UNIVERSITY FOR DEVELOPMENT STUDIES

EVALUATION OF WATER PRODUCTIVITY FOR VINE PRODUCTION OF ORANGE-FLESHED SWEET POTATO (*Ipomoea batatas* (L.) Lam.) UNDER DIFFERENT SUPPLEMENTARY IRRIGATION TECHNIQUES AND FERTILIZER APPLICATION IN EAST MAMPRUSI DISTRICT

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BY

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A THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL ENGINEERING, SCHOOL OF ENGINEERING, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN IRRIGATION AND DRAINAGE ENGINEERING

FEBRUARY, 2026

DECLARATION

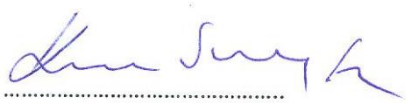
DECLARATION BY CANDIDATE

I, hereby, declare that this thesis is the result of my own original work and that no part of it has been presented for a degree in this university or elsewhere. The work of others, which served as sources of information for this study, has been duly acknowledged in the form of references.

Iddrisu Bapijem Majewen		28/05/2025
(UDS/MID/0006/22)	Signature	Date

DECLARATION BY SUPERVISORS

I, hereby, declare that the preparation and presentation of the thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.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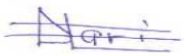
Prof. Ing. Linda Dari		10/02/2026
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ABSTRACT

Orange-Fleshed Sweet Potato (*Ipomoea batatas* (L.) Lam.) is a climate-resilient crop with significant potential for improving food security and livelihoods in semi-arid regions. However, its productivity is often limited by water scarcity and soil nutrient deficiencies. Despite its importance, limited research has been conducted on the combined effects of supplementary irrigation techniques and fertilizer application on vine production and water productivity. This study evaluated the performance of orange-fleshed sweet potato under three supplementary irrigation techniques-drip, rain tube, and furrow irrigation -combined with fertilizer application in the East Mamprusi District. A split-plot experimental design was used, with irrigation technique as the main plot factor and fertilizer application (with and without) as the subplot factor. The experiment consisted of six treatment combinations, replicated three times, making a total of eighteen experimental units. Each plot measured 5 m × 10 m, with a planting density of 33,333 plants per hectare. Supplementary irrigation was applied based on the estimated crop water requirement of 412 mm for the growing season. The hydraulic performance of the irrigation systems showed emitter flow variations of 58.2 % and 61.5 % for drip and rain tube, respectively, indicating poor performance. However, the uniformity coefficients were rated as good, at 82.4% for drip and 78.6% for rain tube. In evaluating the performance of the drip and rain tube irrigation system used on the study site, the ratings were assigned according to ASAE (1999). The emitter flow variation for drip and rain tube irrigation systems was 23.6 % and 30.8 %, respectively, both classified as poor. The uniformity coefficient was 90.45% for drip and 89.76 % for rain tube, rated as very good. Field emission uniformity was 85 % for drip and 81% for rain tube, both rated as good. The coefficient variation was 0.11 for drip (fair) and 0.15 for rain tube (poor), indicating moderate variability in water distribution. The highest vine yield (1.36 ton/ha) and dry above ground biomass (5.51 ton/ha) were recorded under drip irrigation with fertilizer, whereas the lowest yield (0.73

ton/ha) and above- ground biomass (3.12 ton/ha) was observed under rainfed conditions without fertilizer. Water productivity (WP_{ET}) followed a similar trend, with drip irrigation and fertilizer yielding 1.49 kg/m³, while rainfed conditions without fertilizer recorded 0.81 kg/m³. Canopy cover varied significantly, with the highest observed cover (90%) under drip and rain tube irrigation with fertilizer, while rainfed conditions without fertilizer had the lowest (56%). Water use efficiency (WUE) was highest under drip irrigation (2.22 kg/ha/mm), followed by rain tube (1.92 kg/ha/mm), furrow (1.75 kg/ha/mm), and rainfed conditions (1.53 kg/ha/mm). Findings indicate that supplementary irrigation, particularly drip irrigation with fertilizer, enhances vine yield and water productivity. However, rain tube irrigation presents a viable alternative due to its relatively lower cost. This study provides insights for optimizing irrigation strategies in semi-arid environments and serves as a valuable reference for policymakers, researchers, and extension officers promoting climate-smart agricultural practices. The adoption of climate-smart supplementary irrigation techniques with fertilizer support is recommended to improve water productivity and ensure sustainable orange-fleshed sweet potato production.

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May God bless you all abundantly.

DEDICATION

I dedicate this work to my mother, Mrs. Yabilla Majewen.

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LIST OF ACRONYMS AND ABBREVIATION

ANOVA	Analysis of Variance
ASABE	American Society of Agricultural and Biological Engineers
CC	Canopy cover
CIP	International Potato Centre
CROPWAT	Crop Water Assessment Tool
CU	Coefficient of Uniformity
CV	Coefficient of Variation
CWP	Crop Water Productivity
CWR	Crop Water Requirement
DAP	Days After Planting
DU	Distribution Uniformity
ET_C	Crop Evapotranspiration
ETo	Reference Evapotranspiration
EU	Emission Uniformity
FAO	Food and Agricultural Organisation of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical
GMet	Ghana Meteorological Agency
kc	Crop Coefficient
N-RMSE	The Normalized Root Mean Square Error
Ob	Observed
OFSP	Orange Flesh Sweet Potato
Sim	Simulated
UC	Uniformity Coefficient
VAD	Vitamin A deficiency
WP*	Water productivity
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Study Background

Northern Ghana is known for its semi-arid climate and water scarcity, which makes it difficult to sustain crop production (Adekambi et al, 2020). However, cultivating orange-fleshed sweet potatoes (OFSP) has emerged as a promising solution to address the region's food security and nutritional deficits (Global Communities, 2018).

Orange-fleshed sweet potatoes (OFSP) are a significant agricultural crop globally, valued for their nutritional richness, agronomic adaptability, and economic potential. From the perspective of the Food and Agriculture Organization (FAO), Africa, and specifically Ghana, the importance of OFSP transcends mere sustenance, encompassing food security, health promotion, and economic empowerment (Olatinwo, el. al. 2023).

OFSP, scientifically known as *Ipomoea Batatas, L.* is a highly valuable crop, due to its unique and vibrant orange flesh, which signifies its high beta-carotene levels. It is a hardy and flexible crop that can thrive in a wide range of agroecological settings, from tropical to subtropical regions. Successful cultivation of OFSP requires a combination of agronomic practices, including effective land preparation, planting, irrigation, and pest control. By implementing integrated pest management strategies and nutrient management techniques, farmers can significantly improve both yield and quality. OFSP production has enormous potential to improve food security in many regions of the world (FAO, 2020).

The use of Orange-Fleshed Sweet Potato (OFSP) in human nutrition is an optimal strategy for maintaining health and meeting everyday nutritional needs. OFSP is recognized as a functional food because of its dense nutritional profile with high levels of complex carbohydrates, dietary fibre, vitamins, and essential minerals like potassium and manganese. This source of food has a complete range of nutrients vital for human health. A unique benefit of OFSP is its high beta-carotene levels, which are responsible for its orange colour and serve as a precursor to vitamin A. Vitamin A is particularly crucial for children because it is involved in an integral role in immune system functioning, vision, and overall growth and development. In addition, OFSP is rich in antioxidants that help reduce oxidative stress and lower risks related to chronic diseases like cardiovascular diseases and cancer (Escobar et al., 2022).

The Food and Agriculture Organization (FAO) encourages the use of orange-fleshed sweet potatoes (OFSP) in combating vitamin A deficiency (VAD), a major health issue in most areas globally. The use of OFSP may be an efficient way to relieve VAD and its adverse health effects, especially in Sub-Saharan Africa and Southeast Asia. These health effects may include impaired immune responses, increased susceptibility to diseases, and loss of vision.

Research further states that Orange-fleshed sweet potato (OFSP) is a reliable source of dietary fiber which helps in promoting digestive health by aiding digestion, reducing constipation, and lowering the risk of other digestive disorders (Tadesse, 2022). In addition, the complex carbohydrates present in OFSP are slowly digested, providing a steady flow of energy throughout the day (Phorbee et al., 2023).

The OFSP holds great significance not only in terms of its nutritional value and impact on agriculture, but also promises crucial economic benefits, especially for smallholder farmers in developing countries (Chilala, 2019). In Africa, where agriculture serves as the backbone of

many economies, the cultivation of OFSP presents a unique opportunity for generating income, alleviating poverty, and promoting rural development (Girard et al., 2021). By diversifying agricultural production and improving market access, OFSP contributes significantly to food security and economic resilience, particularly considering climate change and other environmental challenges (Chilala, 2019). Additionally, the value-added processing of OFSP into products such as flour, chips, and puree creates pathways for entrepreneurship and agribusiness development, fostering economic growth and employment opportunities along the entire value chain (Stathers, et al., 2015).

According to the International Potato Centre (CIP), the orange-fleshed sweet potato (OFSP) is a highly beneficial crop that can help combat Vitamin A deficiency (VAD) and promote sustainable agriculture, especially in African countries (CIP, 2017). In Ghana, the CIP is promoting the adoption of OFSP among smallholder farmers to address VAD and promote food security (CIP, 2017).

The CIP's OFSP adoption program in Ghana prioritizes training farmers on good agricultural practices, including crop management, pest and disease control, and post-harvest handling. The program also encourages the use of OFSP vines as planting material, which farmers can sell to others, creating an additional source of income (CIP, 2014, Abidin et al., 2015).

Various stakeholders in Ghana are working together to ensure the sustainable adoption of OFSP. Through capacity-building programs, research, and extension services, farmers are empowered to view OFSP as a viable crop that not only improves their livelihoods but also enhances food security in their communities. Integrating OFSP into agricultural policies and practices further supports this goal (CIP, 2015).

Several irrigation techniques can be used to boost agricultural output of OFSP, while minimizing the impact of water scarcity (Levy et al., 2023). For instance, drip irrigation is a

highly efficient and effective technique that delivers water directly to the roots of plants, reducing water loss due to evaporation and runoff (Shareef et al., 2017). Other techniques that can be employed are micro-irrigation (Rain Tube), which is a low-pressure, low-volume irrigation system that delivers water directly to the root zone of plants (Daka, 2006) and furrow irrigation system.

The optimization of water usage in the cultivation of orange-fleshed sweet potato (OFSP) has become a top priority, with various irrigation methods being examined for their potential to boost both root and vine production. Drip irrigation, furrow irrigation, and Rain Tubes systems are among the leading contenders in the search for a balance between crop yield and efficient water consumption. These techniques are being carefully evaluated to determine which is the most effective and to maximize yield, while minimizing water use. The World Bank predicts that these efforts will yield significant benefits in the years ahead, with improved crop yields and more sustainable agricultural practices leading to a healthier and more prosperous future for all (World Bank, 2023).

However, some challenges face cultivation of OFSP. As noted by Makanginya, (2014), OFSP is particularly sensitive to drought stress, which can reduce root yield and quality. To address this challenge, irrigation management strategies that maintain soil moisture at optimal levels throughout the growing season are essential.

Orange-fleshed sweet potato (OFSP) requires adequate moisture throughout the growing season to produce high yields. In many regions where OFSP is grown, water is a scarce and valuable resource, making irrigation management a critical factor in crop production. According to a study by Makanginya, (2014), insufficient water supply can lead to reduced root yield, smaller root size, and inadequate quality, while excess water or poor drainage can cause root rot and other diseases.

Rain/Spray tubes, drip irrigation, and furrow irrigation are all methods that can be utilized while growing orange-fleshed sweet potatoes (OFSP). Each technique has specific principles of operation and efficiency.

Drip irrigation is a highly efficient and sustainable method of watering plants, with a 90% efficiency rate (El-Hendawy et al., 2008). This technique involves placing tubing with emitters on the ground alongside the plants, slowly dripping water into the soil at the root zone and minimizing runoff and evaporation. According to Kumar et al. (2023), drip irrigation also shields plants from disease by minimizing water contact with their leaves, stems, and fruit.

According to research by the Food and Agriculture Organization (FAO) of the United Nations, farmers prefer using drip irrigation due to its ability to deliver a higher return on investment compared to other methods, its efficient use of water and energy, and its ability to support consistently higher crop yields, while saving water (FAO, 2019). Drip irrigation also allows for precise application of nutrients, reducing fertilizer costs and nitrate losses, and can be designed to work uniformly in any topography and soil type. The same research has shown that drip irrigation technology has a positive impact on crop yield, quality, and water productivity. It is observed to improve water use efficiency and reduce water wastage, making it a valuable technique for sustainable agriculture (FAO, 2019).

Furrow irrigation is a traditional irrigation technique that involves digging shallow channels or furrows between rows of crops. Water is then applied to the furrows, and it infiltrates the soil and reaches the roots of the plants. This method uses more water than drip irrigation because it causes water loss through runoff and evaporation. However, it is still a viable option for OFSP cultivation in regions with moderate water availability. (Kassaw, 2020).

Rain tube irrigation, a form of low-volume, low-pressure irrigation designed to supply water directly to the root zone of plants (Shareef et al., 2017). The system consists of plastic tubes

with very small perforations, positioned near the base of each plant. Water flows slowly through these holes, ensuring that moisture reaches the roots efficiently without significant loss from evaporation or surface runoff. This method allows for precise water application, reduces water wastage, and is particularly suitable for small-scale crops such as orange-fleshed sweet potato (OFSP) in semi-arid regions with limited water resources. By maintaining consistent soil moisture, rain tube irrigation supports better crop growth and can improve water productivity in resource-constrained farming systems (Shareef et al., 2017).

1.2 Problem Statement

Ghana's agricultural sector remains important to the country's sustainable growth and development because of its impact on employment and poverty reduction (Danso-Abbeam & Baiyegunhi, 2020; Mensah, 2019). It is also an important source of income and livelihood for many households (GSS, 2017) compared to other sectors and is dominated by staple crops (MoFA, 2007; MoFA, 2019). OFSP is specifically vital among Ghana's staple foods since it has the ability to sustain acceptable yield even under adverse conditions and can be cultivated on a wide variety of agro-ecologies and soils. It thrives with little input requirements and is a low-risk crop that is grown widely in developing countries (Kaguongo et al., 2010 Abidin et al., 2017; Low et al., 2020). It has a short maturity period, flexible harvesting time and drought tolerance, which makes it a suitable household food security crop and thus, an important livelihood option for smallholder farmers (Low et al., 2007; FAO, 2013; Nyor et al., 2017). The production and consumption of OFSP in Ghana is promoted by several agencies such as Helen Keller International, Kofi Anan Foundation, Bill & Melinda Gates Foundation, CIP, MoFA, Ghana Health Services and, CSIR-CRI, among others.

Water scarcity and drought directly reduce soil moisture levels, leading to decreased OFSP yield and quality. Without sufficient water, the tuber formation process is hindered, resulting in smaller and lower-quality sweet potatoes (Binti et al., 2020). Inadequate water availability

hinders OFSP plant growth and jeopardizes root development. This stunted growth not only reduces yields but also affects the nutritional content of the sweet potatoes, undermining their potential to address malnutrition (Low et al., 2017). Water-stressed plants are more susceptible to pest and disease infestations. The weakened state of OFSP plants under drought conditions makes them easy targets for pests and pathogens, further compromising yields and exacerbating food insecurity (Andrade et al., 2019).

Also, OFSP production is mainly rainfed in Ghana, thus highly susceptible to adverse weather conditions. Unlike in the southern Ghana, which has two rainy seasons and where OFSP can be cultivated all year round, the Northern Ghana is characterized by a single rainy season with an extended dry season. This constrains the availability and quality of roots and vines on the market during the off-season, resulting in high price fluctuations (Udemezue and Eluagu, 2021). Empirical studies by Dukuh (2003) in Ghana and Anderson et al. (2019) in Ethiopia, found 67% and 135% increase in roots prices, respectively, during the off season. (Emana & Gebremedhin, 2007) also reported that sweet potato is sold for higher prices for 6 months and at a lower price than average for 4 months, annually.

Inadequate irrigation infrastructure in SSA, including Ghana, restricts farmers' ability to mitigate the effects of water scarcity and drought. Smallholder farmers often lack access to efficient irrigation systems, relying instead on rainfall, which is increasingly unpredictable due to climate change (FAO, 2020). Poor understanding of effective irrigation management practices among farmers exacerbates the impact of water-related challenges on OFSP production. Many farmers in SSA, including Ghana, lack the knowledge and resources to implement water-saving techniques such as drip irrigation or soil moisture monitoring (Alwang et al., 2019). This underscored the need for dry season production of OFSP to (1) explore and identify more efficient irrigation techniques that can optimize water use and enhance crop productivity, specifically tailored to the cultivation of OFSP (2) provide timely and quality

planting material for farmers for all year production, and (3) to ensure all year supply of roots to meet the growing consumption needs of Ghanaians. Thus, the adoption of irrigated farming could lead to sufficient production of OFSP.

This study seeks to fill the information gap by conducting comprehensive assessments on different irrigation methods (drip irrigation, furrow irrigation, and rain tube) to identify the most efficient technique in terms of Crop Water Productivity (CWP) when accompanying Fertilizer Application. By comparing fertilizer and water use and crop yield across these techniques, it aims to determine which method optimizes water resources while maximizing sweet potato production. The present study endeavours to delve into the nuances of the agricultural system prevalent in northern Ghana, with the objective of providing valuable insights into strategies that could potentially augment food security and improve the economic status of smallholder farmers. The overall aim of this research is to attain a greater comprehension of the complexities related to the cultivation of Orange Fleshed Sweet Potato (OFSP) through the utilization of both statistical analysis and mathematical modelling. The findings of this research will aid policymakers, researchers, and practitioners in the development of sustainable agricultural methods in the area.

1.3 Main Research Question

How do different supplementary irrigation techniques influence the water productivity of Orange-Fleshed Sweet Potato, and what are their implications for vine production in the agricultural context of Northern Ghana?

1.3.1 Research Questions

1. What are the differences in crop water productivity (CWP) among various irrigation techniques and fertilizer used in the production of Orange-Fleshed Sweet Potato in Northern Ghana?

2. What is the water use efficiency (WUE) of each irrigation technique employed for sweet potato production in the Northern Ghana?

3. Can the AquaCrop Model be successfully used to predict the crop characteristics of the Sweet Potato grown under different irrigation methods in East Mamprusi District?

1.4 Study Objective

To evaluate the water productivity of different supplementary irrigation techniques for vine production of Orange-Fleshed Sweet Potato in Northern Ghana.

1.4.1 Specific Objectives

1. To evaluate and compare crop water productivity (CWP) for sweet potato production in Northern Ghana using different supplementary irrigation methods and application of fertilizer.

2. To evaluate and compare the water use efficiency (WUE) of each irrigation technique employed for sweet potato production

3. To calibrate of AquaCrop model to predict orange-flesh sweet potato growth, water productivity, and yield under different irrigation practices in East Mamprusi District

1.5 Limitation

The limitation of this study is that the hydraulic performance of the furrow irrigation system is not directly assessed using standard hydraulic indicators. Unlike drip and rain tube systems, which are pressurized and allow direct measurement of emitter flow, emission uniformity, and coefficient of variation, furrow irrigation is a surface, gravity-driven system. Its water distribution depends on soil infiltration, field slope, furrow length, and opportunity time, making it difficult to assess using the same metrics as pressurized systems. Consequently, the performance of furrow irrigation is evaluated indirectly through crop response indicators such as vine yield, water productivity, and water use efficiency

1.6 Significance of the Study

The significance of the study on evaluating the water productivity of different irrigation techniques for roots and vine production of Orange-Fleshed Sweet Potato in Northern Ghana lies in its potential to contribute to the following aspects:

- Improved productivity and sustainability of Orange-Fleshed Sweet Potato (OFSP) production in Northern Ghana, which is crucial for addressing malnutrition and improving nutrition security in the region (Arnold, et al 2023).
- Identification of the most efficient irrigation techniques for OFSP production, which can help farmers in Northern Ghana optimize water resources and reduce water scarcity, particularly in the context of climate change and increasing demand for food.
- Better understanding of water use efficiency (WUE) in OFSP production, which can inform future research and policy development in the field of irrigation and crop production.
- Potential integration of the findings into existing literature and knowledge based on OFSP production, irrigation techniques, and water management practices, thereby contributing to the global effort to combat malnutrition and improve food security (, Masango, 2015; Arnold, et al 2023).

The study is therefore aimed at proposing practical insights and recommendations for improving water productivity in sweet potato production in northern Ghana as part of contributing to global efforts at ensuring food security and combating malnutrition. The study is organized in five chapters. The research problem, research aims, justification, and scope for study are discussed in Chapter One. A critical review on water productivity, different techniques in irrigation, and use of AquaCrop model for simulating crop is demonstrated in Chapter Two. Material and methods, experimental plot, methods used in

data collection, and calibration procedures for model are demonstrated in Chapter Three. Results and discussions are demonstrated in Chapter Four with comparison on different techniques in irrigation on water productivity, vine and above ground biomass yield, water use efficiency, AquaCrop simulation and comparison on effect on inorganic fertilizer treatment on orange flesh sweet potato vegetative growth. Finally, conclusions and recommendations on how to maximize water management for sweet potato production are demonstrated in Chapter Five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Origin, Botany and Physiology of Orange Fleshed Sweet Potato

Extensive research has been conducted regarding the antiquity of orange-fleshed sweet potatoes (Ipomoea batatas (L.) Lam.) (e.g., Austin, 1988; Yen, 1982; Huang and Sun, 2000; Zhang et al. 2000), leading to comprehensive documentation of its origins and botanical properties. According to Austin (1988) and Yen (1982), tropical America is where sweet potatoes were first domesticated at least 5,000 years ago. Based on an examination of the major physical traits of wild Ipomoea species and sweet potatoes, Austin (1988) suggested that the sweet potato originated in the region spanning from Mexico's Yucatan Peninsula to Venezuela's Orinoco River. Molecular marker analysis revealed the highest diversity in Central America, providing support for the hypothesis that Central America is the primary center of diversity and the birthplace of sweet potatoes (Zhang et al. 2000; Huang and Sun, 2000). Sweet potatoes were first brought to Europe by Columbus in 1492, and Portuguese explorers took them to Africa, India, Southeast Asia, and the East Indies in the sixteenth century. In the sixteenth century, the introduction of sweet potatoes to the Philippines was facilitated by Spanish ships that brought these crops from Mexico. (Yen, 1982). Fossil carbonized storage roots discovered in northern New Zealand provide evidence of sweet potatoes appearing in the Pacific islands as early as 1000 years ago (Yen, 1991). This discovery strongly supports the theory of prehistoric transfer, likely by Peruvian or Polynesian voyagers, although there is some controversy surrounding this theory (Yen, 1982). The linguistic similarity between the Quechua and Polynesian names for sweet potato supports the idea of a Peruvian origin and human transfer of the Polynesian sweet potato. However, researches using molecular markers have shown that Papua New Guinean and Peruvian sweet potatoes are not directly connected.

They are distinct from Mesoamerican ones (Zhang et al., 2000 and Zhang et al., 1998). According to Rossel et al. (2001), the Oceania sweet potato most likely originated in Central America and spread by non-human means.

