BUSITEMA UNIVERSITY
Pursuing Excellence

FACULTY OF ENGINEERING

DEPARTMENT OF AGRICULTURAL MECHANIZATION & IRRIGATION ENGINEERING

FINAL YEAR RESEARCH PROJECT REPORT

EVALUATION OF THE EFFECTS OF DEFICIT IRRIGATION LEVELS UNDER DRIP IRRIGATION WITH MULCHING ON TOMATO YIELD AND WATER PRODUCTIVITY.

CASE STUDY; BUSIA, UGANDA

By

ABESIGA DENNIS

(BU/UG/2022/1646)

SUPERVISOR: Dr. DANIEL OTIM

This final year Project proposal is to be submitted to the Department of Agricultural Mechanization & Irrigation Engineering as a partial fulfilment for the requirement of the Award of Bachelor Degree in Agricultural Mechanization & Irrigation Engineering

JUNE, 2026

DECLARATION

I, ABESIGA DENNIS, a student of Agricultural Mechanisation and Irrigation Engineering in the Faculty of Engineering at Busitema University, hereby declare that this research report is my original work. It has not been submitted to any other institution of higher learning for any academic award or publication. All materials and sources used have been duly acknowledged through appropriate referencing.

Name: ABESIGA DENNIS Registration Number: BU/UG/2022/1646

Signature: .... Date: 04/06/2026

APPROVAL

This is to certify that this research was conducted under my supervision and is hereby approved for submission to the Department of Agricultural Mechanisation and Irrigation Engineering, Faculty of Engineering.

Supervisor's Name: ENG. DR. OTIM DANIEL

Signature: .... Date: 04/06/2026

ACKNOWLEDGEMENT

I sincerely thank the Almighty God for the gift of life, wisdom, and strength throughout the preparation of this report. My heartfelt appreciation goes to my supervisor, DR. DANIEL OTIM, for continuous guidance, constructive comments, and valuable encouragement during the completion of this research. I also extend my gratitude to the Department of Agricultural Mechanisation and Irrigation Engineering for providing academic support and learning resources that made this study possible.

Special thanks go to my family and friends for their moral and financial support, and to the farmers and local extension officers in Busia District who shared valuable insights about tomato production and irrigation practices. Their cooperation and openness greatly inspired this research.

DEDICATION

This work is dedicated to my beloved parents and family, whose endless love, prayers, and encouragement have been my greatest source of strength. I also dedicate it to all smallholder farmers in Uganda who tirelessly work to feed the nation despite challenges of water scarcity and climate change. May this study contribute to sustainable solutions that improve their productivity and livelihoods.

ABSTRACT

Tomato production in Busia District, eastern Uganda, is increasingly constrained by seasonal water scarcity and inefficient irrigation practices. This study evaluated the effects of three deficit irrigation levels 100% (I_1), 75% (I_2), and 50% (I_3) of crop evapotranspiration (ETc) combined with two mulching treatments (mulched and non-mulched) on tomato (Money Maker) growth, yield, soil moisture dynamics, and water productivity under drip irrigation. The experiment was conducted at Busitema University Research Field, Busia District, during the dry season from December 2025 to March 2026, using a Randomized Complete Block Design (RCBD) with a 3×2 factorial arrangement replicated three times.

Results showed that both irrigation level and mulching had highly significant effects ($P<0.001$) on all measured parameters. The highest marketable yield of 44.17 t/ha was recorded under I_1+Mulch (full irrigation with mulching), while the lowest yield of 20.39 t/ha was recorded under I_3+No Mulch. Mulching provided a mean yield advantage of 4.41 t/ha (+14.2%) across all irrigation levels. Critically, the I_2+Mulch treatment (75% ETc with mulching) achieved a yield of 39.14 t/ha statistically equivalent to full irrigation without mulch (39.61 t/ha) while using 25% less irrigation water. Soil moisture content was maintained above the permanent wilting point (0.10 g/g) in all treatments throughout the season, validating the 50% management allowable deficit (MAD) scheduling approach. The I_2+Mulch treatment recorded the highest irrigation water use efficiency (IWUE) of 17.70 kg/m^3, surpassing the full irrigation treatment (16.26 kg/m^3), and reduced seasonal irrigation demand by 504 m^3/ha compared to full irrigation.

The I_2+Mulch treatment was identified as the optimal deficit irrigation strategy, offering the best balance between yield, water productivity, and irrigation efficiency for smallholder tomato production under drip irrigation in Busia District. These findings provide practical, evidence-based guidelines for farmers, extension workers, and policymakers on sustainable irrigation water management for tomato production in sub-humid eastern Uganda.

Table of Contents

Table 1-1. list of acronyms

Acronym	Full Meaning
DI	Deficit Irrigation
ET	Evapotranspiration
ETc	Crop water need/ crop Evapotranspiration
ET_0	Reference Evapotranspiration
Kc	Crop Coefficient
WUE	Water Use Efficiency
WP	Water Productivity
RCBD	Randomized Complete Block Design
BCR	Benefit-Cost Ratio
MRR	Marginal Rate of Return
ANOVA	Analysis of Variance
LSD	Least Significant Difference
FAO	Food and Agriculture Organization
SDG	Sustainable Development Goal
$MJ/m^2/day$	Megajoules per Square Meter per Day
°C	Degrees Celsius
kPa	Kilopascal
L	Litre
ha	Hectare
mm	Millimetre
g/cm^3	Grams per Cubic Centimetre

CHAPTER 1 INTRODUCTION

1.1 Background to the Study

Tomato is one of the most important vegetable crops grown around the world. It ranks high in terms of area planted and economic value. Global tomato production reached about 187 million metric tons in recent years, with top producers like China, India, Turkey, and the United States leading the way (Kaundal et al., 2024). Tomatoes are rich in vitamins A and C, potassium, and antioxidants like lycopene, making them key for good nutrition (Ding et al., 2018). They also create jobs and income, especially in rural areas of developing countries (Osei-Bonsu et al., 2022).

