Evaluation of Response of Onion and Tomato Crops to Deficit Irrigation and Evaluation of AquaCrop Model to Simulate Responses

Ararsa Gadefa Worku

A Thesis Submitted to The Department of Water Resources Engineering,

School of Civil Engineering and Architecture

Presented In Partial Fulfillment of The Requirement For The Degree of Master's In Water Resources Engineering (Specialization In Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

October, 2023

Adama, Ethiopia

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Advisor: Zelalem Biru (PhD)

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DECLARATION

I hereby declare that this Master Thesis entitled "**Evaluation of Response of Onion and Tomato Crops to Deficit Irrigation and Evaluation of Aquacrop Model to Simulate Responses**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

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Name of the student Signature Date

RECOMMENDATION

I, the advisors of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Evaluation of Response of Onion and Tomato Crops to Deficit Irrigation and Evaluation of Aquacrop Model to Simulate Responses**" prepared under my guidance by **Ararsa Gadefa Worku** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Water Resources Engineering (Specialization in Irrigation Engineering**).**

Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Zelalem Biru (PhD)	____________________	_________________________
Major Advisor	Signature	Date

APPROVAL PAGE

I, the advisors of the thesis entitled "**Evaluation of Response of Onion and Tomato Crops to Deficit Irrigation and Evaluation of Aquacrop Model to Simulate Responses**" and developed by Ararsa Gadefa Worku, hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

ZelalemBiru (PhD) ______________________ _______________________

Major Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Ararsa Gadefa Worku have read and evaluated the thesis entitled "**Evaluation of Response of Onion and Tomato Crops to Deficit Irrigation and Evaluation of Aquacrop Model to Simulate Responses**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resources Engineering (Specialization in Irrigation Engineering**)**

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ACKNOWLEDGMENT

First and foremost, I express my gratitude to God for His compassion, kindness, and grace upon me and giving me the chance, strength and courage to continue my study and for all things done in my entire life during all my works. I also want to convey my sincere appreciation to my advisor, Dr. Zelalem Biru, for his consistent guidance, support, and encouragement during my research work. His expertise and wisdom in the field have proven immensely precious to me.

I would also like to extend my sincere appreciation to Ambo University, which has provided me with financial support and resources to conduct my research.

Furthermore, I would like to thank the Awash Melkasa Research Center, where I conducted my experiments, for providing me with access to their facilities and resources. The irrigation and drainage staff at the center were always helpful and accommodating, and I appreciate their assistance in making sure that my experiments ran smoothly. I appreciate the assistance of the field laborers in setting up the experiment, planting, watering, and offering guidance during the fieldwork.

Furthermore, I want to recognize my friends and family members who have provided emotional support throughout this journey. Their encouragement and unwavering belief in me have been immensely meaningful, and I deeply appreciate their presence in my life.

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ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
BD	Bulk Density
CC	Canopy Cover
DI	Deficit Irrigation
ETo	Evapotranspiration
ETC	Crop Water Requirement
FAO	Food and Agricultural Organization
FC	Field Capacity
HI	Harvest Index
KC	Crop Coefficient
LSD	Least Square of Difference
MARC	Melkasa Agriculture and Research Center
PWP	Permanent Wilting Point
RCBD	Randomized Completely Block Design
RAW	Readily Available Water
TAW	Total Available Water
Tr	Crop Transpiration
WP	Water Productivity

ABSTRACT

Investigating crop yields in response to water applications is resource-intensive. In this regard, modeling is a valuable approach for studying deficit irrigation strategies. An experiment at Melkassa Agricultural Research Center tested different irrigation levels at various onion and tomato growth stages, comparing 100%, 75%, and 50% ETc applications to assess the model's performance. A randomized complete block design was employed for the treatments; there were six treatments, and each treatment was replicated three times. The AquaCrop Model was calibrated using 100% ETc data on canopy cover and biomass, observed yield at the final, and validated to simulate onion and tomato yield and biomass at the final. The experimental results revealed that the highest yields, amounting to 5.75 tons/ha for onion and 8 tons/ha for tomato, were obtained from non-water stress treatment. Conversely, the lowest yields of 4.30 tons/ha for onion and 6.23 tons/ha for tomato were recorded when applying a 50 percent deficit irrigation strategy across all growth stages. The calibration results for both onion and tomato canopy cover and biomass simulations have a high degree of accuracy. For onion, the statistics included a 'r' of 0.99, a RMSE of 3.4 tons/ha, a NRMSE of 8.2%, an EF of 0.99, and a 'd' of 1 for canopy cover. The above-ground biomass calibration showed an 'r' of 1, an RMSE of 0.5 tons/ha, an NRMSE of 10.7%, an EF of 0.98, and a 'd' of 0.99. Similarly, for tomatoes, the calibration results indicated a high level of accuracy, with a canopy cover 'r' of 0.99, an RMSE of 4.4 tons/ha, an NRMSE of 8.8%, an EF of 0.98, and a 'd' of 0.99. The above-ground biomass calibration for tomato yielded an 'r' of 0.97, an RMSE of 0.6 tons/ha, an NRMSE of 9.2%, an EF of 0.98, and a 'd' of 1. The AquaCrop model successfully simulated the final dry yield for onion with an 'r' of 0.94 to 1, NRMSE of 1.5 to 4.3%, EF of 0.96 to 0.98, and 'd' of 0.95 to 0.98. The total biomass simulation showed good accuracy, with an 'r' of 0.94 to 0.97, a low NRMSE of 6.10 to 10.10%, a high EF of 0.95 to 0.98, and RMSE of 2.1 to 3.5 tons/ha. For tomato, the AquaCrop model also performed well, with a final dry yield simulation resulting in an 'r' of 0.96 to 0.98, an RMSE of 0.42 to 0.8 tons/ha, an NRMSE of 3.2 to 7.0%, an EF of 0.97 to 0.99, and a 'd' of 0.96 to 0.99. Total biomass simulation showed an r of 0.95 to 0.99, an RMSE of 0.4 to 0.92 tons/ha, an NRMSE of 5.6 to 10.50%, an EF of 0.96 to 0.99, and a 'd' of 0.94 to 1 for the study site. This field study indicated the crop's sensitivity to moisture stress during critical bulb and yield formation growth stages for both onions and tomatoes.

Key words: AquaCrop, Deficit Irrigation, Onion, Tomato, Yield

CHAPTER 1: INTRODUCTION

1.1 Background

The scarcity of fresh water is one of the challenges facing agriculture in many parts of the world. There is growing competition for freshwater resources between industry and agriculture. The increase in the human population is driving the competition. Agriculture is responsible for 70% of the world's freshwater withdrawals and over 90% of its consumptive utilization (López *et al*., 2020). Globally, agriculture stands as the primary consumer of water, and there is a common belief that agricultural water usage is frequently inefficient and less valuable compared to other purposes (Karuku and Mbindah, 2020). This indicates that all agricultural areas, and irrigated areas in particular, require appropriate governance of natural water resources, where both practical tools and management methods are essential in solving the current problems and satisfying the increasing worldwide demand for food. These challenges include climate change, salinization of agricultural soils, freshwater scarcity, and overexploitation of water resources. To meet future food demand and the increasing competition for water, innovations are therefore required to improve the efficiency of water use.

Water supply issues in several regions of Ethiopia make it difficult to produce enough food for the population (Enchalew, 2016). The inefficiency of the country's overall water utilization, especially in agriculture, amplifies the demand for water across all sectors of use. This suggests that the establishment of modern irrigation in these countries has a recent past. Ethiopia views irrigation as a fundamental strategy for reducing poverty and ensuring food security. It is beneficial to convert the rain-fed agricultural system, which is dependent on rainfall, into an agricultural system that utilizes both irrigation and rain (Haile, 2015). Nowadays, small-scale irrigation is increasingly used at the household level to produce high-value crops such as vegetables for marketing and personal consumption. Thus, transferring rain-fed agricultural systems to irrigated agricultural systems with deficit irrigation is the best practice (Etissa *et al*., 2014).

Deficit irrigation is a method for optimizing water utilization by eliminating irrigation that has maximal effects on crop yield (Dirirsa *et al*., 2017). In situations where water is limited, employing deficit irrigation (DI) may yield higher economic benefits compared to prioritizing maximum yield per unit of water (Enchalew, 2016; Montoya *et al*., 2016).

Using deficit irrigation (DI) involves subjecting the crop to a certain degree of water stress, either during specific periods or throughout the entire growing season (Enchalew, 2016). Increasing the plant's water intake or boosting its yield can alter water use efficiency. In this context, deficit irrigation offers a way to decrease water usage while mitigating negative impacts on yield (Dirirsa *et al*., 2017). Despite the fact that the use of deficit irrigation can be researched through model simulations or field trials, it is time-consuming and expensive to determine how varied water applications affect yield. In this scenario, precise crop growth models serve as crucial instruments for assessing the impacts of water shortages on crop yields and projecting yields to optimize irrigation in situations with limited water resources, thereby enhancing sustainability and profitability in agriculture. To address this need, the Food and Agriculture Organization (FAO) developed AquaCrop, a water-driven crop model capable of simulating the crop yield response to varying water conditions for a range of herbaceous crops. The model was specifically designed to strike a balance between ease of use, precision, and reliability. AquaCrop is especially well adapted to address situations where water is a major constraint on crop production, and it is broadly applicable with tolerable accuracy. Climate, crop, soil, management, and initial soil water conditions are the key factors and input variables used in AquaCrop. These variables are either commonly used or require simple methods for their determination (Raes *et al*., 2018).

To evaluate the model under specific local conditions, this study was proposed, targeting onion *(Allium cepa L.)* and tomato (*Solanum lycopersicum Mill.*). The onion ***(Allium cepa L.)*** is a highly significant vegetable crop on a global scale. The Ethiopian Central Rift Valley region holds substantial economic importance within the country, as it contributes significantly to both national food security and foreign exchange earnings through the cultivation of export-oriented crops (Dirirsa *et al*., 2017). It is typically grown between September and March, during the dry season, when little precipitation usually falls (FAO, 2012). Tomato ***(Solanum lycopersicum Mill.)*** is a vegetable crop of significant economic importance that is extensively cultivated in Ethiopia, both with rain-fed and irrigated methods (MoA, 2013). In recent times, the expansion of state-owned farms and private investments, primarily concentrated in the rift valley regions of Ethiopia, has led to a rise in commercial production of onions and tomatoes through irrigation agriculture. With increasing crop production, determining the precise water requirements for these crops becomes crucial for efficient management of the limited water resources in the area. The main objective of this study is to evaluate the model performance and impact of deficit irrigation on the yield of onion and tomato crops.

1.2 Statement of the Problem

Ethiopia receives an average annual rainfall of about 850 mm, which should be adequate for crop production. However, ensuring a reliable and sustainable food supply is challenging due to the irregular distribution of rainfall in terms of timing and location. This erratic water availability during crucial periods often leads to crop failures. To address these natural challenges, there is a pressing need to transition to more efficient irrigation methods (Dirirsa *et al*., 2017). To achieve maximum crop yields, it's essential to meet the complete water requirements of the crops.

Onions and tomatoes are extensively cultivated in the central Rift Valley of Ethiopia. These crops are vital for both domestic consumption and export markets due to their high yields per unit area and resistance to diseases and pests. However, the rapid expansion of commercial production has faced a significant obstacle in the form of water scarcity, which has adversely affected crop yields. The available water resources in the region have not kept pace with the increasing demand, leading to reduced irrigation capacity and insufficient soil moisture levels for the crops.

The Rift Valley region, characterized by a semi-arid climate and limited water resources, faces escalating water demands and high evapotranspiration rates, which hamper crop production and overall productivity. Therefore, it is imperative to explore alternative methods and efficiently utilize the available water resources (Enchalew, 2016). In light of these challenges, the adoption of conservative irrigation water management practices becomes critical to maximizing crop yields using deficit irrigation principles. These principles allow for the conservation of irrigation water while still maintaining reasonable yield levels. While studying the impact of deficit irrigation can be accomplished through either field experiments or model simulations, conducting field experiments to assess yield responses under various deficit irrigation levels is resource-intensive and time-consuming. Field experiments cannot cover all possible combinations of drought stress levels or account for all environmental factors affecting yield (Bekele, 2020). Hence, models serve as invaluable tools for evaluating the consequences of water deficits on crop yield and productivity. These models enable the optimization of irrigation practices in situations with limited water resources, ultimately enhancing sustainability and profitability in agricultural production. In the study area, there were no model-based simulations conducted for onion and tomato crops.

1.3 Objectives

1.3.1 General Objective

The general objectives of this research was to evaluate the effects of deficit irrigation on onion and tomato yields and the AquaCop performance.

1.3.2 Specific Objectives

- ✓ To evaluate the effects of deficit irrigation on onion and tomato crop yields at various growth stages,
- ✓ To calibrate and validate Aquacrop models to simulate the productivity of onion and tomato crops under different irrigation water levels,
- ✓ To simulate the yield of onions and tomatoes under different levels of water deficits using Aqua Crop,

1.4 Research Question

1. To what extent does the level of irrigation water application affect the yields of onions and tomatoes?
2. How effectively can Aquacrop models be calibrated and validated to accurately simulate the productivity of onion and tomato crops under varying irrigation water levels?
3. Which deficit level will best suit the simulated onion and tomato production?

1.5 Significance of the Study

The main focus of the study was to enhance the effective utilization of scarce water resources by employing a water allocation strategy that varies with different growth stages. This approach seeks to improve onion and tomato yields by identifying the key growth stages at which water stress significantly reduces yield. This study enhances the understanding of how different deficit irrigation methods affect crop yields using simulation models, reducing the reliance on extensive field experiments. It aids in identifying the threshold deficit irrigation level at which water stress no longer significantly reduces yield.

1.6 Scope of the Study

This study was conducted using a single onion variety and a single tomato variety, with experimental plots situated at the Melkassa Agricultural Research Center. As a result, the calibration and validation of the AquaCrop model were only performed for this specific area and the onion-tomato varieties under investigation. The scope of this research is restricted to determining the effects of water stress on onion and tomato yields. To ensure that water remains the only limiting factor affecting plant growth, proper management practices, including weeding, pest control, and appropriate fertilization, were implemented experimentally in the field.

CHAPTER 2: LITURATURE REVIEW

2.1 Water Resources Potential of Ethiopia

Water resources are abundant in Ethiopia. A large number of rivers covering the majority of the country flow on each side of the rift valley. Ethiopia's twelve river basins together contribute to its entire surface water resources, which are estimated to be in the range of 122 billion cubic meters annually. With regard to groundwater resources, the true potential of the country is not yet known; however, it is widely reported that Ethiopia possesses a groundwater potential of approximately 2.6 billion cubic meters of groundwater (Awulachew *et al.,* 2006).

Ethiopia has a total area of 112 million hectares (Mha). Estimates of the cultivable land area range from 30 to 70 Mha. High estimates indicate that only 15 Mha of the total land area is now being farmed. Ethiopia has developed 3.07 million hectares of land for irrigation (Mekone, 2021). This means that a significant portion of cultivated land in Ethiopia is currently not irrigated, and there are potential opportunities to vastly increase the amount of irrigated land (Awulachew *et al.,* 2010).

In Ethiopia, rivers, streams, groundwater, lakes, artificial ponds, and surface water are the primary sources of water for irrigation, livestock consumption, and domestic use (seasonal). These sources are unequally distributed, abundant in some places but scarce in others. This variability is mainly due to the diversified landscape and agro-climatic conditions the country owns (Goshu, 2007). As reported by Awulachew *et al.* (2005), rainfall is the major source of agricultural water in Ethiopia. They also further stated that high levels of fluctuation and unreliability are the main issues with rainfall-dependent agriculture in the country. As a result, production capacity varies from region to region each year. Due to climate-induced rainfall variability, dry spells, and drought, agricultural production often fails and is doing so more frequently over time.

2.2 Irrigation Development in Ethiopia

Traditional irrigation has a long history in Ethiopia (Awulachew *et al*., 2007). River diversion seems to be the pattern for traditional small-scale schemes. The diversion structures are inadequate and frequently damaged by flooding. Modern irrigation was introduced in the Awash River basin through collaboration between Ethiopia and a Dutch company in the 1950s. The primary aim was to cultivate cash crops like sugarcane and cotton using surface irrigation techniques and less efficient pressurized irrigation systems.

Small-scale traditional irrigation schemes (SSIs) have a long history in Ethiopia, dating back several centuries. Feudal landlords, especially in regions like Hararge, Shewa, and

Gojam, were the primary initiators of these schemes. Initially, these schemes were quite small, typically covering only a few hectares and relying on stream water diversion for supplementary irrigation. However, with growing knowledge and expertise, many of these initiatives have expanded in recent decades, now irrigating areas spanning fifty hectares or more (Awulachew *et al*., 2006).

Ethiopia has primarily focused on state enterprises for large-scale irrigation development and management, primarily for the cultivation of industrial crops such as cotton and sugar cane. The Ministry of Agriculture (MoA) began developing and managing modern small-scale irrigation (SSI) in the 1970s in response to major droughts that resulted in widespread crop failures and consequent famine. The industry might be utilized to lessen the dangers to families that come with agricultural failures brought on by droughts (Awulachew *et al.*, 2006).

2.3 Scarcity of Water Resources

Water is increasingly becoming a point of contention, even in areas that have relatively abundant water resources. While many attribute this to water shortages, the underlying issue is, in fact, global water scarcity, which poses a far greater challenge (FAO, 2012). The availability of water in Africa will be significantly impacted by changing climatic conditions. Valipour (2014) suggests that by 2030, it is expected that an additional 75 to 250 million people in Africa will experience increased water stress due to climate change. The primary driver of pressure on renewable water resources is linked to the agricultural sector, with irrigation being the largest contributor to this demand.

Considering projections of population growth and rising living standards, there exist differing opinions on the pace at which food production must escalate to meet the needs of the growing global population. The Water for Food and Rural Development sector sees the necessity of doubling food production within the next 25 years, whereas the International Food Policy Research Institute suggests that doubling food production will be required within the next 50 years (Schultz *et al*., 2005). The availability of water plays a pivotal role in food production, and an expansion in production needs demands allocating more water resources to the agricultural sector.

Between 2000 and 2025, it is expected that the global average annual water availability per person will decrease from 6,600 m3 to 4,800 m3. Furthermore, due to the uneven distribution of water resources, approximately 3 billion individuals will reside in countries that are entirely or partially arid or semi-arid, with less than 1,700 m3 per person annually. Countries or regions are generally classified as water-stressed when their annual per capita availability ranges from 1,000 to 2,000 m3. When availability falls below 1,700 m3 per person annually, a country is labeled as 'water-scarce,' and when it drops below 1,000 m3 per person annually, it is deemed' severely' water-scarce (ICID, 2002). This information about water availability is a key reason why many scholars agree that the majority of the increase in food production (around 90%) must come from existing cultivated land, achieved through water-saving measures, improved irrigation and drainage practices, and increased storage. The remaining 10% of the increase in food production will likely require reclaiming new land, either in highland or lowland areas (Schultz *et al*., 2005).

Ethiopia receives an average annual rainfall of 744 mm, which might seem sufficient for food crop cultivation and livestock pasture growth. However, the rainfall distribution varies significantly across regions. In the eastern parts, as well as countries like Somalia and Djibouti, rainfall is extremely scarce, measuring less than 100 mm per year. In contrast, the southwest highlands receive a substantial 2400 mm per year. In the southern and eastern highlands, rainfall follows a bimodal pattern, with lighter rains in April and more significant rains in September. The primary dry season spans from October to February and is more extended and drier in the northern regions. Consequently, achieving sustainable and dependable food crop production is challenging due to the uneven distribution of rainfall, resulting in inadequate water availability during crucial periods. Intense rainfall can also lead to flooding, especially along the Awash River, Lower Baro Akobo, and Wabe Shebelle river basins, causing damage to crops (Welderufael, 2006). Variations in rainfall distribution can lead to food shortages, even in Ethiopia's Western Highlands (MoWIE, 2001).

2.4 Irrigated Agriculture

Agricultural production is the primary consumer of the Earth's water resources, and its water requirements are on a continuous rise due to population growth. Currently, agriculture accounts for approximately 70% of the Earth's available water, and it is projected that by 2020, an additional 17% more water will be necessary to meet the world's food demands (Sleper *et al*., 2007).

While irrigation is crucial for enhancing food security and reducing poverty, it currently covers only 17% of the world's cultivated land yet supplies 40–45% of global food and fiber production (Evans and Sadler, 2008). The global water withdrawal for irrigation is projected to rise from 2.6 billion km3 in 2000–2007 to an estimated 2.9 billion km3 in 2050, with most of this increase occurring in lower-income countries (Bruinsma, 2011). In Ethiopia, irrigation contributed to approximately 5.7% of agricultural gross domestic product (GDP) and 2.5% of the overall GDP during the 2005–2006 cropping season (Hagos *et al*., 2009).

In many agricultural practices, water utilization efficiency is suboptimal due to inadequate management and improper water application system designs. Typically, only a fraction of the water withdrawn for agriculture is efficiently utilized in food and agricultural commodity production. According to FAO (1996), crops effectively utilize just 40 to 60% of the total applied water, with the remaining water being lost within the system and in the field, primarily through processes such as evaporation, runoff into drainage systems, or infiltration into groundwater.