In the late 16th century, the crop was brought to China by ship from the Philippine Island of Luzon to the Chinese province of Fujian (O'Brien, 1972). 1594 was a year of famine, resulting in the destruction of a vast region of crops. To prevent starvation, the Fujian governor instructed farmers to plant a large amount of sweet potatoes (Zhang et al. 2009). According to other research, sweet potatoes were imported to China from Vietnam, India, and Burma. It appears that sweet potatoes spread throughout China from south to east along the coast and from south to north along the valleys of the Yangtze and Yellow rivers (Anonymous, 2003).

Sweet potatoes are grown as an annual crop from stem cuttings or plant sprouts from store roots. Sweet potatoes are herbaceous perennials. Sweet potato usually grows in prostrate form, with 1-4 m long vines that run horizontally across the ground. There are three sections to the plant: 1) The photosynthetic canopy is made up of the leaves. 2) The stems play a crucial role in transporting essential nutrients and water from the roots while also delivering energy to the leaves, ensuring the plant thrives and flourishes. 3) The roots, which serve as the plant's anchor, taking up water and nutrients from the soil, and, when fleshy storage roots form, as a place to store energy. Three diverse types of roots are found in sweet potatoes: pencil, fibrous, and storage. (Kays, 1985a; Firon et al., 2009). Young adventitious roots develop out of both the nodal and the internodal regions of an underground stem portion of a vine, cutting roots from the internodal regions Normally, fibrous roots develop and exhibit a tetrarch arrangement of their primary vascular tissue (Smith, 2018). Roots originating from the nodes are typically pentarch or hexarch and have the potential to become enlarged storage roots (Johnson & Lee, 2019). In unfavorable circumstances, many of these roots could become primary fibrous roots or lignify to become pencil roots (Brown et al., 2020). Some of the roots that will eventually

grow into storage roots are among the first to emerge from the nodal areas (Clark, 2017). Therefore, it is crucial to minimize stress during the first month after transplanting to ensure good storage root development (Taylor, 2016). Many cultural approaches for sweet potatoes in highly established production systems include reducing stresses such as high nitrogen levels, low oxygen, or dry circumstances (Davis & Green, 2021). Storage root initiation varies greatly between cultivars and occurs 1-13 weeks after planting, when the amount of storage roots per plant is assessed (Ravi and Indira 1999). The size of the storage root is established before its width, and shape is established by differential rates of longitudinal and lateral growth. The length of the storage root is determined before its width. Its shape is established by differential rates of longitudinal and lateral growth. It is challenging to increase size and shape regularity in sweet potatoes because root set varies greatly, even within the same field and cultivar (Firon et al. 2009). Air and soil temperatures influence the growth and expansion of storage roots (Smith, 2005). Storage root development is enhanced by nocturnal air temperatures ranging from 15 to 25°C, although optimal soil temperatures for storage root growth are between 20 and 30°C (Jones, 2010). Various cultivars have distinct growth durations (Brown et al., 2018). Storage roots come in diverse shapes, lengths, and weights and contain carotenoid and anthocyanin pigments that influence their colour (Johnson, 2013). The vines are prostrate with occasional twining and may create a secondary set of storage roots (Roberts, 2016). Leaves, stems, and flowering also vary under different conditions (Garcia et al., 2017).

2.2 Distribution and Economic Importance

Sweet potatoes are ranked as the seventh most important food crop globally in terms of production. They are grown across approximately nine million hectares, yielding around 140 million tons, which corresponds to an average of about 14 tons per hectare (FAOSTAT, 2001). Sweet potato cultivation is predominantly found in developing countries, which represent over 95% of global production. Approximately 80% of the world's sweet potatoes are cultivated in

Asia, underscoring the region's prominent role in global agriculture. Africa contributes about 15% to the total production, while other regions account for the remaining 5%.. In China, around 6.6 million hectares are devoted to sweet potato farming, which represents an impressive 70% of the total global cultivation area. Notably, China produces over 100 million tons, which is approximately 80% of total global production. The second-largest producer is Vietnam. In China, 65% of the sweet potato harvest is directed towards animal feed, particularly for pigs, highlighting the crop's vital role in livestock nutrition. Similarly, Vietnam has also integrated sweet potato production into its pig farming practices (Bottema, 1992). Additionally, sweet potato-pig systems contribute significantly to the rural economies of various Asian countries, including the Philippines, India, Korea, Taiwan, and certain eastern Indonesian islands such as Bali and Irian Jaya, as well as Papua New Guinea. These systems also find application in some Latin American and African regions, though to a lesser degree (Scott, 1991).

In Brazil, sweet potatoes rank as the fourth most consumed vegetable, offering high energy content through their carbohydrate-rich composition. They also provide essential nutrients, including reasonable amounts of vitamins A, C, and various B vitamins (Miranda, 2002). In the United States, around 37,000 hectares are utilized for sweet potato cultivation, resulting in an impressive annual production of approximately 720,000 tons. In Africa sweet potatoes are a 'poor man's crop', (and traditionally considered as “women’s work”) (Low et al., 2009), with most of the production done on a small or subsistence level. Compared to other food crops worldwide, sweet potatoes yield the highest amounts of nutrients and biomass per hectare (Woolfe, 1992). Sweet potatoes are highly adaptable crops that thrive in fertile tropical soils, making them an excellent choice for sustainable agriculture as they don’t require fertilizers or irrigation for tuber production. Their resilience plays a crucial role in combating famine, particularly in East Africa, where numerous villages in semi-arid, densely populated plains

depend on sweet potatoes to ensure food security. Additionally, in Japan, sweet potatoes have served as a vital resource during natural disasters, such as typhoons that devastate rice fields (Woolfe, 1992; Low et al., 2009).

Sweet potato is produced for both the leaves, which are consumed as greens, and the tubers, which are strong in carbohydrates and beta-carotene (Woolfe, 1992). Yields can differ significantly between various regions or even within individual fields in the same location. On average, African countries achieve around 4.7 tons per hectare. In Africa, the average yield is around 4.7 tons per hectare, but we see some notable differences: Kenya reaches an encouraging 8.9 tons/ha, while Uganda produces 4.3 tons/ha, Sierra Leone is at 2.6 tons/ha, and Nigeria yields 6.5 tons/ha. In terms of crop yields, Asia stands out with significantly higher averages, reaching 18.5 tons/ha. Notably, China, Japan, Korea, Thailand, and Israel boast the highest yields, with around 20, 24.7, 20.9, 12, and 33.3 tons/ha, respectively. Meanwhile, South America follows with an average yield of 12.2 tons/ha, with Argentina, Peru, and Uruguay as the top performers at 18, 11, and 10 tons/ha, respectively. Comparatively, the US demonstrates an average yield of 16.3 tons/ha (all data presented are averages for 2000 and 2001 from FAOSTAT 2002).

The difference in yield is directly due to difference in propagation material quality. Sweet potato is propagated only from vine pieces, root slips or sprouts, and tubers. African and other farmers are accustomed to using field-grown pieces of vine to propagate season to season. Consequently, the presence of virus diseases in the field inevitably leads to their transmission with the propagation material to the newly planted field, ultimately resulting in a significant decrease in yield (Clark et al., 2012).

In recent years, there has been a slight increase in sweet potato consumption in the US. This growth can be attributed to national advertising campaigns that focus on the nutritional benefits

of sweet potatoes, targeting health-conscious consumers (USDA, 2020). Sweet potatoes are highly nutritious and deserve to be more widely consumed. They are considered one of the healthiest vegetables due to their high levels of vitamins A and C, iron, potassium, and fibre (Woolfe, 1992). They serve as a fantastic source of beta-carotene, which is a vital precursor to vitamin A. For instance, one cup of orange-fleshed variety provides four times the recommended daily allowance of this essential nutrient. Furthermore, advancements in curing and storage techniques, along with innovative fresh shipping methods—such as individually wrapping tubers in plastic for convenient microwaving—have greatly enhanced their accessibility. Processed products like sweet potato chips, fries, and canned sweet potatoes are expected to expand the market (USDA, 2020).

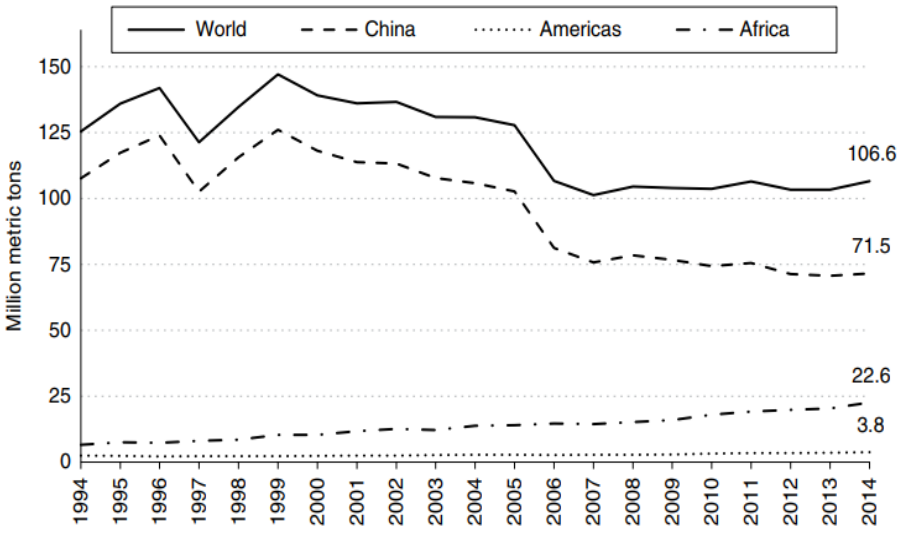

Figure 2.1 Global and regional sweet potato output from 1994-2014.

Source: (FAO, 2012)

2.3 Overview of Sweet Potato Production in Ghana

The annual global production of sweet potato exceeds 133 million tons (FAOSTAT, 1998), making it the most significant crop in terms of fresh weight in developing countries, following rice, wheat, maize, and cassava. A study conducted by CORAF/IFPRI (2006) revealed that

roots and tubers contribute the most to agricultural growth in West and Central Africa, as well as in Ghana. According to FAOSTAT in 2006, Ghana produces 90,000 tons annually from 65,000 hectares of land. According to current information from Ghana's CSIR-CRI, roots and tubers contribute approximately 40% to Ghana's GDP, while cereals contribute 7%. However, Ghana is not providing sufficient production support services to fully realize the potential of sweet potato for food security and poverty reduction (Sam and Dapaah, 2009). Storage, marketing, and utilization are significant concerns in sweet potato production because the tubers are typically sold within two to four weeks after being harvested. Table 2.1 below lists Ghana's production status by region along with each region's proportional share of the nation's total production. In an effort to enhance the production, marketing, and utilization of sweet potato—especially the orange-fleshed variety—the International Potato Centre (CIP) in Ghana has undertaken a community needs assessment, an initiative aimed to collect valuable insights into the current landscape of sweet potato production, marketing, and utilization in northern Ghana. The results of this analysis were anticipated not only to serve as a guide to CIP Ghana identify promising opportunities but also contribute to the design of impactful interventions tailored for selected districts in the three northern regions. Furthermore, this data will serve as a critical reference point for tracking progress and making informed decisions as we move forward.

Table 2.1: Production of sweet potatoes in Ghana (2012)

Region	Area (hectares)	Percentage Contribution	Production (megatons)	Percentage Contribution
Central	371	3.9	6490	4.9
Volta	880	9.1	15340	11.6
Eastern	1030	10.7	34910	26.4
Greater Accra	38	0.4	640	0.5
Ashanti	37	0.4	620	0.5
Brong Ahafo	145	1.5	2390	1.8

Northern	414	4.3	6090	4.6
Upper East	5550	57.7	46000	34.9
Upper West	1157	12.0	19530	14.8
Total	9622	100.0	131990	100.0

Source: MoFA Field Survey, 2012

2.4 Crop Water Requirement of Sweet Potato

Crop water requirements (CWR) include the total amount of water utilized in evapotranspiration. The concept of Crop Water Requirements (CWR) is defined by the FAO (1984) and Mebrahtu et al. (2021) as the depth of water needed to offset the losses due to evapotranspiration in crops. This definition applies to extensive fields where crops are assumed to be free from disease and are grown under non-restrictive conditions, incorporating soil water and fertility, and attaining maximum production potential within the prevailing growing environment." It is typically expressed as Etc. in mm/day and is contingent upon variables such as climate, crop type, area, soil physical properties, and growing seasons (FAO, 2009). The key factors that positively influence CWR values are the crop coefficient (Kc) and potential evapotranspiration (ETo). Evapotranspiration plays a crucial role in the water cycle by facilitating the combined loss of water from the soil surface of crops and through the stomatal pores of plants. Understanding this process is essential for effective irrigation scheduling and can lead to more sustainable agricultural practices (Feng et al., 2021). Additionally, addressing the impacts of climate variability and change on the hydrologic cycle allows us to refine our approaches to managing processes like evapotranspiration, ultimately promoting more resilient ecosystems and agricultural systems (Rezaei et al., 2016).

According to Chowdhury et al. (2015), an increase in temperature leads to increased evapotranspiration, attributed to the widening of stomatal pores in plant leaves during high temperatures, resulting in rapid water vapor loss (Urban et al., 2017; Onyutha, 2020). Scholars (Rotich and Mulungu, 2017; Salman et al., 2020) assert that there could be subsequent effects

on crop water requirements (CWR) and water availability when temperature, evapotranspiration, and rainfall patterns change. Prolonged dry conditions or droughts may occur due to low precipitation and increased temperature, ultimately impacting CWR (Onyutha, 2020).

Yield variations are directly caused by propagating material differences. Sweet potato is planted only by means of vine, root slip (sprouts), or tubers. Vines from open fields are traditionally used by African and other farmers for propagating on a year-round basis.

There are several experimentally tested techniques of CWR estimation have been developed, such as Blaney-Criddle, Radiation, Modified Penman, and Pan Evaporation methods, and the FAO Penman-Monteith method. The Blaney-Criddle method is the oldest and simplest, while the FAO Penman-Monteith is the most recent and accurate method for determining CWR, making it the suggested method for determining reference evapotranspiration with climate data (Ewaid et al., 2019; Feng et al., 2021). Additionally, the FAO has developed a decision-support tool called CROPWAT for irrigation scheduling and management, mostly used to estimate reference evapotranspiration (ETo) and CWR. It includes

The procedure for estimating reference evapotranspiration and crop water requirement enables the simulation of crop water use in varying conditions (climatic, crop, and edaphic). (“CROPWAT 8 parameters applied to compute the crop water ... - ResearchGate”) It assists in adopting suitable irrigation schedules and practices and accurately assessing crop production under irrigation or rainfed conditions (Gabr, 2021). CROPWAT facilitates the estimation of crop evapotranspiration (ETc), agricultural water requirements, and irrigation scheduling. Each crop has specific water requirements under similar weather conditions. Proper estimation of CWR is relevant, especially in arid areas, to enable effective irrigation design and scheduling and judicious water use (Rowshon et al., 2014; Xu et al., 2021). A good understanding of crop

water needs aids in the proper planning of irrigation regimes and management (Mebrahtu et al., 2021).

Kim et al. (2017) noted that the major portion of evapotranspiration in a fully mature, orange-fleshed sweet potato crop during the daytime is the water lost from the soil and crop surfaces. Sweet potatoes have varying water requirements throughout their growth stages. The critical period demanding the highest water supply occurs during root development and enlargement, typically 4-5 weeks after planting the slips (Firon et al., 2012). However, excessive water, such as waterlogging during this stage, can significantly decrease yields (Kano-Nakata et al., 2020).

In the early growth stages, many growers provide 18-20 mm of water per week (Smith, 2018), continuing until mid-season when irrigation rates are typically increased to around 40 mm per week (Jones, 2019). As the crop matures, growers often reduce irrigation to about 20 mm per week to prevent root cracking (Brown et al., 2021). Irrigation typically ceased 2-3 weeks prior to harvesting to mitigate the risk of sweet potato rot (White, 2017). Furthermore, the water requirements of sweet potatoes can differ based on various weather and soil conditions. For instance, heavy clay soil typically requires less irrigation than sandy soil (Smith et al., 2020). Additionally, different varieties of sweet potatoes may exhibit differing water needs (Johnson & Williams, 2018).

2.5 Water Stress

Addressing water scarcity is vital for ensuring global food security, particularly in Africa (Farooq et al., 2009). Discrepancies in crop productivity and achievable yields are attributed to variations in water availability and crop water consumption. Soil water is critical for sweet potato production, given its susceptibility to water fluctuations during establishment, vine growth, tuber initiation, and bulking stages (Gajanayake et al., 2013). Agro-climatic conditions and soil water levels significantly influence root growth and yield. Effective water management

through stomatal closure during the water deficit experienced by vines is imperative, as it directly impacts photosynthesis and vine growth rate (Smart and Coombe, 1983). Unlike cereals, sweet potato roots exhibit the ability to survive dormancy during dry periods and adverse climatic conditions, resuming growth when conditions improve (Ravi et al., 2009). Water stress during the initial stages of development has a detrimental effect on the growth and tuber yield of sweet potatoes (Gajanayake et al., 2013). Furthermore, it is crucial to mitigate low soil water content and drought conditions as they impede storage root development, leading to reduced tuber yield, especially during the tuber bulking stage (Thompson et al., 1992).

Insights from Gomes and Carr's (2003) study in Mozambique highlighted the impact of water availability and vine harvesting frequency on sweet potato productivity, with water consumption ranging from 360 to 800 mm during the growing season. Additionally, research indicates that even mild water stress can hamper leaf expansion during the vegetative growth stage, potentially affecting the leaf area index in most crops. Water consumption by sweet potatoes is an important factor that varies significantly across different regions. For instance, in some areas, sweet potatoes require about 500 mm of water (Norman et al., 1984), while in Cuba, the requirement is around 300 mm (Castellanos, 1984). In Nigeria, it required approximately 450 mm (Onyekwere and Okafor, 1992). It is essential to consider these variations and the dependence on rainfall, as exemplified by research in Mozambique, where water consumption during the rainy season reached 800 mm but significantly reduced to 550 mm during drought conditions. Prolonged water stress remains a considerable concern due to its inhibitory effect on root development, potentially resulting in shorter or misshapen roots. Therefore, ensuring optimal soil moisture conditions, below field capacity (wet but completely drained) and above wilting point, is crucial for maximizing crop performance (Mintz and Walker, 1993).

It is worth noting that sweet potato's resilience to drought stress, resulting in only a 25% reduction in overall production compared to staple crops like maize, which can experience a 50% yield loss or complete failure due to drought (Kivuva, 2013; Oerke and Dehne, 2004), highlights its potential as a drought-tolerant crop. This is further supported by the plant's adaptability to drought-prone environments owing to its high phenotypic plasticity, enabling it to acclimatize effectively to challenging conditions. The classification of sweet potato as a drought-tolerant crop based on C3 metabolism (Xoconostle-Cazares et al., 2010) underscores its increased acclimation capacity and higher yields, positioning it as a potential solution in areas prone to water scarcity and drought conditions.

2.6 Water Use, Efficiency, and Productivity

The terms efficiency (WUE), productivity (WP), and water use (WU) are related but separate concepts that are frequently used interchangeably. Crop growth indices show that WUE measures the quantity of water used in a crop production system. Crop Water Productivity (CWP), a key concept in agronomy which seeks to optimize yield per unit of water used in both rain-fed and irrigated agricultural production. Increasing marketable yields per unit of transpired water, reducing water loss from the soil water balance, and optimizing the use of rainwater in the soil are three ways to improve WP. WU and WUE are closely related to CWP and are used interchangeably. WP is akin to WUE and has been used interchangeably in literature dating back to the 1960s. Additionally, Passioura (2006) highlighted that WUE is reliant on: i) the soil's water storage capacity, ii) the crop's ability to extract water from the soil during its growth phase, and iii) the efficiency of water conversion to plant biomass.

2.6.1 Crop Water Use

Crop water use efficiency (WUE) is essentially the same as evapotranspiration (ETc), which refers to the combined water lost through evaporation from the soil and transpiration from plant leaves. The process of water being released into the atmosphere through plant stomata is what

we know as evapotranspiration. Water is not only involved in the growth process but also serves as a cooling agent during transpiration (Molden, 1997). CWU is closely tied to the interplay between the plant roots' ability to absorb water from the soil surface and the canopy's effectiveness in releasing this water into the atmosphere through transpiration (Morris and Garrity, 1997).

Maintaining adequate soil moisture during the crop's growth stages is crucial for achieving optimal production; this relates to the yield obtained relative to the available soil water (Al-Kaisi and Broner, 2009). When the soil reaches a lower matric potential due to drying, plants use a significant amount of energy to extract water from the soil. This energy could instead be utilized for other biochemical processes (Karuku et al., 2014). Moreover, as soil water levels drop below field capacity, crops use less water, leading to water stress that can hinder the development of leaves and stems. Similarly, inadequate water supply slows cell expansion and division, affecting the development of enzymes and proteins crucial for growth (Fahad et al., 2017).

2.6.2 Water Use Efficiency (WUE)

WUE (water use efficiency) is a crucial measure that quantifies agricultural productivity in water-stressed areas by evaluating the amount of dry matter generated per unit of water used for evapotranspiration (Molden, 1997). This metric is essential for understanding and improving crop performance in regions with limited water availability. WUE allows plants to thrive under low soil moisture conditions by effectively balancing water usage and biomass production (Shao et al., 2008). It is determined by the total biomass produced per unit area through evapotranspiration.

Researchers worldwide have conducted valuable simulations to assess WUE, particularly focusing on cereals and legumes, including monocrops and intercrops. These studies have

provided crucial insights into crop WUE and have significantly contributed to the identification of traits associated with drought tolerance (Juma, 2012). Breeding for improved WUE in crops is imperative, especially in the face of severe drought. Additionally, enhancing water consumption, water use efficiency, and harvest index are all important strategies for maximizing crop performance (Araus et al., 2002).

Implementing effective agronomic practices to minimize water losses and enhance water uptake by the roots can significantly improve WUE. Managing physiological processes to minimize seed transpiration and maximize yield is a key aspect of increasing WUE (Hsiao and Bradford, 1983).

Research in drought-prone regions, such as South Africa and Mozambique, has revealed that WUE can be improved by reducing water usage in crop production. WUE refers to the ratio of crop yield (biomass or grain produced) to the amount of water used in crop production (Zwart & Bastiaanssen, 2004). Improving WUE does not simply mean producing more crops with more water; rather, it often involves strategies to minimize water losses while maintaining or even increasing crop productivity. Reducing water use improves water use efficiency (WUE) by minimizing non-productive losses such as evaporation, runoff, and deep percolation, ensuring more water supports transpiration and yield (Howell, 2001; Fereres & Soriano, 2007). Water-saving practices like deficit irrigation, drip systems, and precise scheduling enhance efficiency while preventing problems linked to over-irrigation, such as nutrient leaching and waterlogging. Controlled water application can also induce mild stress, stimulating deeper roots and better stomatal regulation, which strengthen crop resilience (Blum, 2009). In drought-prone regions, the goal is to optimize yield per unit of water rather than maximize yield per area, making reduced water use a strategy for sustainable production and climate resilience (Rockström et al., 2010). In this regard, supplemental irrigation practices, especially during

critical growth stages, can be highly beneficial, such as during tuber bulking in sweet potatoes (Dalla & Giovanardi, 2000).

To optimize WUE, it is essential to meet the water demands of crops by implementing appropriate irrigation practices. For example, fractional root irrigation has shown promising results in improving WUE and leaf-relative water content in maize plants (Li et al., 2010). Monitoring soil moisture and making timely irrigation decisions are necessary for maximizing WUE (De Pascale et al., 2001).