However, tomato yields face big challenges from climate change, water shortages, pests, diseases, and poor irrigation methods. Droughts and uneven rains are becoming more common, making smart water use a top priority for vegetable farming (Geerts & Raes, 2009). In Africa, tomatoes are a main crop for small farmers, but average yields are low at 7-10 tons per hectare compared to the world average of 37 tons per hectare (Amankwaa-Yeboah et al., 2023). This gap comes from limited irrigation, poor water management, and low use of modern techenology.

In East Africa, including Uganda, tomatoes are a high-value crop for small and big farmers. Countries like Kenya, Tanzania, and Uganda supply much of the regional market. But unreliable rains and dry spells hurt production (Mwangi et al., 2024). Many farmers still use buckets or cans for watering, though drip irrigation is growing. Drip systems save water by putting it right at the plant roots and work well for exact watering schedules (Allen et al., 1998).

In Uganda, tomatoes grow in many areas and help with food security and farmer income. Key districts include Wakiso, Mbale, Busia, and Kabale (Osinde, 2022). Uganda has two rainy seasons, but dry spells often hit during key growth times. Only about 2% of farmland uses irrigation (Mwaura & Katunze, 2014). Drip systems are catching on for tomatoes because they use less water and fit small farms. Still, most uses water without knowing exact crop needs, leading to waste, low yields, and high costs.

Busia District in eastern Uganda, near the Kenya border, shows typical small-scale farming conditions. It gets 1,200-1,500 mm of rain yearly, but it's uneven with dry spells during flowering and fruiting (Babyenda, 2023). This causes water stress, lower yields, and bad fruit quality. More farmers in Busia use drip irrigation to fight this, but they often run it without science-based plans.

Deficit irrigation (DI) means giving plants less than full water needs on purpose to save water and boost efficiency without big yield drops (Geerts & Raes, 2009; Patanè & Cosentino, 2010). Drip systems make DI easy because they control water amount and timing well. Adding mulching saves soil moisture by cutting evaporation and works great with DI (Kakaire et al., 2015). In Busia, drip is growing, but little local data exists on how DI levels plus mulch affect tomato yields and water use. This study fills that gap to help make tomato farming persist against dry times.

1.2 Problem statement.

Tomato production in Uganda, particularly in Busia District, is increasingly constrained by water scarcity, erratic rainfall patterns, and inefficient irrigation practices, despite the crop's high economic value and sensitivity to water stress. In response, drip irrigation systems are being progressively adopted due to their high application efficiency and suitability for precise water management; however, many farmers and institutional users operate these systems without scientifically based irrigation scheduling, often applying water arbitrarily without reference to crop evapotranspiration (ETc) requirements. This has resulted in over-irrigation, low water productivity, increased production costs, and inefficient use of limited water resources. Deficit irrigation offers a potential solution by deliberately applying water below full ETc to improve water use efficiency while maintaining acceptable yields, and drip irrigation systems are particularly well suited for implementing such strategies. Additionally, soil moisture conservation practices such as mulching can further reduce evaporation losses and enhance the effectiveness of applied irrigation water. Despite the increasing adoption of drip irrigation in Busia District, there is limited empirical, location-specific information on the combined effects of different deficit irrigation levels and mulching on tomato yield and water productivity. This knowledge gap limits informed decision-making on efficient irrigation management and undermines efforts to improve productivity and climate resilience of tomato production systems, thereby necessitating a systematic evaluation of deficit irrigation levels under drip irrigation with mulching in Busia District, Uganda.

1.3 Research Hypothesis

Tomato growth and yield differ significantly among crops subjected to different deficit irrigation levels under a drip irrigation system.

1.4 Objectives of the Study

1.4.1 Main Objective

To evaluate the effects of deficit irrigation levels under a drip irrigation system, with mulching, on tomato yield and water productivity in Busia District, Uganda.

1.4.2 Specific Objectives

1. To evaluate the effect of different deficit irrigation levels and mulch treatments under drip irrigation on tomato growth and yield
2. To assess the effect of mulching on soil moisture conservation under drip deficit irrigation.
3. To evaluate the water productivity and IWUE of tomato under different deficit irrigation levels with mulching
4. To identify an optimal deficit irrigation level under drip irrigation that maximizes tomato yield and water use efficiency.

1.5 Research Questions

1. How do different deficit irrigation levels under drip irrigation with mulching treatments affect tomato growth and yield?
2. What effect does mulching have on soil moisture retention under drip deficit irrigation?
3. How does water productivity and IWUE of tomato vary under different deficit irrigation levels with mulching?
4. Which deficit irrigation level under drip irrigation provides the best balance between yield and water use efficiency?

1.6 Justification of the Study

Efficient use of water resources is increasingly critical in Uganda due to climate variability, growing competition for water, and low levels of irrigation development. Tomato, being a high-value and water sensitive crop, requires well-managed irrigation to achieve optimal yields and high-water productivity. Drip irrigation systems offer significant potential for improving irrigation efficiency; however, without proper irrigation scheduling, their benefits are often not fully realized (Allen et al., 1998). Deficit irrigation has been widely recognized as an effective strategy for improving water productivity by reducing irrigation water use while maintaining acceptable crop yields (Geerts & Raes, 2009). Furthermore, mulching has been shown to reduce soil evaporation losses and enhance soil moisture availability, particularly under water-limited conditions (Zribi et al., 2015). Despite the increasing adoption of drip irrigation systems in Busia District, there is limited location-specific information on how deficit irrigation levels combined with mulching influence tomato yield and water productivity. Findings from this study will provide practical guidance to farmers, extension workers, irrigation designers, and policymakers on efficient irrigation water management strategies, thereby contributing to improved productivity, water conservation, and climate resilience in tomato production systems.