Potentially, some of the lost water could be reclaimed, but this would involve incurring additional costs. To progress toward the goal of achieving greater crop yields with less water, it is imperative for irrigators to embrace water-saving techniques and minimize unnecessary waste. Effective irrigation practices that make the most economical use of water resources are essential for water conservation. Enhancing irrigation management to align with the specific water requirements of crops is crucial, allowing for reduced water supply while maintaining high yields (Pereira *et al*., 2002).

2.5 Deficit Irrigation

Deficit irrigation is a deliberate strategy where crops experience controlled water stress at specific growth stages or throughout the entire growing season (Kirda, 2002). While this approach leads to reduced crop yields, it offers the advantage of conserving water resources, which can then be allocated to irrigate additional land on the same farm or support other water users, as highlighted by Engineering (2015).

The scarcity of water resources necessitates the development of innovative approaches focused on water and energy conservation, with a primary emphasis on enhancing water use efficiency (Hendy *et al.*, 2019). Achieving food security requires wise water utilization to increase food production while conserving water resources, particularly in regions facing water scarcity due to rapid population growth (Wale *et a*l., 2022).

One such approach is deficit irrigation, which involves applying irrigation during drought-sensitive growth stages of crops (Geerts and Raes, 2009). This practice optimizes water utilization and economic efficiency (Domínguez *et al.,* 2012). Deficit irrigation offers a way to reduce water consumption while minimizing negative impacts on crop yield (Mermoud *et al*., 2005). However, it requires a deep understanding of how different crops respond to water stress, as drought tolerance varies depending on growth stages, species, and cultivars.

Efficient irrigation scheduling, tailored to local climate and soil conditions, plays a crucial role in maximizing crop yields and optimizing the use of scarce water resources (Dirirsa *et al*., 2017). Additionally, implementing agronomic practices such as varying tillage methods and mulching can help decrease the demand for irrigation water.

According to Bekele (2020), deficit irrigation practices deviate from conventional water supply methods. The manager needs to be aware of the minimum transpiration deficit that can be tolerated without significantly reducing crop production. Deficit irrigation's primary goal is to raise a crop's WUE by removing irrigations that don't significantly affect yield. The reduction in yield that results from this approach may be relatively minor when compared to the advantages of redirecting the saved water to irrigate other crops that would typically face water shortages under traditional irrigation practices.

Chai *et al*. (2016) discussed the effects of different irrigation regimes on onion yield, quality, and water use efficiency and explored the potential benefits and limitations of deficit irrigation in onion production. They also examine the various methods used to determine the optimal irrigation schedule for onion crops, including the use of soil moisture sensors, weather stations, and crop simulation models. Finally, the authors highlight the need for further research to improve the efficiency of deficit irrigation practices in onion production, particularly in regions with limited water resources.

Azag *et al*. (2018) investigated the impact of deficit irrigation on the growth, yield, and water use efficiency of onion plants. The study involves four irrigation treatments, including 100% evapotranspiration (ET), 80% ET, 60% ET, and 40% ET, and evaluates the resulting effects on plant height, leaf area, bulb diameter, and yield. The results show that reducing irrigation water significantly decreases plant height and leaf area but has little impact on bulb diameter and yield. Additionally, the study finds that deficit irrigation leads to increased water use efficiency, with the 60% ET treatment exhibiting the highest water use efficiency among all treatments. Overall, the study suggests that deficit irrigation can be a viable strategy for improving water use efficiency in onion production, particularly in areas with limited water resources.

Alireza *et al*. (2020) examined the effectiveness of deficit irrigation strategies in tomato production under arid conditions. They discussed various deficit irrigation methods, including moderate, severe, and terminal drought stress, and their impacts on tomato yield, fruit quality, and water use efficiency. They also explore the physiological responses of tomato plants to deficit irrigation, such as changes in stomatal conductance, transpiration, and photosynthesis. The author emphasized the importance of adopting suitable deficit irrigation strategies in tomato production to reduce water consumption while maintaining acceptable yields and fruit quality. The authors suggest that moderate deficit irrigation (40-60% of ETc) can result in significant water savings without negatively affecting tomato production, making it a promising approach for sustainable agriculture in arid regions.

2.6 Irrigation Methods

2.6.1 Furrow irrigation

Furrow irrigation is a surface irrigation technique that involves conveying water through narrow, evenly spaced channels across a field. The technique reduces the amount of labor needed for irrigation and land preparation. If proper site preparation and effective water management procedures are used, moderate to high application efficiency can be achieved. Mohmed *et al*. (2020) argue that furrow irrigation is likely to remain an important method of irrigation, especially in developing countries. The initial capital investment is relatively low on lands not requiring extensive land formation, as the furrows are constructed by common farm implements. factors that affect furrow irrigation efficiency, such as the slope of the land, soil type, the length of the furrows, and the amount of water applied (Mohmed *et al*., 2020). This irrigation method is best suited to medium and moderately fine-textured soils with relatively high available water holding capacity and hydraulic conductivity, which allow significant water movement in both the horizontal and vertical directions. Furrow irrigation is beneficial for areas with uneven topography and small irrigation streams (Michael, 1997).

2.6.2 Sprinkler Irrigation

In sprinkler irrigation, water is delivered through a pipe network to sprinklers, nozzles or jets which spray the water into the air, to fall to the soil as an artificial “rain”. The basic components of most sprinkler systems are: a water source, a pump to pressurize the water, a pipe network to distribute the water throughout the field, sprinklers to spray the water over the ground, and valves to control the flow of water (Jensen, 1983). The sprinklers, when properly spaced, give a relatively uniform application of water, and designed usually (there are some exceptions) to apply water at equal or lower rates than the soil infiltration rate.

2.6.3 Drip Irrigation

Drip irrigation involves supplying water to the soil very close to the plants at very low flow rates (0.2 – 8 lt/hr) from a plastic pipe fitted with outlets (drip emitters). The basic concept underlying the drip irrigation method is to maintain a wet bulb of soil in which plant roots suck water. Only the part of the soil immediately surrounding the plant is wetted. The volume and shape of the wet bulb irrigated by each drip emitter are a function of the characteristics of the soil (texture and hydraulic conductivity) and the discharge rate of the drip emitter. Applications are usually frequent (every 1- 3 days) to maintain soil water content in the bulb close to field capacity (Sileshi and Taffa, 2006). Compared to the sprinkler and furrow irrigation methods (with efficiencies of 60 – 70 % in high management systems), drip irrigation can achieve 90 – 95% efficiency (Isaya, 2001). Drip irrigation increases WUE compare to furrow irrigation (Fekadu and Teshome, 1998). Drip irrigation has the potential to be the most efficient irrigation technology when evaluated in terms of either crop production per unit of water consumed by ET or per unit of water applied. This is because the water can be uniformly delivered to each plant through a closed pipe system. Thus, converting from traditional surface irrigation to drip irrigation can significantly increase the area of land that can be fully irrigated with a given volume of water (Keller, 2002). Drip irrigation is more suitable for horticultural crops for increase crop yield and efficient water use. Study conducted in India confirm that drip irrigation give higher yield and water use efficiency in vegetable production compare to furrow irrigation(Jha *et al.,* 2017).

2.7 Crop Water Requirement

Crop water requirement is defined as the quantity of water needed to compensate for the loss through evapotranspiration from a cultivated field. Crop evapotranspiration signifies the water lost through evapotranspiration, while crop water requirement refers to the water that must be provided (Allen *et al*., 1998). Determining crop water requirements involves considering the climate's impact on reference crop evapotranspiration (ETo) and crop characteristics (Kc) (Doorenbos and Pruitt, 1977). The growth and yield of crops are directly linked to their water usage, with soil water content and energy status playing pivotal roles in plant growth (Hillel, 2004). The precision of crop water requirement calculations hinges on the quality of available climatic data and the chosen evapotranspiration estimation method's accuracy (Nuha and Henery, 2000).

Following comparative studies and recommendations by a panel of experts in FAO, Rome, in 1990, the Penman-Monteith equation was internationally recognized as the most reliable method for estimating evapotranspiration (Smith *et al*., 1991). The CROPWAT model facilitates ETo calculation, which employs the FAO Penman-Monteith method (Allen *et al*., 1998), expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a}{\Delta + \gamma(1 + 0.34U_2)} \quad 2.1$$

Where ET_o represents reference evapotranspiration (mm/day), Rn denotes net radiation at the crop surface (MJ/m2/day), G signifies soil heat flux density (MJ/m2/day), T indicates mean daily air temperature at 2 m height (°C), U2 corresponds to wind speed at 2 m height (m/s), e_s signifies saturation vapor pressure (kPa), e_a stands for actual vapor pressure (kPa), $e_s - e_a$ represents saturation vapor pressure deficit (kPa), Δ denotes the slope of the vapor pressure curve (kPa/°C), and γ represents the psychrometric constant (kPa/ °C).

The formula relies on typical climatic data, including solar radiation (sunshine), air temperature, humidity, and wind speed. Allen et al. (1998) established the revised crop coefficient values.

$$ETc = ETo * Kc(mm/day) \quad 2.2$$

Where, ETc is crop water requirement (mm/day), ETo is stands for reference evapotranspiration (mm/day), and Kc is crop coefficients.

Allen et al. (1998) recommend a method to calculate crop evapotranspiration under well-watered conditions using the reference crop approach. This involves estimating reference evapotranspiration (ETo) using the Penman-Monteith equation. Specific crop growth stages and their durations are identified for the target locations, and corresponding crop coefficients (Kc) are determined. These Kc values are then adjusted to account for wetting conditions due to rainfall or irrigation. Crop coefficient curves are developed to calculate Kc values for different time intervals, such as monthly or daily periods. Finally, the total water requirement is computed, assuming an application efficiency of 60% as suggested by FAO (1989).

2.8 Irrigation Scheduling

Irrigation schedules are set times and intervals for irrigation. The amount of water needed for a specific irrigation interval, the soil's ability to hold water, and the uniformity of the irrigation system all affect how long it takes to irrigate. The appropriate soil moisture level for crop use depends on the daily water demand, soil moisture storage capacity, and readily available soil moisture (Barragan and Wu, 2001). Applications are normally timed to replace water before yield-reducing water stress occurs. Water losses occur mainly through crop evapotranspiration (ETc), and exact estimates of ETc are needed to accurately determine soil water depletion. Crop evapotranspiration depends on the weather and on plant and management factors. Assuming there is no plant stress, the actual evapotranspiration is at its maximum value. If properly irrigated, most crops will have the maximum evapotranspiration (Snyder, 2014).

One of the more widely promoted procedures for irrigation scheduling is the water balance technique. The method involves maintaining a favorable soil water balance by monitoring all additions and losses of a field’s water. Often referred to as evapotranspiration or ET scheduling, the most important component of the water balance is an accurate estimate of crop water use. ET-based water balance irrigation scheduling methods are increasingly being used throughout the world because they are easy to apply (Jones, 2004). The general approach to these methods is to maintain a running balance of the current soil moisture available to the plant by tracking the ET losses and the additions from irrigation and precipitation. Because many of the components are estimated, a good field-check program is recommended to test that the calculations are correct (Snyder, 2014).

2.9 Agronomic Aspects of Onion and Tomato

2.9.1 Agronomic aspects of onions

Onions are a biennial cool-season crop known for their tolerance to frost and are primarily cultivated for their bulbs, although salad onions' green shoots are also valuable. In Ethiopia, onions can thrive at altitudes ranging from 500 to 2400 meters above sea level, with the most favorable growth observed between 700 and 1800 meters above sea level (Lemma and Shimeles, 2003). Onions can adapt to various soil types, spanning from sandy to clay loams. Nevertheless, they tend to thrive in loamy soils that are both fertile and well-drained, with a preferred pH range of 6.0 to 8.0 (Olani and Fikre, 2010).

Onions typically do not perform well in soils with a pH below 6.0 due to potential issues such as trace element deficiencies or, in some cases, the presence of aluminum or manganese toxicity. While onions can be cultivated in slightly alkaline soils, they are susceptible to soil salinity. As per FAO (2002), when soil salinity reaches a level of 4.3 dS/m or higher, onion yields may decline by as much as 50%. Onion plants typically have a substantial nutrient requirement. To prevent nutrient losses through leaching or volatilization while the plant roots are still developing, it's important to apply some pre-plant nitrogen as a starter fertilizer, as recommended by Shock et al. (2000). Following plant establishment, one or two additional applications of nitrogen fertilizer during the growing season are necessary. Onions demand frequent irrigation throughout their growth period for several reasons. Their root system is shallow, with the majority of water absorption occurring within the top 0.3 meters of soil, and very little water is extracted from depths greater than 0.6 meters. Moreover, onion roots tend to be non-branching, and all roots originate from the stem or basal plate of the plant. This highlights the importance of maintaining moisture in the upper soil layers to promote root growth. Even mild water stress can lead to reduced rates of transpiration, photosynthesis, and overall growth, as observed by Voss and Mayberry (1997).

2.9.2 Agronomic Aspects of Tomato

Tomato (Solanum lycopersicum L.) stands as one of the most widely consumed vegetables globally (Del *et al*., 2016). Tomatoes are warm-season crops that require full sun and well-drained soil. The ideal soil pH for tomatoes is 6.0-6.5, but they can tolerate a pH range of 5.5-7.5 (Wen *et al*., 2019). Tomatoes are heavy feeders and require regular fertilization, especially during the flowering and fruiting stages. They are also susceptible to a variety of pests and diseases, so it is important to practice good pest management. The growth of tomato plants can be divided into four stages: germination, seedling growth, vegetative growth, and flowering and fruiting. Germination occurs at soil temperatures of 60-85 degrees Fahrenheit. Seedlings should be transplanted when they have two sets of true leaves. Vegetative growth occurs during the first few weeks after transplanting. During this stage, the plant is developing its roots, stems, and leaves. Flowering and fruiting begin when the plant reaches maturity. The number of days to maturity depends on the variety of tomato plant (Ruggieri *et al*., 2019).

2.10 Crop Growth Simulation Model

Understanding how crops respond to water stress and different management techniques can be done using crop simulation models (Farahani *et al*., 2009). The management options can typically be specified in the model, and they can be used to evaluate a variety of management strategies at a low cost. Numerous complex crop-growth models based on physiological processes have been created and used with varied degrees of effectiveness in water management projects. Hybrid models that simulate the growth of crops in water-limited environments include CERES and the Decision Support System for Agro-technology Transfer (DSSAT). These models are some of the most generally accepted cereal models.

An additional example can be found in the CROPWAT model, a valuable resource for irrigation planning. However, it's important to exercise caution when interpreting crop yield loss predictions generated by this model due to its potential inaccuracies in simulating evapotranspiration (Cavero *et al*., 2000). All of these models are complex, necessitating a high level of expertise for their calibration and operation and requiring a lot of parameters (Heng *et al*., 2009). A new crop simulation model called AquaCrop has been created by FAO to address these concerns and in an effort to achieve the best possible balance between accuracy, simplicity, and resilience (Steduto *et al*., 2009; Raes *et al*., 2009).

2.11 Description of the AquaCrop Model

The Land and Water Division of the FAO (Food and Agriculture Organization) developed AquaCrop, a water productivity model that simulates the yield response to water for herbaceous crops using a small number of parameters and input data. This model is specifically designed to address situations where water is a major limiting factor in crop production, and it models the yield potential of herbaceous crops as a function of water consumption (Steduto *et al.*, 2012). One advantage of the application of the AquaCrop model is that it can be used to evaluate the possible against actual yields in a field, farm, or area to identify the constraints limiting crop production and water productivity (bench marking tool) (Dirk Raes *et al*., 2009).

AquaCrop simulates the potential yields of major crops such as forage, vegetables, grains, fruit, oil, roots, and tubers with respect to varying water regimes, which can be from rainfall and irrigation (Dirk Raes *et a*l., 2009). AquaCrop simulates crop transpiration (Tr) and soil evaporation (E) separately, developing a simpler model for canopy growth and senescence, treating the final yield (Y) as a product of final biomass (B) and harvest index (HI), and dividing the effects of water stress into canopy growth, canopy senescence, crop transpiration (Tr), and harvest index (HI) (Steduto *et al*., 2012). AquaCrop models stand out from other crop models because they emphasize water, utilize ground canopy covers instead of leaf area index, and employ water productivity values that are adjusted for atmospheric evaporative demand and carbon dioxide concentration.

AquaCrop can be used as a management tool or planning aid for both irrigated and rain-fed agriculture (Raes *et al*., 2018). The model can be used to evaluate achievable and actual yields in a field or farm, identify restrictions limiting crop output, and increase water productivity. The study of the impact of climate change on food production, the development of strategies under conditions of water scarcity to maximize water productivity through irrigation strategies, and planning objectives through the analysis of scenarios useful for water administrators and managers, economists, policy analysts, and scientists are other objectives (Raes *et al*., 2018).

2.12 Aqua Crop Calculation Scheme

Development of green canopy cover (GCC): In Aqua Crop foliage development is expressed through green canopy cover (GCC). The percentage of the soil surface that is covered by the canopy is known as the green canopy cover. The ground canopy cover can range from zero during sowing, indicating no soil surface covered by the canopy, to one at the midpoint of the growing season, indicating full soil surface coverage by the canopy. Aqua Crop monitors potential stresses in the root zone by changing the soil's water content in the soil profile each day (Engineering, 2015).

Crop transpiration (T_r): To determine Tr in well-watered conditions, multiply the reference evapotranspiration (ETo) by a crop coefficient (Kc). The crop coefficient varies throughout the crop's life cycle in accordance with the simulated canopy cover since it is proportional to GCC. Water stress may cause stomata to close, which directly affects crop transpiration in addition to affecting canopy development.

Above-ground biomass (B): The above-ground biomass produced is determined by the cumulative amount of water transpired (Tr), which translates into a proportional amount of biomass produced through biomass water productivity. AquaCrop uses normalized water productivity for atmospheric demand and air CO2 concentrations (WP*). Beyond the partitioning of biomass into yield, there is no partitioning of above-ground biomass among various organs, which avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood and most difficult to model (Raes e*t al*., 2018).

$$B = Wp * \sum \frac{T_r}{ET_0} \qquad 2.3$$

Where, B is above-ground biomass (kg/m^2), WP is water productivity (mm/day), and Tr is daily transpiration (mm/day), ETo is reference evapotranspiration (mm/day)

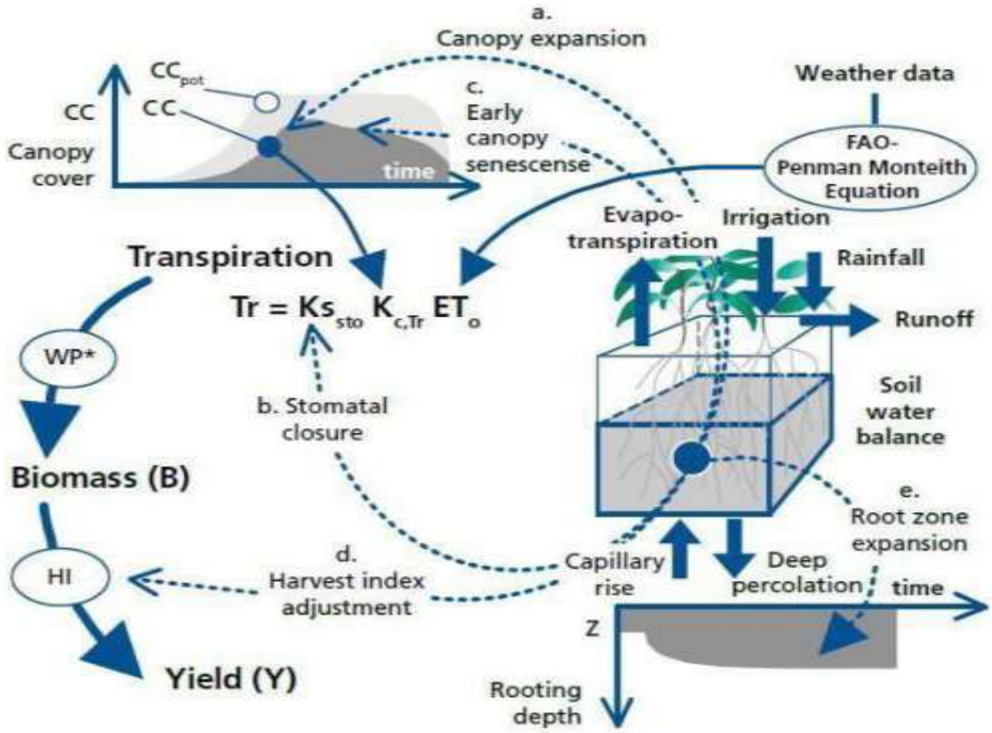


Figure 2.1 AquaCrop Calculation Scheme Flow Chart (**source: Raes et al., 2009**)

Crop yield was obtained with the help of the simulated above-ground biomass (B) and the harvest index (HI). In response to water and temperature stresses, HI was continuously adjusted during yield formation.

$$Y = HI * B \qquad 2.4$$

Where, Y is crop yield (kg/m^2) and HI is harvest index (constant)

2.13 Related Studies

Takács *et al*. (2021) conducted an evaluation of the performance of the AquaCrop model in simulating processing tomato biomass, fruit yield, and water stress indicators in Hungary over three growing seasons (2017–2019). The objective of the study was to evaluate the tomato biomass and yield simulation performance of the AquaCrop model. The results of the study showed that the AquaCrop model was able to accurately simulate processing tomato biomass and fruit yield under all water supply levels. The model slightly overestimated biomass and yield at the 100% ETc water supply level and slightly underestimated biomass and yield at the 50% ETc water supply level. However, the overall accuracy of the model was good, and the model can be used to simulate processing tomato biomass and fruit yield under different water supply conditions.