2.6.3 Crop Water Productivity (CWP)

Water productivity can be measured in a variety of ways by a number of industries that use water for production, including agriculture, fishing, and residential and commercial water use. Water productivity in crop production is represented by the symbol CWP, which stands for the relationship between crop productivity and water use. Mathematically, CWP is expressed as:

$$CWP = \frac{\text{Biomass produced}}{\text{Total crop water transpired}} \quad \text{(E.q 2. 1)}$$

CWP is measured in kgm-1. Furthermore, CWP can be expressed in any currency, such as USD m-1, as the economic return from crops produced per unit volume of water. Kadigi et al. (2004) and SWMRG (2003). CWP offers valuable insights into the potential increase in crop yield due to improved water supply (Burke et al., 1999). It also enables a swift assessment of whether yield is limited by water availability or other factors (Augus van Herwaarden, 2021). Additionally, by displaying the percentage increase in yield per unit of water consumption, CWP is a helpful metric for assessing the effectiveness of an irrigation scheduling process. This makes it possible to calculate the impact and worth of an expanded water supply. For

agricultural irrigation systems to be implemented successfully in every region, quantitative data on CWP is therefore essential.

2.7 Agro-climatic factors affecting growth and yield orange fleshed sweet potato.

Orange fleshed sweet potato storage root growth and yield are a result of Agro-climatic conditions. In contrast to cereal grains, orange fleshed sweet potato can undergo period of arrested growth during adverse climatic conditions and then proceed to grow when conditions improve

2.7.1 Soil Water

The orange-fleshed sweet potato crop thrives well in regions with an annual rainfall ranging from 750 to 1000mm. Adequate growth can also be sustained with an average rainfall of 500mm during the growing season. This crop is generally tolerant to drought, attributed to its low plant growth habit and extensive root system (Belehu, 2005). However, it is important to note that the plant is sensitive to water stress during the establishment phase, early vine development, and storage root initiation (Gajanayake et al., 2013). Early season water stress significantly impacts sweet potato growth, development, and final yield (Gajanayake et al., 2016). It is crucial to adjust crop water requirements as the plant grows, as low water availability and dry spells can hinder storage root growth and yield, particularly during the initial storage formation (Thompson et al., 1992).

Jones et al. (1986) observed that sweet potatoes exhibit a significant increase in total root yield when water stress is introduced 30 days after planting. It would be valuable to further investigate this result. Notably, during storage root initiation, sweet potato plants cannot tolerate waterlogging, hence proper soil drainage is essential (Belehu, 2005). Excess soil water can stimulate shoot growth, but hinder storage root formation, leading to excessive top growth

(Laurie & Niederwieser, 2004). Wet soils at harvest can promote root rot and negatively impact yield.

2.7.2 Temperature

Optimal night temperatures ranging between 15°C and 25°C are crucial for encouraging the formation and growth of storage roots, with a specific range of 14°C to 22°C resulting in the maximum sweet potato yield as per (Belehu, 2005). However, it is important to note that night temperatures exceeding 25°C may hinder tuber formation while promoting shoot growth, according to Du Plooy (1989). Conversely, cooler night temperatures ranging between 11.3°C and 26.4°C, coupled with irrigation during the 5 to 13-week growth period, have shown to significantly boost the rate of storage root growth (Goswami et al., 1995).

Furthermore, it is essential to maintain soil temperatures between 20°C and 30°C to promote optimal storage root formation and growth, while keeping it at 15°C will encourage fibrous root development. Soil temperatures exceeding 30°C may lead to an excessive focus on shoot growth (Spence & Humphries, 1972). Lastly, it is worth noting that maintaining a slightly cooler soil temperature, such as 20°C, can facilitate a greater conversion of sucrose to starch in the storage root, thus favouring its development.

2.8 Crop modelling

The use of crop models has become increasingly common in research, teaching, crop systems, natural resources management, and policy advisory (Seligman, 1990). Crop modelling has evolved from a marginal activity to a tool that is now routinely used for research, greatly improving the effectiveness of field research through the extrapolation beyond the limits of the site, season, and management (Robertson and Canberry, 2010). These models are classified based on several criteria. Equations, primarily regression, that depict how crops react to field management variables like fertilizer application and watering are known as empirical models.

Mechanistic models, on the other hand, incorporate the physiological processes of crops as they interact with environmental factors (Motha, 2011). Based on the crop growth engines, crop models can be classified as carbon-driven, solar radiation-driven, and water-driven models (Todorovic et al., 2009). Figure 2.2 illustrates the conceptual framework of biomass production in crop models, highlighting the pathways of carbon, radiation, and water-driven processes. The diagram shows how carbon assimilation, radiation use efficiency (RUE), and water productivity (WP) contribute to biomass accumulation under different modelling approaches. Carbon-driven models, often computational or theoretical are those that base crop growth on the assimilation of carbon during the photosynthesis process (Todorovic et al., 2009). The World Food Studies (WOFOST) and Crop Growth (CROPGRO) models, which are part of the Decision Support System for Agrotechnology Transfer (DSSAT), are two instances of carbon-driven models.

In radiation-driven models, biomass is proportional to the Radiation Use Efficiency (RUE), representing the interception of direct solar radiation by the crop (Todorovic et al., 2009). Examples include Crop Environment Resource Synthesis (CERES), Erosion Productivity Impact Calculator (EPIC), Simulator Multidisciplinary for Crop Standard (STICS), and Agricultural Production Systems Simulator (APSIM)

In water-driven models, the amount of biomass is directly proportional to the rate at which the crop transpires water through the water productivity (WP) components (Todorovic et al., 2009). Incorporating Hydrological and Crop Models for Improved Agricultural water management allows for better simulation of crop growth under varying water availability some examples of the models in this category include CropSyst (Cropping System simulation) and the AquaCrop model. CropSyst utilizes both water-driven and radiation-driven modelling approaches (Stöckle et al., 2003). However, Bauböck (2014) noted that in CropSyst, the biomass–transpiration relationship becomes unstable under low vapour pressure deficit, and

consequently, the radiation-driven modelling approach takes precedence. As a result, AquaCrop is unique among water-driven models in literature currently. Water-driven models have an advantage over radiation-driven models in that they can normalize the WP parameter to take climate conditions into account, which increases the model's extrapolative capability and robustness. This normalization is achieved through the reference evapotranspiration rate, in contrast to the vapour pressure deficit commonly used in radiation-driven models (Steduto and Albrizio, 2005). The conservative nature of the WP parameter allows water-driven models to be extrapolated for various locations and future climates, especially when CO_2 concentration is expected to increase (Steduto et al., 2007).

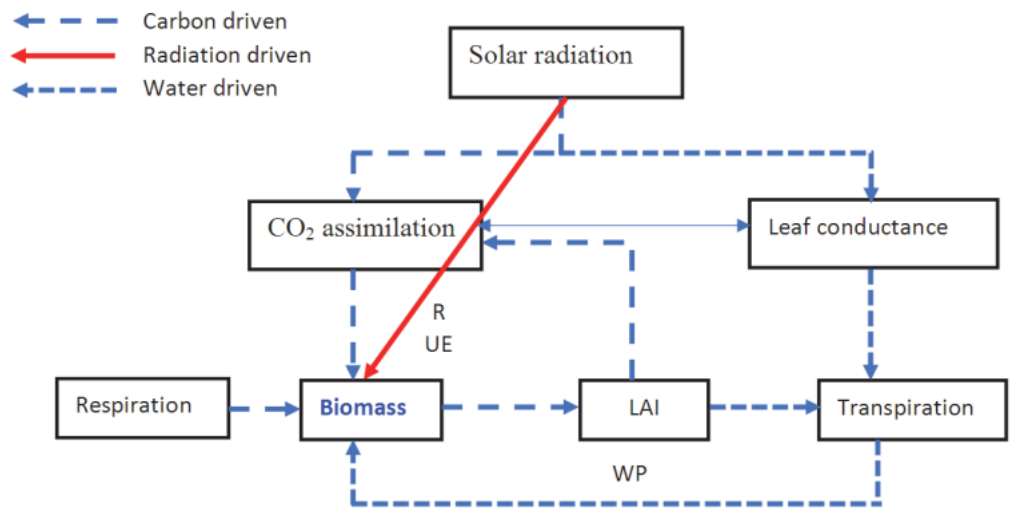

Figure 2.2: Simulation of biomass production in crop models

Source: (Edwin et al., 2018)

2.8.1 AquaCrop Model

The AquaCrop model, developed by the Food and Agricultural Organization (FAO), is designed to be user-friendly and requires minimal input data. It focuses on important

physiological processes and agronomic practices in crop production and caters to various professionals such as agricultural officers, water resource and irrigation officers, agricultural economists, and policy experts who need accessible models for decision-making (Steduto et al., 2009; Hsiao et al., 2009).

AquaCrop simulates the potential yields of major crops under varying water regimes, including rainfall and irrigation. Its unique description of canopy development using canopy cover (CC)—which represents the fraction of ground shaded by the crop—rather than leaf area index (LAI), which quantifies total leaf surface area, makes the model simpler and more adaptable under water stress conditions (Evett and Tolk, 2009). A simplified model for canopy growth and senescence, as well as the division of evapotranspiration (ET) into crop transpiration (Tr) and soil evaporation (E), are noteworthy aspects of the model. Additionally, it takes into account how water stress affects Tr, HI, canopy senescence, and canopy growth (Steduto et al., 2009).

AquaCrop has been effectively used to simulate crop response to water stress for various crops such as Teff, barley, cotton, maize, canola, tomatoes, and potatoes (Farahani et al., 2009; Heng et al., 2009; Araya et al., 2010a; Araya et al., 2010b; Zeleke et al., 2011; Tsegay et al., 2012; Katerji et al., 2013; Montoya et al., 2016). Furthermore, it has been applied in irrigation management strategies like deficit irrigation, as well as field management practices such as weed control, soil fertility, and mulching, all aimed at improving water productivity and water use efficiency of crops (Shrestha et al., 2013; Linker et al., 2016; Tsegay et al., 2012; Van Gaelen et al., 2014; Van Gaelen et al., 2015; Van Gaelen et al., 2016). However, in a comparative study with HYDRUS-1D, AquaCrop was found to be ineffective in simulating soil water dynamics, especially at depths greater than 10 cm (Al-daisy et al., 2011).

2.9 Irrigation Methods

2.9.1 Drip Irrigation

Drip irrigation, a low-pressure system that applies water slowly at a predetermined rate directly to the crop through drippers or emitters, has been shown to significantly enhance water use efficiency. Research indicates that a well-designed and managed drip system can achieve up to 95% irrigation efficiency, with minimal water loss in conveyance and reduced water loss to soil evaporation (Oke et al., 2022). This method offers the potential to increase yields while minimizing water usage, agrochemicals, and labour, making it suitable for various crops, such as vegetables, orchards, and plantations (Singh, 2012). Moreover, empirical evidence from different regions illustrates the effectiveness of drip irrigation. For instance, in Kenya, a low-cost small-scale drip irrigation system resulted in 2.8 times higher yield and 45% less water usage compared to traditional bucket irrigation systems. Similarly, in Tanzania, drip irrigation led to a fourfold increase in tea yield compared to rainfed, non-irrigated tea, while in Sudan, it saved 60% of irrigation water and boosted onion yields by 40% compared to surface irrigation (Rodolfo, 2015).

2.9.2 Hydraulics of Drip Irrigation System

A lot of attention has been given to the analysis of the hydraulics of flow in drip irrigation systems by researchers and designers. A number of researchers (Bucks and Myers, 1973; Wu and Giltin, 1973; Howell and Hiler, 1974) have concentrated on this area. Keller and Karmeli (1974) introduced a design procedure to determine various aspects such as irrigation depth and interval, system capacity, emitter flow characteristics, and hydraulic design considerations. They proposed that a sample of emitters operating at a reference pressure head could be used to calculate the emitter-manufacturer coefficient of variation for the emitters. Furthermore, they suggested two formulas to calculate the design emission uniformity for trickle irrigation

systems under the presumption that, at a specific pressure head, the emitter discharges are normally distributed around their mean. Burt (2004) later confirmed that these equations were similar to those created by Bralts et al. (1981). Merriam and Keller (1978) expounded a rationale for evaluating the uniformity of water application from trickle irrigation systems in the field. ("Hydraulic and Statistical Analyses of Design Emission Uniformity of ...") Solomon (1979) classified emitters based on the manufacturing coefficient of variation. Handley et al. (1983) evaluated the uniformity of emitter discharge by low-volume systems in the field under normal operating conditions. Boman (1987) demonstrated that there is no evidence of a correlation between pressure and the coefficient of variation of discharges for the emitters evaluated. Ortega et al. (2002) investigated local trickle irrigation units and calculated average emission uniformity, average absolute emission uniformity, and system emission uniformity.

Ageel (2002) created a computer program to design trickle irrigation systems and then examined how the cost of the system varied with the size of the subunits. According to Burt (2004), one way to express a trickling subunit's emission homogeneity is as follows:

EU = EUmEUh .....(E.q 2.2)

Where:

EUm = emission uniformity due to manufacturing variation; and

EUh = emission uniformity due to pressure differences

The effect of different manufacturing coefficients of emitter variation on flow rate design and consistency was examined by Kirnak et al. (2004) ("Determination of hydraulic performance of trickle irrigation emitters"). ("Determination of trickle irrigation emitters' hydraulic performance") When irrigating date palm trees, Al-Amoud (2008) examined the effectiveness of a bubbler irrigation system and contrasted it with a conventional trickle irrigation system. As stated by Haijun and colleagues (2009), operating pressure had the greatest impact on all

the influencing elements they provided, with an exponential relationship between emission rate and operating pressure. ("Hydraulic and Statistical Analyses of Design Emission Uniformity of drip Irrigation Systems") ("Hydraulic and Statistical Analyses of Design Emission Uniformity of drip Irrigation Systems") (Noori, 2012) examined drip irrigation systems' emission uniformity and created a simplified formula to determine the hydraulic component of emission uniformity. At each node of the pipelines, the Newton Raphson approach was utilized to work out and calculate pressure heads using a different form of the Darcy-Weisbach's and Bernoulli's equations, with assumptions that the flow is steady, constant density and Friction losses are negligible. Hazen-William's formula and Darcy- Weisbach's Formula were accepted for computing head loss because of friction in drip line on account of its simplicity. Manufacturers of pipes for drip irrigation recommended a C (friction coefficient to consider pipe material) value of 150 for the plastic pipe and tubing. However, Watters and Keller (1978) showed that C =150 underestimates the pipe friction losses for the flow normally encountered in drip irrigation systems. According to Howell et al. (1982), C = 130 for pipes with a diameter of 14–15 mm, C = 140 for pipes with a diameter of 19–20 mm, and C = 150 for pipes with a diameter of 25–27 mm are the ideal values for drip irrigation systems. It has been established that the Blasius equation for smooth pipes accurately predicts the friction factor for simple plastic pipes with small diameters. However, because emitter protrusions are present in drip irrigation laterals with inserted emitters, the flow regime becomes semi-smooth (Amin, 1990).

In an experiment conducted by Watters and Keller (1978), it was demonstrated that the Darcy-Weisbach formula can be used for estimating frictional head losses in smooth plastic pipes and tubes. They suggested a simplified version of the Darcy-Weisbach formula that includes a friction factor calculated from the Blasius equation for smooth pipes with a kinematic viscosity of 1.0 ×10-6 m2 /sec and water temperatures of 200 C. Christiansen (1942) created the "F" factor, a friction factor, to circumvent the laborious stepwise analysis. Jensen and Fratini (1957)

developed an adjusted factor F which permitted the calculation of the head loss caused by friction in pipelines with multiple outlets, with the first outlet at one-half of outlet spacing from the pipeline inlet. Scaloppi (1988) derived an expression for the adjusted factor Fα. This expression calculates the adjusted factor for a pipeline with numerous outlets, including the initial outlet at any fractional spacing (α) from the pipeline.

2.9.3 Drip Irrigation System Performance Indicators

2.9.3.1 Coefficient of Uniformity

Uniformity measures a micro-irrigation system emitter's ability to discharge water evenly throughout the irrigation unit. Ideally, it is impossible to attain perfect uniformity in irrigation without flaws, and this is a well-established fact in agricultural and environmental engineering literature. Several factors such as water pressure variations, emitter performance inconsistencies, and environmental conditions contribute to the inherent challenges in achieving perfect irrigation uniformity. According to Keller and Bliesner (1990), perfect uniformity in irrigation systems is theoretically impossible due to these inevitable variances. Furthermore, Pereira et al. (1999) also emphasize that while modern irrigation technologies aim to maximize uniformity, absolute perfection remains an impractical goal due to physical and operational limitations inherent in any irrigation system. Since uniformity is a critical concern in choosing, designing, and managing irrigation systems, Christiansen (1942) developed the Uniformity Coefficient (CU) to address this issue. The CU provides a quantifiable measure of how evenly water is distributed by an irrigation system, which is essential for optimizing agricultural productivity and water use efficiency (Christiansen, 1942). The most generally recognized and utilized criterion for defining uniformity in irrigation systems is Christiansen's Uniformity Coefficient (CU) criteria. This criterion has been widely adopted due to its effectiveness in evaluating the evenness of water distribution (Zoldoske et al., 1994). Uniformity Coefficient (CU) is calculated using catch-can data, which involves

collecting water in a series of containers placed at regular intervals within the irrigated area to measure the distribution uniformity of water application. It is calculated by dividing the absolute deviation from the mean by the average. The CU can be written as (Bralts & Kesner, 1983)

$$CU = (1 - \frac{\sum_n |Ds - \underline{D}|}{\sum_n Ds}) \times 100\% \quad \text{.....(E.q 2. 3)}$$

CU: Coefficient of Uniformity

D_s: depth of application in catch cans

$\underline{D}$: Mean depth of application in catch cans

n: Number of catch cans

2.9.3.2 Emission Uniformity

Emission uniformity also known distribution uniformity is a vital parameter in micro-irrigation systems. It serves as a tool for evaluating variation among emitters in an irrigation unit. It measures how water is uniformly distributed through the field during irrigation. Emission uniformity is used to characterize the uniformity of micro-irrigation system, expressed in percentage. It was given by Keller and Karmeli (1974):

$$EU = (1 - 1.27 \frac{CV}{\sqrt{n}}) (\frac{Qlq}{Qavg}) \times 100\% \quad \text{.....(E.q 2.4)}$$

Where:

EU: emission uniformity (%)

CV: manufacturing coefficient of variation for point or line-source emitter (%)

N: number of emitters per plant

Q_{lq}: Average low-quarter emitter discharge(l/h)

Q_{avg}: total average of emitter discharges (l/h) with similar pressure – discharge associated for all emitters.

The various terms in Equation 2.2 account for the system pressure variation and emitter variation. The equation is simple, and widely accepted (Ascough & Kiker, 2002). Unfortunately, low- quarter average do not always merge ways, and their appropriate form does not in itself mirror the clarity of the preceding calculations (Clement et at., 1997).

In drip irrigation, field emission uniformity is a measure of the uniformity of emissions from all the emission points(emitters) within an entire drip irrigation system. As per Keller and Karmeli (1974), the emission uniformity is given by.

$$EU = \frac{Qmin}{Qavg} \times 100\% \quad \text{.....(E.q 2.5)}$$

EU: Field emission uniformity

Q_{min}: average of lowest ¼ of emitter flow rate (l/h)

Q_{av}: average emitter flow rate(l/h)

High water application uniformity is one major advantage of a well-designed drip irrigation system relative to other irrigation methods (Pitts et al., 1986). Conversely, poor water application uniformity can result in significant disparities in soil moisture levels, which can adversely affect crop growth and development. Areas receiving insufficient water may suffer from drought stress, while areas receiving excess water can experience waterlogging, both of which can lead to reduced crop yields. Application uniformity in irrigation systems is influenced by numerous factors, including emitter clogging, hydraulic variance caused by land slope, manufacturing variation, emitter sensitivity to temperature, pressure variation, and in-pipe head losses (Smith, 2018; Johnson & Lee, 2020). Smith (2018) discusses the impact of emitters clogging on application uniformity, emphasizing the importance of regular

maintenance to prevent this issue. Similarly, Johnson and Lee (2020) highlight the significance of hydraulic variance due to land slope, suggesting strategies for mitigating its effects on uniformity. Manufacturing variation can also affect application uniformity (Brown et al., 2019). Moreover, the sensitivity of emitters to temperature and pressure fluctuations poses challenges in maintaining uniformity (Garcia, 2017). In addition, in-pipe head losses contribute to non-uniform application (Jones & Williams, 2021). Understanding and addressing these factors are crucial for optimizing irrigation system performance and ensuring uniform water distribution across the field.

2.9.3.3 Emitter flow variation

Emitter flow variation refers to the inconsistency or variability in the discharge rate of emitters within a drip irrigation system (Sánchez-Maranón et al., 2019). emitter flow variation can result from a combination of factors including manufacturing defects, clogging, pressure variations, water quality changes, and temperature fluctuations (Sánchez-Maranón et al., 2019). It can be derived from the formula given by Bralts and Kesner in 1983

$$Q_{avg} = \frac{(Qmax - Qmin)}{Qmax} \times 100\% \quad \text{.....(E.q 2.6)}$$

Where.

Q_{avr}: Variation in emitters' flow along the lateral line (%)

Qmin: The lowest emitter flow rate (l/h) observed along the lateral line

Qmax: the highest emitter flow rate (l/h) measured along the lateral line

2.9.3.4 Coefficient of Variation

This parameter is the measurement of the emitter's flow variation caused by manufacturing variances. In drip irrigation, the design criteria are generally based on an emitter flow variation of less than 20% for lateral line, and flow variation of less than 5% (about 10% pressure

variation) for sub-main (Alebachew, 2017). Common causes of this variation are the inability to hold dimensional tolerances due to moulding pressures and temperature and variation in the materials used for production. This statistical parameter was given by Keller and Karmeli (1974) and expressed as:

$$CV = \frac{sd}{q} \times 100\% \quad \text{.....(E.q 2.7)}$$

Cv: Coefficient of variation

Sd: Standard deviation depths of water of all catch cans (l/h).

q: Mean depths of water of all catch cans (l/h).

2.9.4 Overview of Rain/Spray Tube Irrigation

Rain/spray tube irrigation systems, often referred to as rain pipe or rain hose systems, represent a hybrid approach to micro-irrigation that mimics natural rainfall through perforated tubes with laser-punched holes. These systems are particularly suited for closely spaced crops, offering advantages such as high water use efficiency, reduced evaporation losses, and uniform moisture distribution. The hydraulics of these systems encompass critical parameters like pressure-flow relationships, friction losses, discharge rates, and water distribution uniformity, which directly influence irrigation efficiency and crop productivity. This literature review synthesizes key research on the hydraulic aspects of rain/spray tube systems, drawing from empirical studies and performance evaluations. It highlights methods, findings, and implications for design optimization, with relevance to sustainable agriculture in water-scarce regions.

2.9.5 Hydraulic Principles and Performance Metrics

Rain/spray tube irrigation systems, often referred to as rain pipe or rain hose systems, represent a hybrid approach to micro-irrigation that mimics natural rainfall through perforated tubes with

laser-punched holes. These systems are particularly suited for closely spaced crops, offering advantages such as high water use efficiency, reduced evaporation losses, and uniform moisture distribution. The hydraulics of these systems encompass critical parameters like pressure-flow relationships, friction losses, discharge rates, and water distribution uniformity, which directly influence irrigation efficiency and crop productivity. This literature review synthesizes key research on the hydraulic aspects of rain/spray tube systems, drawing from empirical studies and performance evaluations. It highlights methods, findings, and implications for design optimization, with relevance to sustainable agriculture in water-scarce regions.