1.7 Scope of the Study

1.7.1 Conceptual Scope

The study is limited to investigating the impact of different deficit irrigation levels (100%, 75%, and 50% of crop evapotranspiration) on the growth, yield, and water productivity of the Money Maker tomato variety.

It also examines the interactive effect of mulching on soil moisture conservation and crop performance.

The research is primarily focused on irrigation engineering concepts, including water requirement estimation using the FAO Penman Monteith method, irrigation scheduling, water productivity analysis, and irrigation water use efficiency (IWUE).

The study does not cover other agronomic practices such as pest control, fertilizer optimization, or post-harvest handling.

1.7.2 Geographical Scope

The research was conducted in Busia District, located in eastern Uganda. The district was selected because it represents a small-scale farming environment where water scarcity and erratic rainfall often limit tomato production.

The study site will be a demonstration field within Busitema university

Busia's proximity to Lake Victoria and its exposure to seasonal dry spells make it suitable for studying the effectiveness of deficit irrigation and mulching under real smallholder conditions.

1.7.3 Time Scope

The study was carried out over a period of one cropping season (approximately 3-4 months) corresponding to the dry season from December 2025 to march 2026.

This period was chosen because it represents the time when irrigation is most critical due to limited rainfall.

Data collection covered all major tomato growth stages from transplanting to harvest while data analysis, interpretation, and report writing was conducted between march and April 2026.

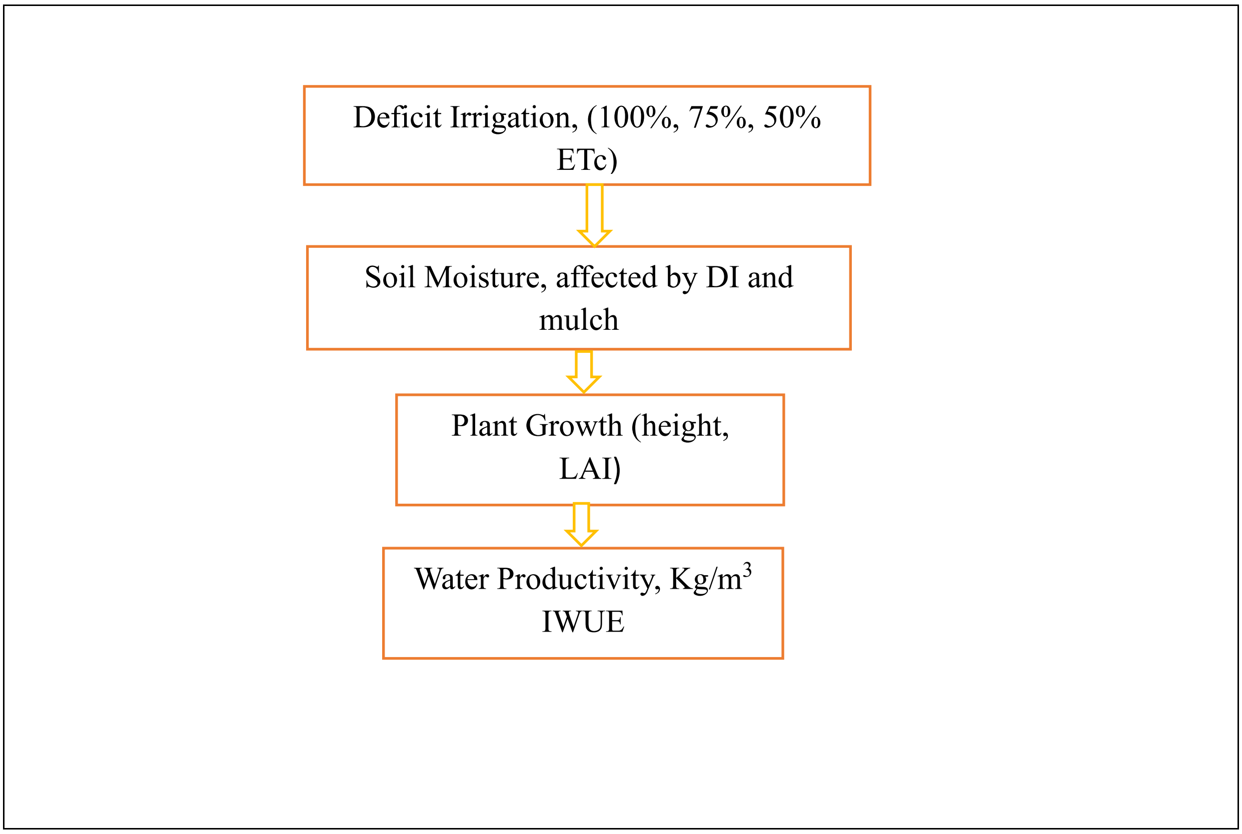

Figure 1-1 Conceptual framework showing the relationship between deficit irrigation, mulching, and tomato yield and water productivity

Figure 1-2. Tomato plants under drip irrigation

1.8 Significance of the study

The results of this study contributed to improved understanding of efficient irrigation water management for tomato production under drip irrigation systems. The findings benefited smallholder farmers by providing practical recommendations on deficit irrigation scheduling that can reduce water use and production costs while maintaining acceptable yields. Extension agents and irrigation practitioners will gain evidence-based information to support farmer training and advisory services. Additionally, the study will provide useful reference data for future research and policy formulation aimed at promoting sustainable and climate-resilient irrigation practices in Uganda and similar agro-ecological zones.