Nyakudzuka *et al*. (2021) studied the evaluation of the FAO AquaCrop model for its ability to simulate acceptable yields and water use for field tomatoes grown under deficiency irrigation in Harare, Zimbabwe. The objectives of the study were to evaluate the AquaCrop model for its ability to simulate water use and tomato (Lycopersicon esculentum Mill.) fruit yields under deficit irrigation conditions. A field experiment was conducted at the University of Zimbabwe Farm during the 2019–2020 cropping season. There were four irrigation treatments: (1) 100% crop evapotranspiration (ETc), (2) 75% ETc, (3) 50% ETc, and (4) 25% ETc. The AquaCrop model was calibrated with data from the full irrigation treatment and validated with data from the deficit irrigation treatments. The study results showed that the AquaCrop model was able to accurately simulate tomato yield and water use under all irrigation treatments. The study also showed that deficit irrigation can reduce tomato yield, but the reduction in yield is less severe when deficit irrigation is applied only during the vegetative growth stage. Overall, the study showed that the AquaCrop model is a valuable tool for simulating tomato yield and water use under deficit irrigation conditions.

Abdelrahim *et al*. (2023) conducted a simulation of the effect of deficit irrigation schemes on tomato crop production using the AquaCrop model. The objective of the study was to investigate the actual effect of applying different deficit irrigation schemes on the growth parameters and yield of the tomato crop. The study was conducted in Egypt during the 2015–2016 and 2016–2017 growing seasons. Five irrigation treatments were applied: full irrigation (100% ETc), deficit irrigation at 80% ETc applied throughout the growing season, deficit irrigation at 80% ETc applied only at the initial and maturity growth stages, deficit irrigation at 60% ETc applied throughout the growing season, and deficit irrigation at 60% ETc applied only at the initial and maturity growth stages. The results of the study showed that the AquaCrop model was able to accurately simulate tomato crop production under all irrigation treatments. The model slightly overestimated tomato yield at the 100% ETc irrigation treatment. However, the overall accuracy of the model was good, and the model can be used to simulate tomato crop production under deficit irrigation schemes. The study also showed that deficit irrigation can reduce tomato yield, but the reduction in yield is less severe when deficit irrigation is applied only at the initial and maturity growth stages.

Nura Jafar Shanono *et al.* (2022) conducted an evaluation of an aqua-crop model using onion crops under deficiency irrigation in semi-arid Nigeria. The objective of the study was to calibrate and validate the Aqua-Crop Model for simulating onion growth, yield, and water use parameters under different irrigation levels in the semi-arid region of Nigeria. The experiment was conducted in Kano State, Nigeria, with Four irrigation levels (100%, 75%, 50%, and 25% of crop evapotranspiration, ETc) were applied in a factorial experiment. Results of the study showed that the AquaCrop model was able to accurately simulate onion crop production under all irrigation levels. The model slightly overestimated onion yield at the 100% ETc irrigation level. However, the overall accuracy of the model was good, and the model can be used to simulate onion crop production under deficit irrigation.

Agbemabiese *et al*. (2018) conducted a validation of Aquacrop for Different Onion (Allium cepa) Irrigation Regimes in the Bontanga Irrigation Scheme. The main objectives of the study were to calibrate the AquaCrop model for varying onion irrigation regimes and assess its impact on crop growth and yield parameters within the Bontanga irrigation scheme during the 2016–2017 dry season. Four distinct irrigation treatments were administered, corresponding to 117%, 100%, 80%, and 60% of the crop water requirements (CWR) for onions. The calibration of the AquaCrop model utilized data from the 100% CWR treatment, while validation involved data from the remaining three treatments. The study's findings demonstrated the AquaCrop model's ability to accurately predict onion yield and water productivity across all irrigation regimes. Overall, the model displayed commendable accuracy and can serve as a valuable tool for simulating onion yield and water productivity under diverse irrigation conditions in northern Ghana.

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of the Study Area

The research was conducted at the Melkassa Agricultural Research Center experimental farm, situated in the Oromia regional state near Awash Melkassa town within the central rift valley of Ethiopia. The geographical coordinates of the center are approximately 8°24'53" N latitude and 39°19'40" E longitude, with an average altitude of 1,550 meters above mean sea level. It is located 17 kilometers southeast of Adam town and approximately 107 kilometers from Addis Ababa. According to the climate data collected from the Melkassa agro-meteorological observatory station between 1977 and 2017, the average annual rainfall in the area is 824.9 mm. The highest monthly rainfall, which is 204.2 mm, occurs in August, while the lowest monthly rainfall, which is 9.6 mm, happens in November, with mean maximum and minimum temperatures of 28.72°C and 13.82°C, respectively. The local climate is characterized as semi-arid, with irregular and limited rainfall following a bimodal pattern.

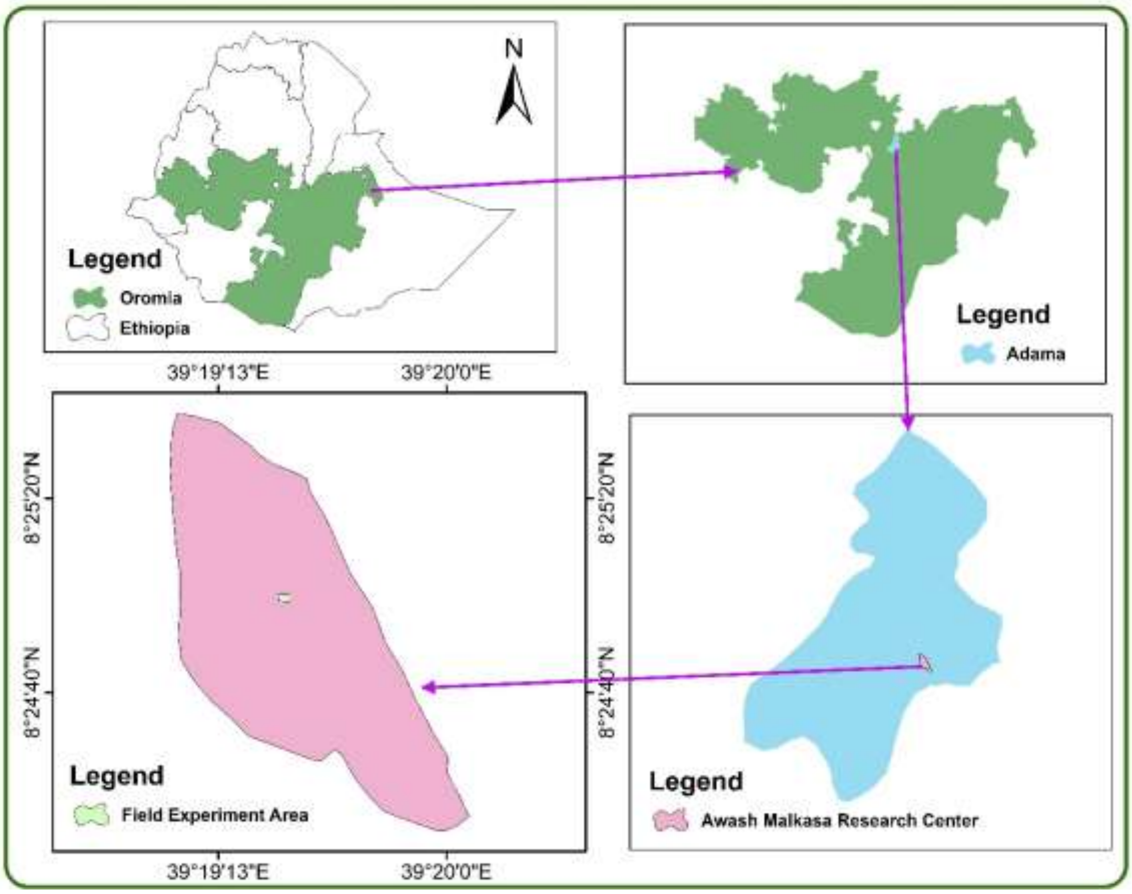


Figure3.1 Location map of the study area

3.2 Experimental Design and Treatment

The study involved four distinct growth phases, which included the initial, development, mid-season, and late-season stages. These growth stages were exposed to three different irrigation levels, representing 100%, 75%, and 50% of the crop's water needs. With the exception of the control treatment, deficit irrigation was applied during the crop's growth stages. There were six treatments, including the control treatment, set up in a randomized complete block design (RCBD) with three replications.

In this experiment, the furrow irrigation method was employed, and a suitable distance from the water source to the plot block was required to reduce the impacts of lateral flow. Each field block was designed to receive irrigation through the field channel. A 3-inch Parshall flume was used to apply the precise amount of irrigation water to each area. The irrigation program was implemented in excess of the control treatment (100% ETc). Based on their percentage moisture stress level, the other treatments received less irrigation water than the control treatment.

3.2.1 Experimental Design and Treatment of the Onion

Overall, there were 18 experimental plots, each with a 4.5 m × 3.60 m experimental area. The overall measurement of the experimental area was 42.4 m by 20.5 m. Five planting ridges spaced 60 cm apart were used in each plot.

Table 3. 1Onion and Tomato Experimental Treatments

Treatments	Growth Stage			
	Initial (ETc%)	Development (ETc%)	Mid- season (ETc%)	Late season (ETc%)
T1	100	100	100	100
T2	75	75	75	75
T3	50	50	50	50
T4	75	100	100	75
T5	50	100	100	50
T6	100	75	50	100

The treatments are assigned as follows: T1 receives full irrigation throughout all growth stages, T2 receives 75% ETc throughout all growth stages, T3 receives 50% ETc throughout all stages, T4 receives 75% ETc at the initial and maturity stages and full irrigation at the developmental and mid stages, T5 receives 50% ETc at the initial and maturity stages and full irrigation at developmental and mid-stages, and T6 receives full irrigation at the initial and maturity stages and 75% ETc and 50% ETc at development and mid-stages, respectively.

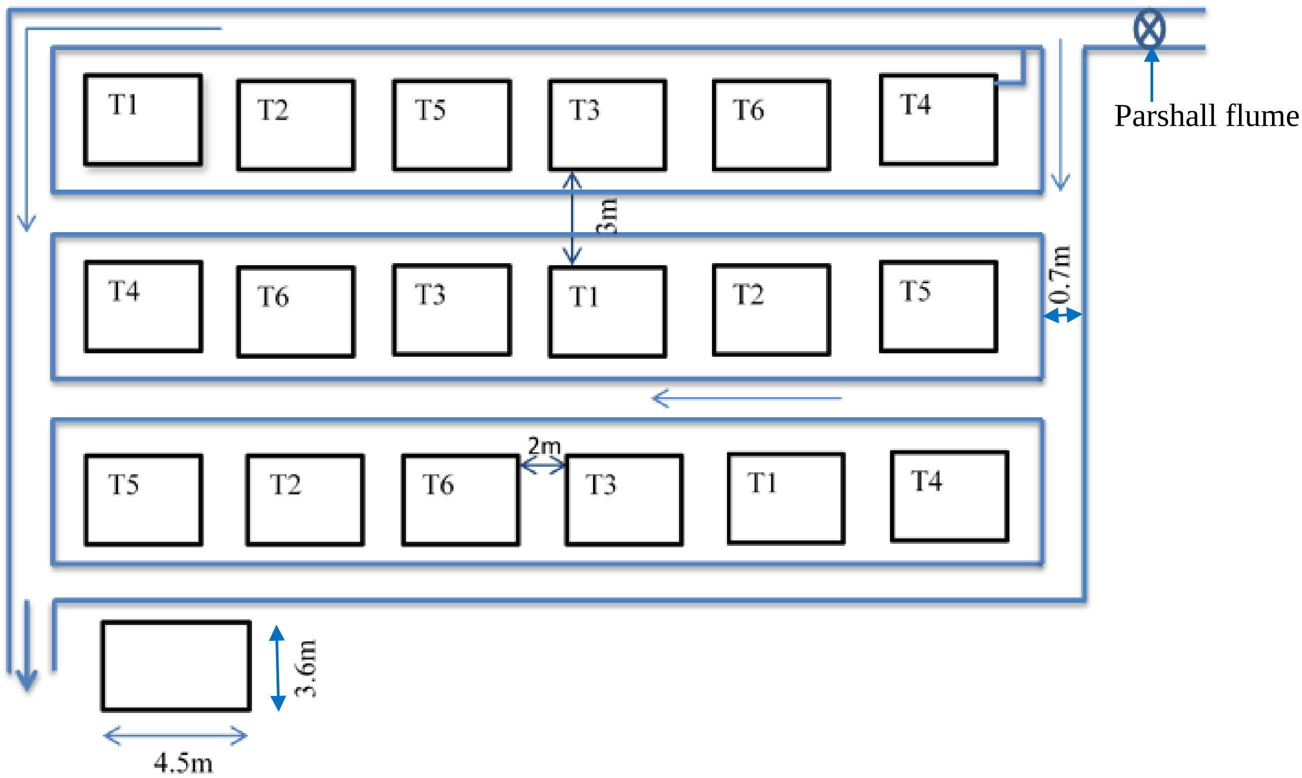


Figure 3.2 Onion Experimental Setup

3.3.1.1 Onion Crop Establishment and Management Practices

The onion variety Nafis red, Allium cepa L., is a high-yielding, early-maturing variety that was utilized as seed. At a seed rate of 70 grams per bed, the seeds were sown on October 15, 2022, in well-constructed 1 m by 5 m seed beds. The seed was managed up until the transplant stage in accordance with MARC's suggestion. The seedlings were then planted on December 4, 2022, in carefully prepared experimental plots located on either side of a ridge, with a row-to-seed spacing of 60 cm and 10 cm, respectively.

To enhance plant establishment, onion seedlings that were transplanted into the experimental field were provided with two consistent irrigations. Diammonium phosphate (DAP) was applied once during transplantation, while urea was applied twice: once during transplantation and again after 30 days, with application rates of 200 kg/ha and 100 kg/ha, respectively. Pesticides, including Agrolaxun, Mancoze, and Profit, were utilized to safeguard the crop from harmful fungi and insects.

Following the FAO's recommendation, the crop's phenological development was categorized into four distinct stages (FAO, 1998). These stages are delineated as follows:

Stage 1, the initial stage, spanning 15 days (from 14th December to 28th December); Stage 2, the developmental stage, extending over 30 days (from 29th December to 27th January); Stage 3, the bulb formation stage, covering 40 days (from 28th January to 7th March); and Stage 4, the maturity stage, encompassing 35 days (from 8th March to 11th April). The entire growth cycle of the onion, considering treatment application, spanned 120 days from establishment, with an additional two weeks before harvesting.

3.2.2 Experimental design and treatment of tomatoes

Overall, there were 18 experimental plots, each with a 4.5 m × 6 m experimental area. The overall measurement of the experimental area was 42.4 m by 27.7 m. Five planting ridges spaced 100 cm apart were used in each plot.

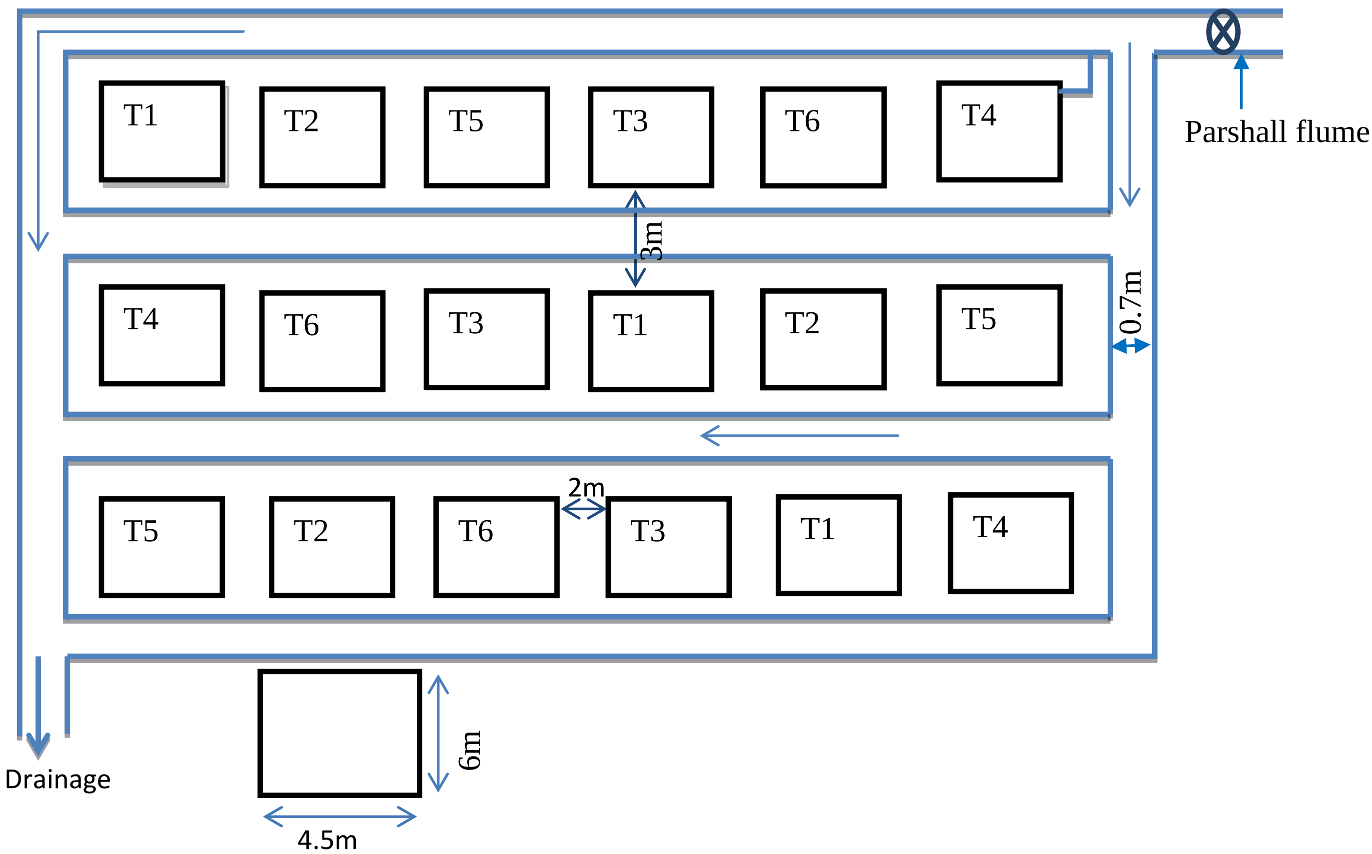


Figure 3.2 Tomato Experimental Setup

3.2.2.1Tomato Crop Establishment and Management Practices

A Galilema variety of tomatoes was used as seed material on a two-seed bed of 1m by 5m seed beds. Seed rates of 10 grams per bed were prepared, and the seeds were sown on December 11, 2022. The seedlings were later planted on January 5, 2022, in carefully prepared experimental plots located on one side of a ridge. The spacing between rows and seeds was set at 100 cm and 30 cm, respectively.

To ensure optimal plant establishment, tomato seedlings transplanted into the experimental field received two regular irrigations. DAP was applied once during transplantation, while urea was applied twice: once at transplantation and again 30 days later, both through manual placement at rates of 240 kg/ha and 70 kg/ha, respectively. Pesticides such as Agrolaxun, Mancoze, and Profit were used to protect the crop from harmful fungi and insects. The crop's phenological differentiation was divided into four developmental stages based on FAO's recommendations (FAO, 1998). These stages were as follows: Stage 1: initial stage: 15 days (from 13th January to 27th January); Stage 2: developmental stage: 30 days (from 28th January to 26th February); Stage 3: fruit formation stage: 35 days (from 27th February to 1st April); Stage 4: maturity stage: 40 days (from 2nd April to 11th May). The total duration of treatment application for tomatoes was 120 days after establishment, with an additional two weeks before harvesting.

3.3 Irrigation scheduling and management

The soil contains water in an "available" form, which can be extracted by plant roots. The depth of the root system plays a crucial role in determining how much water can be effectively taken up from the soil profile. It's important to note that roots do not absorb all the water present in the root zone. Allen et al. (1998) calculated the total available water (TAW) by considering the water content at field capacity and the permanent wilting point.

$$\mathrm{TAW} = (\mathrm{FC} - \mathrm{PWP}) * \mathrm{BD} * \mathrm{DZ}/100 \qquad 3.1$$

Where, FC is field capacity in weight base, PWP is permanent wilting point expressed as percentages based on weight, BD represents the soil's bulk density measured in grams per cubic centimeter (gm/cm^3), and Dz indicates the maximum effective depth of the root zone in millimeters (mm).

Bulk density is quantified as the mass of soil per unit volume when the soil is in an undisturbed state, and it is represented as:

$$\mathrm{BD} = \frac{\mathrm{M_s}}{\mathrm{V_t}} \qquad 3.2$$

Where, Ms is the weight of oven-dry soil (gm) and Vt is the volume of the sample soil (cm^3).

