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	7949.1	3974.5	18.89	<.001
Watering_Regime.Season	4	746.6	186.6	0.89	0.482
Planting_density.Season	4	501.2	125.3	0.60	0.668
Watering_Regime.Planting_density.Season	8	2107.9	263.5	1.25	0.298
Residual	36	7574.5	210.4		

Total	80	49429.3			

Appendix 9: ANOVA for harvest index (%)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.50	2.25	0.05	
Block.Watering_Regime stratum					
Watering_Regime	2	321.69	160.85	3.86	0.116
Residual	4	166.54	41.64	1.09	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	162.82	81.41	2.13	0.162
Watering_Regime.Planting_density	4	166.12	41.53	1.09	0.407
Residual	12	459.22	38.27	0.56	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	12777.88	6388.94	93.03	<.001
Watering_Regime.Season	4	336.55	84.14	1.23	0.317
Planting_density.Season	4	5.81	1.45	0.02	0.999
Watering_Regime.Planting_density.Season	8	748.86	93.61	1.36	0.246
Residual	36	2472.41	68.68		
Total	80	17622.40			

Appendix 10: Two-sided test of taro yield components correlations different from zero

	CL	CD	CM	TB	CY	HI
CL	-					
CD	< 0.001	-				
CM	0.0013	< 0.001	-			
TB	< 0.001	< 0.001	0.0301	-		
CY	0.2858	0.1991	< 0.001	< 0.001	-	
HI	0.0014	< 0.001	< 0.001	0.0886	< 0.001	-

Appendix 11: ANOVA for water use (mm)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.000E+01	1.000E+01	5.47	
Block.Watering_Regime stratum					
Watering_Regime	2	5.041E+08	2.520E+08	1.379E+08	<.001
Residual	4	7.308E+00	1.827E+00	6.41	

Block.Watering_Regime.Planting_density stratum					
Planting_density	2	3.414E+08	1.707E+08	5.992E+08	<.001
Watering_Regime.Planting_density					
	4	9.752E+07	2.438E+07	8.557E+07	<.001
Residual	12	3.419E+00	2.849E-01	0.05	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	1.069E+06	5.344E+05	98695.82	<.001
Watering_Regime.Season	4	1.231E+01	3.078E+00	0.57	0.687
Planting_density.Season	4	1.942E+00	4.854E-01	0.09	0.985
Watering_Regime.Planting_density.Season					
	8	2.250E+01	2.812E+00	0.52	0.834
Residual	36	1.949E+02	5.414E+00		
Total	80	9.441E+08			

Appendix 12: ANOVA for water use efficiency (kg ha^{-1} mm^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	112.44	56.22	1.20	
Block.Watering_Regime stratum					
Watering_Regime	2	2993.62	1496.81	31.96	0.003
Residual	4	187.32	46.83	2.94	
Block.Watering_Regime.Planting_density stratum					
Planting_density	2	32.47	16.24	1.02	0.390
Watering_Regime.Planting_density					
	4	157.23	39.31	2.47	0.101
Residual	12	191.00	15.92	1.47	
Block.Watering_Regime.Planting_density.*Units* stratum					
Season	2	706.81	353.40	32.60	<.001
Watering_Regime.Season	4	148.32	37.08	3.42	0.018
Planting_density.Season	4	193.86	48.47	4.47	0.005
Watering_Regime.Planting_density.Season					
	8	133.39	16.67	1.54	0.179
Residual	36	390.26	10.84		
Total	80	5246.71			