CHAPTER 2 . LITERATURE REVIEW

2.1 Overview

Tomato production faces growing water challenges worldwide, especially in sub-humid regions like eastern Uganda where dry spells disrupt rain-fed farming. This review covers tomato importance, water scarcity effects, deficit irrigation benefits, mulching roles, evapotranspiration calculations, drip system designs, and water productivity measures. While many studies exist on these topics separately, there remains a critical research gap in field experiments combining specific deficit irrigation levels (100%, 75%, 50% ETc) with mulching specifically for tomato production under drip irrigation in Busia District's tropical climate, where rainfall varies seasonally within humid conditions (Geerts & Raes, 2009).

2.2 Tomato Production and Importance

Tomatoes rank among the top five most valuable vegetable crops globally by cultivated area and market value. Global production exceeds 180 million metric tons annually, led by China, India, and the United States (Ndondo & Ndondo, 2023). The crop provides essential vitamins A and C, potassium, and lycopene antioxidants that support human health and nutrition. In Uganda, small scale farmers grow tomatoes mainly in open fields as both a cash crop for market sales and subsistence food source, with rising demand driven by population growth and urban consumption (Ddamulira et al., 2019).

Despite this economic importance, average Ugandan tomato yields remain critically low at 5-10 tons per hectare compared to potential yields of 30-50 tons per hectare under optimal management. Major constraints include limited water access during dry spells, pest and disease pressure, poor agronomic practices, and minimal adoption of irrigation technologies (Wakaabu, 2023). Tomatoes prove particularly sensitive to moisture stress during reproductive stages like flowering and fruit development, where water deficits cause flower drop, reduced fruit set, and smaller berry sizes (Dorji et al., 2005). While general production challenges receive attention in Ugandan literature, no published field studies specifically examine how deficit irrigation scheduling combined with mulching affects yield components of determinate tomato varieties like Money Maker under Busia District's bimodal rainfall pattern with frequent in-season dry spells.

2.3 Water Scarcity and Irrigation in Sub-Humid Regions

Busia District receives 1200-1500 mm annual rainfall distributed across two seasons, yet prolonged dry spells frequently occur during critical tomato growth periods from flowering through fruit maturation (Kishaija et al., 2024). These intermittent droughts create temporary water stress that severely limits rain-fed smallholder productivity. Climate records show increasing dry spell frequency and intensity in eastern Uganda over the past decade, threatening horticultural output (Nsubuga & Rautenbach, 2018).

Supplementary irrigation emerges as the primary strategy to buffer these rainfall gaps. Neighbouring Kenyan studies demonstrate that even slight drip irrigation volumes applied during stress periods can double tomato marketable yields compared to rain-fed controls (Owino et al., 2025). Ugandan policy increasingly promotes low-pressure drip systems for smallholders through NGO and university extension programs (Barungi et al., 2024). However, existing irrigation research in Uganda concentrates predominantly on semi-arid northern regions or large-scale schemes, leaving a significant knowledge gap regarding optimal drip irrigation management including deficit strategies for high-value vegetables in sub-humid eastern districts like Busia where water scarcity manifests as seasonal dry spells rather than chronic drought.

2.4 Deficit Irrigation and Crop Water Use Efficiency

Deficit irrigation deliberately supplies crops with less than full evapotranspiration requirements to maximize water productivity while accepting least yield reductions. This approach works because controlled mild water stress during vegetative growth redirects plant resources from excessive canopy development toward reproductive structures and fruit quality (Geerts & Raes, 2009).

Multiple field experiments confirm deficit irrigation increases tomato water use efficiency by 15-35% across various environments. Italian researchers found 75-85% ETc replacement during fruit bulking produced optimal combinations of total yield, fruit size, and soluble solids content (Patanè & Cosentino, 2010). A Chinese study reported peak water productivity at precisely 75% ETc applied through drip laterals during the fruiting stage (Wu et al., 2021). Algerian trials showed moderate deficits improved fruit firmness and total soluble solids key market quality traits without compromising marketable yield (Kopa et al., 2023).

Table 2-1 Comparison of Crop Yields Between Irrigated and Non-Irrigated Farms in Wukro, Ethiopia *after* (Misgina et al., 2024).

Crop Type	**Non-Irrigated Farms (qt/ha)**	**Irrigated Farms (qt/ha)**	**% Increase**
Maize	25.75	43.75	69
Onions	102	172	68
Pepper	11	17.75	61
Tomato	200	300	50
Carrot	226	305.25	35
Potato	174.8	250	43
Cumin	4.25	7.50	76