The hydraulic performance of rain/spray tube systems is primarily evaluated through metrics such as discharge rate, uniformity coefficient (UC), distribution uniformity (DU), mean application rate (MAR), and coverage area. These parameters are influenced by operating pressure, lateral length, spacing, and soil type.

A comprehensive study on rain pipe irrigation system performance emphasized the system's role in sustainable farming by analyzing pressure-discharge relationships and uniformity under varying configurations (Bhadarka et al., 2023). The research highlighted that discharge increases with pressure, following a power-law relationship, and optimal uniformity is achieved at moderate pressures to balance jet breakup and droplet size. Similarly, in an evaluation under lateritic soils in the Konkan region, the rain pipe irrigation system was tested using a factorial design with pressures of 0.8, 1.0, and 1.2 kg/cm², lateral lengths of 10, 20, and 30 m, and spacings of 2, 3, and 4 m (Gohil et al., 2024). Methods involved replicated field trials measuring uniformity via catch-can tests and pressure gauges. Results indicated superior performance at 0.8 kg/cm², 20 m length, and 3 m spacing, with DU of 72.40% (categorized as "good"), UC of 82.50% ("good"), MAR of 21.38 mm/h, and coverage area of 73%. Friction

losses were minimal at shorter lengths, but increased with extension, underscoring the need for pressure compensation in longer laterals.

In related work on innovative irrigation for closed-spaced crops like blackgram and groundnut, rain hose systems demonstrated hydraulic efficiency through experiments assessing spray width, discharge, and uniformity (Mahmoud et al., 2025). Using catch-can methods and factorial randomized designs, the study found discharge rates of 200 L/h per meter at 1 kg/cm², with spray widths extending 10–15 feet per side. Optimal hydraulics were observed at 1.5 kg/cm² pressure, 30 m length, and 4 m spacing, yielding UC of 87.83%, DU of 76.29%, and MAR of 6.81 cm/h. Friction losses were accounted for in the linear pattern along the hose, with maximum discharge per meter at the optimal setup. These findings suggest that rain hose systems reduce hydraulic inefficiencies compared to traditional sprinklers, achieving over 60% water savings.

Mini sprinkler systems, which share hydraulic similarities with spray tubes through nozzle-based emission, have been evaluated for performance under controlled pressures and spacings (Rank, 2015). In a completely randomized design with double-nozzle full-circle sprinklers, tests at 1.0, 1.5, and 2.0 kg/cm² pressures and 8×8 m, 10×10 m, and 12×12 m spacings measured discharge, jet breakup index (P_d), UC, DU, MAR, and wetted area. Discharge followed a power series (q = C_d * A * (2gh)^N, N=0.274), increasing from 332 L/h at 1.0 kg/cm² to 445 L/h at 2.0 kg/cm². UC ranged from 79.14% to 87.68%, with optimal values (>80%) at closer spacings and higher pressures. DU varied from 66.7% to 78.8%, and P_d was ideal (near 4) at 1.5 kg/cm², indicating balanced droplet size for minimal wind drift. The study recommended 10×10 m spacing at 1.5 kg/cm² for economical hydraulic efficiency.

2.9.6 Modeling and Design Considerations Rain Tube

Hydraulic modeling in spray irrigation systems often integrates empirical equations for friction loss and pressure distribution. For linear-move sprinkler systems, which parallel larger-scale spray tubes, models evaluate friction losses and pressure head variations along laterals (Zerihun et al., 2019). Although focused on center-pivot variants, the approach—using finite element methods—applies to rain tubes by simulating energy losses in perforated pipes, ensuring uniform outlet pressures.

Smart irrigation integrations enhance hydraulic management in drip and sprinkler systems, including spray tubes (Bhatnagar et al., 2023). IoT-based systems monitor pressure and flow in real-time, adjusting for uniformity; studies report improved DU (>85%) through automated valves, reducing friction-induced variations.

Eco-hydrological models for wetting patterns under drip systems have been extended to perforated tubes, predicting soil moisture distribution based on hydraulic conductivity and emitter flow (Karimi et al., 2023). Empirical models like those by Al-Ogaidi and Li accurately estimate wetted dimensions, aiding hydraulic design for rain tubes in clay soils.

Rain/spray tube systems outperform conventional methods in water productivity. In groundnut trials, rain hose at 100% potential evapotranspiration achieved 3.29 benefit-cost ratio, higher than drip or sprinklers, due to lower hydraulic setup costs (Mahmoud et al., 2025). Comparisons with mini sprinklers show similar uniformity but lower energy requirements for rain tubes (Rank, 2015). Challenges include clogging in perforated holes and pressure drops in long laterals, mitigated by optimal lengths (<30 m) and pressures (1.0–1.5 kg/cm²).

The hydraulics of rain/spray tube irrigation systems are well-documented in recent literature, with key studies emphasizing pressure optimization for high uniformity and efficiency.

Configurations around 1.0–1.5 kg/cm², 20–30 m lengths, and 3–4 m spacings consistently yield UC >80% and DU >70%, supporting sustainable water use.

2.9.7 Overview of Furrow Irrigation

Furrow irrigation is one of the earliest and most popular type-controlled irrigation methods. ("Sediment transport in furrow irrigation | Irrigation Science - Springer") It involves creating small, evenly spaced shallow channels, or furrows, across or down a field slope. Water is introduced to these furrows at low discharge rates to promote infiltration as the water moves down the field. This method, which is categorized as a partial surface flooding technique and is primarily used on clean-tilled soil, applies water through rows or furrows that have the capacity to guarantee adequate irrigation (Hoffman et al., 2007). For furrow irrigation to be effective, proper management is crucial. Mismanagement can lead to inefficiency, as inflow discharge must be carefully regulated to prevent excessive runoff or infiltration at the top of the field. Additionally, the fields need to have a gentle slope to ensure even water distribution (Brouwer et al., 1989).

Traditionally, short furrows controlled manually were the norm. However, modern furrow irrigation techniques now involve longer, precisely levelled furrows with automated or semi-automated water control systems. Trees, vegetables, potatoes, and maize are among the crops that prefer furrow irrigation. It works best in loam soil, which allows for optimal water movement, while sandy soils may cause excessive infiltration at the furrow's upper end, and clay soil might require standing water for proper infiltration. The system also demands slightly sloped land, ranging from 0.5% to 2%, and is ineffective in undulated or zigzag terrain (Walker & Skogerboe, 1987).

Numerous factors affect the performance of furrow irrigation systems. One of the primary factors is the soil characteristics and field conditions, which play a critical role in determining

the system's overall efficiency. Soil conditions dictate water advance rates, while inflow rates determine how efficiently water moves down the furrows. The stream size used in furrow irrigation must also be chosen carefully to prevent erosion, especially on steeper slopes, where non-erosive stream sizes are required. Although high inflow rates can reduce deep percolation losses, they may result in excessive runoff (Walker, 1989).

The irrigation run's duration is another important consideration. Because long furrows take longer time for water to move through, there is a greater chance that deep percolation will occur at the head of the furrow before the lower end of the furrow receives enough irrigation (Strelkoff & Clemmens, 2007). The cutoff ratio, or the timing of water cessation, directly impacts deep percolation and runoff. In addition, tailwater reuse systems are often necessary to ensure high irrigation efficiency and distribution uniformity, particularly in managing water runoff. Lastly, the furrow intake, or the amount of water absorbed by the soil, is influenced by the wetted perimeter, which varies depending on the inflow rate, slope, and hydraulic conditions of the field (Hoffman et al., 2007).

2.9.8 Hydraulics of Furrow Irrigation System

Furrow irrigation involves the distribution of irrigation water to the furrows at the topmost part of an agricultural field. The water then moves down the furrows, eventually reaching the bottom part of the field and irrigating the soil completely. The time over which the soil is exposed to this water is known as the infiltration opportunity time. Infiltration occurs both laterally and vertically along the furrow's wetted border. Wetting The forms found in furrows can have great variation depending on the nature of the soil. Ideally, neighboring Patterns of wetting cross each other, enabling water to rise (capillary rise) and wet the whole ridge. To ensure optimal furrow irrigation performance, the infiltration opportunity time should be equal to the time required to apply the requisite depth of water (to meet the moisture deficit). Researchers have developed many methods to simulate infiltration and surface flow in furrows.

The models developed by Hall (1956) and Davis (1961) were based on the mass conservation equation solution under the presumption of a normal depth of flow. Models by other authors, including Walker and Humphreys (1983), Wallender and Rayej (1990), Schmitz and Seus (1992), and Katapodes and Strelkoff (1977), were based on the numerical solution of the partial differential equations of mass and momentum in open-channel flow applied to borders and furrows. The algebraic model that Levien and de Souza (1987) provided simulated furrow irrigation.

In a furrow system, continuous inflow discharge results in an unstable and gradually varying flow as infiltration moves along the furrow. Ordinarily, the water's advancement velocity on the furrow's surface is greater than the infiltration rate, or infiltration velocity. Water therefore appears as a two-dimensional flow perpendicular to the furrow's flow direction when it enters and exits the soil at each cross-section. "Irrigation System Designing - SpringerLink" states that the flow of water in a furrow is similar to the flow in an initially dry open porous channel. Consequently, wave propagation in the furrow during the advance phase, flow discharge fluctuation during the supply and recession phases, and the movement of water penetration and redistribution in the soil should all be considered in the mathematical formulation defining water flow in a furrow. Saint Venant (1871) unsteady gradually varied flow can be described by the partial differential equations.

2.9.9 Some Relevant Terminologies in furrow irrigation

2.9.9.1 Intake Rate

The rate at which water is absorbed by the soil in furrow irrigation is known as the intake rate. This rate is not constant and varies over time. Initially, water is absorbed rapidly due to the dry soil conditions, but as the soil becomes saturated, the rate decreases. Over time, the intake rate stabilizes, reaching a constant value known as the basic intake rate (Walker & Skogerboe,

1987). Understanding and managing the intake rate is crucial for optimizing irrigation efficiency and preventing water loss through deep percolation or runoff (Hoffman et al., 2007).

2.9.9.2 Infiltration Opportunity Time

Infiltration opportunity time refers to the duration during which water can infiltrate the soil in a furrow irrigation system. It is defined as the difference between the time when water recedes and when it first advances to a specific location along the furrow (Walker & Skogerboe, 1987). The infiltration opportunity time varies at different points along the length of the furrow due to the difference in the times water reaches (advance) and leaves (recession) each location. The rate of water advanced down the field typically differs from the rate at which it recedes, creating variations in infiltration opportunity time (Hoffman et al., 2007). Achieving more uniform infiltration opportunity time along the furrow is a key strategy for improving water distribution uniformity and optimizing irrigation efficiency (Strelkoff & Clemmens, 2007).

2.9.9.3 Distribution Uniformity

Distribution uniformity (DU) is a metric used to quantify the degree of infiltration homogeneity. According to Burt et al. (1997), the depth of penetration at the low quarter is commonly employed as a reference when expressing DU.

("Irrigation System Designing - SpringerLink")

That is,

$$DU = \frac{\text{(average low quarter infiltration depth)}}{\text{(average infiltration depth)}} \times 100 \quad \text{.....(E.q 2.8)}$$

The soil infiltration characteristic (soil type, variability, and moisture content), the rate of water flow into the furrow (inflow), and the duration of this water flow (time to cut off) are the main factors influencing distribution uniformity during a furrow irrigation event (Hoffman et al., 2007). Other factors that influence uniformity include field slope variability and field length (Walker & Skogerboe, 1987). Irrigation efficiencies have a direct relation with the uniformity

of water application (distribution uniformity) on the individual fields. Furrow-irrigated field distribution uniformity is directly proportional to the advance ratio and the average depth of water infiltrated per hour (Strelkoff & Clemmens, 2007). For uniform soil with good land grading, the distribution uniformity of water infiltration for furrows is dependent upon the uniformity of opportunity times. ("Irrigation System Designing - SpringerLink") ("Irrigation System Designing - SpringerLink") ("Irrigation System Designing - SpringerLink") Making opportunity times more uniform down a furrow is a desirable strategy for improving DU for furrow irrigation (Walker, 1989). A DU value of 80% is considered excellent for all irrigation methods (Hoffman et al., 2007).

2.9.9.4 Time Ratio

Time ratio (Rt) is defined as the ratio of the time required for the infiltration of total net amount of water required for the root zone to the time when the waterfront reaches the end of the run. It plays a significant function in determining optimum furrow length to achieve maximum irrigation efficiency. ("Studies on hydraulic performance of furrow irrigation to optimize ...")

$$Rt = \frac{ti}{tL} \quad \text{.....(E.q 2.9)}$$

Where

t_i = time required for infiltration of net irrigation depth

t_L = time required for waterfront to reach the end of run

A value of Rt equal to 1.0 indicates the time taken by water to pass through the soil during irrigation. Depth is related to the length of advancement. The advancement rate is an essential element in managing a furrow irrigation system. Water should get to the end of a furrow in less than 1 / 2 of the set time to achieve good distribution uniformity. Whether that should be as quickly as 1 / 4 of the set time lasts depending on the soil's texture and condition.

2.9.9.5 Cutoff Ratio or Advance Ratio

Advance ratio or cutoff ratio is defined as the ratio of time to reach the waterfront at the end of furrow, to the time set for irrigation. Mathematically, it can be expressed as

$$R_{cut} = \frac{te}{tirr} \quad \text{.....(E.q 2.10)}$$

Where

te = time required for water advance to reach the end of furrow

t_{irr} = time of irrigation

The cutoff ratio refers to the proportion of runoff to the uniformity of the water infiltration in the furrow. ("(Updated June 2007) Operation of Furrow Irrigation Systems") ("(Updated June 2007) the optimal cutoff ratio of 0.5 is essential to efficiently operate furrow irrigation systems. For example, in an 8h irrigation set time, the advance time should be about 4 h. The easiest way to change the technique to accelerate time is by altering the furrow stream volume, that is, by varying the irrigation size. This will affect the cutoff ratio and thereby the uniformity of the water distribution. ("Management of Furrow Irrigation Systems - Nebraska Extension Publications") Both level and Systems with sloping furrows and uniformities above 85% require comparatively moderate advance ratio.

2.9.10 Gross Water Needed for Furrows

Gross water to apply.

$$WR_N = \frac{WRN}{DU} \times \left(1 - \frac{R}{100}\right) \times F_S \quad \text{.....(E.q.2.11)}$$

where

WRG = gross water to be applied (mm)

WR_N = net water required for root zone soil (determined with any recommended technique) (mm)

R = percent of water which runs off the field and is not re-circulated to that field

DU = distribution uniformity expressed as a decimal (DU = 0.80 is often used)

F_S = salinity factor, which takes into consideration the increased need for irrigation brought on by maintenance leaching. If salinity is not involved, $F_S = 1$

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was carried out in Ghana's North-East Region's East Mamprusi District. Legislative Instrument (LI) 1776 (2004) created the East Mamprusi District (EMD), with Nalerigu serving as its capital. Latitudes 10.5° to 10.7° N and longitudes 0.3° to 0.7° W are where the district is located. Because of the tropical maritime air mass (MT), the district, which is located on the tropical continental western margin, has a distinct rainfall pattern. April through October is when this rainy season occurs every year. The dry season, which lasts from late November to March, is then signaled by the tropical continental air mass (CT). Rainfall ranges from 1,000 to 1,500 mm on average per year, with July through September seeing the highest totals. March through April marks the height of the district's protracted dry season. With an annual mean temperature that varies by season from 27.4 °C to 35 °C. The Harmattan season has the lowest recorded temperature, while the dry season has the highest. The East Mamprusi District distinctly resides in the interior woodland savannah belt, marked by a dominant presence of grass vegetation and notable trees like dawadawa, baobab, and shea. The grasses grow in tussocks and can reach heights of 3 meters or more, with vegetation changing significantly during the two climatic seasons. During the rainy season, animals graze on the grass, reducing the burden on owners to find feed. The shea tree is economically valuable, especially for women who gather the nuts to process into shea butter (Agyare, 2020).

he East Mamprusi District features a gently undulating terrain, with the Gambaga Escarpment marking the northern boundary of the Voltain Sandstone basin (Ghana Geological Survey Authority, 2021). Apart from the mountainous regions near the escarpment, there is limited

runoff during rainfall. The district is characterized by a diverse range of rock formations, transitioning from flat-bottom valleys to steep highlands. The upper section is underlain by the middle Voltain formation, which encompasses shale, mudstone, iron pans, and sandstone. The area enjoys efficient water drainage, with major rivers such as the White Volta, Red Volta, Nawong, and Moba coursing through the district. There are two main soil types: Savannah Ochrosols, which cover most of the district and are moderately drained with sandy-to-sandy loam texture, and Groundwater Laterite, found in the southern part, consisting of concretionary soils developed from Voltain shale and mudstone. These soils are suitable for annual crops like maize, millet, and sorghum, as well as tree crops like shea, dawadawa, and cashew, which have economic significance (Agyare, 2020).

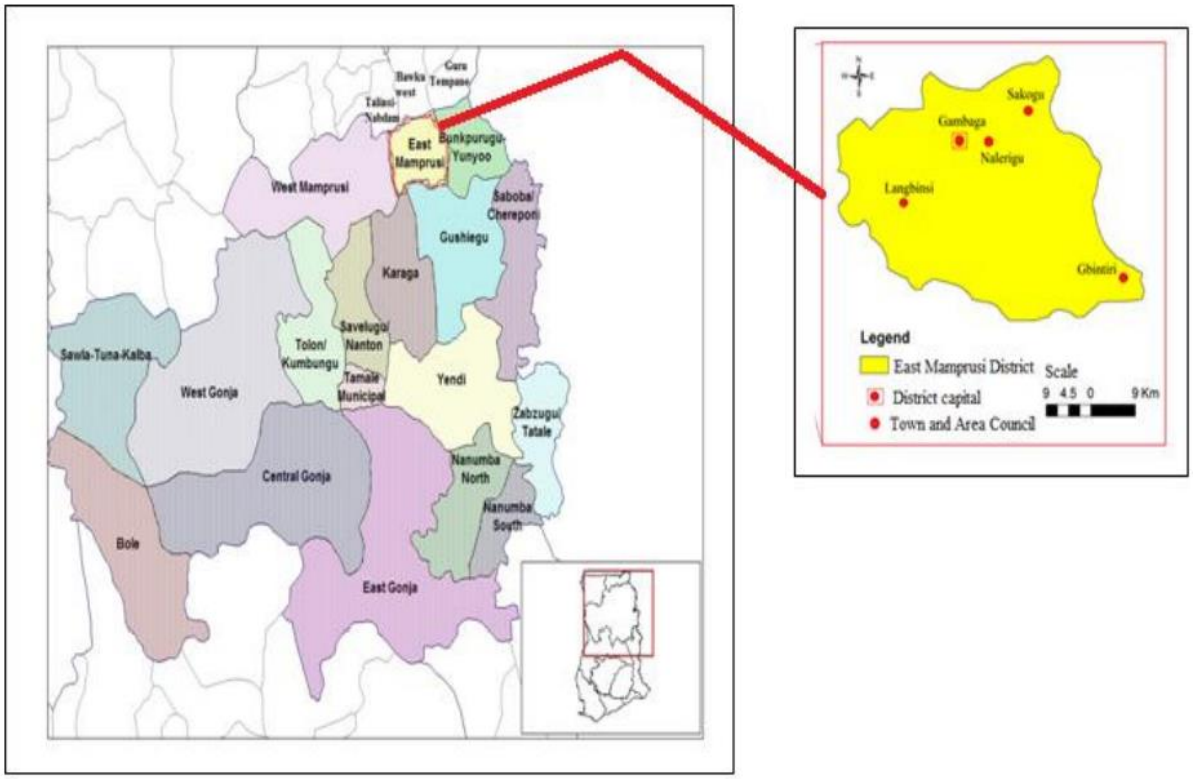

Figure 3.1: Map of East Mamprusi District

(Source: http://mapsof.net/ghana/northern-ghana-districts, 2024)

3.2 Materials and Equipment used for the Study.

3.2.1 FAO CROPWAT model 8.0

This is the decision support software which is used to estimate the CWR of a particular crop. It was used to estimate the CWR of orange-fleshed sweet potato (*Ipomoea batatas*) with meteorological data sourced from the Ghana Meteorological Agency.

3.2.2 FAO AquaCrop 7.1 Model

AquaCrop is a crop water-driven driven/productivity model that models how herbaceous crops respond to water (Steduto et al., 2012). Using the soil water and salt balance, specific atmospheric parameters (temperature, rainfall, ET0, and atmospheric CO_2 concentration), crop characteristics (such as water productivity, thermal time, crop coefficient, etc.), and crop management (such as irrigation schedule, irrigation system type, and soil fertility), the model models the biomass progression. Grain crop phenology, biomass accumulation, and the harvest index (HI) are all impacted by extreme temperatures. The soil water balance, when combined with some essential crop factors (canopy development ability, stomatal control of transpiration, canopy senescence, and HI), allows us to simulate the influence of water stress on crop development (Steduto et al., 2009).

Two categories of crop parameters are defined by the model: conservative and non-conservative. Although the conservative traits vary by crop, they are not greatly affected by time, management strategies, location, or climate. Additionally, unless otherwise demonstrated, it is assumed that they do not vary with cultivars (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). Daily calculations were made to determine the water balance and the division of evapotranspiration into crop transpiration and evaporation. Steduto et al. (2009) provided a crop growth equation that includes the WP^* factor, which was applied to the daily

transpiration value. This parameter improves the model's robustness by remaining constant throughout a wide range of climatic circumstances and crop management practices (Steduto et al., 2007).

$$B = WP^{*} \times \sum \left(\frac{Tr}{ET}\right) \quad \text{(E.q 3.1)}$$

$$Y = B \text{ X } HI \quad \text{(E.q 3.2)}$$

Where:

Tr is crop transpiration (in mm)

WP^{*} is a measure of water productivity expressed in kilograms of biomass, m^{-2} of land area, and mm−1 of total water transpired during the biomass's production period.

Y = Yield (kg)

B= Biomass(kg)

3.2.3 A catch can experiment

is a field method used to assess the technical performance of pressurized irrigation systems by placing containers across the irrigated area, running the system, and measuring the water collected. The data help determine water application rates, distribution uniformity, and emitter performance, allowing detection of pressure imbalances and uneven watering, and providing a practical measure of how efficiently the system delivers water.

Catch cans, stopwatch, and a measuring cylinder: These materials were used to assess the performance of the drip system. Twenty (20) catch cans of capacity 300 ml each were used to collect water from emitters and Spray Nozzles for drip and rain tubes respectively, which was measured with a calibrated plastic cup over an hour period measured by a stop clock. Five laterals (one from each bed) and four locations on each lateral were chosen. The five (5) laterals

were chosen with the help of the functions: n/5, 2n/5, n/2, 4n/5 and far end (the last lateral) where n is the number of selected laterals on each bed of the field. The various positions on the laterals were chosen with the help of the functions: l/4, l/2, 3l/4 and far end. The catch cans were arranged linearly at relevant positions on the laterals. This measurement was replicated twice. The averages were used to determine the technical performance of the system (coefficient of uniformity, Emission uniformity, Emitter flow variation) .