The irrigation schedule was established based on readily available soil water for maximizing crop production (RAW). RAW represented the maximum amount of water that plants could extract from their root zone before experiencing water stress. RAW was calculated using the following formula:

$$RAW = p * TAW \tag{3.3}$$

Where, RAW is measured in millimeters, p is a fraction that indicates the allowable or permissible soil moisture depletion under no stress, and TAW represents the total available water in millimeters.

The allowable or permissible soil moisture depletion values for tomato and onion crops can vary depending on several factors, including the specific variety, local climate conditions, and soil type. According to Allen et al. (1998), the values of the depletion fraction for the onion and tomato crops were 0.25 (25%) and 0.4 (40%), respectively.

3.4 Soil moisture mentoring

The irrigation schedule was established using climate, soil, and crop data. Nevertheless, it was essential to monitor the soil moisture content in the experimental plots both before and after irrigation, which was accomplished through the gravimetric method. One of the most commonly employed techniques for determining soil water content involves the gravimetric method, where a moist sample is weighed, oven-dried at 105°C for 24 hours, reweighed, and the water loss is calculated as a percentage of the dried soil mass. Soil moisture content was monitored at the time of sampling during the experimentation, specifically at field capacity (FC) and the permanent wilting point (PWP). The following equation determines the soil moisture constant:

$$Q_m = \frac{M_t - M_s}{M_s} = \frac{M_w}{M_s} \tag{3.4}$$

Where: Qm is the gravimetric moisture content as a fraction, Mt is the total mass of the wet soil, Mw stands for the mass of water in grams, and Ms corresponds to the mass of the dry soil in grams.

To transform the gravimetric soil moisture into volumetric moisture content, the product of Qm was divided by the bulk density (BD), and this result was divided by the density of water (ρw), which can be considered to have a value of 1.

$$Q_v = \frac{BD - Q_m}{\rho w} \tag{3.5}$$

Additionally, volumetric moisture content was converted into an equivalent depth by multiplying it by the chosen root depth.

$$\text{Water depth (mm)} = Dz * Qv \quad 3.6$$

Where, Qv is volumetric water content (fraction), BD is bulk density, ρw is density of water, and Dz is root depth.

Equation 3.7 determines the depth of irrigation water delivered to the full irrigation treatment.

$$d = \frac{(FC - MC) * DZ * BD}{100} \quad 3.7$$

Where, d is the quantity of water applied in millimeters (mm); FC denotes the moisture content at field capacity in weight base; and MC signifies the moisture content at the time of soil sampling or within the soil before irrigation.

3.5 Determination of deficit irrigation depth and management of the application

Deficit irrigation depths were determined by calculating the difference between the crop's water requirement and the available water supply. The soil moisture balance method was used in this study, which calculated the change in soil moisture storage between two points in time. Thus, deficit irrigation depth is calculated by subtracting the decrease in soil moisture storage from the total water requirement of the crop.

Once the deficit irrigation depth has been calculated, managing the application in the field requires careful planning and monitoring. Thus, through both soil moisture measurement and allowable depletion level determination, the application was managed in the field. Measurement of soil moisture was used to monitor soil moisture regularly and apply deficit irrigation effectively. The determination of the allowable depletion level was used to refer to the maximum amount of water that can be depleted from the soil without adversely affecting crop yields. This value varies depending on the crop type, soil type, and climate conditions. Generally, for onion and tomato, an allowable depletion level was described above to be considered safe for the crops, respectively.

The depth of irrigation provided at any given time was calculated using a simplified water balance equation, as expressed below:

$$In = ET_c - P_e \quad 3.8$$

Where, In is the net irrigation depth in millimeters, ET_c is the crop water requirement in millimeters, and P_e is the effective rainfall in millimeters. Effective rainfall refers to the portion of rainfall that enters the soil and becomes available for crop use.

Effective rainfall was determined using the dependable rain method as outlined by Allen et al. (1998) as follows:

$$P_e = 0.6 * P - 10 \text{ For month} \leq 70 \text{ mm} \quad 3.9$$

$$P_e = 0.8 * P - 24 \text{ For month} \geq 70 \text{ mm} \quad 3.10$$

Where, P_e is the effective rainfall in millimeters (mm), and P stands for the total rainfall in millimeters (mm).

The gross irrigation requirement was calculated using an application efficiency of 60% (FAO, 1989). The normal ranges of furrow irrigation application efficiency recommended are 50–70%, but they can be higher depending on soil types and management practices (Yadeta *et al*., 2022). Water was accurately applied in this experimental arrangement, utilizing short furrows with end-diking, which prevented any runoff or excessive percolation. As a result, the following calculation applied a larger value of application efficiency (60%).

$$Ig = \frac{In}{Ea} \quad 3.11$$

Here, Ig represents the gross irrigation depth in millimeters, while Ea stands for the furrow application efficiency expressed as a percentage.

The quantity of irrigation water applied to the plots was measured using a Parshall flume with a 3-inch throat width, positioned on the upstream edge adjacent to the experimental field. Accordingly, the equation below was used to determine how long it would take to supply the specified depth of water to each plot (Kandiah, 1981).

$$t = \frac{Ig * A}{60 * q} \quad 3.12$$

Where, t is the application time in minutes, Ig is the gross depth of water applied in millimeters, A is for the area of the plots in square meters, q is the flow rate in liters per second at a specific Parshall flume head, and 60 serves as a unit conversion factor.

3.6 Data Collection

The data collection was structured to fulfill the criteria for evaluation of the performance of onions and tomatoes under varying irrigation water levels and for the calibration and validation of the AquaCrop model. Some of the data collected during field experiments at the Awash Melkassa Research Center was employed in the calibration and validation processes of the AquaCrop model. The accessible files are suitable for storing the necessary climate, crop, soil, irrigation, and field management data that the model requires.

3.6.1 Weather Data

Daily climate data for the site were collected from the Awash Melkassa Research Center metrological station during the field experiment, such as rainfall, temperature, humidity, sunshine hours, and wind speed. The model required daily minimum and maximum temperature, daily rainfall, daily reference evapotranspiration, and annual CO_2 concentration as input data. Reference evapotranspiration (ETo) was calculated using meteorological data, the FAO Penman-Monteith equation as described in Allen et al. (1998), and the CROPWAT version 8.0 tool.

3.6.2 Soil Data

Soil samples, both disturbed and undisturbed, were collected from specific locations in the field at regular intervals for the analysis of soil physical properties and chemical characteristics.

3.6.2.1 Soil texture

The hydrometer method was used to analyze the soil's particle size and determine its texture class using the USDA Textural Triangle.

3.6.2.2 Bulk density

The bulk density was determined by collecting undisturbed soil samples from various depths (0–15 cm, 15–30 cm, 30-45 cm, 45–60 cm, 60–90 cm, and 90–120 cm). These samples were subsequently oven-dried for 24 hours at 105°C and weighed to obtain their dry weight. The bulk density was then calculated using the following formula:

$$\rho_b = \frac{W_s}{V_c} \qquad 3.13$$

Here, ρ_b is the soil bulk density in g/cm³, W_s is the mass of dry soil in grams (g), and V_c is the volume of soil in the core in cubic centimeters (cm³).

3.6.2.3 Field capacity and permanent wilting point

Soil samples were collected from various depths (0–15 cm, 15–30 cm, 30-45 cm, 45–60 cm, 60–90 cm, and 90–120 cm) to determine their moisture content at field capacity (FC) and permanent wilting point (PWP). Pressure plate and pressure membrane equipment were used to estimate FC and PWP, respectively. The soil samples were saturated for 24 hours, and then pressures of 1/3 bar and 15 bar were applied until no water droplets remained for the determination of FC and PWP, respectively.

3.6.2.4 Soil chemical properties

The chemical characteristics of the soil at the experimental site, including soil pH, OM, ECe, OC, and total nitrogen, were subjected to laboratory analysis, and their values were determined following standard procedures. This analysis aimed to assess the soil's suitability for growing onions and tomatoes.

3.6.3 Crop Data

The necessary crop data consisted of key phenological growth parameters for onions and tomatoes. These parameters, such as emergence, maximum canopy cover, flowering, senescence, and physiological maturity, were observed in terms of calendar days and documented in the field throughout the experimental period.

3.6.3.1 Green canopy cover

Field images were captured with Canopeo software on a mobile device, positioned at a one-meter height above the crop, to assess canopy cover. The software promptly calculated the average canopy cover percentage, which was then integrated into the Aquacrop model. The timing of maximum canopy cover was established when no further change in the percentage of canopy cover was evident.

3.6.3.2 Biomass

For both onion and tomato plants, a random 1 m^2 area from each plot was selected for biomass estimation at the final but for the growth stage, the sample was taken at a two-week interval after establishment. Leaves, onion stems, and tomatoes from these areas were separately weighed to determine above-ground biomass. Leaf biomass was determined by harvesting, labeling with paper bags, and weighing leaves from individual plots, followed by oven-drying at 65°C for 48 hours to obtain dry weights. The total dry leaf biomass for each treatment was then calculated. Similarly, bulb and fruit biomass was estimated by collecting, labeling, and weighing bulbs and fruits from individual plots, followed by oven-drying at 65°C for 48 hours to obtain dry weights. The total dry bulb biomass for each treatment was subsequently estimated. Total biomass was calculated as follows:

$$\text{Total biomass} = \text{Bulb/Fruit biomass} + \text{Above-ground biomass} \quad (3.14)$$

3.6.3.3 Plant height and leaf number

Measuring plant height (cm) involved determining the distance from the soil surface to the tip of the longest mature leaf for onions. Leaf count per plant was conducted manually, with random plant selection and tagging in each plot for data collection. Plant height and leaf count for onions in each experimental unit were based on five selectively sampled plants from the central three ridges. Two ridges on the right and left sides and 0.5 m both alongside were not sampled because those areas were accounted for as border effects. The random sampling of these plants ensures even distribution across the area to prevent sample bias. Plant height was measured using a ruler. The average plant height and leaf count for each experimental unit were calculated based on the data from the five collected samples.

3.6.3.4 Bulb diameter and fruit height

The bulb diameters of onion and tomato fruits were selected randomly from five plants in each plot and measured with an automatic caliper at right angles to the longitudinal axis. whereas onion bulb height and tomato fruit height were measured at the vertical axis by using a caliper.

3.6.3.5 Marketable yield

The experimental data on the tomato fruit yield and onion bulb yield in each experimental plot was collected and weighed. The yield was obtained after manually removing the onion bulb's roots and stock with a sickle and picking the fruit from the tomato plant. Marketable yield (kg/ha) was calculated for tomato fruit from the sampled plant that was healthy and unharmed, unrotten, non-white, non-split, and of marketable size. The marketable bulb yield was measured in kilograms per plot.

Finally, the yield obtained from the sampled area was converted to kilograms per hectare using equation 3.15 (Yield and Density, 2018).

$$\text{Yield} = \frac{\text{Weight of sample yield}}{\text{Net harvested area}} * 10000\text{m}^2 \qquad 3.15$$

Where, Yield is in kg/ha, weight of sample yield in kg, net harvest area in m^2, and 10000-unit conversion

3.7 Statistical analysis

The gathered data underwent statistical analysis using statistical software, specifically Statistix 10, employing the general linear model for variance analysis. Analysis of variance

(ANOVA) was utilized to assess growth and yield based on irrigation data. To manage and compare all collected data, the least squares of differences (LSD) was employed. The results concerning growth, yields, and yield component parameters were analyzed using statistical 10.

3.8 Calibration and Validation of the AquaCrop Model

Calibration involves modifying specific model parameters to align the model with the observed values at a specific location. In the calibration process, calendar days were used to measure crop phenological parameters like emergence, maximum canopy cover, flowering, senescence, and physiological maturity. Calibration started by adjusting the canopy cover (CC) and then fine-tuning the above-ground dry matter. Further refinements and parameter adjustments were performed until good agreement between the simulated and observed values for each respective variable was achieved. In the calibration phase, field data was used to directly determine non-conservative parameters that describe crop development under optimal irrigation conditions.

In the validation stage, the model is applied without making any modifications to its parameters or code, and the results are compared to independent experimental data. The model's validation was performed by using the calibrated model and data from treatments that were not included in the calibration process. Specifically, the following crop growth parameters were examined: final biomass and harvestable yield. To validate the Aquacrop model for parameters such as above-ground biomass (AGB) in tomatoes, total biomass in onions, and grain yield (Y), the model's simulated results were compared with observed field data using the following statistical methods:

3.9 Statistical Evaluation of Model Performance

To evaluate the agreement between AquaCrop simulation results and actual biomass, canopy cover, and yield, various statistical indicators were employed, including root mean squared error (RMSE), Willmott's index of agreement (d), normalized root mean squared error (NRMSE), Pearson correlation coefficient (r), and Nash-Sutcliffe model efficiency coefficient (EF).

The root mean square error (RMSE) serves as a quantification of the average difference between observed and simulated values, offering a composite measure of the absolute uncertainty in the model. It is expressed in the same units as the variable being simulated, and as such, a smaller value closer to zero indicates better model simulation.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2} \quad 3.17$$

RMSE can undergo normalization by employing the mean of the observed variable, resulting in a percentage representation that reflects the relative difference. An NRMSE value below 10% signifies excellent simulation quality, while a range of 10–20% is deemed good, 20–30% is considered fair, and anything exceeding 30% is categorized as poor (Saad *et al*., 2014).

$$\mathrm{NRMSE} = \sqrt{\frac{1}{n}\sum_{n}^{1}(M - S)^2} * \frac{100}{Mi} \quad 3.18$$

Nash *et al*. (1970) introduced the Nash-Sutcliffe model efficiency coefficient (EF) to gauge the extent of residual variance compared to the variance of the observations. EF ranges from negative infinity to 1, with a score of 1 indicating a perfect match between the model and observations. An EF value of 0 suggests that the model predictions align with the observed data's average. A negative EF occurs when the mean of the observations outperforms the model as a predictor (Saad *et al*., 2014).

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}[M_i - S_i]^2}{\sum_{i=1}^{n}[M_i - \bar{M}]^2} \quad 3.19$$

Willmott's index of agreement (d) quantifies the similarity between simulated and observed data, with values ranging from 0 (no agreement) to 1 (perfect agreement).

$$d = 1 - \frac{\sum_{i=1}^{n}[S_i - M_i]^2}{\sum_{i=1}^{n}[|S - M| + |M_i - M|]^2} \quad 3.20$$

Where Si represents simulated values, Mi represents observed values, M represents the observed mean, S represents the simulated mean, and n is the number of observations.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Soil Physical Properties

The laboratory analysis of the soil's physical properties revealed that the average percentages of sand, silt, and clay composition were 34.66%, 29.93%, and 35.48%, respectively. As a result, based on the USDA soil textural classification, the soil at the experimental site is categorized as clay loam soil.

The soil bulk density results in the experimental field indicated a minor difference with depth. A bulk density of 1.1 g/cm^3 is typical for clay loam soil, but it can range from approximately 1.0 to 1.4 g/cm^3 (Hazelton and Murphy, 2019). The laboratory results for bulk density indicate a slight increase with increasing depth, as illustrated in Table 4.1. This increase in bulk density within the experimental area could be attributed to tractor plowing, which might compact the lower layers or result from the weight of the overlying soil (Brady and Weil, 2002). Bulk density ranged from 1 g/cm^3 in the upper root zone (0–15 cm) to 1.2 g/cm^3 in the lower root zone layer (90–120 cm), with an average bulk density of 1.1 g/cm^3 observed across the experimental site, as depicted in Table 4.1.

The moisture content, expressed as a percentage of weight, at field capacity (FC) with a tension of 1/3 bar was 35.44%, while it was 19.73% at permanent wilting point (PWP) with a tension of 15 bar. Variations in FC and PWP directly influenced the total available water (TAW), which represents the amount of water a crop can extract from its root zone. According to laboratory findings from the Awash Melkasa Research Center, the TAW within the depths of 0–15, 15–30, 30-45, 45–60, 60–90, and 90–120 cm displayed variations of 24.10, 26.83, 27.72, 26.65, 46.25, and 52.45, respectively. Consequently, the volumetric TAW for the experimental site was calculated at 170 mm/m (204/1.2).

Table 4.1 Physical properties of the soil at the experimental location

Soil Property		Soil Depth (cm)						
		0 - 15	15 -30	30-45	45-60	60-90	90-120	Average
Particle Size Distribution	Sand (%)	34.99	34.84	35.02	34.31	34.40	34.42	34.66
	Silt (%)	30.51	29.68	28.57	30.22	30.28	30.31	29.93
	Clay (%)	34.5	35.48	36.4	35.47	35.50	35.53	35.48
Textural Class		Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Bulk Density (g/cm^3)		1	1.1	1.1	1.1	1.1	1.2	1.1

FC (%)	34.76	34.95	35.65	35.65	35.67	35.98	35.44
PWP (%)	18.69	18.71	18.85	19.5	21.2	21.41	19.73
TAW (mm)	24.10	26.83	27.72	26.65	46.25	52.45	204

4.2 Soil chemical properties

The soil pH measured at 6.65 falls within the recommended range (6.0–8.0) for both onion and tomato cultivation (Olani and Fikre, 2010). The average electrical conductivity registered at 0.25 dS/m is below the critical threshold for causing a reduction in onion yield, which is 1.2 dS/m (Smith *et al*., 2011). Organic matter (OM) content is known to enhance water retention, nutrient release, and soil structure. The soil's organic matter content, denoted as OM, along with organic carbon (OC), had average values of 6.2% and 4.2%, respectively.

Table 4.2 Chemical properties of the soil at the experimental location

Soil Property	Soil Depth (cm)				
	0 - 15	15 -30	30-45	45-60	Average
PH	6.45	6.68	7.03	6.45	6.65
ECe (ds/m)	0.3	0.2	0.2	0.3	0.25
%OC	5.6	5.5	3.2	2.54	4.2
%OM	9.6	5.5	5.5	4.37	6.2
%TN	0.4	0.2	0.252	0.24	0.27

pH indicates the soil's acidity and alkalinity, ECe represents soil electrical conductivity, OC denotes the percentage of organic carbon, OM stands for the percentage of organic matter, and TN signifies the percentage of total nitrogen.

4.3 Crop Water Requirements

4.3.1 Crop water requirement of onions

Table 4.3 illustrates that water demand was minimal at the outset and reached its maximum level during the mid-season growth stage. Notably, the crop's highest water requirements occur during the mid-growth stage, encompassing flowering and yield formation, in comparison to other growth stages.

Table 4.4 presents the net irrigation water depths applied across various treatments throughout the experimental duration. The total net irrigation depths ranged from a minimum of 201.0 mm (T3) to a maximum of 401.32 mm (T1), excluding the standard irrigation provided during the establishment phase. The treatment with the highest total net water depth was the control, which received 100% ETc at all growth stages, while the treatment with the lowest total net water depth was the one receiving 50% ETc at all stages.

According to Doorenbos and Kassam (1979), onion yields ranging from 35 to 45 t/ha can be achieved with irrigation ranging from 350 to 550 mm of water through furrow irrigation. These findings align with those of Halim and Ener (2001), who observed a seasonal evapotranspiration (ET) for irrigated onions in arid Turkish climates in the range of 394 to 438 mm, resulting in yields of 35.8 to 43.1 tons/ha. Similarly, Kadayifci *et al*. (2005) reported that seasonal ET for onion crops in Turkey falls within the range of 350 to 450 mm, leading to a bulb yield of 40 tons/ha.

Table 4.3 Crop water requirement and net irrigation requirements of onions

Month	Stages	Kc	ETc (mm)	Peff (mm)	IRn (mm)
December	Initial	0.5	11.88	0	11.88
December	Initial	0.5	21.83	0	21.83
January	development	0.61	23.05	13.2	9.85
January	development	0.71	34.40	0	34.40
January	development	1.01	45.29	0	45.29
February	Bulb formation	1.1	50.82	0	50.82
February	Bulb formation	1.1	52.21	0	52.21
February	Bulb formation	1.1	49.38	0	49.38
March	Bulb formation	1.1	51.48	0	51.48
March	maturity	1.07	39.26	51.1	0
March	maturity	1.01	39.70	23.8	15.9
April	maturity	0.95	41.47	8.4	33.07
April	maturity	0.91	25.21	0	25.21
Total			485.98	96.5	401.32

Table 4.4 The net and total irrigation needs applied for all onion treatments

Treatments	Irrigation Level (%)	Stages	IRn (mm)	IRg (mm)
T1	100	All stage	401.32	668.87
T2	75	All stage	301	501.67
T3	50	All stage	201	335
T4	75	At initial and maturity stage	374.35	623.9
T5	50	At initial and maturity stage	347.38	578.96
T6	75 and 50	At development and bulb formation stage	277	461.67

4.3.2 Crop water requirement for tomatoes

The total irrigation water applied to the tomato crops was 375 mm for the non-stressed treatment (100% ETc) and 187.5 mm for the highly stressed treatment (50% ETc) (Table 4.5). in all treatments irrigation was managed by replacing the water lost in crop evapotranspiration (ETc) based on a deficit level, assuming a 60% irrigation efficiency. The result of tomato seasonal water demands of 375 mm was obtained from optimal irrigation scheduling. The result agreed with Doorenbos and Kassam (1986), who reported that the seasonal crop water requirement of tomatoes ranges from 350 to 600 using furrow irrigation. All treatments were irrigated on the same days because the only difference was the depth of water on deficit levels.