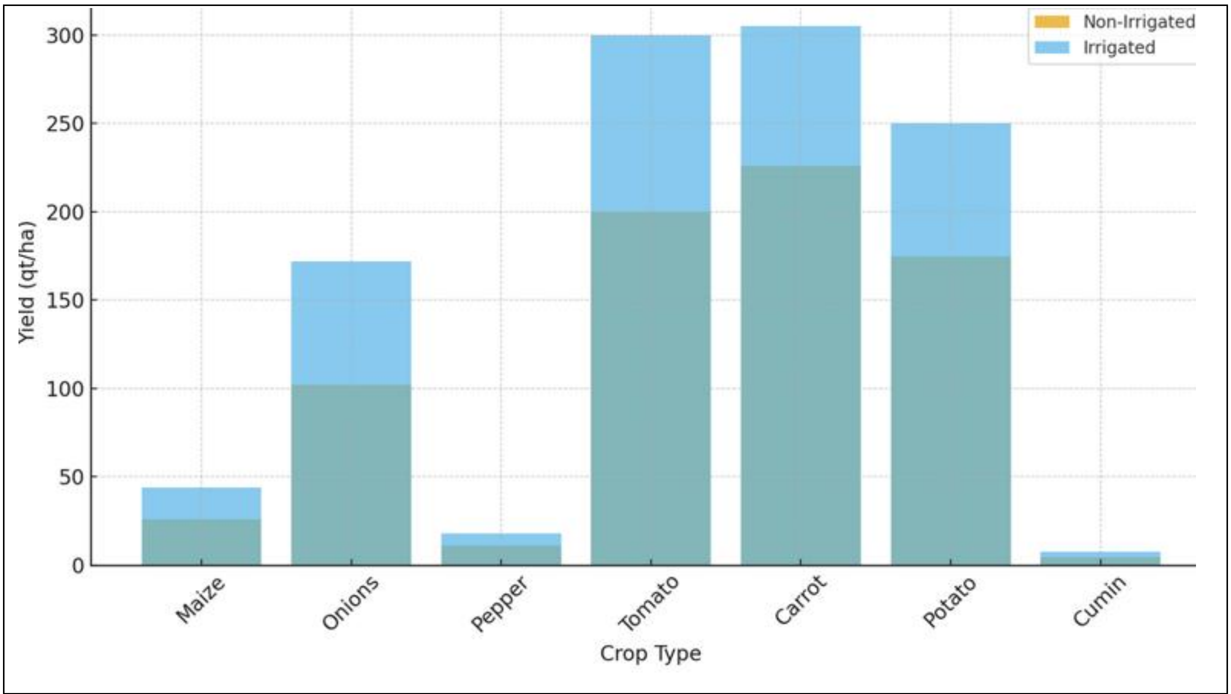

Figure 2-1 comparison between irrigated and non-irrigated fields in terms of output (Misgina et al., 2024)

Despite consistent DI benefits across arid and Mediterranean environments, field validation remains scarce for tropical sub-humid conditions like Busia where high atmospheric humidity modifies crop water stress responses, and no published work tests the specific 100%/75%/50% ETc levels combined with mulching under small scale drip systems.

2.5 Tomato Water Requirements and Crop Evapotranspiration (ETc)

Tomato growth and productivity depend heavily on consistent soil moisture supply, particularly during flowering and early fruit development when stress causes irreversible flower abortion and poor fruit set (Patanè & Cosentino, 2010). Sub-Saharan African tomato yields suffer more from irrigation mismanagement than absolute water shortages, as farmers typically apply water based on visual wilting rather than calculated crop needs (Bacha et al., 2011).

Crop water requirement is expressed as crop evapotranspiration (ETc):

$ETc = Kc \times ET_0$..2-1

Where:
ETc=cropevapotranspiration(mm/day)
Kc=cropcoefficient
ET_0 = reference evapotranspiration (mm/day) (Allen et al., 1998)

While FAO-56 methodology provides robust ETc estimation globally, local validation of tomato Kc values remains limited for Ugandan conditions, particularly for determinate varieties like Money Maker grown under field drip irrigation with seasonal rainfall contributions.

2.6 Principles of Drip Irrigation Systems design

Drip irrigation is a pressurized irrigation method that applies water directly to the crop root zone through a network of pipes, laterals, and emitters. Drip irrigation achieves higher application efficiency than surface and sprinkler irrigation due to reduced evaporation, runoff, and deep percolation losses (Keller & Bliesner, 1990). Proper system design, including emitter spacing, discharge rate, wetted area, and irrigation scheduling, is essential for optimal system performance (Ghinassi et al., 2024).

Design equations include:

Daily crop transpiration demand:

$$Td = ETc \times Pd \quad \text{......} 2\text{-}2$$

Where:

Td = daily crop transpiration (mm/day)

ETc = crop evapotranspiration (mm/day)

Pd = fraction of soil surface shaded by the crop canopy

Net irrigation depth:

$$dx = MAD \times Pw \times AW \times Rz \quad \text{......} 2\text{-}3$$

Where:

dx = net irrigation depth (mm)

MAD = management allowable deficit

Pw = percentage wetted area

AW = available soil water (mm/m)

Rz = effective root depth (m)

Irrigation frequency:

$$fx = \frac{dx}{Td} \quad \text{......} 2\text{-}4$$

Where:

fx = irrigation frequency (days)

Small-scale drip installations in Uganda frequently bypass these hydraulic calculations, resulting in mismatched emitter flows and over-irrigation that undermines the precision advantages essential for deficit irrigation scheduling.

2.7 Deficit Irrigation under Drip Systems

Drip systems enable precise deficit irrigation implementation by controlling applied depth as a fraction of calculated ETc:

$$IR = ETc \times DI \qquad \text{2-5}$$

Where:

IR = irrigation requirement (mm)

DI = deficit irrigation fraction

This formulation allows clear differentiation between treatments receiving 100%, 75%, and 50% of ETc. (Fereres & Soriano, 2007), report that drip irrigation systems provide the level of control necessary to accurately impose such deficit levels.

The irrigation time for each treatment is then calculated from;

$$Ti = \frac{IR}{Q} \qquad \text{2-6}$$

Where:

Ti = irrigation time (hours)

Q = system discharge rate (L/hr)

This methodology ensures treatment differences arise purely from water quantity rather than system performance variations. Although drip precision facilitates exact DI control, no Ugandan field experiments document soil moisture dynamics, yield responses, and economic returns across these precise ETc percentages when combined with mulching under smallholder conditions.