3.2.4 Davis Weather Station

With real-time data updates every 2.5 seconds, this professional-grade system offers precise and dependable weather monitoring (https://www.davisinstruments.com/products/cabled vantage-pro2-plus-iss). While the wireless sensor suite can send data to multiple devices, including Weather Link Live, wireless Vantage Connect, Vantage Vue console, Envoy8X, or wireless Weather Envoy (https://www.weathershack.com/products/davis/manuals/vantage pro2-ISS-installation.pdf), the Integrated Sensor Suite gathers outside weather data and sends it to a Vantage Pro2 console. The cabled sensor suite gets power from the same cable and sends data to a single-cabled Vantage Pro2 console, Weather Envoy, or Vantage Connect. The purpose of the Davis Weather Station is to track temperature (max and min), relative humidity, sunshine, solar radiation, wind direction, and wind speed.

3.2.5 Time-domain reflectometry (TDR)/ Profile Probe, type PR2 with access tubes

The Profile Probe is an advanced instrument designed to measure soil moisture at multiple depths throughout the soil profile. It features a durable, sealed polycarbonate rod with a diameter of approximately 25 mm. Along its length, pairs of stainless-steel rings serve as electronic sensors, meticulously arranged at fixed intervals to collect accurate moisture readings. Specifically, the Profile Probe type PR2 was employed to continuously monitor the

moisture content of the soil, enabling the creation of optimal irrigation schedules to enhance agricultural efficiency and promote healthier crop growth.

3.2.6 Digital Measuring Scale

A digital stainless steel measuring scale with a maximum weight bearing threshold of 30 kg and tape measure. The measuring scale was employed to accurately weigh the aboveground biomass, providing precise data on the plant's mass. Meanwhile, the tape measure was used to meticulously measure both the length of the vine and the internode length, allowing for a detailed understanding of the plant's growth structure.

3.2.7 Lorentz Submersible Solar Pump

A Lorentz submersible (PS2-1800 series) solar pump with a power rating of 2.3 HP (~1.72 kW) was used. It delivers a maximum flow rate of 12–18 m^3/h and operates within a maximum head range of 50–120 meters, making it ideal for various water sources. The pump runs efficiently at –130V DC with a brushless DC motor and it requires 1.1–2.0 kW solar input, which is provided by 3 solar panels. Equipped with an MPPT-based controller, the system optimizes performance under different sunlight conditions.

3.2.8 Fertilizer Application

The fertilizer 23-10-5 fertilizer (23% N, 10% P_2O_5, 5% K_2O) was applied to enhance vegetative growth, root development, and plant health. Sweet potatoes were planted at 0.15m × 0.20m spacing in three $100m^2$ plots for drip, furrow, and Rain tube irrigation. In each plot, half received fertilizer, while the other half remained unfertilized for comparison. Each $100m^2$ plot contained approximately 3,333 plants, translation to 333,333 plants per hectare. The fertilizer was applied at 174 kg/ha, equating to 0.52g per plant, within the first two weeks after planting to support early growth.

Figure 3.2: Equipment used for the study.

(Source: Author, 2024)

3.3 Measurements and Relevant Calculations

3.3.1 Crop Water Requirement

3.3.2 Source of Data

The Ghana Meteorological Agency (GMet) provided the East Mamprusi with minimum and maximum temperatures, humidity, wind speed, and sunshine hours. Monthly averages were then computed. Additionally, the average rainfall for each month was calculated using long-term rainfall data (from 1997 to 2023) that went to GMet. While the FAO handbook provided the kc values for the different growth stages, crop parameters like planting and harvesting dates and plant rooting depth were obtained from the farm. Sand loam is the predominant type of soil that was removed from the farm. For sandy loam, the Soil Science Laboratory at the University for Development Studies provided the corresponding soil characteristics, including the bulk density, maximum rooting depth, permanent wilting point, field capacity, etc.

3.3.3 Orange-Fleshed Sweet Potato Crop Parameters

Table 3.2: Orange-Fleshed Sweet Potato Parameters for Computing CWR with FAO CROPWAT

Parameter (Unit)	Growth Stage	Value
Plant Stages duration (days)	Initial season	15
	Development	30
	Mid-season	50
	Late season	30
Crop coefficients, (kc)	Initial season	0.5
	Mid-season	1.2
	Late season	0.8
Rooting depth (m)	Initial season	0.1
	Mid-season	1.0
Crop height (m)	Mid-season	0.6
Critical depletion fraction	Initial season	0.3
	Mid-season	0.3
	Late season	0.5

Source: (FAO CROPWAT 8.0, 2009), and Allen et al. (1998)

3.3.4 Crop Water Requirement Estimation

Crop water requirement (CWR) is the quantity of water commensurate to the water lost from a cultivated field by evapotranspiration, which is expressed as ETc in mm/day (Mebrahtu et al., 2021). CWR depends on climate, and irrigation scheduling ETc are used as CWR values, and it was derived using Equation 3.3

$ETc = kc \times ETo$ …… (E.q 3.3)

where:

ETc – Crop evapotranspiration (mm/day)

kc – Crop coefficient (dimensionless)

ETo – Reference evapotranspiration (mm/day)

To have a reliable CWR estimate, it is necessary to adopt the right tools and/or approaches, for enhanced water productivity (Guerra et al., 2015). The FAO CROPWAT 8.0 software was developed on the bases of the Penman-Monteith method, and it factors in the various procedures involved in calculating the reference evapotranspiration (ETo) and CWR, allows for the simulation of CWR under various climate, soil, and crop factors (Mebrahtu et al., 2021). FAO CROPWAT 8.0 software was used in this study to estimate the crop water requirement of Orange Fleshed Sweet Potato. The model estimates the ETo with the FAO Penman-Monteith method as presented in Equation 3.4

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma\left(\frac{900}{T+273}\right)U2(es-ea)}{\Delta+\gamma(1+0.34U2)} \quad \text{(E.q 3.4)}$$

Where:

ETo= reference evapotranspiration [mm day-1],

Rn = net radiation at the crop surface [MJ m-2 day-1],

G = soil heat flux density [MJ m-2 day-1],

T = mean daily air temperature at 2 m height [°C],

U_2 = wind speed at 2 m height [m s-1],

es = saturation vapor pressure [kPa],

ea = actual vapor pressure [kPa],

es - ea = saturation vapor pressure deficit [kPa],

Δ = slope vapor pressure curve [kPa °C-1],

γ = psychometric constant [kPa °C-1].

3.3.5 Irrigation Water Requirement

Monthly rainfall data was compiled, and effective rainfall was estimated using the average for each month. The FAO CROPWAT software was utilized to run the model using the USDA soil conservation approach. The following conditions must be met for the procedure to work:

If Total Rainfall, P_{tot}< 250 mm, then Effective rainfall, R_{eff} will be.

Effective Rainfall, Reff = $P_{tot} \times \frac{125-0.2Ptot}{125}$ ……. (E.q 3.5)

If Total Rainfall, Ptot> 250 mm, then Effective Rainfall, Reff will be.

Reff = $125 + 0.1 \times P_{tot}$……..…… (E.q 3.6)

3.4 Input Data Description

Data entered into the CROPWAT 8.0 software included the following: country (Ghana), planting date, crop type, and soil details (textural class, field capacity, permanent wilting point), rooting depth, percentage of plant-covered area, initial soil moisture, and irrigation criteria. In order to calculate the CWR, the monthly mean climate variables from 1989 to 2019—minimum and maximum temperatures (°C), relative humidity (%), windspeed (km/day), sunshine hours (hours), and rainfall—were used. The meteorological data are shown in Appendix I. Radiation values (MJ^2m /da), reference evapotranspiration, ETo (mm/day), effective rainfall (mm), and total irrigation requirements (mm/dec) for O were produced by the CROPWAT 8.0 software. Orange-Fleshed Sweet Potato.

3.5 Hydraulic Flow Calculation and Performance Evaluation of the Drip System

3.5.1 Flow Variation

Emitter flow variation Q_{var} was calculated using the equation:

$Q_{var} = \frac{100\ (Qmax-Qmin)}{Qmax} \times 100\%$ .....(E.q 3.7)

where:

Q_{var} – Emitter flow variation (%)

Q_{max}– maximum emitter (drip hole) flow rate (l/h)

Q_{min}– minimum emitter (drip hole) flow rate (l/h)

3.5.2 Coefficient of Variation

Coefficient of Variation is a statistical measure used to evaluate the uniformity of water distribution across an irrigated field. It is calculated as the ratio of the standard deviation of applied water to the mean applied water. It is a statistical parameter expressed as in Equation 3.8 as given by Keller and Karmeli (1974).

Coefficient of variation, $CV = \frac{s}{q}$ .....(E.q 3.8)

where:

CV – Coefficient of variation

s – standard deviation of (drip flow) emitter flow rate (l/h)

q – Mean of discharge (q) (l/h)

3.5.3 Uniformity coefficient

Uniformity Coefficient is the ability of the emitters in a drip irrigation system to distribute the water in the whole field equally, as given by Christiansen (1942) and it was calculated with equation 3.9.

Uniformity coefficient, $UC = 100\ \% \times \left[1 - \frac{\frac{1}{n}\sum_{i=1}^{n} |qi - \bar{q}|}{\bar{q}}\right]$.....(E.q 3.9)

where:

$\bar{q}$ – Mean of discharge (q) (l/h)

q – discharge (l/h)

n – number of (drip holes) emitters to evaluate

3.5.4 Emission Uniformity

Emission uniformity is the ratio expressed as a percentage of average emitter discharge from the lower quarter ($1/4^{th}$) of emitter to the average discharge of all the emitters of the drip system. The average of lowest quarter ($1/4^{th}$) of emitter was selected as a practical value for minimum discharge, as recommended by the United State Soil Conservation Services for field evaluation of irrigation systems as expressed in Equation 3.8 (Bralts et al., 1987).

$$EU = 1 - \left[\frac{0.8CV}{n\text{^}0.5}\right] \times 100\% \quad \text{.....(E.q 3.10)}$$

where:

EU – Emission Uniformity (%)

CV – Coefficient of variation,

n – number of emitters per plant

3.6 Assessment of Hydraulic Performance of the Drip and Rain Tube Irrigation System

The source of water for the farm is spring. The pump station installed on the farm is a solar-powered centrifugal pump which abstracted water into a poly tank and supplied it to the laterals. The pump station is equipped with filters which ensure that particles in the water are filtered out before the water is released to the poly tank before it is then released to the laterals. The drip irrigation system used in this study had a lateral size of 16 mm of 10 m length with emitters spaced at 30 cm. The distribution of water applications and discharges from emitters along the lateral were measured according to ASABE Standards (ASAE, 1999).

1. First, the entire area for the performance assessment of the drip irrigation system was determined. Five drip lines, measuring 10 m each were selected.

2. Drippers for the assessment were chosen based on the use of a standard approach. The criteria for selection of the laterals and emitters are given by the function: n/5, 2n/5, n/2, 4n/5, last line; l/4, l/2, 3l/4, end where n is the number of lines, and l is the length of line. 20 emitter points were determined.

3. Catch cans were placed at each of these positions to collect water for a period of 20 minutes. The volume of water collected in each catch can was measured with a graduated container. This was done for all the five drip lines. At each of the 20 predetermined emitter points, two values were recorded; water collected in a catch can at a point and its adjacent point (i.e A and B)

4. The procedure was repeated, and the average volume of the water was considered as the discharge for a position.

5. The average emitter discharge for each of the twenty locations was then calculated.

6. The selected performance indicators were computed using the applicable equations (i.e., equations 3.7 to 3.11).

3.7 Assessment of Hydraulic Performance of Furrow Irrigation System

Direct determination of hydraulic indicators (e.g., flow velocity profiles, Manning's roughness coefficient *n*, hydraulic radius, shear stress, or spatial infiltration rates) in furrow irrigation is challenging due to the complex, dynamic nature of surface flow. Unlike pressurized systems, furrow irrigation involves open-channel, gravity-driven flow with unsteady, spatially variable conditions influenced by soil heterogeneity, erosion, deposition, crop interference, and temporal changes in roughness and infiltration during advance, storage, and recession phases (Bautista et al., 2017; Xu et al., 2019). These factors cause high variability in flow geometry,

wetted perimeter, and depth, making precise, non-invasive point measurements difficult and resource-intensive (Gillies & Smith, 2005; Strelkoff & Clemmens, 2007). Practical constraints, such as the need for specialized equipment across large fields and disruption of natural flow, further limit direct quantification, especially in resource-scarce settings (Bautista et al., 2018).

Indirect determination was used. Indirect determination relies on observable field data and analytical methods. Advance and recession curves—measured via simple timing at multiple stations—are combined with inflow/outflow volumes to infer infiltration parameters (e.g., Kostiakov-Lewis equation) and roughness using volume balance or optimization techniques (Elliott & Walker, 1982; Walker & Skogerboe, 1987). Models like WinSRFR or SIRMOD calibrate these from advance/recession data to estimate performance indicators such as application efficiency, distribution uniformity, and losses (Walker, 2005; Bautista et al., 2017).

3.8 Planting and agronomic practices

3.8.1 Experimental design

The experimental design was a split-plot design, where the main plots represent the three irrigation methods (drip, rain tubes, and furrow) and production purposes (roots and vines), while the subplots represent the fertilizer treatments (with and without fertilizer application). Each main plot was further divided into two subplots, resulting in 36 experimental units (18 main plots × 2 subplots per plot).

The split-plot design is appropriate for this research because it allows for the investigation of both primary factors (irrigation methods and production purpose) and secondary factors (fertilizer treatments) simultaneously while also considering the inherent variability within the system. This design accommodated the nested structure of the experiment, where the irrigation

methods and production purposes represented the whole plot treatments, whereas the fertilizer treatments represented the subplot treatments within each main plot.

According to Montgomery (2017), split-plot designs are particularly useful when certain factors are more difficult or costly to change than others, as is the case with irrigation methods compared to fertilizer treatments. This design also accounted for potential interactions between the main and subplot factors, providing a more robust analysis of the experimental outcomes.

Additionally, split-plot design is known to be efficient in terms of both time and resources, making it well suited for agricultural experiments where practical constraints often exist (Smucker et al., 2023).

Table 3.2: Layout of field experimental design

Drip irrigation		**Rain Tube irrigation**		**Furrow irrigation**	
V_0	**V_f**	**V_f**	**V_0**	**V_f**	**V_0**
V_f	**V_0**	**V_0**	**V_f**	**V_0**	**V_f**
V_0	**V_f**	**V_f**	**V_0**	**V_f**	**V_0**
V_f Represents fertilizer treatment		V_0 Without fertilizer treatment			

(Source: Author, modified from https://online.stat.psu.edu/stat503/lesson/14/14.3#paragraph--388, 2024)

3.9 Agronomic practices

3.9.1 Land preparation and Land clearing

Land preparation, which is a critical pre-irrigation activity in agriculture, encompasses various activities, such as land clearing, bed preparation, and ridge formation. These activities were aimed at optimizing the soil structure, water distribution, and crop growth. The debris, rocks, and unwanted vegetation were removed from the field to create a clean and uniform surface for subsequent operations. This process facilitates efficient infiltration of water and reduces the

risk of obstruction during irrigation. According to Tadesse et al. (2014), effective land clearing enhances soil aeration and promotes root development, thereby improving crop productivity. Following land clearing, the beds were prepared for vine production. The width of the beds was 1m, the length was 10m, the height was 0.2m and the space between beds was 1m. This was repeated for all the treatments.

3.10 Crop Parameters: Yield, Biomass, and Canopy Cover

Three destructive assessments of above-ground biomass were conducted during the crop season and at the end of harvest. In order to determine yield per unit area in t/ha, the average of five plants from each plot was used. Throughout the crop season, canopy cover (CC) was measured using the meter rule every 21 days. In all cases, the mean canopy cover and above-ground biomass was obtained from the average of the five plants in each treatment.

The canopy cover of Orange-Fleshed Sweet Potato (OFSP) was measured manually using a 1 m meter rule. Each experimental unit was first marked out with pegs to form a 1 m × 1 m plot. The meter rule was then placed across the plot to determine the portion of ground covered by the crop canopy. Areas that were not covered by the leaves were measured and subtracted from the total 1 m length to obtain the canopy-covered portion. The same procedure was repeated in the perpendicular direction, and the average canopy coverage was recorded.

3.11 AquaCrop Model calibration

The AquaCrop model calibration was conducted using experimental data from a field study held between June 18 and August 20, 2024. This process involved adjusting model parameters to ensure that outputs, primarily aboveground biomass and canopy cover (CC), closely match observed data. Calibration was achieved by inputting field data, running simulations, and making iterative comparisons with measured results through a trial-and-error approach (Raes et al., 2009; Steduto et al., 2012). Calibrating crop parameters for sweet potato was crucial for

accurately capturing the crop's physiological responses. The AquaCrop crop file includes parameters governing growth stages, such as canopy and root development and the impacts of water and nutrient stresses (Steduto et al., 2009). Key parameters adjusted for canopy cover included the canopy growth coefficient (CGC), canopy decline coefficient (CDC), and maximum canopy cover (CCx). The final calibrated values were CGC at 14.5% per day, CDC at 11.5% per day, and maximum canopy cover at 97%. The maximum crop transpiration coefficient (Kcbx) was calibrated to 1.15 for fully irrigated sweet potatoes without fertilizer stress, aligning with FAO-56 guidelines (Allen et al., 1998). Water productivity (WP) was set at 17 g m^{-2}, and the harvest index (HI) was calibrated at 30% (Dahniya, 1985; Olorunnisomo, 2007; Ahmed et al., 2012) on a dry matter basis, validated with field data. To model water stress impacts, parameters for canopy expansion, stomatal conductance, and early senescence were calibrated. These included upper and lower thresholds for canopy expansion (0.25 and 0.60), a stomatal closure upper threshold at 0.5, and early senescence thresholds (0.65). These settings effectively simulate reductions in growth, biomass, and yield under water deficit conditions Irrigation management in AquaCrop was calibrated to match the experimental field conditions, using a management-allowed depletion (MAD) of 65%. The actual irrigation schedule was entered manually based on field records. Three irrigation methods were used: drip, rain tube, and furrow irrigation, simulated in AquaCrop with 30%, 100%, and 80% of the soil surface wetted, respectively. Irrigation application efficiency was estimated separately and included in the gross irrigation calculations. Soil fertility levels and runoff characteristics were adjusted based on the fertilizer treatments applied in the field. Surface runoff was modeled with a curve number of 72, reflecting the sandy loam soil's behavior, as noted by Rajput et al. (2009). No mulch or crop residues were used, so these were excluded from the model. AquaCrop settings indicated that no water ponding occurred during the experiment.

3.12 Data Analysis

The FAO Cowpat model was used to analysed crop water requirement data, which was entered as outlined in section 3.5.1. Using Microsoft Excel and mathematical formulas for the various indicators, the irrigation system performance indicators were calculated using field data on irrigation system discharge. The FAO ACQUACROP 7.1 model was used to calculate and calibrate the water productivity of orange-fleshed sweet potatoes. Analysis of Variance (ANOVA) was employed to determine if the differences in water productivity and other dependent variables (canopy cover, biomass, yield etc.), between the different irrigation methods are statistically significant.

The good fitness of the simulated results with the measured field test data was assessed based on two statistical measures: the normalized root means square error (N-RMSE) and the coefficient of efficiency (E) (Nash and Sutcliffe, 1970):

$$NRMSE = \frac{100}{\bar{O}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - \bar{O}_i)^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (\text{E.q } 3.13)$$

The overall deviation between observed and simulated values deviates from the overall deviation between observed values (Oi) and their mean value (M) to the magnitude indicated by the N-RMSE. As the season progresses, the various deviations from (Oi–M) are considered by N-RMSE, which also provides a percentage-based representation of the model performance efficiency. Additionally, the relative difference between the simulated and observed data is expressed as a percentage by normalized RMSE. If the simulation's normalized RMSE is less than 10%, it is deemed excellent; if it is between 10% and 20%, it is deemed good; if it is between 20% and 30%, it is deemed fair; and if it is more than 30%, it is deemed poor.

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - \bar{O_i})^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (\text{E.q } 3.14)$$

Where,

M is the mean value of Oi, n is the number of observations, and Si and Oi are the simulated and observed (measured) values as samples collected during the season (such as biomass and CC) or at the end of the season (such as tuber yield). The overall difference between observed and simulated values during the crop season, as well as the overall difference between observed values Oi and their mean value (ó), is measured by the coefficient of efficiency. E values are unitless and range from -∞ to 1. The model's simulation efficiency improves as the values approach 1. Several previous AquaCrop parameterization investigations have utilized similar statistical methods (comparing measured and simulated values using E and RMSE) with success (Heng et al., 2009; Hsiao et al., 2009; Farahani et al., 2009; Birhanu et., at 2021)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Crop Water Requirement of Orange-Fleshed Sweet Potato (Orange Fleshed Sweet potatoes (*Ipomoea batatas* (L.) Lam.)

4.1.1 Long-term Weather Data and other Parameters for CWR Estimation

The results of CROPWAT 8.0 for the East Mamprusi District study area are shown in Table 4.1. Between 1993 and 2023, the minimum and maximum air temperatures were 21.8 °C and 33.3 °C, respectively, and the relative humidity ranged from 30% to 86%, with an average of 62 %. The monthly sunshine hours ranged from 4.7 to 10.4 hours, with an average of 7.5 hours, while the average wind speed ranges from 173 to 359 km/day. The months of January and September had the lowest and highest monthly rainfall, respectively, at 2 mm and 231 mm. With an average of 5.85 mm/day, the ETo values for the different months of the year varied from 3.59 to 8.93 mm/day. February had the highest ETo readings, measuring 8.93 mm/day.

Table 4.1: Long-term (1993 - 2023) Monthly Averages of Climatic Data

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m²/day	Eto mm/day	Rain mm	Eff rain mm
January	16.8	34	34	359	10.4	22.3	8.03	2	2.0
February	20.1	36.7	30	346	10.2	23.6	8.93	9	8.9
March	24.3	38.5	40	288	9.2	23.3	8.32	50	46.0
April	25.6	37.2	56	307	8.0	21.9	7.35	77	67.5
May	24.9	34.9	67	295	7.1	20.1	6.03	113	92.6
June	23.6	32.4	75	257	6.4	18.7	4.88	155	116.6
July	22.7	30.2	82	228	5.4	17.3	4.01	169	123.3
August	22.5	29.2	86	209	4.7	16.5	3.59	203	137.1
September	22.5	29.6	85	173	4.9	16.7	3.60	231	145.6
October	22.4	31.1	81	175	6.0	17.6	3.96	77	67.5
November	19.9	32.7	64	200	8.3	19.6	4.98	11	10.8

December	16.6	32.7	47	302	9.9	21.1	6.47	3	3.0
Average/ Total	21.8	33.3	62	262	7.5	19.9	5.85	1100	820.8

(Source: Ghana Meteorological Agency Database, 2023)

Reference evapotranspiration signifies the evaporative power or demand of the atmosphere, it determines the rate of the crop transpiration and soil evaporation under enough water supply conditions. Reference evapotranspiration is affected by meteorological factors such as solar radiation, temperature, and windspeed relative humidity, amongst others (Allen et al., 1998). Therefore, the range of ETo values recorded in this study is as a result of the variations in atmospheric conditions (temperature, humidity, wind speed, etc.) throughout the various months of the year. Low temperatures, limited sunshine hours, and reduced wind speeds clearly lead to low reference evapotranspiration. In contrast, elevated levels of meteorological factors—such as temperature, wind speed, solar radiation, and sunshine hours—significantly enhance reference evaporation, resulting in higher crop water requirements. The findings of this study align with the existing literature by supporting the conclusions of Liu et al. (2019), who established a positive correlation between sunshine, temperature, and reference evapotranspiration (ETo). It is evident that during the dry season, temperatures tend to rise while relative humidity decreases, contrasting with the rainy season, which features high rainfall, elevated relative humidity, and lower temperatures. This seasonal variation likely explains the lower ETo values recorded during the rainy season, particularly in June.