Table 4.5 The net and total irrigation demands implemented across all tomato treatments

Treatments	Irrigation Level (%)	Stages	IRn (mm)	IRg (mm)
T1	100	All stage	375	625
T2	75	All stage	281.25	468.75
T3	50	All stage	187.5	312.5
T4	75	At initial and maturity stage	333.71	556.18
T5	50	At initial and maturity stage	292.41	487.35
T6	75 and 50	At development and mid stage	297.82	496.36

Table 4.6 Crop water requirement and net irrigation requirements of tomatoes

Month	Stages	Kc	ETc (mm)	Peff (mm)	IRn (mm)
January	Initial	0.5	7.82	0	7.82
January	Initial	0.5	16.18	0	16.18
February	development	0.61	24.88	0	24.88
February	development	0.81	39.08	0	39.08
February	development	1.01	44.38	0	44.38
March	Bulb formation	1.1	52.11	0	52.11
March	Bulb formation	1.1	38.42	65.1	0
March	Bulb formation	1.1	41.93	9.8	32.13
April	Bulb formation	1.1	25.64	8.4	17.24
April	maturity	1.06	57.77	0	57.77
April	maturity	0.98	52.60	4.8	47.8
May	maturity	0.91	34.43	48	0
May	maturity	0.83	39.61	4	35.61
Total			474.85	140.1	375

4.4 Effects of Deficit Irrigation on Crop Parameters: Onion and Tomato

4.4.1 Effects of deficit irrigation on onion leaves

The results showed that the number of leaves per plant varied significantly among the different treatments and growth stages. Treatment 1 (T1) had the highest number of leaves per plant at all four stages, while treatment 3 (T3) had the lowest number of leaves per plant at the bulb formation and maturity stages. At the initial and developmental stages, T1, T4, and T6 had significantly greater number of leaves per plant compared to T2, T3, and T5. However, at the bulb formation and maturity stages, T1 and T4 had significantly higher numbers of leaves per plant compared to T2, T3, T5 and T6.

These results suggest that deficit irrigation has a significant effect on the number of leaves per plant in onion production. The highest number of leaves per plant was observed in treatments with less water stress (T1, T4, and T6), while the lowest number of leaves per plant was observed in treatments with more water stress (T2 and T3). Several studies have reported that deficit irrigation can reduce the number of leaves per plant in onion production. Metwally (2011) reported that water stress during the vegetative stage of onion growth reduced the number of leaves per plant. These results are in line with the findings of Bizuneh (2019), who reported that the highest growth components of onions were recorded from non-water stress and the lowest leaves were recorded from high-stress treatment. These results agreed with those of Biswas *et al*. (2017), who stated that an increasing number of leaves per plant was recorded in higher-regime irrigated treatments.

Table 4.7 Average leaf number per plant of onion at the end of each growth phase

Treatment	Initial	Developmental	Bulb formation	Maturity
T1	3.97^{a}	7.20 ^{a}	11.47 ^{a}	11.53 ^{a}
T2	3.7^{ab}	6.93 ^{a}	10.67 ^{b}	10.30 ^{b}
T3	3.43^{b}	6.0 ^{b}	7.53^{d}	7.93^{c}
T4	3.9^{a}	7.13 ^{a}	11.13 ^{a}	10.37 ^{b}
T5	3.47^{b}	6.87 ^{a}	8.73 ^{c}	9.90 ^{b}
T6	3.93^{a}	7.00 ^{a}	7.87 ^{d}	8.03 ^{c}
LSD (0.05)	0.35	0.52	0.39	0.47
CV	5.20	4.18	2.26	2.71

4.4.2 Effect of deficit irrigation on the plant height of onions

The plant height measured at the end of the initial stage was statistically comparable to treatments T1 except T3 and T5. The optimum height was obtained from full irrigation treatment, as presented in Table 4.8. However, significantly shorter plant heights were observed from treatments T3 and T5, which received 50% ETc at the initial stage.

By the end of the developmental stage, the plant in treatment T1 revealed the greatest height, with no significant difference as compared to T6. In contrast, the shortest plant height was recorded in T3, where 50% ETc was applied during both the initial and developmental stages.

The plant height measurement conducted at the end of the bulb formation stage revealed that the tallest plant, measuring 59.40 cm, was observed in T4. In T4, the irrigation regime involved 75% ETc during both the initial and maturity stages, along with full irrigation (100% ETc) during both the development and bulb formation phases. In contrast, onion plants subjected to 75% ETc during the developmental stage and 50% ETc during the bulb formation stage, as seen in T6 and T3 (both receiving 50% ETc throughout all stages), displayed shorter plant heights, particularly during the bulb formation stage.

Upon reaching the maturity stage, the tallest plants were found in the treatment (T1) that received full water irrigation levels consistently throughout the entire growth season. The plant heights of both T1 and T4 indicated no significant differences. Conversely, the shortest plants were observed in treatments (T3 and T6) that received 50% ETc at all stages, with no significant difference in plant heights between T3 and T6.

The obtained results were in line with Singh (2018), who reported that decreasing deficit levels (stresses) increased plant height. The obtained results align with the research by Kebede (2003), which noted a decrease in onion plant height when exposed to water deficits during the vegetative and bulb formation stages. Similarly, Metwally (2011) found that increased water supply led to enhanced vegetative parameters, while Al-Moshileh (2007) reported that higher soil water supply resulted in significant increases in plant height, the number of green leaves, and bulb diameter.

Table 4.8 The effect of deficit irrigation on onion plant height at the end of each growth stage

Treatment	Initial (cm)	Development (cm)	Bulb formation (cm)	Maturity (cm)
T1	21.29^{a}	39.07^{a}	59.33^{ab}	59.63^{a}
T2	20.72^{a}	37.87^{abc}	56.93^{ab}	56.77^{ab}
T3	18.05^{b}	36.90^{c}	50.23^{c}	40.63^{c}
T4	20.56^{a}	38.83^{ab}	59.40^{a}	58.87^{a}
T5	18.30^{b}	37.37^{bc}	56.67^{b}	52.80^{b}
T6	20.99^{a}	38.97^{a}	52.57^{c}	42.17^{c}
LSD(0.05)	0.92	1.53	2.67	4.09
CV	2.54	2.21	2.63	4.34

4.4.3 Effect of deficit irrigation on onion yield and yield components

The effect of reduced irrigation levels on onion plant yield and its components are presented in Table 4.9.

4.4.3.1 Effect of deficit irrigation on onion bulb yield

The greatest yield of marketable bulbs, reaching 59.67 tons/ha, was achieved in the control treatment and did not reveal any significant variation when compared to T4. This indicates that a 25% reduction in irrigation levels had no significant impact when applied across various combinations of growth stages, except during the bulb formation stage.

The marketable lowest yield, amounting to 31.23 tons/ha, was achieved in T3, where 50% ETc was applied across all growth stages. This was followed by a yield of 38.70 tons/ha in T6, where 50% ETc was applied during the bulb formation stage and 75% ETc at the developmental stage.

This indicates that the most significant yield reduction occurred when stress was applied during the bulb formation stage. Therefore, it was noted that the bulb formation stage was observed to have the highest susceptibility to water stress. Moreover, deficit irrigation applied during the bulb formation stage resulted in a lower yield compared to other stages. These findings align with Bazza (1999), demonstrating that subjecting the crop to stress during the third growth stage led to a more substantial yield reduction than stress applied during any other stage. Table 4.9 illustrates a linear relationship between the irrigation water quantity applied and the marketable onion yield. These results agreed with those of Temesgen (2018), who stated that the minimum yield was recorded at 50% ETC. These results are in line with the findings of Piri and Naserin (2020), who reported that onion yield was reduced by reducing the amount of irrigation water. This result is in line with the result of Bizuneh (2019), who stated that the marketable bulb yield from non-stressed treatments was the highest, while the most stressed treatment had the lowest marketable bulb yield of onion. Dirirsa *et al*. (2017) also reported that maximum and minimum onion bulb yields were obtained from 100% and 50% ETC with the maximum and minimum water applications, respectively. The onion yield increases with an increase in irrigation level (Kahlon, 2017).

4.4.3.2 Effect of deficit irrigation on onion bulb diameter and length

As shown in Table 4.9, the bulb diameters of T1 were significantly different from the other treatments (5.65cm), whereas the smallest bulb diameter, measuring 4.43 cm, was observed in T3, which was inferior to all other treatments. This implies that the application of a 75% and 50% deficit level at either the initial or maturity stages gave comparable bulb diameter.

The results showed that the bulb lengths of Treatment (T1) and Treatment (T4) were not significantly different from each other, despite T1 having the longest bulb length (5.35 cm). On the other hand, Treatment (T2), Treatment (T5), and Treatment (T6) had significantly different bulb lengths from each other. Notably, T3 had the shortest bulb length (4.43 cm) among all treatments, indicating that applying a 75% deficit level during either the initial or maturity stages resulted in comparable bulb diameters.

However, the 75% and 50% deficit levels applied at the bulb formation stage resulted in significantly smaller bulb diameters than the control treatment. The result also showed the effect of deficit irrigation application at all stages on reducing the bulb size of onions, particularly at the 50% deficit level. These results agreed with Abdelkhalik *et al*. (2020), who reported that irrigation amount had an effect on plant growth and quality parameters.

These findings are consistent with the study conducted by Diribsa *et al*. (2017), which found that treatments receiving the highest water supply resulted in the largest bulb diameter components, whereas treatments receiving the lowest water supply produced the smallest average bulb diameter. Similarly, David *et al.* (2016) concluded that bulb size showed a proportional variation with the quantity of irrigation water applied, with the largest bulbs obtained from 100% ETc and the smallest from 50% ETc treatments.

4.4.3.3 Effect of deficit irrigation on onion dry matter

As shown in Table 4.9, the highest dry matter content was observed in T1, and there were no statistically significant differences between T4 and T5. Conversely, the lowest dry matter content was obtained from T3, and it was lower than all the other treatments. This outcome indicates that applying deficit irrigation levels of 75% and 50% during both the initial and maturity stages, as well as their combinations, except during the bulb formation stage, yielded similar results to the control treatment. In general, treatments characterized by greater deficit levels led to decreased dry matter content, while treatments with lower deficit levels exhibited higher dry matter content. These findings are consistent with the conclusions of Sorensen and Grevsen (2001), who determined that water deficits lead to reduced dry matter in onions.

Table 4.9 Effects of deficit irrigation on onion crop yield and components

Treatment	Bulb diameter	Bulb length	Marketable yield (ton/ha)	Dry matter (ton/ha)
T1	5.65^{a}	5.35^{a}	59.67^{a}	5.75^{a}
T2	5.05^{bc}	4.76^{ab}	45.17^{c}	5.10^{b}
T3	4.43^{d}	4.53^{b}	31.23^{e}	4.30^{c}
T4	5.46^{ab}	5.31^{a}	59.30^{a}	5.80^{a}
T5	5.33^{abc}	5.08^{ab}	53.40^{b}	5.65^{a}
T6	5.01^{c}	4.87^{ab}	38.70^{d}	4.85^{b}
LSD(0.05)	0.41	0.69	4.39	0.40
CV	4.39	7.62	5.04	4.22

4.4.4 Effect of deficit irrigation on the yield component of tomatoes

The analysis of variance showed that no significant difference was observed between treatments in fruit diameter and length of tomato at all deficit irrigation levels, as shown by Table 4.10. Even when the maximum amount of water was applied, a reasonable tomato fruit size was obtained. The highest tomato fruit diameter was obtained from the control treatment at 3.70 cm and the lowest from T3, which received 50% ETc at all growth stages at 3.56 cm. As the result showed in Table 4.6, the full irrigation treatment (100% ETc) had the highest fruit length of 5.81 cm, which is not significantly different from other treatments, and the lowest fruit length value was obtained from T3, which received 50% of the deficit levels at all growth stages. This may be attributed to the use of tomato canopy covers as mulch. The results were in line with the findings of Bekele (2017), who reported that deficit levels have no significant effect on plant and fruit height.

There were no significant differences between T1, T4, and T5, but the highest yield of tomato from T1 (100% ETc) was 48.71 tons/ha, followed by 47.96 tons/ha and 47.78 tons/ha. This indicated that treatments that received 25% and 50% of the deficit level at the initial and maturity stages had a comparable yield to full irrigation treatments. The lowest yield was obtained from treatment three (T3) of 39.94 tons/ha, which received 50% of the deficit level as presented in table 4.10. This result agreed with the Kere *et al*. (2003), who found that the yield attributes of tomatoes were not significantly affected by either irrigation amount. The results agree with the findings of Al-Selwey *et al*. (2023) and Ikram Ullah *et al*. (2022) that indicated deficit irrigation reduced the total yield of tomatoes, but the extent of the reduction varied depending on the severity of the water stress.

The results of the dry matter of the tomato indicated that there were significant differences between each treatment except treatment (T3). The result indicated that the high application of water stress affects the dry matter of the tomato. The result was in line with the finding of Mohamad (2019), who reported that treatment that received 50% ETc resulted in a 5% decrease in dry matter of tomato compared to the control treatment.

Table 4. 10 Effect of deficit irrigation on tomato yield components

Treatment	Fruit diameter	Fruit length	Marketable yield (ton/ha)	Dry matter (ton/ha)
T1	3.70[a]	5.81[a]	48.71[a]	8.00 [a]
T2	3.64[a]	5.76[a]	46.04[b]	7.53[a]
T3	3.56[a]	5.67[a]	39.94[c]	6.23[b]
T4	3.68[a]	5.77 [a]	47.96 [a]	7.51 [a]
T5	3.61[a]	5.68[a]	47.78[a]	7.47 [a]
T6	3.67[a]	5.70 [a]	45.16[b]	7.38[a]
LSD(0.05)	0.63	0.14	0.39	1.68
CV	2.18	3.77	2.01	4.73

4.5 Calibration and Validation of the AquaCrop Model

Before running the model, the input data files containing the plant, irrigation, and soil information for the specific crop growth season were first created. In order to get the best matching between observed and simulated output, the model was calibrated by modifying a few of its parameters. The model has been calibrated based on the measured crop data from treatments that were not subjected to water stress. Because of its ability to accurately simulate crop growth and water use under optimal water conditions, AquaCrop is calibrated for full irrigation treatments. This enables the evaluation of the impact of various irrigation regimes and management practices on crop yield and water use efficiency. Overall, using AquaCrop to simulate full irrigation treatments provides valuable insights into the optimal management of cropping systems, leading to improved productivity and sustainability.

4.5.1 Calibration of the AquaCrop model to simulate onion

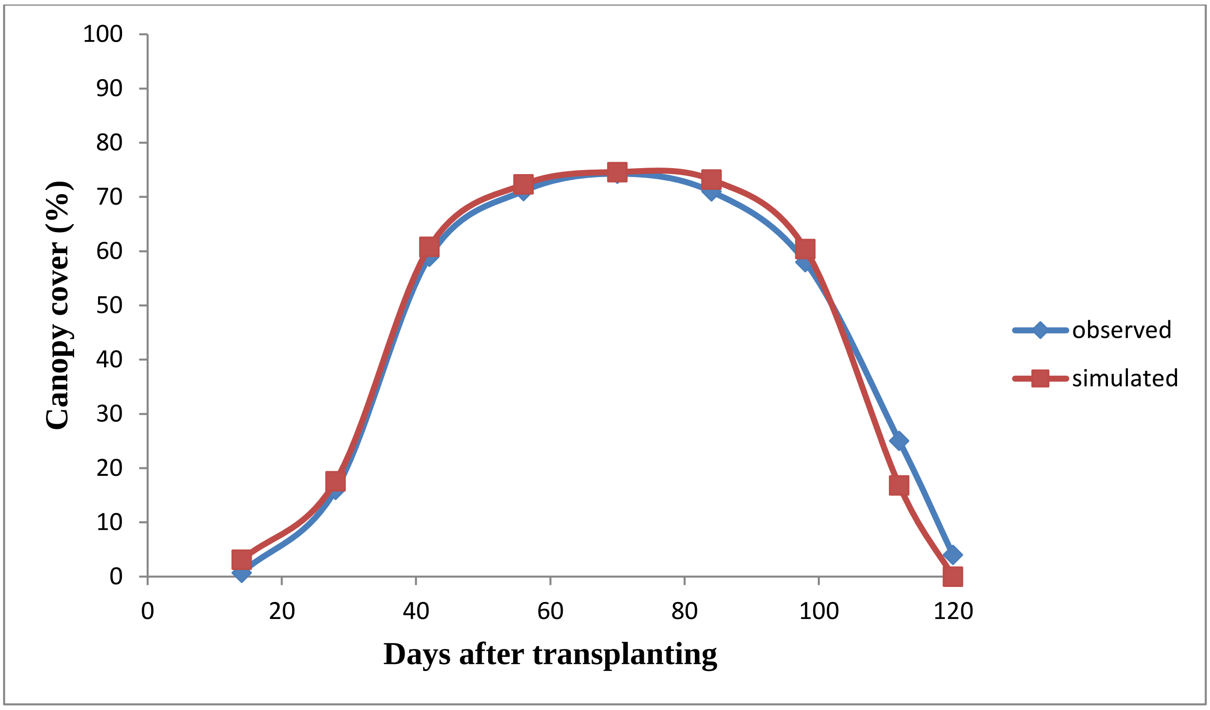
The crop model parameters used to calibrate and validate the AquaCrop model in this study are presented in Table 4.11. During calibration, some of the crop parameters were modified: time to emergence, initial canopy cover, time to reach maximum canopy cover, time to reach flowering and effective root depth.

Table 4.11The onion crop parameters derived following the calibration process

Description	Value	Unit
Plant Density	16.7	Plant/m^2
Time to emergence	9	Days
Initial Canopy cover	0.71	%
Maximum canopy cover	75	%
Time to reach maximum canopy cover	70	Days
Time to start senescence	80	Days
Time to reach flowering	66	Days
Time from transplanting to reach maturity	120	Days
Maximum effective root depth	35	cm
Time from transplanting to maximum root depth	80	Days
Duration of flowering	19	Days
Reference harvest index	80	%
Crop water productivity- normalized for climate and [CO2]	0.17	Ton/ha
The threshold temperature for crop development-Base	10	^{0}C
The threshold temperature for crop development- Upper	30	^{0}C

4.5.1.1 Onion Green Canopy Cover

Figure 4.1 shows the calibration results for the model from the complete irrigation treatment on the canopy cover. Statistical analysis methods were used to compare the actual canopy cover with the simulated canopy cover for the full irrigation treatment (100% ETc), as shown in Table 4.13. The model's simulation of the canopy cover demonstrated a good fit, with person correlation coefficient (r) of 1, root mean square error (RMSE) of 2.5 tons/ha, normalized root mean square error (NRMSE) of 5%, Nash-Sutcliffe efficiency (EF) of 0.99, and index of agreement (d) values equal to 1.