2.8 Mulching and Soil Moisture Conservation

Mulching covers soil surfaces with organic materials, plastic films, or living covers to reduce evaporation, moderate soil temperatures, and conserve moisture. Under drip irrigation, mulch particularly reduces non-productive water loss from wetted inter-row areas (Chakraborty et al., 2008). Both plastic and organic mulches decrease irrigation requirements by 20-40% in vegetable production.

Soil moisture content is commonly monitored using digital soil moisture sensors, which provide continuous, real-time volumetric water content readings. These sensors measure the dielectric permittivity of the soil, which is directly related to its water content, and output values in volumetric units (g/g). The general relationship between sensor output and volumetric moisture content is expressed as:

$\theta\ (g/g) = \frac{VWC \times \rho w}{\rho b}$..2-7

Where

VWC= volumetric moisture content (m^3/m^3)

ρb = bulk density of soil

ρw =density of water

Few tropical field studies quantify how mulch type and thickness interact with specific drip deficit levels to influence root zone moisture dynamics and corresponding tomato water productivity throughout the full crop cycle.

2.9 Tomato Growth and Yield Response to Irrigation

Tomato yield is influenced by irrigation level, soil moisture availability, and crop management practices. Severe water stress reduces vegetative growth and fruit yield, while moderate deficit irrigation can improve fruit quality with minimal yield reduction (Fereres & Soriano, 2007).

Tomato yield is calculated as:

$$Y = Total\ fruit\ weight\ per\ plot$$

Where:

Y = tomato yield (kg/ha)

Stage-specific deficit response curves for determinate field tomatoes under Ugandan rainfall regimes combined with drip irrigation and mulching remain undocumented in peer-reviewed literature.

2.10 Water Productivity and Irrigation Water Use Efficiency

Water productivity (WP) and irrigation water use efficiency (IWUE) are key performance indicators used to evaluate the effectiveness of irrigation management strategies, particularly under conditions of water scarcity. In modern irrigation research, emphasis has shifted from maximizing crop yield per unit area to maximizing crop yield per unit of water used, due to increasing pressure on limited water resources (Molden et al., 2010).

Water productivity describes the relationship between crop yield and the amount of water consumed through evapotranspiration. It reflects how efficiently the crop converts water into economic yield and is particularly relevant in deficit irrigation studies where reductions in water application are intentional. Water productivity is calculated as:

$$WP = \frac{Y}{ETc} \quad \text{.......... 2-8}$$

Where:

WP = water productivity (kg m^{-3}),

Y = crop yield (kg ha^{-1}),

ETc = crop evapotranspiration (mm).

A higher water productivity value indicates that more yield is produced per unit of water consumed, suggesting more efficient water use. Under deficit irrigation, WP often increases even when yield declines slightly, because the reduction in water consumption is proportionally greater than the reduction in yield (Fereres & Soriano, 2007). Several studies have demonstrated that moderate deficit irrigation can significantly improve water productivity in tomato without substantial yield penalties (Geerts & Raes, 2009).

Irrigation water use efficiency (IWUE) focuses specifically on the relationship between crop yield and the volume of irrigation water applied, rather than total water consumed. IWUE is particularly important in drip irrigation experiments where precise measurement of applied irrigation water is possible. It is expressed as:

$$IWUE = \frac{Y}{I} \quad \text{.......... 2-9}$$

Where:

IWUE = irrigation water use efficiency (kg m^{-3}),

Y = crop yield (kg ha^{-1}),

I = total irrigation water applied (m^3 ha^{-1}).

IWUE provides a direct measure of how effectively irrigation water is converted into yield and is therefore highly sensitive to irrigation scheduling and system performance. Under ETc-based drip irrigation, irrigation water applied varies systematically among treatments (100%, 75%, and 50% ETc), allowing meaningful comparison of IWUE across deficit levels. Research indicates that IWUE typically increases as irrigation depth decreases, up to a threshold beyond which excessive water stress leads to sharp yield reductions (English & Raja, 1996).

In drip irrigation systems, high IWUE values are often attributed to reduced non-productive water losses such as evaporation and deep percolation. The localized water application characteristic of drip systems ensures that a larger fraction of applied water contributes directly to crop transpiration (Keller & Bliesner, 1990). When combined with mulching, irrigation efficiency is further enhanced due to reduced soil surface evaporation and improved soil moisture retention (Chakraborty et al., 2008).

The combined evaluation of WP and IWUE provides a comprehensive assessment of irrigation performance. While WP reflects the crop's physiological response to water consumption, IWUE reflects the technical and managerial efficiency of the irrigation system. Using both indicators allows researchers to distinguish between improvements due to crop response and those due to improved irrigation management.

In deficit irrigation studies, treatments receiving 75% ETc often exhibit optimal balance between yield and water savings, resulting in the highest WP and IWUE values. Treatments receiving 50% ETc may achieve higher IWUE but risk significant yield reduction if water stress exceeds the crop's tolerance threshold (Fereres & Soriano, 2007). Consequently, WP and IWUE together provide a scientific basis for identifying irrigation strategies that maximize productivity under limited water supply.

Although extensive research exists on tomato water requirements, drip irrigation, deficit irrigation, mulching, and water productivity individually, limited integrated studies combine ETc-based scheduling, deficit irrigation levels, and mulching within a single experimental framework under humid tropical smallholder conditions. This study addresses this gap by quantifying irrigation water applied, soil moisture dynamics, yield response, and water productivity under drip deficit irrigation with mulch.