Throughout the year, ETo values reflect the influence of climatic factors such as relative humidity, temperature, and solar radiation. The observed fluctuations in ETo reinforce the idea that it is a climatic variable, varying significantly across different months and particularly between the two distinct seasons. Furthermore, our ETo output aligns with the results from FAO (2020), Mebrahtu et al. (2021) and Adeniran et al. (2010), which highlight that ETo peaks during the dry season and reaches its lowest point during the wet season.

4.1.2 Monthly Total and Effective Rainfall in East Mamprusi District (2024)

Data presented in Table 4.2 show the total (Rain/mm) and effective monthly rainfall (Eff rain/mm) measured at East Mamprusi study site in 2024. Rainfall is a critical climatic factor in agricultural water management, particularly in semi-arid regions like East Mamprusi District. Effective rainfall refers to the amount of total rainfall that is available for crop use, disregarding losses due to runoff and deep percolation (Allen et al., 1998). The effective rainfall values in this table are slightly lower than total rainfall in some months, reflecting the adjustments for these losses. Rainfall in East Mamprusi is highly seasonal, with significant precipitation occurring between June and September, accounting for the bulk of the annual total. The dry season spans from November to April, with almost negligible rainfall. This seasonal pattern is characteristic of semi-arid climates, where rain-fed agriculture may be challenging without supplemental irrigation (Rockström et al., 2010). The USDA soil conservation method was used to run the model with the FAO CROPWAT software and calculate effective rainfall. Details are provided in Chapter three.

Table 4.2: Monthly Total and Effective Rainfall at East Mamprusi (2024)

Month	Rain Mm	Eff rain Mm
January	0.1	0.1
February	0.2	0.2
March	0.6	0.6
April	2.4	2.4
May	80.5	70.1
June	294.4	154.4
July	300	155
August	150	114
September	338.4	158.8
October	175.5	126.2
November	0.2	0.2
December	0.1	0.1
Total	1342.4	782.2

(Source: Field measurements at East Mamprusi Weather Station, 2024)

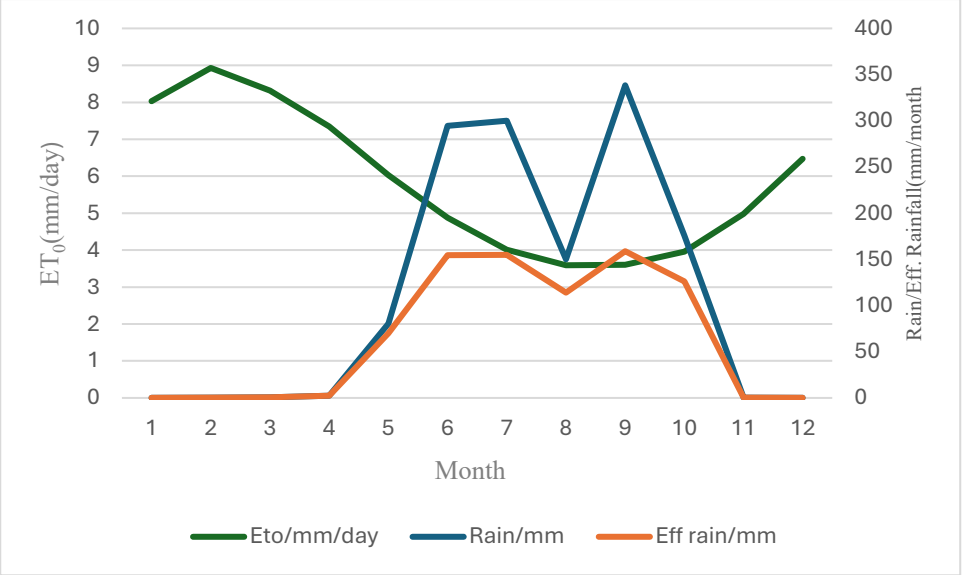

Figure 4.1: Monthly ET0, actual and effective rainfall of East Mamprusi District 2024 (source: Author, 2024)

Table 4.3: Crop Water Requirement, Effective Rainfall, and Irrigation of sweet potato

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Rainfall mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jun	2	Init	0.50	2.44	7.3	18.4	16.6	7.3
Jun	3	Init	0.50	2.29	22.9	60.2	54.2	0.0
Jul	1	Deve	0.57	2.46	24.6	58.8	52.9	0.0
Jul	2	Deve	0.77	3.09	30.9	59.6	53.6	0.0
Jul	3	Deve	0.98	3.80	41.8	53.8	48.4	0.0
Aug	1	Mid	1.10	4.12	41.2	44.3	39.9	1.3
Aug	2	Mid	1.10	3.96	39.6	37.8	34.0	5.7
Aug	3	Mid	1.10	3.96	43.6	44.8	40.3	3.3
Sep	1	Mid	1.10	3.97	39.7	56.0	50.4	0.0
Sep	2	Mid	1.10	3.97	39.7	62.9	56.6	0.0
Sep	3	Late	1.03	3.83	38.3	57.6	51.8	0.0
Oct	1	Late	0.90	3.45	34.5	54.0	48.6	0.0
Oct	2	Late	0.77	3.04	30.4	51.7	46.5	0.0
					434.5	659.9	593.7	17.6

(Source: CROPWAT, 2024)

The total crop water requirement for the production period was estimated to be 434.5 mm. In contrast, the net irrigation water requirement for sweet potato ranges from 0 to 7.3 mm per decade, totaling 17.6 mm for the season when effective rainfall is considered. The information of when to irrigate and the appropriate amount of water to supply is crucial for effective

irrigation management, as it is based on the crop's water needs and proper irrigation scheduling. (Mebrahtu et al., 2021). The overall objective of water management in an irrigation scheme is to regulate the amount of water and the rate of application on time to ensure that crop water needs are met without wasting water, plant nutrients, soil, or energy. The results presented in Table 4.3 show that sweet potato requires 434.5 mm of water, an effective rainfall amount of 593.7 mm, and 17.6 mm of irrigation requirement for the entire growing season.

The data indicates that throughout most of the growing season, effective rainfall was sufficient to meet the crop water requirements, eliminating the need for irrigation in many decades. Only a few instances, particularly in the middle of the growing season, required supplementary irrigation. For instance, in August (second and third decades), the crop experienced irrigation demand of 5.7 mm and 3.3 mm, respectively, due to a decline in rainfall. Similarly, in June (second decade), an irrigation requirement of 7.3 mm was observed, indicating that supplemental irrigation was necessary at the initial growth phase to ensure adequate soil moisture for early development.

4.2 Soil Physical Properties of The Experimental Fields

The findings presented in Table 4.4 provide a comprehensive overview of the soil properties and water-holding capacities within the study area across various depths. These insights are essential for understanding key factors that influence soil health, effective water management, and overall crop productivity.

Table 4.4: Soil Properties and Water Holding Capacities at Different Depths at East Mamprusi

Lab No.	Soil Depth	% OC	Om	% Sand	% Silt	% Clay	Soil Texture	%Vol FC	%Vol PWP	Kg/cm^3 BD
1	0-15cm	1.84	3.16	88.32	5.16	6.52	Sandy Loam	11.42	6.12	1.45
2	16-30cm	0.88	1.51	82.32	10.16	7.52	Sandy Loam	13.11	6.81	1.43
3	31-45cm	0.52	0.89	86.36	9.12	4.52	Sandy Loam	12.81	7.41	1.46

(Source: Soil science Lab, UDS, 2024)

One significant observation is the decline in soil organic carbon (OC) content with increasing depth, as expected. In the top layer, ranging from 0 to 15 cm, the OC content is recorded at 1.84%. However, this figure drops to 0.52% in the deeper 31–45 cm layer. This pattern is consistent with established soil science principles, which suggest that surface layers generally have higher concentrations of organic carbon owing to the accumulation of plant residues and the activity of soil microorganisms (Lal et al., 2004). The relationship between soil OC and organic matter (OM) content is equally important; as the OC diminishes with depth, the OM content exhibits a similar downward trend. This highlights the crucial role that surface organic inputs play in maintaining nutrient availability for crops.

In terms of soil texture, all measurements categorize the soil as sandy loam, characterized by sand particle percentages exceeding 82%. This particular texture is known for its excellent drainage and aeration properties, which are beneficial for root development and soil life. However, it also presents challenges regarding water retention, as sandy soils typically hold less moisture compared to finer-textured soils such as clay loam (Brady & Weil, 2016). While the amounts of silt and clay are relatively low, they do contribute some retention capacity and influence the overall soil structure, aiding in the formation of aggregates that can enhance water infiltration and aeration.

Field capacity (FC) refers to the highest amount of water the soil can hold after any surplus has drained, with values ranging from 11.42 % to 13.11 %. On the other hand, the permanent wilting point (PWP) signifies the lowest moisture level at which plants cannot access water, which falls between 6.12 % and 7.41 %. These figures indicate that the available water capacity (AWC) of the soil is moderate. Such characteristics align with typical properties attributed to sandy loam soils, which generally have lower water-holding capabilities than soils with finer textures (Hillel, 1998). Additionally, the average bulk density (BD) of the soil is roughly 1.45 g/cm^3, which suggests that the soil is moderately compacted. This level of compaction allows

for adequate porosity, promoting beneficial root penetration and facilitating efficient water movement through the soil profile (Blanco-Canqui & Rattan, 2023).

The implications of these findings underline the critical necessity for implementing effective water management strategies, especially in scenarios where organic matter is limited at greater soil depths. One recommended approach is to enhance the surface organic matter content through practices such as mulching or applying organic amendments. These actions could significantly improve the soil's ability to retain water and increase nutrient availability for plants (Lal, 2004). Moreover, the moderate AWC observed in the soil indicates that irrigation practices should be carefully scheduled, with a focus on the upper layers of the soil profile. This strategy is particularly pertinent for optimizing water use efficiency in sensitive crops, such as orange-fleshed sweet potatoes, which have a heightened sensitivity to changes in soil moisture levels. By prioritizing shallow soil layers for irrigation, farmers can ensure that these crops have access to the necessary moisture for optimal growth and productivity

4.3 Hydraulic Performance of Drip Spray Tube Irrigation System.

A couple of performance metrics estimate emitter efficiency and uniformity in real field conditions. Our analysis focuses on four main metrics: emitter flow variation, coefficient of variation, uniformity coefficient, and field emission uniformity. The interpretations and ratings for these metrics, as established by the American Society of Agricultural Engineers (ASAE) in 1999, are presented in Table 4.1.

For the drip irrigation system, the field data resulted in the following values: 23.6% for emitter flow variation, 0.11 % for coefficient of variation, 90.45 % for uniformity coefficient, and 85 % for field emission uniformity. In comparison, the Rain tube irrigation system indicated emitter flow variation to be 30.8 %, coefficient of variation was 0.15 %, uniformity coefficient was 89.76%, and field emission uniformity was 81 %.

Table 4.5: Hydraulic Performance of the Drip and Rain Tube Irrigation System at East Mamprusi Experimental Set up

Performance Indicators	ASAE (1999) Rating		Drip		Rain Tube	
			Field values and remark		Field values and remark	
	Range	Interpretation	Value	Remark	Value	Remark
Emitter flow Variation	90 -100%	Excellent	23.6	Poor	30.8	Poor
	80 -90%	Good				
	70 - 80%	Fair				
	< 70%	Poor				
Uniformity Coefficient	≥ 100%	Excellent	90.45%	Very Good	89.76%	Very Good
	80 -90%	Very Good				
	70 - 80%	Fair				
	60 - 70%	Poor				
	< 60	Unacceptable				
Field Emission Uniformity	90 -100%	Excellent	85%	Good	81%	Good
	80 -90%	Good				
	70 - 80%	Fair				
	< 70%	Poor				
Coefficient of variation	<0.05	Excellent	0.11	Fair	0.15	Poor
	0.05 -0.07	Very Good				
	0.07 - 0.11	Fair				
	0.11 - 0.15	Poor				
	> 0.15	Unacceptable				

ASAE – American Association of Agricultural Engineers
(source: Author, 2024)

The hydraulic performance of the drip and rain tube irrigation systems evaluated at the East Mamprusi experimental site is presented in Table 4.5. This evaluation was conducted using key performance indicators recommended by the American Society of Agricultural Engineers (ASAE, 1996) standards, particularly EP405.1 for field evaluation of micro irrigation systems. The results reveal a mixed performance, highlighting both acceptable overall uniformity and critical limitations in emitter discharge consistency.

A notable finding is the poor emitter flow variation recorded for both systems — 23.6% for drip and 30.8% for rain tube irrigation. According to ASAE guidelines, emitter flow variation below 10% is considered excellent, 10–20% good, and values above 20–30% are generally rated poor. Both systems therefore fall into the poor category. The rain tube system exhibited substantially higher flow variation than the drip system, which is expected given the reliance of rain tubes on simple laser-punched holes. These holes are more susceptible to manufacturing inconsistencies, pressure fluctuations, and partial clogging compared to precision-engineered drip emitters (Bhatnagar et al., 2023).

Interestingly, despite the poor emitter flow variation, both systems achieved very good ratings for Uniformity Coefficient (UC), with drip recording 90.45% and rain tube 89.76%. This apparent contradiction is well-documented in microirrigation literature. The Uniformity Coefficient (Christiansen's CU) is relatively insensitive to a few extremely low-flow emitters, while emitter flow variation heavily penalizes the minimum discharge rate. Similarly, Field Emission Uniformity (EU) was rated "Good" for both systems (drip = 85%; rain tube = 81%). These results suggest that although average water distribution across the field was reasonably uniform, a significant proportion of emitters delivered substantially less water than the mean, which may lead to spatial variability in soil moisture and crop performance.

The Coefficient of Variation (CV) further confirms this trend, with the drip system rated "Fair" (CV = 0.11) and the rain tube rated "Poor" (CV = 0.15). Higher CV values in the rain tube system indicate greater discharge inconsistency, which is a major concern for water use efficiency and crop uniformity.

In the context of smallholder irrigation in northern Ghana, these findings are significant. The relatively high flow variation observed in both systems can be attributed to unstable operating pressure, inadequate filtration, sediment accumulation, and the absence of pressure-

compensating emitters — common challenges in resource-limited settings. While the rain tube system offers lower initial cost and easier installation, its hydraulic performance is clearly inferior to the drip system under field conditions.

Overall, although the systems achieved acceptable average uniformity, the poor emitter flow variation and high CV values suggest sub-optimal hydraulic performance. This has important implications for irrigation scheduling, water productivity, and crop yield stability.

4.4 Evaluation and comparison of crop water productivity (CWP) for sweet potato production in Northern Ghana using different supplementary irrigation methods

Table 4.6 presents a comparison of evapotranspiration water productivity (WPET) and yield (observed (Ob) and simulated (Sim)) for orange-fleshed sweet potato (OFSP) under different supplementary irrigation methods, with and without fertilizer treatments, during the production period from June 18 to August 20, 2024. The study used the AquaCrop model to simulate yield and evaluate model performance using the efficiency factor (EF) and normalized root mean square error (N-RMSE, %).

Table 4.6: Comparison of ET Water productivity, yield (observed and simulated) of OFSP under different irrigation method with and without fertilizer treatment.

Irrigation Method	WP_{ET}	Yield (ton/ha)			
	Kgm^{-3}	Ob	Sim	EF	N-RMSE (%)
Drip With Fertilizer	1.49	1.36	1.41	0.95	12.0
Drip Without Fertilizer	0.93	0.84	0.87	0.80	5.2
Rain tube with Fertilizer	1.37	1.21	1.42	0.52	13.2
Rain tube without Fertilizer	0.85	0.87	0.83	0.80	11.0
Furrow with Fertilizer	1.23	1.12	1.24	0.73	13.1
Furrow without Fertilizer	0.8	0.75	0.78	0.80	16.0
Rainfed with fertilizer	1.12	0.91	1.04	0.97	8.6
Rainfed without fertilizer	0.81	0.73	0.75	0.99	5.6

(Source: Field data, 2024)

Water productivity (WP_{ET}), expressed as kg of yield per m^3 of water consumed, serves as a key indicator of how efficiently water is utilized in crop production. The results reveal that WPET varied across irrigation methods and fertilizer treatments, but the differences observed among irrigation methods were relatively small. This suggests that while supplementary irrigation had an impact, it was not the primary determinant of yield. Instead, fertilizer application played a more significant role in enhancing both water productivity and yield, a finding consistent with previous studies (Ghimire et al., 2022).

Among the irrigation methods, drip irrigation with fertilizer exhibited the highest WPET (1.49 kg/m^3) and yield (1.38 ton/ha). This can be attributed to the efficient water delivery mechanism of drip irrigation, which minimizes losses and ensures that water is applied directly to the root zone. Furthermore, fertilizer applications likely improved nutrient uptake, enhancing overall crop performance (Ayers & Westcot, 1985). In contrast, the lowest WPET (0.8 kg/m^3) was observed under furrow irrigation without fertilizer, which can be explained by inefficient water application, leading to losses through runoff and deep percolation combined with nutrient limitations (Ali et al., 2023).

Rain tube irrigation with fertilizer recorded a WPET of 1.37 kg/m^3, followed by furrow irrigation with fertilizer (1.23 kg/m^3). These results indicate that while rain tube irrigation is more efficient than furrow irrigation, it remains less effective than drip irrigation. Rainfed conditions with fertilizer had a WPET of 1.12 kg/m^3, which, though lower than the irrigated treatments, highlights that fertilizer application significantly enhances water productivity even under rainfed conditions. Across all irrigation methods, the presence of fertilizer consistently improved WPET values, reinforcing the critical role of nutrient availability in water use efficiency. Similar discoveries have been reported by Zhou et al. (2023), emphasizing that balanced nutrient application improves water productivity by enhancing root development and photosynthetic efficiency.

The observed and simulated yields for all treatments were closely aligned, further validating the accuracy of the AquaCrop model. The highest EF (0.99) was recorded for rainfed treatments without fertilizer, indicating near-perfect agreement between observed and simulated values (Moriasi et al., 2007). EF values for other treatments ranged from 0.52 to 0.97, demonstrating the model's overall reliability in capturing yield variability across different irrigation and fertilizer treatments. The N-RMSE values were all below 20%, indicating good to excellent model performance (Singh et al., 2021). The lowest N-RMSE (5.2%) was recorded for drip irrigation without fertilizer, suggesting minimal error in simulating yields under this treatment. These results confirm that while irrigation methods influenced yield and WPET, fertilizer application was the key determinant of productivity outcomes.

4.4.1 Canopy Cover and Biomass of Orange-Fleshed Sweet Potato

Table 4.7 presents the observed and simulated canopy cover and aboveground biomass of OFSP under different irrigation techniques, with and without fertilizer treatments. The AquaCrop model was again used to evaluate the accuracy of these indicators using EF and N-RMSE. The analysis provides further understanding into the impact of irrigation and fertilizer treatments on crop growth.

Table 4.7: Observed and Simulated Canopy Cover and Aboveground Biomass of OFSP under Different Irrigation Methods with and without Fertilizer.

Irrigation Method	**Canopy Cover (%)**				**Biomass(ton/ha)**			
	Ob	Sim	EF	N-RMSE (%)	Ob	Sim	EF	N-RMSE (%)
Drip With Fertilizer	90	84.0	0.92	10.8	5.51	5.63	0.96	9.8
Drip Without Fertilizer	60	54.0	0.44	18.3	3.40	3.48	0.96	11.9
Rain tube with Fertilizer	90	84.6	0.59	12.5	6.50	5.68	0.90	19.5
Rain tube without Fertilizer	65	50.2	0.33	23.3	3.64	3.32	0.94	15.9
Furrow with Fertilizer	83	76.0	0.45	22.3	4.57	4.95	0.98	7.8
Furrow without Fertilizer	63	46.0	0.51	24.0	3.28	3.13	0.85	26.0
Rainfed with fertilizer	70	63.0	0.94	13.0	4.30	4.18	0.99	5.2
Rainfed without fertilizer	56	45.0	0.83	13.0	3.12	2.99	0.99	5.0

(Source: field data, 2024)

A critical examination of the results indicates that while supplementary irrigation was applied across all methods, its influence on canopy cover and biomass accumulation was minimal. Instead, fertilizer application emerged as the dominant factor influencing these agronomic parameters. For example, under drip irrigation with fertilizer, the observed canopy cover reached 90%, while biomass accumulation was 5.507 tons per hectare. However, in the absence of fertilizer under the same irrigation method, canopy cover was reduced to 60%, and biomass declined to 3.40 tons per hectare. This trend was consistent across all irrigation methods, underscoring the essential role of fertilizer in enhancing OFSP growth and productivity.

The beneficial effects of fertilizer can be attributed to its role in supplying essential nutrients necessary for physiological processes such as photosynthesis, root development, and biomass accumulation. Previous studies have demonstrated that appropriate fertilizer application significantly increases fresh weight and yield in sweet potatoes by promoting vigorous root and canopy development (Zhou et al., 2023). Despite the implementation of supplementary irrigation across all methods, its influence on canopy cover and biomass was negligible. This observation can be explained by the water dynamics during the growing season. The crop water requirement (CWR) for OFSP was 434.5 mm, while effective rainfall during the cultivation period was 593.7 mm—exceeding the CWR. Consequently, the supplementary irrigation requirement was minimal, totalling only 17.6 mm.

According to Gernot et al. (2015), in situations where effective rainfall surpasses crop water requirements, additional irrigation provides limited agronomic benefits. Excessive irrigation under such conditions may even lead to resource inefficiencies. Studies suggest that over-irrigation can negatively impact the allocation of photosynthetic products to storage roots in sweet potatoes, leading to suboptimal yields (Zhou et al., 2023). The AquaCrop model demonstrated varying degrees of accuracy in predicting canopy cover and biomass. The model's efficiency factor (EF) and N-RMSE values provided insight into its reliability.

Notably, the model exhibited high predictive accuracy for biomass, with EF values ranging from 0.85 to 0.99 and N-RMSE values between 5.0% and 26%. This indicates a strong correlation between observed and simulated biomass values, affirming the model's robustness in biomass prediction. However, the model's performance in simulating canopy cover was less consistent, with EF values ranging from 0.33 to 0.94 and N-RMSE values between 10.8% and 24%. These discrepancies suggest that while the model is proficient in biomass prediction, further calibration may be necessary to improve its accuracy in canopy cover simulation under varying agronomic conditions.

4.5 Evaluation and comparison of the water use efficiency (WUE) of each irrigation technique employed for sweet potato production

The results presented in Table 4.8 provide insight into the Water Use Efficiency (WUE) of orange-fleshed sweet potato (OFSP) under different irrigation methods (all of which were supplementary in nature) with fertilizer treatment in East Mamprusi District. The results highlight the variation in WUE across the different irrigation methods, with drip irrigation exhibiting the highest efficiency (5.78 kg/ha/mm) and rainfed conditions the lowest (3.98 kg/ha/mm). Though a significant amount of the water was supplied through rainfall, the variation observed across the irrigation method is due to the efficiency of the irrigation system in delivering the necessary supplementary irrigation requirement of 17.6 mm.