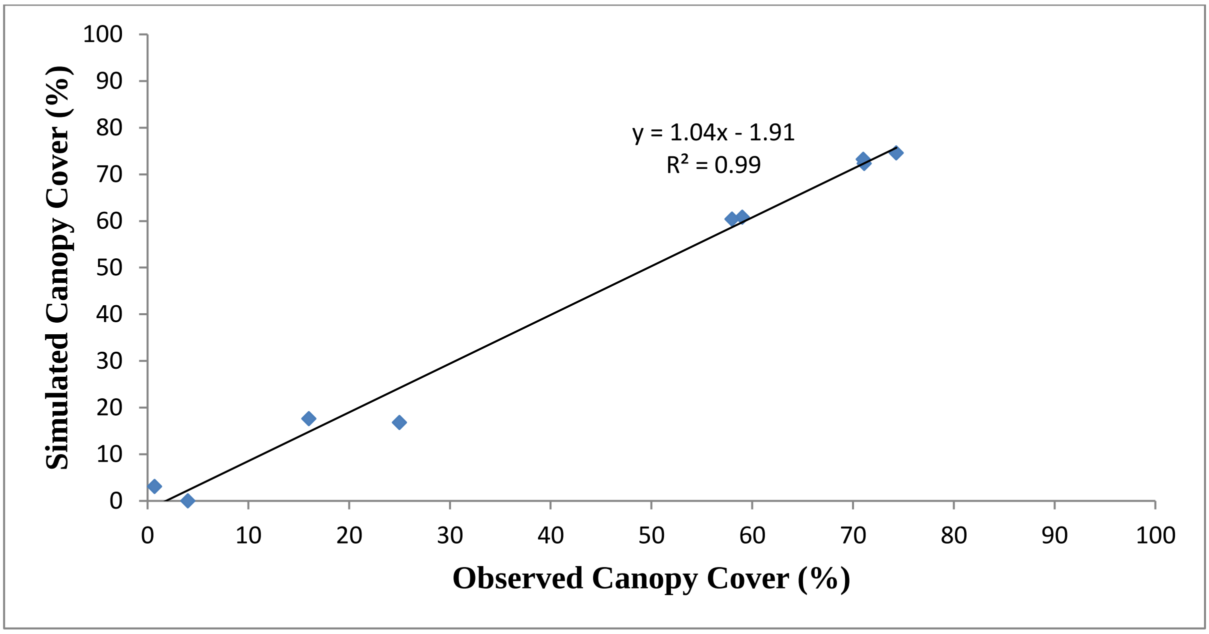
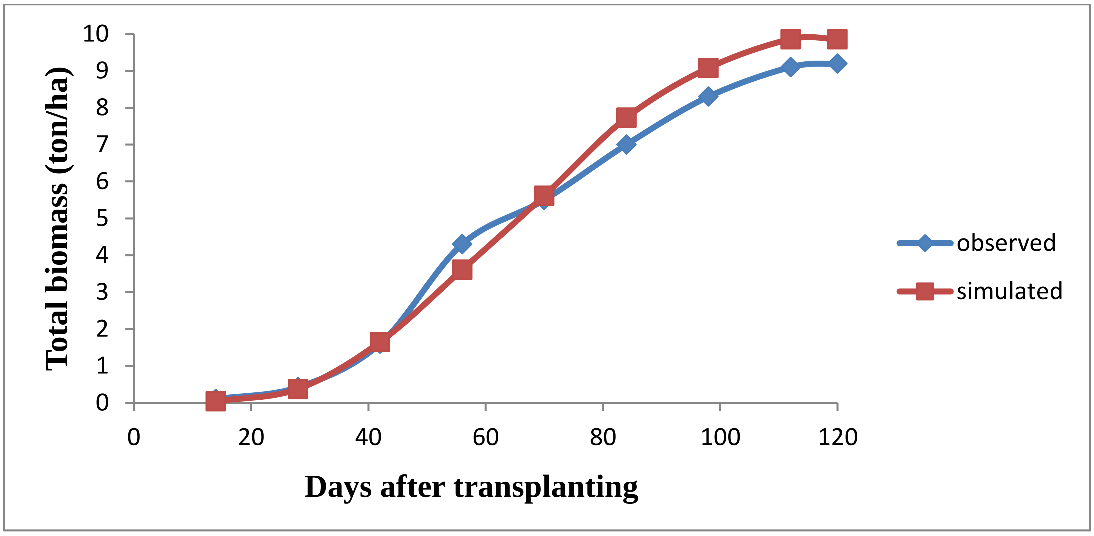


Figure 4.1 Measured and simulated data for onion crop canopy cover during the calibration process

4.5.1.2 Total biomass

The total biomass of onions was calculated by combining the above-ground biomass and the bulb or underground biomass of the onion plant. These observations were collected two weeks after transplanting. The development of both measured and simulated total biomass throughout the crop growth seasons is illustrated in Figure 4.2. As indicated by the statistical indices provided in Table 4.13, the measured and simulated values for the calibration treatment generally indicate a strong agreement with observed and simulated.



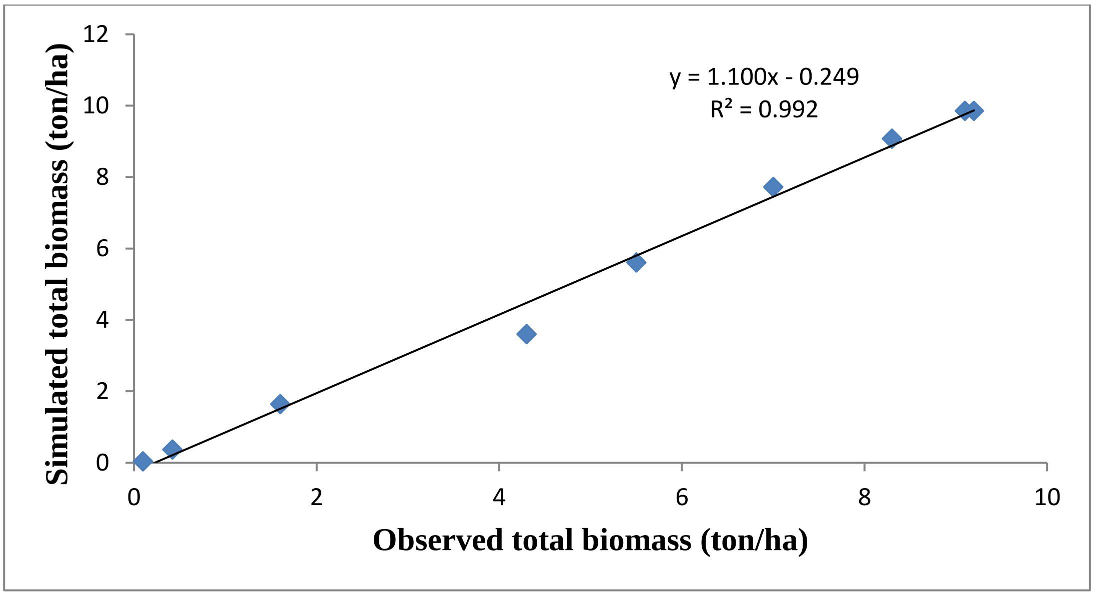


Figure 4.2 Measured and simulated data for onion crop biomass during the calibration process

4.5.2.3 Yield

The yield was measured from the field at the end of the season after harvesting. The simulated yield and biomass outputs under full irrigation were found to be reasonably similar to the data when the model was run during calibration. As indicated in table 4.12, the measured yield and simulated yield were 5.75 and 5.98 tons/ha, respectively, and the measured biomass and simulated biomass were 9.72 and 9.86 tons/ha, respectively.

Table 4.12 Measured and Simulated Dry Yield and Biomass Results for Calibrated of Onion

Treatment	Dry yield (ton/ha)		Total biomass (ton/ha)	
	observed	simulated	observed	simulated
T1	5.75	5.98	9.72	9.86

Table 4.13 Statistical indicator for AquaCrop-simulated results in the calibration dataset for onions

Statistics	Biomass	Canopy cover
r	1	0.99
RMSE (ton/ha)	0.5	3.4
NRMSE (%)	10.7	8.2
EF	0.98	0.99
d	0.99	1

4.5.2 Calibration of the AquaCrop model to simulate tomato

During calibration crop parameters were adjusted: those are initial canopy cover, time to reach maximum canopy cover, duration of flowering, and time to start senescence.

Table 4.14 The calibrated crop parameters for tomato crops

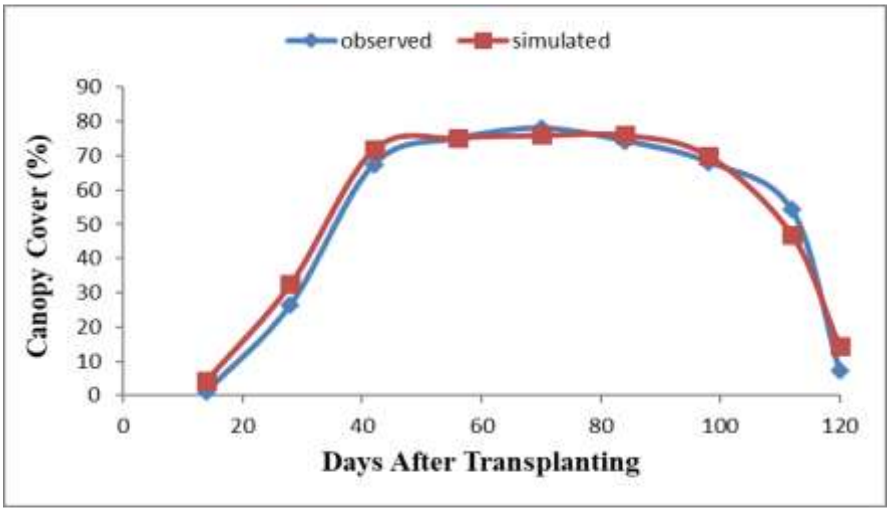
Description	Value	Unit
Plant Density	6	Plant/m^2
Time to emergence	8	Days
Initial Canopy cover	1.2	%
Maximum canopy cover	80	%
Time to reach maximum canopy cover	70	Days
Time to start senescence	80	Days
Time to reach flowering	38	Days
Time from transplanting to reach maturity	120	Days
Maximum effective root depth	0.71	cm
Time from transplanting to maximum root depth	70	Days
Duration of flowering	42	Days
Reference harvest index	58	%
Crop water productivity- normalized for climate and [CO2]	17.0	g/m2
The threshold temperature for crop development-Base	10	^{0}C

The threshold temperature for crop development- Upper	30	^0C

4.5.2.1 Tomato green canopy cover

The AquaCrop model demonstrated effective performance in simulating canopy cover, as confirmed by the statistical indicators 'r,' 'RMSE,' 'NRMSE,' 'EF,' and 'D' presented in Figure 4.3 and Table 4.16. These results align with the findings of Adeboye et al. (2017), who reported a strong correspondence between observed and simulated canopy cover, supported by Willmott's Index of Agreement (0.95), Nash-Sutcliffe Efficiency (0.81), and a Pearson correlation coefficient value of 0.91. These values collectively indicate the model's proficiency in predicting canopy cover accurately.

The performance indicators further underscore that the calibrated canopy cover for the full irrigation treatment fell within a favorable range. The AquaCrop model's simulation of canopy cover exhibited excellent agreement with the actual canopy cover observed during the calibration treatment.



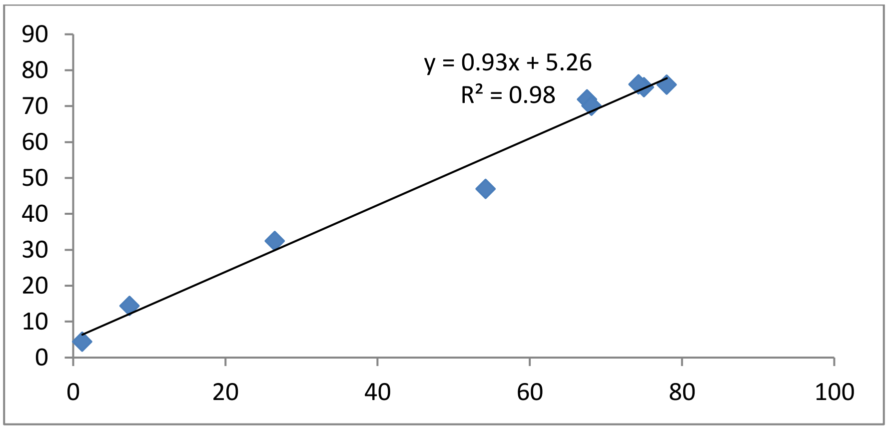


Figure 4.3 Observed and modeled tomato crop canopy cover values in the calibration treatment

4.5.2.2 Above-ground biomass

The progression of both observed and modeled aboveground biomass over the course of the crop-growing season is depicted in Figure 4.4, with observations conducted at two-week intervals following crop establishment. In general, there's a strong match between the observed and simulated values in the calibration treatment, as shown in Table 4.16.

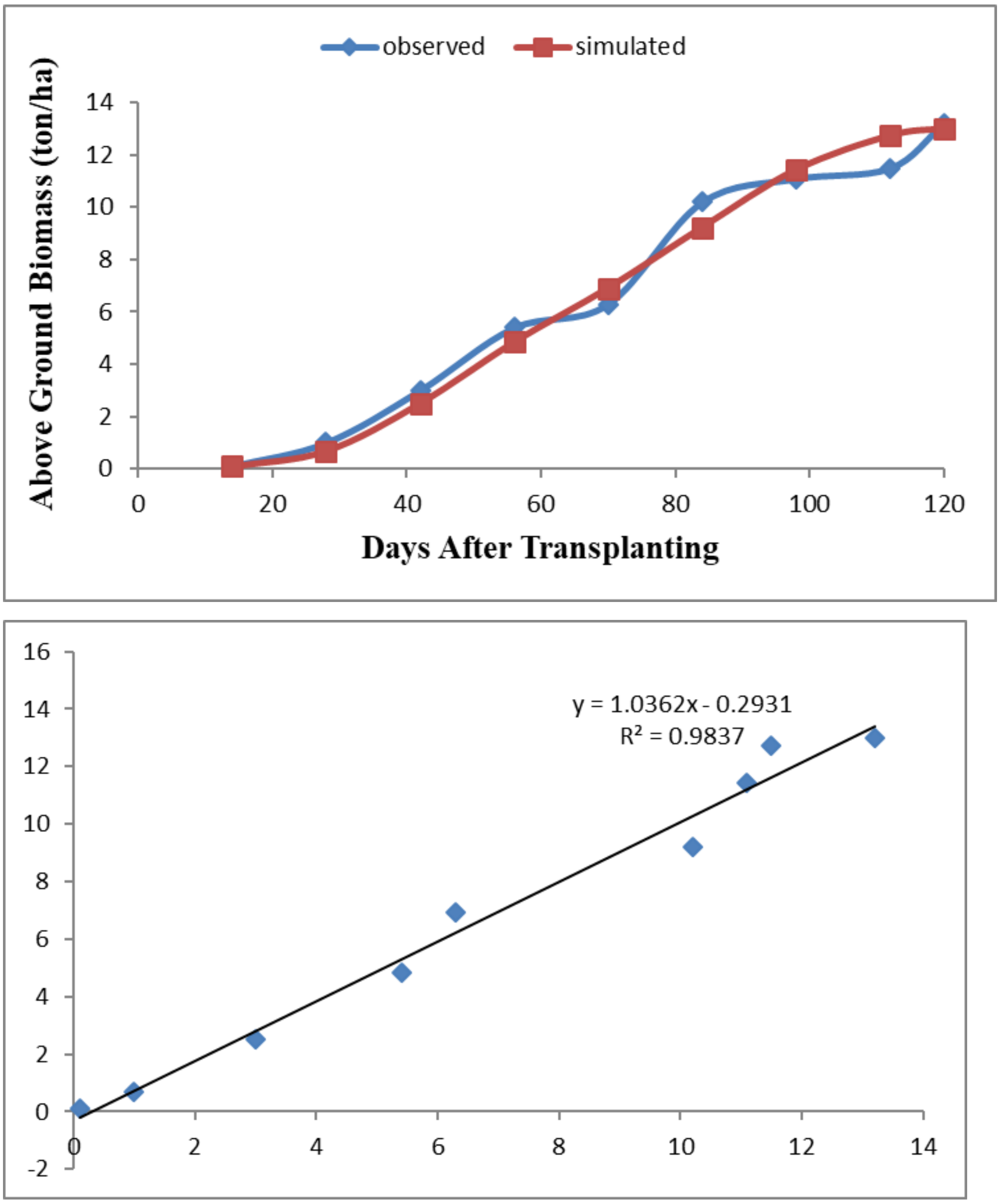


Figure 4.4 Observed and simulated above-ground biomass values for the tomato crop in the calibration treatment

4.5.2.3 Yield

The yield data was collected from the field after harvesting. The simulated yield and biomass outputs under full irrigation were found to be in good agreement with the data when the model was run during calibration. As indicated in Table 4.15, the measured yield was 5.75 tons/ha and the simulated yield was 5.98 tons/ha. The measured biomass was 13.2 tons per hectare, and the simulated biomass was 13 tons per hectare. Generally, the model simulates the yield well.

Table 4.15 Measured and simulated dry yield and biomass results for calibrated tomato crops.

Treatment	Dry yield (tons/ha)		Total biomass (tons/ha)	
	Observed	Simulated	Observed	Simulated
T1	8	7.56	13.2	13

Table 4.16 Statistical indicator for AquaCrop-simulated calibration data of tomatoes

Statistics	Biomass	Canopy cover
r	0.97	0.99
RMSE (ton/ha)	0.6	4.4
NRMSE (%)	9.2	8.8
EF	0.98	0.98
d	1	0.99

4.5.3 Validation of the AquaCrop Model to Simulate Onions

The AquaCrop validation was performed with a calibration model and data from the field observation that was not used for the calibration. In the process of model validation, the measured yield and biomass of all treatments except T1, were compared against the model's simulated results separately for each treatment. The model was validated using the adjusted crop parameters outlined in Table 4.11. The results of this validation study demonstrate that the model effectively simulates yield and biomass outcomes for treatments experiencing water stress.

4.5.3.1 Model performance evaluation for final total biomass

Figure 4.5 shows that the model successfully simulated biomass, and the statistical indicators (r, RMSE in tons/ha, NRMSE in%, EF, and d) had values which are considered acceptable for all treatment but model slightly underestimate T3. These results are consistent with a study by Marjan et al. (2022) that found the model's biomass predictions to be generally accurate, except for the 50% ET treatment, where RMSE was 0.335 and the d-index was 0.995. Overall, these results underscore the model's commendable performance and reliability.

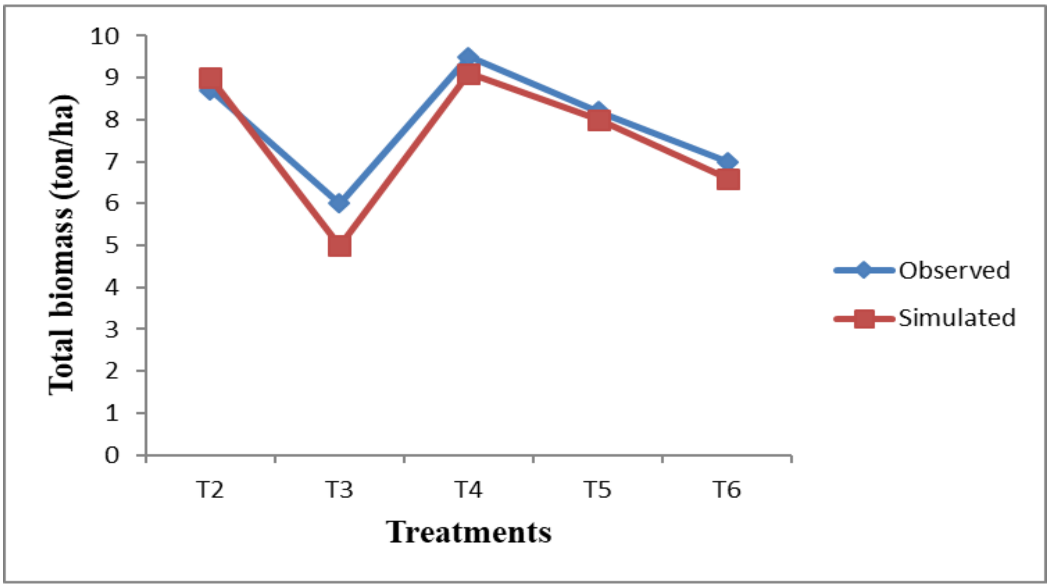


Figure 4.5 Evaluation of Model Performance for Onion's Final Biomass

4.5.3.2 Model performance evaluation for final dry yield

The model's accuracy can be evaluated through the examination of metrics such as the person correlation coefficient (r), root mean square error (RMSE), normalized root mean square error (NRMSE), Nash-Sutcliffe efficiency coefficient (EF), and Willmott index of agreement (d). The closer these values are to 1, the higher the model's accuracy. A value of 0 for RMSE indicates a perfect fit between the simulated and observed data.

In this study, the model yielded values of 'r', 'EF' and 'd' ranges between 0.94 to 1. These values, nearing 1, signify a high level of accuracy in the model's performance. Comparable results have been reported in previous studies as well. Similar findings have been reported by other studies. The findings align with Agbemabiese's (2015) research, which reported an RMSE of 0.09, a Willmott's modified index of 0.99, and a Nash-Sutcliffe efficiency of 0.96 while simulating onion yields under various irrigation regimes in Ghana. Similarly, Kiptumet et al. (2013) observed an RMSE value of 0.38 when simulating cabbage biomass in Kenya. Thus, the model employed in this study demonstrates a high degree of accuracy, as evidenced by the strong values of the person correlation coefficient, RMSE, NRMSE, EF, and d. The model in this study had high accuracy, as indicated by the values of r, RMSE, NRMSE, EF, and d.