CHAPTER 3 METHODOLOGY

3.1 Description of the Study Area

The study was conducted at the university agricultural research field in Busia District, eastern Uganda, where a drip irrigation system is installed and accessible for research purposes. The area is characterized by a humid tropical climate with bimodal rainfall distribution and average annual rainfall of approximately 1,200–1,500 mm. Mean daily temperatures range from 20 °C to 30 °C.

Table 3-1 Coordinates for Each Plot

ID	LATITUDE	LONGITUDE
P1	0.545355°	34.024771°
P2	0.545336°	34.024779°
P3	0.545324°	34.024787°
P4	0.545310°	34.024788°
P5	0.545294°	34.024791°
P6	0.545264°	34.024786°
P7	0.545347°	34.024731°
P8	0.545333°	34.024743°
P9	0.545304°	34.024742°
P10	0.545289°	34.024754°
P11	0.545286°	34.024767°
P12	0.545253°	34.024780°
P13	0.545339°	34.024688°
P14	0.545314°	34.024694°
P15	0.545282°	34.024699°
P16	0.545261°	34.024718°
P17	0.545243°	34.024731°
P18	0.545219°	34.024742°

The soils at the experimental site are predominantly loamy, well-drained, and suitable for tomato cultivation and drip irrigation studies. The availability of controlled irrigation infrastructure and uniform field conditions makes the site appropriate for evaluating deficit irrigation and mulching effects on tomato growth, yield, and water productivity.

3.2 Experimental Design and Treatment Structure

The experiment was laid out in a Randomized Complete Block Design (RCBD) to minimize the effects of spatial variability across the field. Blocking was done across the dominant field gradient to ensure homogeneity within blocks.

The treatments consisted of:

Three deficit irrigation levels based on crop evapotranspiration (ETc):

I_1: 100% ETc (full irrigation)

I_2: 75% ETc (moderate deficit irrigation)

I_3: 50% ETc (severe deficit irrigation)

Two mulching levels:

M: Mulched

N-M: Non-mulched

This results in six treatment combinations (3 × 2). Each treatment was replicated three times, giving a total of 18 experimental plots.

3.3 Experimental Layout and Drip Irrigation System Setup

Each experimental plot was clearly demarcated and separated by buffer zones to prevent lateral water movement between plots. Tomato seedlings were transplanted at recommended spacing to maintain uniform plant population density across all treatments.

Drip laterals were installed along each crop row, with emitters positioned close to the base of each plant to ensure direct water application to the root zone. All plots were connected to a single sub-main line, ensuring uniform pressure conditions across the experimental field.

Different deficit irrigation levels were imposed by varying irrigation duration for each treatment while keeping the emitter discharge rate and system configuration constant. This ensures that differences in water application arise solely from irrigation scheduling rather than system design.

3.4 Crop Establishment and General Agronomic Management

Tomato seedlings were raised in a nursery under uniform conditions and transplanted into the experimental plots at the four- to five-leaf stage. Immediately after transplanting, all plots received uniform irrigation for a short establishment period to ensure uniform crop stand.

Mulches were applied immediately after transplanting in designated plots. All agronomic practices, including fertilizer application, pest and disease control, staking, and weed management, were uniformly applied across all plots to eliminate non-treatment effects.

To ensure that observed differences in tomato growth parameters (including plant height, Leaf Area Index, and fruit count) and marketable yield were attributable solely to the imposed irrigation and mulching treatments, all other agronomic management practices were standardised and applied uniformly across all 18 experimental plots throughout the growing season. These included fertilizer application (type, rate, and timing), pest and disease control, staking, weeding, and transplanting density. Although fertilizer application contributes to LAI development and overall plant growth, its uniform application across all treatments ensured that it did not confound treatment comparisons. Water application rate was the only intentionally varying input across irrigation treatments (I_1, I_2, and I_3), while mulching presence or absence constituted the second treatment factor. All other variables were treated as constants to maintain experimental integrity and internal validity of the RCBD design.

3.5 Methodology for Objective One

Deficit irrigation treatments were imposed based on crop evapotranspiration (ETc) following the procedures described in Section 2.4 and Section 2.5 of the Literature Review. Reference evapotranspiration (ET_0) was obtained from local climatic data, and appropriate crop coefficient (Kc) values for tomato growth stages were adopted.

The selection of 100%, 75%, and 50% ETc as the three deficit irrigation levels was grounded in published literature. Full irrigation at 100% ETc served as the control benchmark, representing the theoretical maximum crop water requirement with no intentional deficit. The 75% ETc level was selected based on findings by Geerts & Raes, (2009), who demonstrated through a meta-analysis of 22 field studies that moderate deficits in the range of 70–80% ETc consistently maximise water productivity across diverse crops without inducing severe yield penalties. This level was further supported by Patanè & Cosentino, (2010), who reported the optimal yield-water balance for processing tomatoes at 75–85% ETc, and by Wu et al., (2021), who identified 75% ETc as the peak efficiency point for drip-irrigated tomatoes. The 50% ETc level was included to represent a severe deficit scenario, intended to establish the lower boundary of acceptable water supply and to quantify the yield penalty associated with excessive water restriction, consistent with the approach used by Fereres & Soriano, (2007), who recommended testing beyond the expected optimum to fully characterise the crop's water-yield response curve.