Table 4.8: The comparison of water use efficiency for production of OFSP under drip, furrow and rain tube

Irrigation method	Total Water Applied (mm) 18/06/2024	Yield(ton/ha)	WUE (kg/ha/mm)
Drip	613.2	1.363	2.22
Rain Tube	628.1	1.205	1.92
Furrow	641.0	1.120	1.75
Rainfed	593.7	0.908	1.53

(Source: Author, 2024)

Water Use Efficiency (WUE) is a crucial parameter in assessing the effectiveness of irrigation strategies in crop production, particularly under semi-arid conditions where water availability is limited.

The drip irrigation method recorded the lowest amount of water applied (613.2 mm) among the irrigated treatments, yet it produced the highest yield (1.363 ton/ha). This aligns with studies showing that drip irrigation minimizes water losses through deep percolation and evaporation while delivering water directly to the root zone (FAO, 2020). Conversely, the furrow irrigation method used the highest amount of water (641.0 mm) but resulted in the lowest yield (1.120 ton/ha). This is attributed to inefficient water distribution and greater evaporative losses, typical of surface irrigation techniques (Ali et al., 2023). The rain tube system, which applied an intermediate volume of water (628.1 mm), achieved a moderate yield (1.205 ton/ha), suggesting that its efficiency lies between drip and furrow irrigation. The rainfed condition required the least water (593.7 mm), as it solely depended on rainfall. However, its yield (0.908 ton/ha) was the lowest among all treatments. This result underscores the limitation of relying solely on rainfall, particularly in semi-arid regions, where erratic precipitation often fails to meet crop water requirements (Ghimire et al., 2022).

The WUE values, calculated as the ratio of yield to water applied, demonstrate clear distinctions among the irrigation methods. Drip irrigation achieved the highest WUE (2.22 kg/ha/mm), emphasizing its superior capability to convert water into crop yield efficiently. This is consistent with findings by Ayers and Westcot (1985), who reported that drip irrigation enhances WUE by reducing non-productive water losses. Rain tube irrigation had a lower WUE (1.92 kg/ha/mm), reflecting moderate efficiency. Although this method improves uniformity compared to furrow irrigation, its water application still results in some non-productive losses Tamiru Bekele, Z. (2021). . Furrow irrigation exhibited the lowest WUE among the irrigated treatments (1.75 kg/ha/mm), reaffirming its inefficiency due to higher

runoff and deep percolation rates. Rainfed conditions recorded a WUE of 1.53 kg/ha/mm, slightly lower than that of furrow irrigation. This agrees with studies on semi-arid agriculture (Rockström et al., 2010), which state that while rainfed farming is water-conservative, its yield potential is limited by the inconsistency and inadequacy of natural rainfall.

Researchers suggest that water use efficiency (WUE) should range from 3 to 9 kg/ha/mm (Howell, 2001; Zwart & Bastiaanssen, 2004). However, this is not the case in this study because the orange-fleshed sweet potato (OFSP) was still in its early growth stages, with most of the vegetative parts contributing to above-ground biomass. This suggests that a significant portion of the plant's dry matter allocation was directed toward vegetative growth rather than storage roots, which would have contributed to higher final yield and WUE. Previous studies indicate that further crop maturation leads to improved WUE as more biomass is partitioned into economic yield (Steduto et al., 2012).

4.6 Calibration of the AquaCrop Model for the Orange Fleshed sweet potato in East Mamprusi

4.6.1 Calibration of the AquaCrop Model for Green Canopy Cover, About-ground biomass (Dry Matter), and soil Water Content

The calibrated AquaCrop model focused on forecasting orange-fleshed sweet potato (OFSP) yields, above-ground biomass, and soil water content. Table 4.8 presents the conservative parameters, which are crop-specific and largely independent of management or agroclimatic zone (Hsiao et al., 2022). Additionally, it outlines the non-conservative (crop-dependent) parameters successfully calibrated in this study.

Table 4.9 summarizes the simulation outcomes, including the simulated above-ground biomass (dry matter), canopy cover (CC) of OFSP, and soil water content during the growing period,

compared to measured values. Crop parameters were used to simulate CC, attaining a strong agreement between simulated and observed values. After calibration, the model estimated the water productivity (WP*) as 17.0 g m^{-2} (Table 4.9), which falls within the range suggested by Raes et al. (2012b) for C3 crops (15–20 g m^{-2}) and aligns with field observations. The calibration results demonstrated the model's capability to simulate CC under the given growing conditions (Figure 4.2).

Overall, the model effectively captured the seasonal trend in CC. However, it slightly overestimated CC at 35 and 49 days after planting and underestimated CC at 63 days after planting, though with minimal deviation. This agrees with findings by Greaves and Wang (2016). Similarly, Montoya et al. (2016) demonstrated AquaCrop's ability to simulate potato CC under various water application scenarios. This research aligns with other studies (Ngetich et al., 2012) that reported a strong match between measured and simulated CC across different irrigation treatments. The statistical parameters further validated the model's accuracy. The normalized root mean square error (NRMSE) was 15.6%, while the Nash-Sutcliffe model efficiency coefficient (EF) was 0.67, indicating good model performance.

Table 4.9: Conservative (constant) parameters (conservative across all locations, water treatments, and cultivars) used for simulation of sweet potato in East Mamprusi

Parameter	Units/Meaning	Value	source
Base temperature	°C	10	FAO(2009a)
Upper temperature	°C	35	FAO(2009a)
Soil H_2O depletion factor, canopy expansion	Upper threshold(p-exp)	0.25	FAO(2009a)
Soil H_2O depletion factor, canopy expansion	Lower threshold(p-exp)	0.60	FAO(2009a)
Coefficient of positive impact on HI	Vegetative growth	10	FAO(2009a)
Coefficient of negative impact on HI	Stomatal closure	8	FAO(2009a)
maximum possible increase of specified HI	%	15	FAO(2009a)

H_2O productivity normalized for ETo & CO_2	g/m² (WP*)	17	FAO(2009a)
H_2O productivity normalized for ETo & CO_2 during yield formation	g/m² (WP*)	100	
Stomatal stress coefficient curve shape		3.0	

User specific parameters: Phenological observations, cultivar specific and calibrated parameters

Parameters	Units/Meaning	Value	source
Number of plants per hectare	ha^{-1}	333333	Measured
Time from transplanting to recover	Days	8	Measured
Initial canopy cover (CC_0)	%	5	Measured
Maximum Canopy Cover (CC_x)	%	97	Measured
Time to maximum canopy cover	%	56	Measured
Time from transplanting to maturity	Days	120	Measured
Time from transplanting to flowering	Days	45	Measured
Maximum effective rooting depth	(m)	1	Measured
Time from sowing to maximum rooting depth	Days	63	Measured
Reference Harvest Index (HI_O)	%	25	Calibrated
Water productivity (WP*)	g/m²	17	Calibrated
Soil texture	sandy Loam		Analyzed
Canopy growth coefficient (CGC	Fr per calendar day	1.14	Calibrated
Canopy decline coefficient (CDC) at senescence	Fr per Calendar Day	1.1	Calibrated
Soil fertility level	%	64	Calibrated

(Source: Various, 2024)

Table 4.10: Comparison of Simulated and Measured Canopy Cover and Aboveground Biomass of OFSP

	Canopy Cover (%)		Biomass(ton/ha)		Soil water content	
DAP	Measured	Simulated	Measured	Simulated	Measured	Simulated
21	43	21.8	0.37	0.514	212	240.3
35	67	71.7	3.00	2.315	165	140.4
49	84	87.2	5.00	4.904	127	137.2
63	95	90	6.573	7.611	153	142.8
	EF=0.67 N-RMSE=15.6%		EF= 0.93 N-RMSE=16.8%		EF=0.57 N-(RMSE) =12.2%	

(Source: Field studies, 2024)

The simulated above-ground biomass closely matched the observed biomass (Fig. 4.3). To enhance accuracy, adjustments were made using stress coefficients, such as Pupper for stomatal regulation, ensuring that the simulated biomass aligned with observed values. A strong correlation was observed between simulated and measured biomass, with a normalized root mean square error (NRMSE) of 16.8% and a Nash-Sutcliffe model efficiency coefficient (EF) of 0.93. The reference harvest index (HI_0) was calibrated to 0.70, which falls within the range of 0.70–0.85 proposed by Raes et al. (2012) for potato.

During calibration, the model exhibited slight overestimation and underestimation at specific growth stages, particularly at 21 and 63 days after planting (DAP). This finding aligns with (Abera et al., 2013), who reported that AquaCrop tends to overestimate biomass during flowering and maturity stages while maintaining an overall good simulation accuracy. The negative value of the coefficient of residual mass (CRM) in this study further supports this trend. The model efficiency (EF = 0.93) indicates strong predictive capability, consistent with results from Greaves and Wang (2016), who reported a good agreement between measured and simulated biomass, with statistical values of RMSE = 1.16 and EF = 0.97. Additionally, Abedinpour et al. (2012) found that the model's coefficient of efficiency varied between 0.65 and 0.99 under different irrigation treatments. These findings suggest that the AquaCrop model can be effectively adjusted to simulate biomass, yield, and water use efficiency for potatoes in the study area, making it a valuable tool for irrigation decision-making.

The model's performance in simulating soil water content was evaluated at various growth stages. At 21 DAP, the measured soil water content was 212 mm, while the simulated value was 240.3 mm, indicating a moderate overestimation in the early growth phase. This discrepancy may be attributed to model assumptions regarding water dynamics when root development and uptake are minimal (Steduto et al., 2009). By 35 DAP, the model underestimated soil water content, with measured values at 165 mm and simulated values at 140.4 mm. This underestimation may be due to variations in soil infiltration rates or inaccuracies in capturing rainfall and irrigation events (Raes et al., 2012). At 49 DAP, the discrepancy between measured (127 mm) and simulated (137.2 mm) values narrowed, demonstrating improved accuracy during peak vegetative growth—a critical period for water management due to high evapotranspiration rates. By 63 DAP, the measured soil water content increased to 153 mm, while the simulated value decreased slightly to 142.8 mm, possibly due to the model's inability to fully account for soil heterogeneity or microclimatic variations.

Overall, the model's ability to simulate soil water dynamics was assessed using the Nash-Sutcliffe efficiency coefficient (EF) and normalized root mean square error (NRMSE). An EF of 0.57 indicates moderate reliability in simulating soil water content, while the NRMSE of 12.2% suggests reasonable accuracy in estimating soil moisture under field conditions (Moriasi et al., 2017).

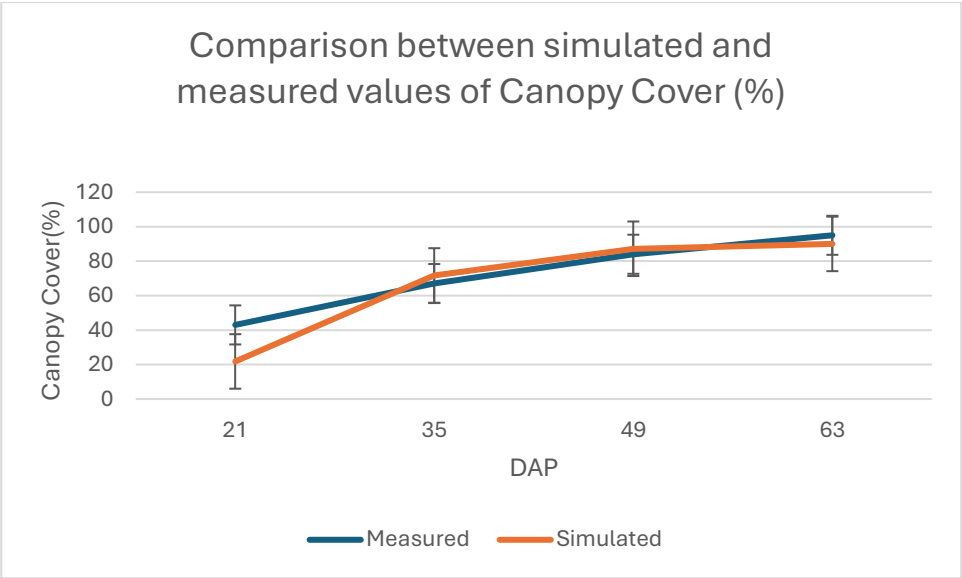

Figure 4.2: Comparison between simulated and measured values of Canopy Cover (%)

(Source: Field studies, 2024)

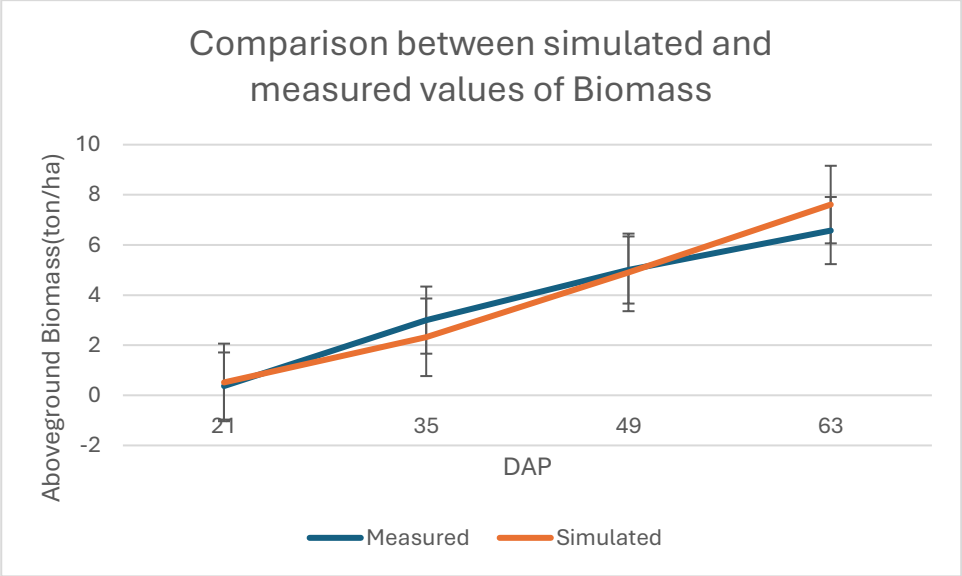

Figure 4.3: Comparison between simulated and measured values of Biomass

(Source: Field studies, 2024)

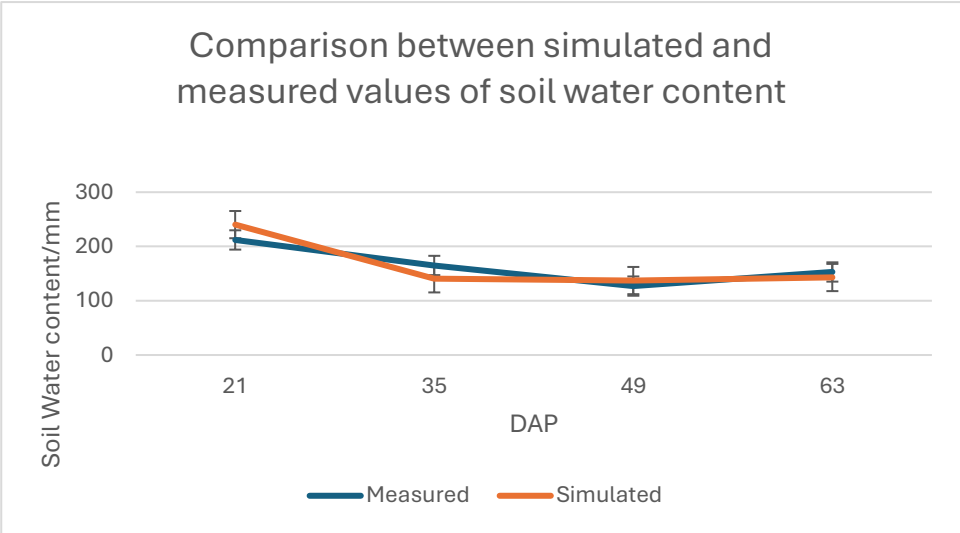

Figure 4. 4: Comparison between simulated and measured values of soil water content

(Source: Field studies, 2024)

4.7 Evaluation of the impact of fertilizer treatment on vegetative growth and vine yield under different irrigation methods

The data presented in Table 4.11 illustrates the impact of fertilizer treatment on the vegetative growth and vine yield of orange-fleshed sweet potato (OFSP) under different irrigation methods. The performance metrics analyzed include vine length, canopy cover, aboveground biomass, rooting depth, vine yield, and internode length. The table also provides a statistical analysis of the variations in these parameters across the irrigation methods, with the source of variation including sample, columns (parameters), and their interactions.

Table 4.11: Comparison of the performance of OFSP under different Irrigation method with fertilizer treatment

Crop Parament	count	Sum				Average			
		Drip	Rain Tube	Furrow	Rainfed	Drip	Rain Tube	Furrow	Rainfed
Vine Length/cm	5	2025	2006	1887	1683	405	401.2	377.4	336.6

Canopy Cover (%)	5	448	449	415	350	89.6	89.8	83	70
Aboveground Biomass/kg	5	2.05	1.97	1.74	1.59	0.41	0.394	0.348	0.318
Rooting Depth/cm	5	440	436	390	377	88	87.2	78	75.4
Vine Yield/cuttings	5	126	118	106	94	25.2	23.6	21.2	18.8
Internode Length/cm	5	45	38	36	29	9	7.6	7.2	5.8

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	6407.36	3	2135.787	2.663293	0.052301	2.699393
Columns	2069690	5	413938.1	516.1743	1.03E-67	2.309202
Interaction	10466.4	15	697.7577	0.870093	0.598782	1.7718
Within	76985.7	96	801.9347			
Total	2163550	119				

(Source: Field studies, 2024)

Vine length was highest under drip irrigation (405 cm), followed by rain tube (401.2 cm), furrow (377.4 cm), and rainfed conditions (336.6 cm). The observed trend suggests that drip irrigation provides an optimal water supply for vine elongation compared to other methods. The results align with findings by Zwart and Bastiaanssen (2004), who reported that efficient irrigation methods like drip improve water availability in the root zone, promoting vegetative growth. Canopy cover followed a similar trend, with rain tube irrigation slightly outperforming drip irrigation (89.8% vs. 89.6%), while furrow (83%) and rainfed conditions (70%) were significantly lower. The comparable performance of drip and rain tube irrigation indicates their ability to support robust vegetative growth by maintaining favourable soil moisture levels (FAO, 2011). Conversely, the lower canopy cover in rainfed conditions highlights water stress as a limiting factor, corroborating reports by Farooq et al. (2009) on the impact of water stress

on crop canopy development. Aboveground biomass was also highest under drip irrigation (0.41 kg), followed by rain tube (0.394 kg), furrow (0.348 kg), and rainfed conditions (0.318 kg). This finding emphasizes the role of consistent moisture supply in biomass accumulation, with drip irrigation proving most effective. According to Steduto et al. (2012), maintaining a consistent water supply enhances photosynthetic activity and biomass production. The data reveals a descending trend in rooting depth across the irrigation methods, with drip irrigation leading (88 cm) and rainfed conditions having the lowest rooting depth (75.4 cm). Deeper rooting under drip irrigation may be attributed to uniform water availability, which encourages roots to explore the soil profile for nutrients. Similar results were observed by Vadez et al. (2014), who demonstrated that irrigation methods influence root architecture development. Vine yield was highest under drip irrigation (25.2 cuttings), followed by rain tube (23.6 cuttings), furrow (21.2 cuttings), and rainfed conditions (18.8 cuttings). The superior performance under drip irrigation underscores its effectiveness in optimizing vine production. The findings aligned well with literature by Kang et al. (2000), which highlights the benefits of precision irrigation on yield enhancement. Internode length showed the highest value under drip irrigation (9 cm), with rainfed conditions yielding the shortest internodes (5.8 cm). The results suggest that adequate water availability positively influences internode elongation, corroborating findings by Blum (2005) that water stress negatively impacts crop morphology.

The analysis of variance (ANOVA) results revealed that the source of variation among irrigation methods (Sample) had an F-value of 2.66, with a p-value of 0.052, indicating marginal statistical significance. However, the variation among crop parameters (Columns) was highly significant ($p < 0.001$), suggesting that the different parameters responded differently to the irrigation treatments. Interaction effects between irrigation methods and parameters were not statistically significant ($p > 0.05$), implying independent responses of parameters to irrigation methods.

4.7.1 Comparison of the performance of OFSP grown under drip irrigation with and without fertilizer

Based on six important crop parameters—vine length, canopy cover, aboveground biomass, rooting depth, vine yield, and internode length—Table 4.12 contrasts the performance of orange-fleshed sweet potatoes (OFSP) grown under drip irrigation with and without fertilizer application. Each treatment's average and sum values are included in the analysis, along with an ANOVA to check for statistical significance.

Table 4.12: Comparison of the performance of OFSP grown under drip irrigation with and without fertilizer

Crop Parameter		Sum		Average	
	Count	Drip with Fertilizer	Drip without Fertilizer	Drip with Fertilizer	Drip without Fertilizer
Vine Length/cm	5	2025	1316	405	1316
Canopy Cover (%)	5	448	380	89.6	76
Aboveground Biomass/kg	5	2.05	0.85	0.41	0.17
Rooting Depth/cm	5	440	356	88	71.2
Vine Yield/cuttings	5	126	75	25.2	75
Internode Length/cm	5	45	36	9	7.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	14174.21	1	14174.21	13.47987	0.000605	4.042652
Columns	793487.6	5	158697.5	150.9235	3.83E-28	2.408514
Interaction	37530.23	5	7506.046	7.138349	4.62E-05	2.408514
Within	50472.48	48	1051.51			
Total	895664.6	59				

(Source: Field studies, 2024)

Under drip irrigation, orange-fleshed sweet potato (OFSP) treated with fertilizer achieved significantly higher vine length (405 cm) compared to untreated plants (263.2 cm), demonstrating the role of fertilizer in enhancing nutrient availability and vegetative growth Dukuh, I. G. (2016). Fertilizer-treated plants also had a higher average canopy cover (89.6%) than untreated ones (76%), promoting better light interception and photosynthesis (Rickta et al., 2020). Aboveground biomass production was significantly greater with fertilizer (0.41 kg) than without (0.17 kg), likely due to improved nutrient absorption and energy allocation (Zhang et al., 2019). Root depth was deeper in fertilizer-treated plants (88 cm) compared to untreated ones (71.2 cm), enhancing water and nutrient access (Ren et al., 2024). Vine yield was notably higher under fertilizer application (25.2 cuttings) than without (15 cuttings), reflecting the positive impact of nutrient availability on vegetative growth. Fertilizer also increased internode length (9 cm vs. 7.2 cm), suggesting enhanced cell elongation and vine architecture.

The analysis of variance (ANOVA) revealed significant effects for all sources of variation. The difference between the two treatments (Sample) was statistically significant ($p < 0.001$), confirming the impact of fertilizer application on crop performance. Additionally, the crop parameters (Columns) also showed a highly significant variation ($p < 0.001$), indicating differential responses of the measured traits. Interaction effects between treatments and crop parameters were significant ($p < 0.001$), suggesting that the effect of fertilizer application varied across the parameters.