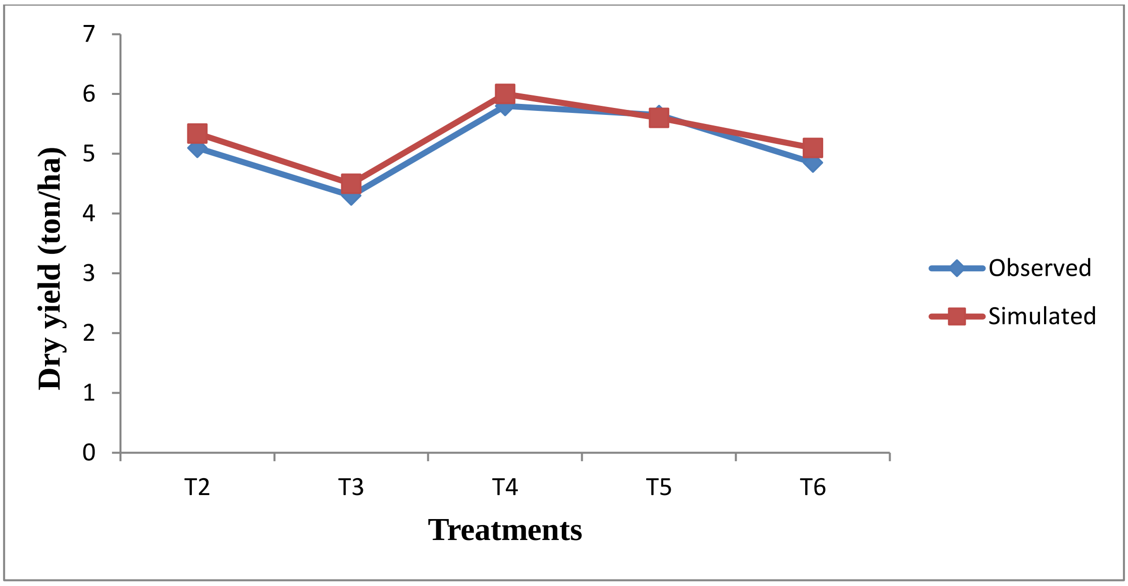


Figure 4.6 Model Performance evaluation for dry yield of onion

Table 4.17 Measured and simulated dry yield and biomass data for onion crop validation

Treatments	Total biomass (tons/ha)		Dry Yield (tons/ha)	
	Observed	Simulated	Observed	Simulated
T2	8.7	9	5.1	5.34
T3	6	5	4.3	4.5
T4	9.5	9.1	5.8	6
T5	8.2	8	5.65	5.6
T6	7	6.6	4.85	5.1

Table 4.18 Statistical indicators for onion validation dataset via AquaCrop simulations

Treatments	Statistics	Total Biomass (tons/ha)	Dry Yield (tons/ha)
T2	r	0.96	0.97
	RMSE (ton/ha)	2.2	0.6
	NRMSE (%)	7.9	3.2
	EF	0.96	0.96
	d	0.97	0.98
T3	r	0.94	0.99
	RMSE (ton/ha)	3.5	0.62
	NRMSE (%)	10.1	4.10
	EF	0.95	0.97
	d	0.96	0.98

T4	r	0.97	0.99
	RMSE (ton/ha)	1.9	0.53
	NRMSE (%)	6.7	2.89
	EF	0.97	0.98
	d	0.98	0.97
T5	r	0.96	1.00
	RMSE (ton/ha)	1.2	0.33
	NRMSE (%)	6.4	1.50
	EF	0.98	0.98
	d	0.96	0.99
T6	r	0.95	0.94
	RMSE (ton/ha)	2.0	0.81
	NRMSE (%)	7.2	4.30
	EF	0.96	0.97
	d	0.97	0.95

4.5.4 Validation of AquaCrop Model for Tomato Simulation

To validate the AquaCrop model, the model's simulated yield and biomass for all treatments were compared against the measured yield and biomass obtained from field observations that were not employed during the calibration process separately for each treatment. The model's validation utilized the adjusted crop parameters presented in Table 4.14, and the outcomes indicated that the model effectively simulated yield and biomass for treatments experiencing water stress.

4.5.4.1 Model performance evaluation for final above-ground biomass

The AquaCrop model effectively simulated aboveground biomass for all treatments, except for treatment three, which received half the irrigation amount of the full irrigation treatment. For treatment three (T3), the model showed a slight overestimation, but the statistical indicators values, for ‘r’, EF, and ‘d’, ranges between 0.94 to 1, and for RMSE range between 0.40 tons/ha to 0.92 tons/ha, and for NRMSE between 5.6% to 10.5% respectively. These values indicated the model's good accuracy in simulating aboveground biomass.

The validation dataset for biomass demonstrated a Willmott’s index of agreement of 0.94 to 1, emphasizing a strong and favorable agreement between the simulated and observed data. Additionally, a Nash-Sutcliffe efficiency of 0.96 to 0.99 and a person correlation coefficient of 0.95 to 0.99 provided further evidence of the robust agreement between the simulated and measured data. In a similar study conducted by Adeboye et al. (2017), the simulated above-ground biomass exhibited a significant correlation with the measured data of the person correlation coefficient of 0.92 and had an RMSE of 0.36 tons/ha.

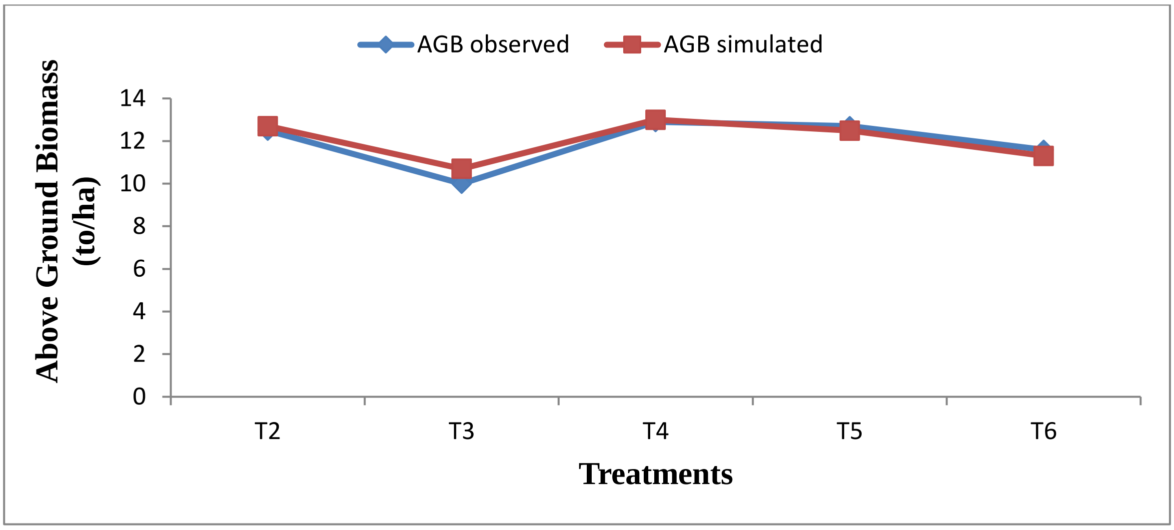


Figure 4.7 Model performance evaluation for above-ground biomass of tomatoes

4.5.4.2 Model performance evaluation for final dry yield

The model effectively simulated the dry yield of tomatoes within acceptable performance ranges, as indicated in Table 4.20. These results are in line with those observed by Sandor et al. (2021), who found the model's predictions for tomato yield to be highly accurate based on evaluation criteria, including an NRMSE of 3.6%, an EF of 0.99, and a d-index of 0.99. Overall, the AquaCrop model performed effectively in simulating both biomass and yield, supported by statistical measures such as 'r,' 'd,' and 'EF.'

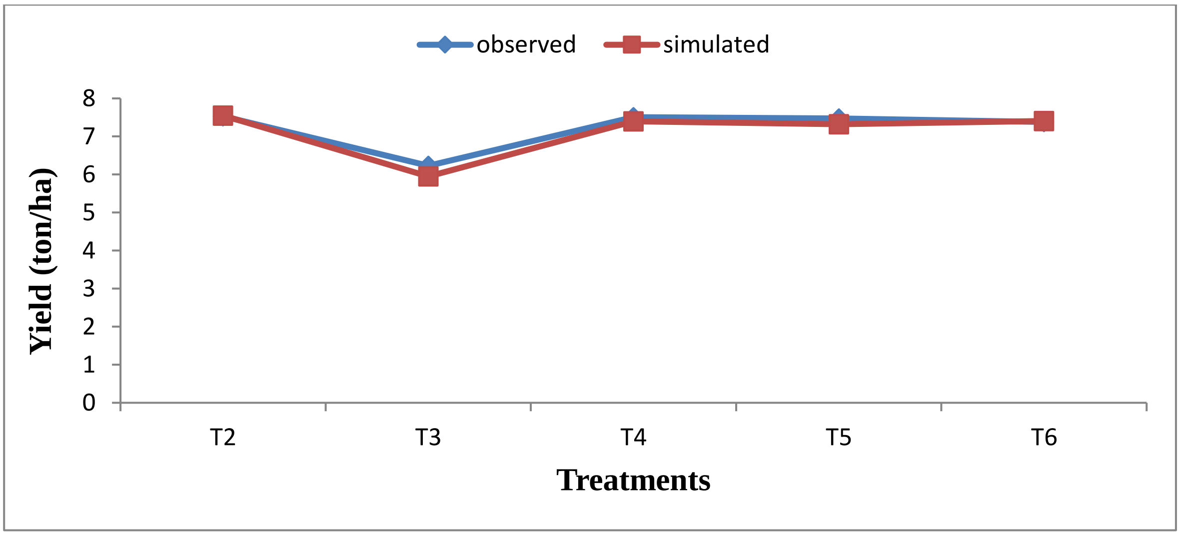


Figure 4.8 Model Performance evaluation for Dry yield of tomato

Table 4.19 Measured and simulated dry yield and biomass data for tomato crop validation

Treatments	Total biomass (tons/ha)		Dry Yield (tons/ha)	
	Observed	Simulated	Observed	Simulated
T2	12.5	12.7	7.53	7.55
T3	10	10.7	6.23	5.95
T4	12.9	13	7.51	7.4
T5	12.7	12.5	7.47	7.32
T6	11.6	11.3	7.38	7.41

Table 4.20 Statistical indicators for tomato validation dataset via AquaCrop simulations

Treatments	Statistics	Total Biomass (tons/ha)	Dry Yield (tons/ha)
T2	r	0.97	0.99
	RMSE (ton/ha)	0.75	0.54
	NRMSE (%)	8.00	3.20
	EF	0.98	0.99
	d	0.99	0.99
T3	r	0.95	0.96
	RMSE (ton/ha)	0.92	0.80
	NRMSE (%)	10.50	4.70
	EF	0.96	0.97
	d	0.94	0.96
T4	r	0.99	0.99
	RMSE (ton/ha)	0.4	0.50
	NRMSE (%)	5.6	4.30
	EF	0.98	0.98
	d	1	0.98
T5	r	0.98	0.98
	RMSE (ton/ha)	0.69	0.47
	NRMSE (%)	6.10	4.20
	EF	0.99	0.98
	d	1	0.98
T6	r	0.97	0.99
	RMSE (ton/ha)	0.71	0.42
	NRMSE (%)	0.72	3.90
	EF	0.98	0.99
	d	0.99	0.99

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The adoption of deficit irrigation practices represents a significant approach to efficient water management in agriculture, primarily aimed at conserving water and enhancing water productivity by reducing water consumption. By intentionally maintaining soil moisture levels below the optimal range during specific growth phases of the crop cycle, farmers can make more efficient use of their limited water resources, ultimately increasing water productivity. Nevertheless, it is essential to validate these technologies across various crop types, crop varieties, and local environmental conditions. In the current study, deficit irrigation was applied to onions and tomatoes during specific growth stages under Melkassa conditions.

The study reveals that applying deficit irrigation at various growth stages of onion and tomato has a substantial impact on yield and biomass. The highest yields, reaching 5.75 tons per hectare and 8 tons per hectare, were achieved when providing 100% of the crop's evapotranspiration needs (100% ETc) throughout the entire growing season for both onion and tomato, respectively. In contrast, the lowest yields of 4.30 tons per hectare and 6.23 tons per hectare were recorded when maintaining a consistent deficit irrigation rate of 50% ETc throughout the growing season for both onion and tomato, respectively. Notably, deficit irrigation accelerated the flowering and maturation phases compared to the control irrigation (100% ETc). Applying deficit irrigation at a level of up to 25% during the initial and maturity stages proved effective in conserving water without significantly compromising yield. However, reducing irrigation levels below 25% ETc during the flowering and bulb formation stages led to a substantial yield reduction.

The model calibration results for canopy cover and biomass demonstrated strong performance with several key indicators for onion. The model performed very well for onion biomass, showing excellent results with r = 1, RMSE = 0.5 tons/ha, NRMSE = 10.7%, EF = 0.98, and d = 0.99, which means it matched the data exceptionally well. Similarly, the model excelled in predicting onion canopy cover, achieving r = 0.99, RMSE = 3.4tons/ha, NRMSE = 8.2%, EF = 0.99, and d = 1, underscoring its well-fitted simulations. For tomato canopy cover and biomass, the model also delivered highly accurate results. The simulation for tomato canopy cover showed a strong fit with r = 0.99, RMSE = 4.4 tons/ha, NRMSE = 8.8%, EF = 0.98, and d = 0.99, while the biomass simulation displayed a well-fit with r = 0.97, RMSE = 0.6 tons/ha, NRMSE = 9.2%, EF = 0.98, and r = 1, respectively.

The validation results, comparing simulated outcomes with actual measurements, showed a strong agreement, especially for biomass and yield at different irrigation levels. Notably, a high degree of accuracy was achieved in the prediction of both biomass and yield under all irrigation scenarios. This field study indicated the crop's sensitivity to moisture stress during critical bulb and yield formation growth stages for both onions and tomatoes.

5.2 Recommendation

Based on the findings of this study, the following recommendations were made:

- This experiment was conducted at a single site for just one cropping season, utilizing a single variety, specifically Awash Melkassa Research Center local. This study did not factor in various field management aspects such as fertility stress, field surface practices, and weed control when assessing yield reduction. It is advisable to conduct similar research studies over multiple seasons, incorporating different varieties, optimizing fertility levels, and implementing comprehensive field crop management practices. Furthermore, it is crucial to consider the influence of disease and pest incidence on crop yields, as these factors can significantly affect overall productivity.
- The difference in yield between full irrigation and a 75% ETc irrigation approach is found to be insignificant during the initial, developmental, and maturity stages. Consequently, in scenarios of water scarcity and heightened water competition, it is advisable to adopt T4 of the 75 ETc% deficit irrigation strategy at the initial and maturity stages.
- The test crop under examination is onion and tomato; however, since other crops like wheat, maize, sorghum, and others are also extensively cultivated in the study area, it is recommended to explore deficit irrigation strategies tailored to growth stages and varieties for these crops as well.
- This study found that applying 50% and 75% of the recommended irrigation levels during the bulb and fruit stages resulted in greater yield reductions compared to the non-water stress treatment. Hence, the bulb and fruit formation stages are identified as the most susceptible to these levels of deficit. Therefore, future research endeavors will explore deficit levels below 25% during the bulb and fruit formation stages to ascertain the point at which yield reduction becomes less significant.

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APPENDIX

Appendix Table

Table 1:Monthly climatic data averaged over the study period

Month	RF (mm)	Tmax (^{0}C)	Tmin(^{0}C)	RH (%)	WS (m/s)	SSH (hr)	ETo (mm/day)
December	0	10.325	28.5	64.21	2.945	8.155	4.11
January	0.85	11.60	28.40	83.50	2.53	9.64	4.30
February	0	9.38	29.84	82.71	2.86	9.54	4.64
March	5.35	14.08	28.69	73.68	2.21	5.77	4.05
May	5.09	14.33	29.28	63.98	1.74	8.42	4.95
April	3.98	14.42	28.75	69.83	1.53	7.16	4.45
Mean	2.55	12.36	28.91	72.99	2.30	8.11	4.42

Table 2:Daily climate conditions and ETo (Evapotranspiration) data for the month ofDecember as observed at the Awash Melkassa Research Center in 2022

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
4	0	11	27.5	60	3	10	21.9	3.45
5	0	10	28.5	65	3	10.2	22.1	3.56
6	0	10	30	59	2	9.7	21.4	3.45
7	0	9	31	53	2	9.8	21.6	3.41
8	0	19	31	64	3	10.2	22.1	3.95
9	0	5	29	65	2	10.3	22.2	3.44
10	0	4	31	62	2	10	21.8	3.43
11	0	4	31	65	3	9	20.4	3.29
12	0	4	31	65	3	9	20.4	3.28
13	0	10	29	63	2.7	10.1	21.9	4.89
14	0	11	29	65	2.2	10	21.7	4.63
15	0	13	29	68	3	10	21.7	4.83
16	0	13	28.5	69	3	9.8	21.5	4.69
17	0	9	28.5	62	2.4	10	21.7	4.71
18	0	9	28.5	58	2.6	9.3	20.8	4.83
19	0	9	27.5	61	2.6	10	21.7	4.71
20	0	7	27	56	2.2	8.1	19.1	4.32

21	0	4	27.5	67	2	9.1	20.5	4.19
22	0	4	30	58	1.5	5.9	16.1	3.86
23	0	8	30	69	1.6	8.3	19.4	4.1
24	0	9	29	61	1.7	8	19	4.15
25	0	11	29.5	62	2.4	7.4	18.2	4.46
26	0	14.5	30	65	1.8	7.9	18.9	4.24
27	0	12	31	60	4.3	1.5	10	4.8
28	0	13	28	73	2.5	6	16.3	3.78
29	0	14	26.5	67	2.3	7.2	17.9	3.96
30	0	14	26.5	67	2.7	7.6	18.5	4.16
31	0	11	27.5	66	2.6	8.5	19.8	4.39

Table 3:Daily climate conditions and ETo (Evapotranspiration) data for the month of January as observed at the Awash Melkassa Research Center in 2023

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
1	26.5	14	22.5	80	2.4	5	14.9	2.94
2	0	13	21.5	86	2.7	6.5	17	2.89
3	0	13	23.5	88	2.9	8.5	19.8	3.29
4	0	5	24	84	2.6	9.2	20.8	3.57
5	0	4	29.5	73	1.9	10.2	22.2	4.48
6	0	8	29	77	1.8	10.2	22.2	4.29
7	0	10	29	85	2.3	10.2	22.3	4.23
8	0	8	28.5	83	2.8	10.3	22.4	4.35
9	0	12	29.5	84	2.5	8.9	20.5	4.12
10	0	12	30	84	2.9	10	22.1	4.44
11	0	14	29.5	87	3.2	8.5	20	4.01
12	0	14	28.5	87	3.3	10.2	22.4	4.21
13	0	12	27	73	3.3	10.1	22.3	4.57
14	0	12	27.5	82	2.6	10	22.2	4.2
15	0	12	27.5	84	3	9.1	21	4.03
16	0	12	28.5	82	3	9.7	21.9	4.32
17	0	14	28.5	86	2.9	10.6	23.2	4.32
18	0	4	28.5	81	2.6	10.8	23.5	4.57

19	0	6	27.5	87	2.8	11.2	24.1	4.34
20	0	5	28	84	2.6	9.8	22.2	4.28
21	0	5	28.5	83	2.8	9.8	22.2	4.42
22	0	9	28	82	2.2	10	22.5	4.24
23	0	7	31	84	2.2	10	22.6	4.59
24	0	13	30	84	2.3	10	22.6	4.47
25	0	13	31	85	2.3	10	22.7	4.56
26	0	29.5	31.5	86	2.8	10	22.7	5.07
27	0	30.5	31.5	86	2.1	10	22.8	5.16
28	0	13	29	83	2.7	10	22.8	4.47
29	0	12	30	86	1.8	10	22.8	4.39
30	0	13.5	30.5	86	1.2	10	22.9	4.39
31	0	9	31.5	87	2	10	22.9	4.6

Table 4:Daily climate conditions and ETo (Evapotranspiration) data for the month of February as observed at the Awash Melkassa Research Center in 2023

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
1	0	4	31	85	1.8	10	23	4.6
2	0	7	29.5	84	2.7	10	23	4.62
3	0	8	30	85	2.4	10	23.1	4.58
4	0	9	30.5	80	2.7	10	23.1	4.84
5	0	11	29.5	82	2.2	10	23.2	4.55
6	0	7	29.5	83	2.6	10	23.2	4.65
7	0	6	30	88	2.5	10.2	23.6	4.63
8	0	5	30	82	2.8	10.2	23.6	4.9
9	0	14	28	86	3.1	10	23.4	4.38
10	0	12	31	83	3.1	10.2	23.7	4.96
11	0	8	30	85	3.2	10	23.5	4.81
12	0	6	30	84	2.3	10	23.5	4.71
13	0	5	30.5	84	2	10	23.6	4.73
14	0	5	31	78	2.1	10.3	24.1	5.01
15	0	8	30.5	82	2.1	9.5	22.9	4.68
16	0	9	29.5	78	2.1	9.8	23.4	4.72

17	0	13.5	29	81	3.8	10.8	25	4.99
18	0	14	27.5	85	3.6	10.8	25	4.62
19	0	14	27	84	2.8	10	23.9	4.4
20	0	11	28	84	3.3	10.1	24.1	4.59
21	0	6	30	81	1.9	10	24	4.76
22	0	4	31	79	1.9	9.9	23.9	4.93
23	0	10	31.5	85	1.6	8.9	22.4	4.56
24	0	11	32	87	1.5	8.3	21.5	4.44
25	0	15	29	81	1.6	1.7	11.6	2.88
26	0	13	29	83	2.4	6.4	18.7	4
27	0	15	30	84	2.7	10	24.2	4.86
28	0	12	31	74	2.1	10	24.3	5.15

Table 5:Daily climate conditions and ETo (Evapotranspiration) data for the month of March as observed at the Awash Melkassa Research Center in 2023

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
1	2.3	11	33	84	1.8	9.3	23.3	4.95
2	5	15	30	74	1.9	6.8	19.5	4.34
3	0	15	30	83	1.3	6.4	18.9	3.94
4	0	14	29.5	79	2.3	7.6	20.8	4.43
5	0	14	31.5	82	3	9.8	24.2	5.17
6	0	14	31	82	4.4	9.7	24.1	5.28
7	0	12	32	85	0.1	10	24.6	4.68
8	0	15	32	81	0.8	9.6	24	4.82
9	0	12	33	83	0.8	8.6	22.5	4.59
10	0	14.5	30	81	0.5	6.8	19.7	3.92
11	0	14	29	76	2.5	3.2	14.2	3.67
12	55.5	14	25	74	1.5	1.5	11.6	2.8
13	7.5	15	25	70	1.8	2.3	12.8	3.17
14	25.5	14	27.5	73	2.1	2.3	12.8	3.35
15	7.4	14	27	72	2.1	5	17	3.89
16	0	14	26	76	1.3	3.3	14.4	3.16
17	0	14	26.5	77	2	3.1	14.1	3.3

18	27.5	15	26	64	1.3	5.5	17.9	3.84
19	0	14	27.5	66	1.5	4.8	16.8	3.83
20	0	15	27.5	71	1	5.7	18.2	3.78
21	0	14	30	66	1.5	0.5	10.1	3.13
22	14.3	15	29.5	66	1.6	6.1	18.9	4.34
23	13.2	13	26.5	70	0.7	1.3	11.4	2.63
24	0	14	29.5	63	1.2	9.3	23.9	4.88
25	0	14	29.5	64	1.9	8.3	22.3	4.97
26	0	15	26	68	1.1	0	9.4	2.57
27	0	14	29	61	1.9	10	25	5.32
28	0	16	27	79	3.6	4.2	16	3.8
29	7.5	15	26.5	76	1.2	1	11	2.7
30	2.3	13	28.5	73	1.9	6.7	19.9	4.33
31	5	14	28.5	65	0.1	10.3	25.5	4.54

Table 6:Daily climate conditions and ETo (Evapotranspiration) data for the month of April as observed at the Awash Melkassa Research Center in 2023

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
1	17.5	14	29	63.4	1.6	6.3	19.3	4.4
2	0	14	28.5	71.4	1.2	8.2	22.2	4.48
3	0	14	27	74.2	1.7	6.7	19.9	4.12
4	0	15	29.5	67	2.2	8.6	22.9	5.1
5	0	15	28	65	2.2	7.3	20.8	4.74
6	0	15	31	61.6	1.4	10	25	5.33
7	0	15	31	61.8	1.8	7.5	21.1	4.98
8	0	14	31	60.6	2.2	8.9	23.3	5.49
9	0	14	29.5	59.4	2.2	10.8	26.3	5.72
10	0	13	31	53.2	2.1	10.8	26.3	5.97
11	0	14	31	53.6	1.9	9	23.5	5.51
12	0	14	32	54.2	1.9	10.5	25.8	5.91
13	0	15	31	58.6	2.3	10.3	25.5	5.88
14	0	14	30	67.2	3	11.5	27.3	5.97

15	0	14	31	51.8	2.4	10.5	25.7	6.13
16	0	14	31	54.4	2.3	11	26.5	6.1
17	0	14	30	53.6	2	9.1	23.5	5.47
18	0	14	32	51.6	1.9	11	26.5	6.04
19	0	13	32	60.8	1.8	11.3	26.9	5.86
20	63.5	15	32	46.4	1.6	10.3	25.4	5.79
21	0	14	27.5	62.6	1	9.3	23.8	4.63
22	0	16	22	79.6	1.8	2.3	13	2.79
23	0	14	28	70	1	8.9	23.1	4.52
24	0	16	31.5	67.4	1.4	9.5	24	5.17
25	0	14	29	70.6	1.3	9.4	23.9	4.8
26	2.5	14	30	70	2.1	6.2	18.9	4.49
27	36.5	15	23	86.8	1.2	2.6	13.4	2.66
28	0	14	28	74.6	0.5	4	15.5	3.21
29	18.3	15	27	74	0.9	3.8	15.2	3.26

Table 7:Daily climate conditions and ETo (Evapotranspiration) data for the month of May as observed at the Awash Melkassa Research Center in 2023

Month	RF (mm)	Tmax (^{0}C)	Tmin (^{0}C)	RH (%)	WS (m/s)	SSH (hr)	Rad. (MJ/m2/day)	ETo (mm/day)
1	14.3	14	25	74	1.3	7	19.3	3.85
2	27.5	14	26	73.2	1.2	6.5	17.5	3.64
3	2.5	14	27	73.2	1.1	5.3	10.9	2.79
4	0	16	26	71.4	1.3	1	21.8	4.47
5	0	14	28	69	1.4	8.2	17.1	3.57
6	10.5	14	26	72.2	1.2	5.1	25.7	5.18
7	0	13	29	70.2	1.8	10.8	12.2	3.51
8	0	17	30	66.4	1.7	1.9	22.8	4.84
9	7.3	14	29.5	66.8	1.6	8.9	25.2	5.01
10	0	13.5	29.5	72.6	1.4	10.5	24	5.09
11	0	15	31	73	1.7	9.7	24.4	5.39
12	0	12.5	31	60.6	1.8	10	21.4	5.05

Table 8:Analysis of variance for the number of onion plant leaves at the initial growth stages

Source	DF	SS	MS	F	P
Replication	2	0.49000	0.24500		
Treatment	5	0.85333	0.17067	4.53	0.0203
Error	10	0.37667	0.03767		
Total	17	1.72000			
Grand Mean	3.7333				
CV	5.20				

Table 9:Analysis of variance for the number of onion plant leaves at the developmental stages

Source	DF	SS	MS	F	P
Replication	2	0.45778	0.22889		
Treatment	5	2.86444	0.57289	6.97	0.0048
Error	10	0.82222	0.08222		
Total	17	4.14444			
Grand Mean	6.8556				
CV	4.18				

Table 10:Analysis of variance for the number of onion plant leaves at the bulb formation stages

Source	DF	SS	MS	F	P
Replication	2	1.2133	0.60667		
Treatment	5	44.9800	8.99600	192.77	0.0000
Error	10	0.4667	0.04667		
Total	17	46.6600			
Grand Mean	9.5667				
CV	2.26				

Table 11:Analysis of variance for the number of onion plant leaves at the maturity stages

Source	DF	SS	MS	F	P
Replication	2	0.0178	0.00889		
Treatment	5	30.3044	6.06089	87.98	0.0000
Error	10	0.6889	0.06889		

Total	17	31.0111
Grand Mean	9.6778	
CV	2.71	

Table 12:Analysis of variance for onion plant height at the initial growth stages

Source	DF	SS	MS	F	P
Replication	2	0.3297	0.16484		
Treatment	5	30.4960	6.09921	23.66	0.0000
Error	10	2.5777	0.25777		
Total	17	33.4034			
Grand Mean	19.984				
CV	2.54				

Table 13:Analysis of variance for onion plant height at the development growth stages

Source	DF	SS	MS	F	P
Replication	2	7.8033	3.90167		
Treatment	5	12.6867	2.53733	3.58	0.0409
Error	10	7.0900	0.70900		
Total	17	27.5800			
Grand Mean	38.167				
CV	2.21				

Table 14:Analysis of variance for onion plant height at the bulb formation growth stages

Source	DF	SS	MS	F	P
Replication	2	4.564	2.2822		
Treatment	5	206.711	41.3422	19.11	0.0001
Error	10	21.629	2.1629		
Total	17	232.904			
Grand Mean	55.856				
CV	2.63				

Table 15:Analysis of variance for onion plant height at the maturity growth stages

Source	DF	SS	MS	F	P
Replication	2	51.97	25.984		

Treatment	5	1063.38	212.677	42.04	0.0000
Error	10	50.59	5.059		
Total	17	1165.94			
Grand Mean	51.811				
CV	4.34				

Table 16:Analysis of variance for onion bulb diameter

Source	DF	SS	MS	F	P
Replication	2	0.41268	0.20634		
Treatment	5	2.78496	0.55699	10.86	0.0009
Error	10	0.51272	0.05127		
Total	17	3.71036			
Grand Mean	5.1572				
CV	4.39				

Table 17:Analysis of variance for onion bulb length

Source	DF	SS	MS	F	P
Replication	2	0.06143	0.03072		
Treatment	5	1.54932	0.30986	2.15	0.1414
Error	10	1.43930	0.14393		
Total	17	3.05005			
Grand Mean	4.9817				
CV	7.62				

Table 18:Analysis of variance for the marketable yield of onions

Source	DF	SS	MS	F	P
Replication	2	15.08	7.541		
Treatment	5	2005.66	401.132	68.74	0.0000
Error	10	58.36	5.836		
Total	17	2079.10			
Grand Mean	47.911				
CV	5.04				

Table 19:Analysis of variance for the dry yield of onions

Source	DF	SS	MS	F	P
Replication	2	0.13588	0.06794		
Treatment	5	5.41276	1.08255	22.16	0.0000
Error	10	0.48852	0.04885		
Total	17	6.03716			
Grand Mean	5.2428				
CV	4.22				

Table 20:Analysis of variance for tomato fruit diameter

Source	DF	SS	MS	F	P
Replication	2	0.00210	1.050E-03		
Treatment	5	0.03993	7.987E-03	1.26	0.3507
Error	10	0.06317	6.317E-03		
Total	17	0.10520			
Grand Mean	3.6433				
CV	2.18				

Table 21:Analysis of variance for tomato fruit length

Source	DF	SS	MS	F	P
Replication	2	0.50154	0.25077		
Treatment	5	0.05116	0.01023	0.22	0.9461
Error	10	0.46646	0.04665		
Total	17	1.01916			
Grand Mean	5.7328				
CV	3.77				

Table 22:Analysis of variance for the marketable yield of tomato

Source	DF	SS	MS	F	P
Replication	2	23.619	11.8094		
Treatment	5	155.202	31.0404	36.36	0.0000
Error	10	8.536	0.8536		
Total	17	187.357			
Grand Mean	45.932				

CV	2.01

Table 23:Analysis of variance for the dry matter of tomato

Source	DF	SS	MS	F	P
Replication	2	0.35243	0.17622		
Treatment	5	5.24445	1.04889	8.68	0.0021
Error	10	1.20897	0.12090		
Total	17	6.80585			
Grand Mean	7.355				
CV	4.73				

Appendix Figure

Figure. 1 onion at initial stage and field managements

Figure. 2 Onion at development stage and data record

Figure. 2 Tomato at initial stage and data record

Figure. 3 Tomato at fruit formation and harvest

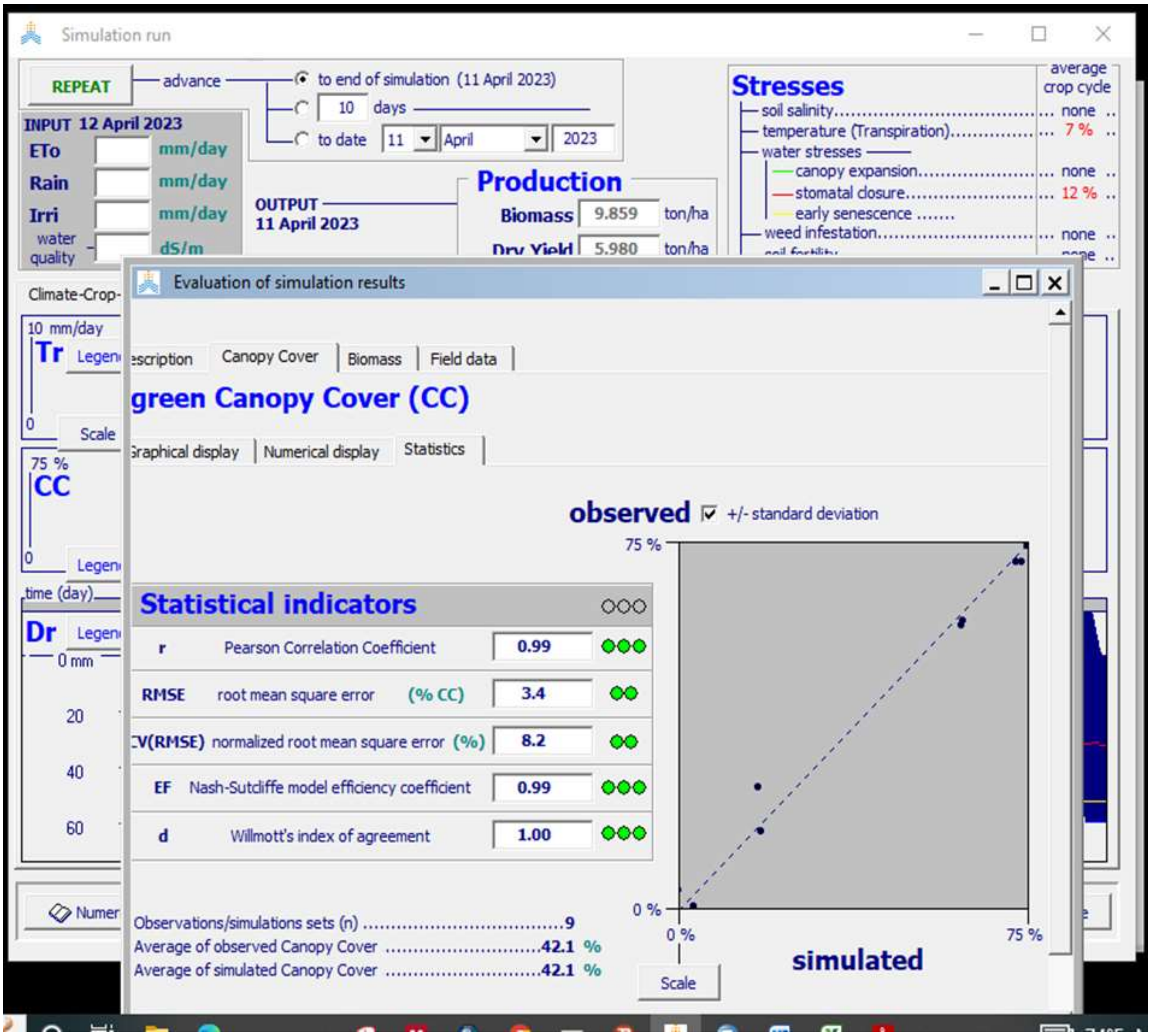

Figure. 4 Calibration of onion green canopy cover

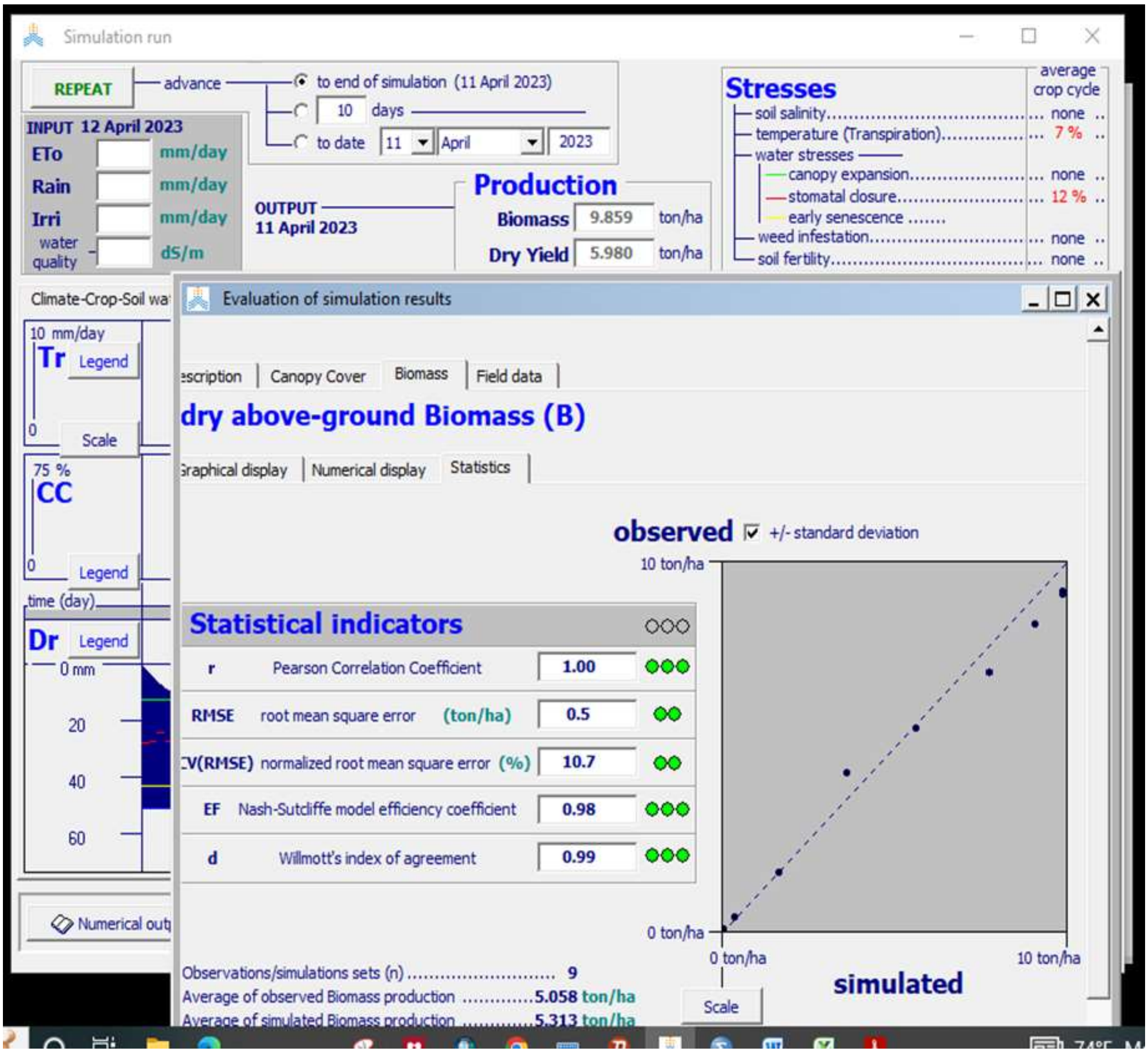

Figure. 5 Calibration of onion Total biomass

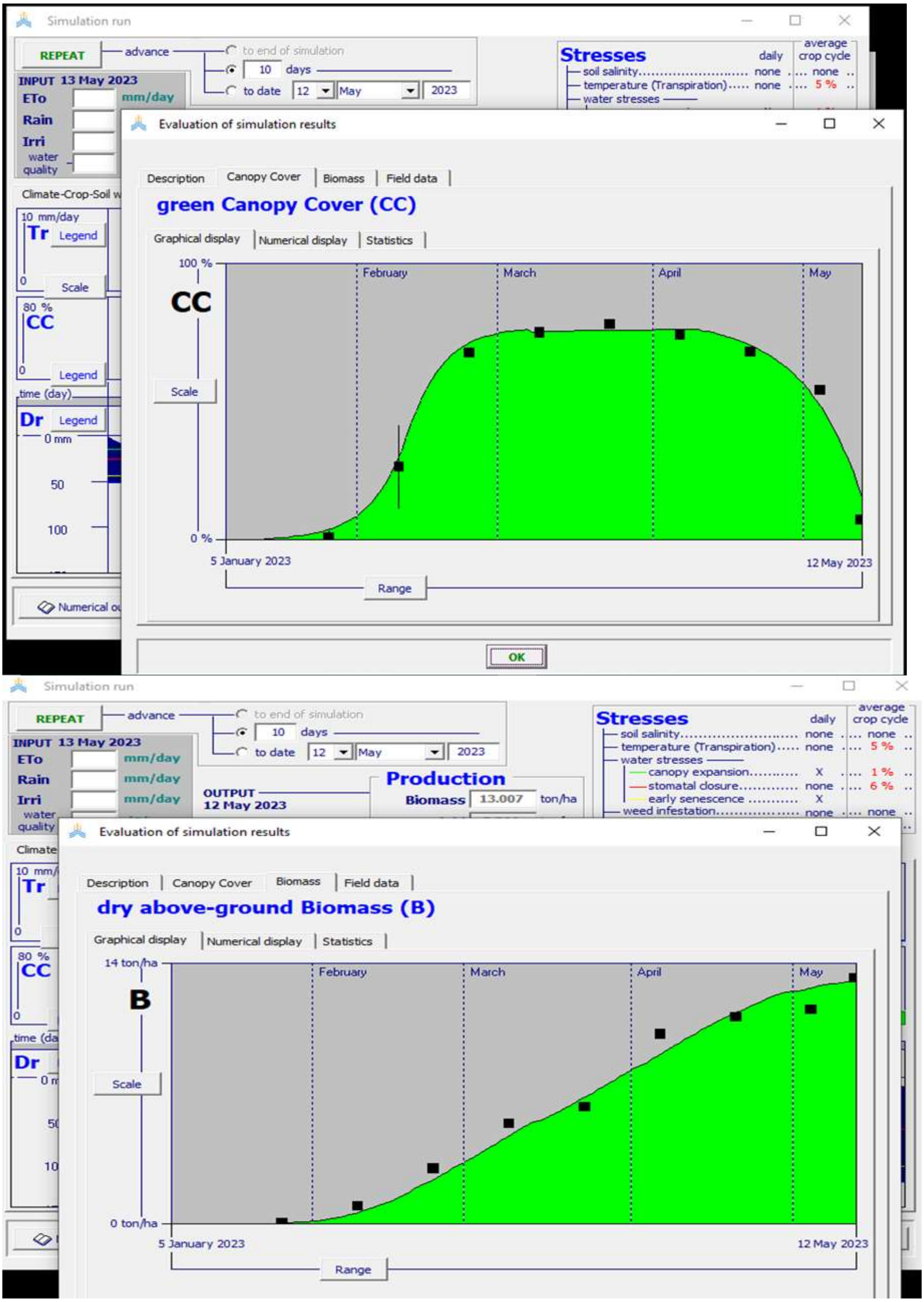

Figure. 6 Calibration of tomato green canopy cover