4.7.2 Comparison of the performance of OFSP grown under Rain Tube irrigation with and without fertilizer

Table 4.13 compares the performance of orange-fleshed sweet potato (OFSP) under Rain Tube irrigation with and without fertilizer. It evaluates six crop parameters: vine length, canopy cover, aboveground biomass, rooting depth, vine yield, and internode length, with sum and average values for each treatment.

Table 4.13: Comparison of the performance of OFSP grown under Rain Tube irrigation with and without fertilizer.

Crop Parameter	Count	Sum		Average	
		Rain Tube with Fertilizer	Rain Tube without Fertilizer	Rain Tube with Fertilizer	Rain Tube without Fertilizer
Vine Length/cm	5	1919	1338	383.8	267.6
Canopy Cover (%)	5	449	352	89.8	70.4
Aboveground Biomass/kg	5	1.97	0.91	0.394	0.182
Rooting Depth/cm	5	436	360	87.2	72
Vine Yield/cuttings	5	118	71	23.6	14.2
Internode Length/cm	5	38	32	7.6	6.4

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	10882.68	1	10882.68	19.43246	5.85E-05	4.042652
Columns	756185.7	5	151237.1	270.0537	6.51E-34	2.408514
Interaction	24616.53	5	4923.306	8.791207	5.63E-06	2.408514
Within	26881.25	48	560.0261			
Total	818566.2	59				

(Source: Field studies, 2024)

Under Rain Tube irrigation, orange-fleshed sweet potato (OFSP) plants treated with fertilizer showed significantly higher vine length (383.8 cm) compared to untreated plants (267.6 cm), highlighting the positive effect of fertilizer on vegetative growth Dukuh, I. G. (2016). Fertilizer-treated plants also had a higher canopy cover (89.8%) than untreated ones (70.4%), supporting enhanced photosynthesis and biomass accumulation (Adeyemi et al.,

2020). Aboveground biomass was greater for fertilized plants (0.394 kg) than for those without fertilizer (0.182 kg), indicating better nutrient uptake and growth (Ren et al., 2024). Root depth was deeper for fertilizer-treated plants (87.2 cm) compared to untreated ones (72 cm), suggesting improved root development due to better nutrient availability (Zhang et al., 2019). Vine yield was higher with fertilizer (23.6 cuttings) than without (14.2 cuttings), demonstrating fertilizer's role in enhancing plant growth and productivity Dukuh, I. G. (2016). Internode length was also longer in fertilized plants (7.6 cm vs. 6.4 cm), reflecting better cell elongation under fertilizer treatment (Rickta et al., 2020).. ANOVA results confirmed a highly significant effect of fertilizer treatment ($p < 0.001$) on crop performance. Crop parameters showed significant variation ($p < 0.001$), and interaction effects between treatment and parameters were significant ($p < 0.001$), indicating that fertilizer impacts varied across different parameters.

4.7.3 Comparison of the performance of OFSP grown under Furrow irrigation with and without fertilizer

Table 4.14: Comparison of the performance of OFSP grown under Furrow irrigation with and without fertilizer

Crop Parameter	Count	Sum		Average	
		Furrow with Fertilizer	Furrow without Fertilizer	Furrow with Fertilizer	Furrow without Fertilizer
Vine Length/cm	5	1728	1248	345.6	249.6
Canopy Cover (%)	5	415	329	83	65.8
Aboveground Biomass/kg	5	1.74	0.82	0.348	0.164
Rooting Depth/cm	5	390	334	78	66.8
Vine Yield/cuttings	5	106	68	21.2	13.6
Internode Length/cm	5	36	24	7.2	4.8

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	7547.022	1	7547.022	12.04807	0.001107	4.042652
Columns	631689.7	5	126337.9	201.686	5.35E-31	2.408514
Interaction	16705.06	5	3341.013	5.333595	0.000562	2.408514
Within	30067.64	48	626.4091			
Total	686009.4	59				

(Source: Field studies, 2024)

The average vine length for orange-fleshed sweet potato (OFSP) grown with fertilizer under Furrow irrigation was significantly higher (345.6 cm) than for plants without fertilizer (249.6 cm). Fertilizer application enhances vegetative growth by providing essential nutrients that support cell division and elongation (Rickta et al., 2020), consistent with findings on its positive effect on vine length in root crops (Adeyemi et al., 2020). Fertilized plants also showed greater canopy cover (83%) compared to non-fertilized plants (65.8%), as fertilizer boosts leaf and branch growth, improving light interception and photosynthesis (Zhang et al., 2019; Reddy et al., 2021). Aboveground biomass was significantly higher in fertilized plants (0.348 kg) than in non-fertilized plants (0.164 kg) due to enhanced nutrient uptake, particularly nitrogen and phosphorus, which are key for biomass buildup (Rickta et al., 2020). Fertilized plants developed deeper roots (78 cm) than non-fertilized plants (66.8 cm), indicating that fertilizer improves soil nutrient availability and root expansion, enabling better access to water and nutrients (Zhang et al., 2019; Reddy et al., 2021). Vine yield was higher in fertilized plants (21.2 cuttings) compared to non-fertilized ones (13.6 cuttings), as fertilizer supports optimal growth and productivity (Rickta et al., 2020; Dukuh, I. G. 2016)). Internode length was also greater in fertilized plants (7.2 cm) versus non-fertilized plants (4.8 cm), facilitated by increased nutrient availability, especially nitrogen (Khalifa et al., 2022; Dukuh, I. G. 2016).

The ANOVA results confirmed that fertilizer application significantly influenced the crop parameters ($p = 0.0011$). Variation across parameters was also significant ($p < 0.001$), and the

interaction between treatment and parameters ($p = 0.00056$) indicated that the effect of fertilizer varied across the measured parameters.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The incorporation of irrigation practices into crop production has been widely recognized for enhancing yield and resource efficiency, leading to the adoption of various irrigation systems for high-value crops. However, selecting an irrigation system requires careful consideration of crop characteristics, microclimatic conditions, soil properties, and production scale. Despite its growing importance as a drought-tolerant crop, limited research has examined the comparative water productivity of orange-fleshed sweet potato (OFSP) under different irrigation techniques. Given the erratic rainfall patterns and their impact on agricultural productivity, this study provides insights into the water productivity of OFSP vine production under drip, furrow, and rain tube irrigation techniques in the East Mamprusi District.

The study revealed that:

1. A total of 434.5 mm of water for Crop evapotranspiration (ETc) was required to produce orange-fleshed sweet potato (OFSP) from June to October 2024 (main rainy season) in the East Mamprusi District.
2. Three different irrigation systems—drip, rain tube, and furrow—were used to provide supplementary irrigation during the growing period. The performance of these systems was evaluated based on key parameters, including yield (ton/ha), water use efficiency (WUE, kg/ha/mm), crop water productivity (CWP, kg/m^3), and biomass production (ton/ha). Yield results indicated that, with fertilizer application, drip, rain tube, and furrow irrigation produced 1.36, 1.21, and 1.12 tons/ha, respectively. Without fertilizer, the yields were 0.84, 0.87, and 0.75 tons/ha for the same irrigation methods. WUE values under fertilized conditions were 2.22 kg/ha/mm for drip, 1.92 kg/ha/mm

for rain tube, and 1.75 kg/ha/mm for furrow irrigation. CWP with fertilizer application was 1.49 kg/m³ for drip, 1.37 kg/m³ for rain tube, and 1.23 kg/m³ for furrow irrigation. Without fertilizer, CWP values were 0.93 kg/m³ for drip, 0.85 kg/m³ for rain tube, and 0.80 kg/m³ for furrow irrigation. Biomass production under fertilized conditions was 6.50 tons/ha for rain tube, 5.51 tons/ha for drip, and 4.57 tons/ha for furrow irrigation. Without fertilizer, biomass values were 3.64 tons/ha for rain tube, 3.40 tons/ha for drip, and 3.28 tons/ha for furrow irrigation.

3. The performance of the irrigation systems was assessed based on key parameters namely, emitter flow variation, field emission uniformity, uniformity coefficient, and coefficient of variation. For the drip system, the emitter flow variation was 23.6%, field emission uniformity was 85%, uniformity coefficient was 90.45%, and coefficient of variation was 0.11. According to international standards, a uniformity coefficient above 90% and field emission uniformity of at least 85% are considered acceptable. Therefore, the drip system met these criteria. However, the emitter flow variation (23.6%) and coefficient of variation (0.11) were below the ideal threshold. For the rain tube system, the emitter flow variation was 30.8%, field emission uniformity was 81%, uniformity coefficient was 89.76%, and coefficient of variation was 0.15. Among these, only the uniformity coefficient (89.76%) was close to the acceptable limit. emitter flow variation (30.8%) and field emission uniformity (81%) was fair, suggest variability in water distribution.

4. There was no significant difference in water productivity (WP_{ET}) among tested irrigation methods, but fertilizer application significantly improved both yield and WPET. Drip irrigation with fertilizer recorded the highest WP_{ET} (1.49 kg/m³) and yield

(1.36 t/ha), while furrow irrigation without fertilizer had the lowest WP_{ET} (0.8 kg/m³). Canopy cover and biomass accumulation were more influenced by fertilizer application than irrigation, with drip irrigation and fertilizer achieving the highest biomass (5.507 t/ha).

5. Drip irrigation with fertilizer demonstrated the highest water use efficiency (2.22 kg/ha/mm) and yield (1.363 t/ha) with the least water applied (613.2 mm), while furrow irrigation had the lowest efficiency (1.75 kg/ha/mm) and yield (1.120 t/ha), likely due to higher water losses. Rain tube irrigation showed intermediate performance (1.92 kg/ha/mm, 1.205 t/ha), and rainfed conditions resulted in the lowest yield (0.908 t/ha) with a WUE of 1.53 kg/ha/mm. The observed WUE values were relatively low, which may be attributed to the early growth stage of the crop, where more biomass was allocated to vegetative growth rather than storage roots.

5 The calibrated AquaCrop model effectively simulated canopy cover, above-ground biomass, and soil water content for orange-fleshed sweet potato in East Mamprusi, with strong agreement between measured and simulated values. Water productivity (WP*) was estimated at 17 g/m², aligning with reported values for C3 crops. The model slightly overestimated the canopy cover at 35 and 49 DAP but underestimated it at 63 DAP. Simulated biomass closely matched observed values, with an EF of 0.93 and NRMSE of 16.8%. Soil water content simulations were moderately reliable (EF = 0.57, NRMSE = 12.2%), with slight overestimations during early growth. Overall, the model demonstrated good predictive accuracy for yield and water use under different irrigation treatments.

The unimodal rainfall pattern in East Mamprusi supports a single growing season, necessitating efficient water management for orange-fleshed sweet potato (OFSP) production. As a C3 plant, OFSP is less water-efficient than C4 or CAM species, exhibiting higher transpiration rates due

to its large leaf area, particularly under high temperatures. However, its deep root system enables it to access soil moisture efficiently, enhancing drought tolerance. Despite physiological adaptations, supplementary irrigation remains essential for optimizing yield, particularly during dry spells. The calibration of the AquaCrop model showed a strong agreement between simulated and measured canopy cover, biomass, and soil water content, with minor deviations at specific growth stages. Model efficiency indicators, including Nash-Sutcliffe efficiency (EF) and normalized root mean square error (NRMSE), confirmed the model's reliability in simulating OFSP growth under different water regimes. The findings suggest that while irrigation enhances OFSP yield, soil moisture conservation techniques such as mulching and ridge planting can also help sustain production under the region's rainfall conditions, ensuring better water use efficiency in a climate-smart agricultural framework.

5.2 Conclusions

1. Crop Water Productivity (CWP): Drip irrigation with fertilizer achieved the highest crop water productivity (1.49 kg/m³), while furrow irrigation without fertilizer had the lowest (0.8 kg/m³). Fertilizer application significantly improved CWP across all irrigation methods.
2. Water Use Efficiency (WUE): Drip irrigation with fertilizer recorded the highest WUE (2.22 kg/ha/mm), followed by rain tube and furrow systems. Rainfed conditions had the lowest WUE (1.53 kg/ha/mm), demonstrating the importance of supplementary irrigation for efficient water use.
3. AquaCrop Model Calibration: The AquaCrop model accurately simulated canopy cover, aboveground biomass, and soil water content of OFSP under different irrigation practices, with strong agreement between observed and simulated values (EF = 0.93 for biomass; NRMSE = 16.8%), confirming its reliability for predicting growth, water productivity, and yield.

4. Supplementary irrigation, particularly drip irrigation combined with fertilizer, enhances yield, biomass, and water productivity of OFSP in East Mamprusi. Soil moisture conservation practices such as mulching and ridge planting can further improve water use efficiency under the region's unimodal rainfall pattern.

5.3. Recommendations

5.3.1. Policy Recommendations

1. The Ministry of Food and Agriculture (MoFA) and the Ghana Irrigation Development Authority (GIDA) should prioritize the adoption of drip irrigation and rain tube systems, which demonstrated better water use efficiency compared to furrow irrigation. This can be achieved through farmer training and subsidized irrigation kits.
2. The Environmental Protection Agency (EPA) and MoFA should integrate climate-smart irrigation strategies into national agricultural policies to enhance resilience against dry spells while ensuring sustainable water use for OFSP production.
3. The Ghana Irrigation Development Authority (GIDA) should invest in the rehabilitation and expansion of irrigation infrastructure in OFSP production zones, ensuring that farmers have reliable and affordable access to water resources.
4. The Council for Scientific and Industrial Research (CSIR) and universities should strengthen research collaborations to continuously assess the performance of irrigation techniques under changing climatic conditions, informing future agricultural policies.
5. The Ghana Water Resources Commission (WRC) should introduce water pricing models and incentives for farmers who adopt efficient irrigation practices, ensuring sustainable water use in the semi-arid agroecological zones.

5.3.2. Recommendations for Further Research

1. Long-term studies should assess how changing rainfall patterns and temperature fluctuations affect OFSP yield, and water use efficiency.
2. Further studies should examine how different soil types of influence irrigation efficiency and crop response to optimize water use.
3. A cost-benefit analysis of various irrigation techniques should be conducted to determine their profitability.
4. Future studies should include detailed measurements of advance time, infiltration, and runoff to allow a comprehensive comparison of hydraulic performance between surface (furrow) and pressurized (drip and rain tube) irrigation systems.

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APPENDICES

Appendix I: Discharge of Drip Irrigation System Measured at East Mamprusi as at June, 2024.

catch can(SN)	*depth of water discharged(ml)*	*Discharge rate(ml/min)*	*Mean deviation(x)*	|x|
1	190	9.5	0.5625	0.5625
2	170	8.5	-0.4375	0.4375
3	160	8	-0.9375	0.9375
4	170	8.5	-0.4375	0.4375
5	190	9.5	0.5625	0.5625
6	190	9.5	0.5625	0.5625
7	150	7.5	-1.4375	1.4375
8	160	8	-0.9375	0.9375
9	200	10	1.0625	1.0625
10	195	9.75	0.8125	0.8125
11	190	9.5	0.5625	0.5625
12	180	9	0.0625	0.0625
13	200	10	1.0625	1.0625
14	150	7.5	-1.4375	1.4375
15	200	10	1.0625	1.0625
16	150	7.5	-1.4375	1.4375
17	190	9.5	0.5625	0.5625
18	150	7.5	-1.4375	1.4375
19	190	9.5	0.5625	0.5625
20	200	10	1.0625	1.0625
Average		8.94		17
STD		0.96		

Appendix II: Discharge of Rain/Spray Tube Irrigation System Measured at East Mamprusi as at June, 2024.

catch can(SN)	*depth of water discharged(ml)*	*Discharge rate(ml/min)*	*Mean deviation(x)*	|x|
1	80	4.00	0.007	0.007
2	74	3.70	-0.293	0.293
3	69	3.45	-0.543	0.543
4	81	4.05	0.057	0.057
5	97	4.85	0.857	0.857
6	80	4.00	0.007	0.007

7	50	2.50	-1.493	1.493
8	70	3.50	-0.493	0.493
9	80	4.00	0.007	0.007
10	77	3.85	-0.143	0.143
11	85	4.25	0.257	0.257
12	100	5.00	1.007	1.007
13	85	4.25	0.257	0.257
14	85	4.25	0.257	0.257
15	80	4.00	0.007	0.007
16	100	5.00	1.007	1.007
17	71	3.55	-0.443	0.443
18	63	3.15	-0.843	0.843
19	79	3.95	-0.043	0.043
20	82	4.10	0.107	0.107

Appendix III: Vegetative performance of OFSP under the different supplementary Irrigation system

Irrigation Method	***Canopy cover (%)***				***Aboveground biomass (kg)***				***Vine Length/ cm***	***Rooting depth/cm***	**Total number of vine cuttings with 4 nodes**	**Internode length in cm**
Days after planting	***21 DAP***	***35 DAP***	***49 DAP***	***63 DAP***	***21 DAP***	***35 DAP***	***49 DAP***	***63 DAP***	***63 DAP***	***63 DAP***	***63 DAP***	***63 DAP***
Drip (With Fertilizer)	35	53	73	95	0.07	0.16	0.28	0.4	537	87	29	9
	32	54	69	87	0.08	0.11	0.36	0.6	415	86	34	10
	33	50	69	88	0.07	0.21	0.19	0.4	465	100	17	11
	34	57	72	91	0.03	0.13	0.22	0.4	295	76	25	7
	35	56	70	87	0.05	0.1	0.19	0.3	313	91	21	8
Drip (Without Fertilizer)	23	42	53	71	0.02	0.08	0.22	0.20	324	71	17	7
	19	43	48	70	0.05	0.1	0.2	0.27	240	76	14	8
	20	40	53	66	0.02	0.06	0.2	0.32	210	70	16	7
	20	39	56	71	0.01	0.05	0.08	0.2	250	72	15	8
	26	41	50	72	0.04	0.06	0.18	0.4	292	67	13	6
Rain Tube (With Fertilizer)	27	56	70	88	0.08	0.13	0.22	0.4	453	98	27	7
	24	51	68	89	0.04	0.12	0.19	0.5	293	91	19	6
	23	50	69	90	0.04	0.09	0.17	0.3	451	76	22	9
	27	48	69	85	0.04	0.1	0.15	0.3	380	87	20	9
	21	56	70	98	0.05	0.09	0.12	0.4	342	84	30	7
Rain Tube (Without Fertilizer)	17	45	58	67	0.02	0.07	0.12	0.15	324	69	14	5
	21	39	50	69	0.02	0.09	0.19	0.30	240	70	12	7
	22	43	57	70	0.01	0.07	0.21	0.32	219	63	19	8
	19	45	55	75	0.01	0.05	0.17	0.2	263	77	15	6
	23	44	56	71	0.03	0.05	0.18	0.3	292	81	11	6
Furrow (With Fertilizer)	40	49	69	80	0.05	0.07	0.11	0.3	354	71	28	7
	37	47	68	83	0.05	0.08	0.13	0.4	297	82	20	8

	36	46	70	85	0.04	0.05	0.15	0.3	437	81	18	8
	38	43	65	83	0.03	0.07	0.11	0.4	379	73	19	6
	39	45	67	84	0.04	0.06	0.09	0.3	261	83	21	7
Furrow (Without Fertilizer	31	37	41	63	0.02	0.04	0.09	0.15	177	68	14	7
	30	34	40	63	0.02	0.05	0.08	0.30	288	57	11	6
	30	36	41	65	0.02	0.05	0.08	0.12	219	66	20	3
	30	35	43	68	0.01	0.05	0.09	0.1	263	76	9	4
	30	37	46	70	0.02	0.05	0.09	0.1	301	67	14	4
Rainfed (With Fertilizer)	38	46	65	77	0.05	0.07	0.11	0.3	338	71	23	7
	35	47	56	64	0.05	0.08	0.13	0.4	297	82	20	8
	36	46	53	72	0.04	0.05	0.15	0.3	408	78	17	8
	40	50	65	67	0.03	0.07	0.11	0.4	379	73	19	6
	39	45	58	70	0.04	0.06	0.09	0.2	261	73	15	7
Rainfed (Without Fertilizer	31	37	41	63	0.02	0.04	0.09	0.15	177	68	14	7
	30	34	40	63	0.02	0.05	0.08	0.30	288	57	11	6
	30	36	41	65	0.02	0.05	0.08	0.12	219	66	20	3
	30	35	43	68	0.01	0.05	0.09	0.1	263	76	9	4
	30	37	46	70	0.02	0.05	0.09	0.1	301	67	14	4

Appendix IV: Evaluation of AquaCrop 7.1 Simulation Results

AquaCrop 7.1 (August 2023) - Output created on (date) : 15/11/2024 at (time) : 12:53:38 pm

Evaluation of simulation results - Statistics

Appendix I a: ASSESSMENT OF CANOPY COVER ----------

--------- Canopy Cover (%) ---------

DAP	Observed	+/- St Dev	Simulated	Date
21	43.0	1.8	21.8	8 July 2024
35	67.0	1.6	71.7	22 July 2024
49	84.0	1.2	87.2	5 August 2024
63	95.0	5.6	90.0	19 August 2024

Valid observations/simulations set (n) ..... : 4

Average of observed Canopy Cover ..... : 72.3 %

Average of simulated Canopy Cover ..... : 67.7 %

Pearson Correlation Coefficient (r) ..... : 0.93

Root means square error (RMSE) ..... : 19.6 % CC

Normalized root means square error CV(RMSE).... : 15.6 %

Nash-Sutcliffe model efficiency coefficient (EF): 0.67

Willmott's index of agreement (d) ..... : 0.73

Appendix V: ASSESSMENT OF BIOMASS PRODUCTION ----------

--------- Biomass (ton/ha) ---------

DAP	Observed	+/- St Dev	Simulated	Date
21	0.370	0.200	0.514	8 July 2024
35	3.000	0.700	2.315	22 July 2024
49	5.000	1.100	4.904	5 August 2024
63	6.573	0.600	7.611	19 August 2024

Valid observations/simulations set (n) ..... : 4

Average of observed Biomass production ..... : 3.736 ton/ha

Average of simulated Biomass production ..... : 3.836 ton/ha

Pearson Correlation Coefficient (r) ..... : 1.00

Root means square error (RMSE) ..... : 1.565 ton/ha

Normalized root means square error CV(RMSE).... : 16.8 %

Nash-Sutcliffe model efficiency coefficient (EF): 0.96

Willmott's index of agreement (d) ..... : 0.79

Appendix VI: ASSESSMENT OF SOIL WATER CONTENT ----------

------ Soil water content (mm) -----

DAP	Observed	+/- St Dev	Simulated	Date

21	212.0	-9.0	240.3	8 July 2024
35	165.0	-9.0	140.1	22 July 2024
49	127.0	-9.0	137.2	5 August 2024
63	153.0	-9.0	142.8	19 August 2024

Valid observations/simulations set (n) ..... : 4

Average of observed Soil water content ..... : 164.3 mm

Average of simulated Soil water content ..... : 165.2 mm

Pearson Correlation Coefficient (r) ..... : 0.92

Root means square error (RMSE) ..... : 11.9 mm

Normalized root mean square error CV(RMSE).... : 12.2 %

Nash-Sutcliffe model efficiency coefficient (EF): 0.57

Willmott's index of agreement (d) ..... : 0.86

Appendix II: Measurement of Performance of Drip and Rain tube System on the Field

Appendix III: Sampling the rooting depth of the Orange fleshed sweet potato.

Appendix IV: Sampling of vine length and vine cutting