The full irrigation treatment (100% ETc) was calculated first and used as the reference. Moderate (75% ETc) and severe (50% ETc) deficit irrigation levels were then be derived as fractions of the full ETc value. Irrigation duration for each treatment was adjusted accordingly while maintaining the same drip system discharge rate as discussed in section 2.6 and 2.7 of the literature review

The specific irrigation volumes applied to each treatment were controlled by varying irrigation duration while maintaining a constant emitter discharge rate of 2 L/hr per emitter. The mean daily reference evapotranspiration (ET_0) recorded at the study site during the experimental period was 4.6 mm/day. Using the mid-season crop coefficient (Kc = 1.15 for tomato), the crop evapotranspiration was calculated as ETc = 4.6 × 1.15 = 5.29 mm/day. The net irrigation depth for full irrigation (I_1) was therefore 5.29 mm/day, while I_2 received 75% × 5.29 = 3.97 mm/day and I_3 received 50% × 5.29 = 2.65 mm/day. Irrigation frequency was set at every 5 days based on the management allowable deficit (MAD = 50%) and available soil water capacity. For each irrigation event, the required volume per plot was calculated and converted to irrigation time using the Equation 2.6. This approach ensured that differences in water application among treatments arose purely from the calculated ETc fractions rather than from any variability in system hardware or pressure conditions, since all plots shared the same sub-main line and emitter configuration.

Tomato growth parameters including plant height, number of leaves, and phenological stages (flowering and fruiting) were recorded at regular intervals throughout the growing period. At harvest, fruits were collected, weighed, and total fruit yield per plot was determined. Tomato yield was calculated on a hectare basis following the procedure described in Section 2.9 of the Literature Review. Yield data was used to evaluate the effect of different deficit irrigation levels on tomato growth and productivity.

3.6 Methodology for Objective Two

Mulched and non-mulched plots were maintained throughout the growing season. Soil moisture content was monitored periodically using digital soil moisture sensors installed at the 0–20 cm root zone depth in each plot.

Soil samples were collected from the crop root zone at specified depths before irrigation and at selected intervals after irrigation. Moisture content values from mulched and non-mulched plots under the same irrigation levels were compared to assess the effect of mulching on soil moisture conservation under drip deficit irrigation.

3.7 Methodology for Objective Three

Water productivity was evaluated using tomato yield and crop water use data following the procedure outlined in Section 2.10 of the Literature Review. Crop evapotranspiration values corresponding to each irrigation treatment were used to compute water productivity.

Yield data obtained from each treatment combination were related to ETc values to determine the amount of yield produced per unit of water consumed. Comparisons were made among irrigation and mulching treatments to assess how deficit irrigation and mulching influenced tomato water productivity.

3.8 Methodology for Objective Four

The optimal deficit irrigation level was identified by jointly evaluating tomato yield, water productivity, and irrigation water use efficiency (IWUE). IWUE was calculated using total irrigation water applied per treatment following the procedure described in Section 2.10 of the Literature Review.

Yield, WP, and IWUE values across the different irrigation levels (100%, 75%, and 50% ETc) were compared. The irrigation level that achieved the best balance between high yield and efficient water use was identified as the optimal deficit irrigation level under drip irrigation.

3.9 Data Analysis

All collected data was subjected to statistical analysis using analysis of variance (ANOVA) appropriate for RCBD. Treatment means was compared using suitable mean separation tests at a 5% level of significance. Statistical analysis was performed using standard statistical software.

CHAPTER 4 RESULTS AND DISCUSSION

This chapter presents the results obtained from the field experiment conducted at Busitema University Research Field, Busia District, Uganda, from December 2025 to March 2026. The experiment evaluated the effects of three deficit irrigation levels, I_1 (100% ETc), I_2 (75% ETc), and I_3 (50% ETc), combined with two mulching treatments (mulched and non-mulched) on tomato (Money Maker) growth, yield, soil moisture dynamics, water productivity, and irrigation water use efficiency. The experimental design was a Randomized Complete Block Design (RCBD) with a 3 × 2 factorial arrangement replicated three times. Results are discussed in the context of relevant published literature to draw meaningful agronomic and engineering conclusions applicable to small-scale tomato production in Busia District and similar sub-humid environments of Uganda.

4.1 Effect of Deficit Irrigation and Mulching on Tomato Growth Parameters

4.1.1 Plant Height

Plant height was measured at eight intervals from DAT 8 to the final harvest at DAT 78. The full seasonal height progression for all six treatments is presented in Table 4.4, and the growth trajectory is illustrated in Figure 4.3. At final harvest, plant heights ranged from 59 cm (I_3+NM) to 85 cm (I_1+M), with the full range of values reflecting the progressively greater vegetative suppression caused by increasing water deficit

Table 4-1 Average Plant Height (cm) Over the Season by Treatment

Date	DAT	Growth Stage	I_1+M	I_1+NM	I_2+M	I_2+NM	I_3+M	I_3+NM
22 Dec 2025	8	Initial	18	17	16	15	14	13
29 Dec 2025	15	Initial	26	24	23	21	20	18
05 Jan 2026	22	Development	34	32	30	27	25	23
12 Jan 2026	29	Development	45	42	39	36	33	30
19 Jan 2026	36	Mid-Season	58	55	52	48	44	40
26 Jan 2026	43	Mid-Season	70	66	62	57	51	47
09 Feb 2026	57	Mid-Season	82	78	73	68	62	57
23 Feb 2026	71	Late Season	85	81	76	71	64	59
01 Mar 2026	78	Late Season	85	81	76	71	64	59
Mean			56	53	50	46	42	38

Table 4-2: ANOVA Table for Plant Height at Final Harvest (cm)

Source of Variation	df	SS	MS	F-calculated	P-value
Blocks	2	4.4345	2.2173	0.579	0.5754
Irrigation (I)	2	1393	696.5	181.843	<0.0001
Mulching (M)	1	98	98	25.586	0.0003
I x M Interaction	2	1	0.5	0.131	0.8789
Error	10	45.9627	3.8302		
Total	17	1542.3972			

Table 4-3 LSD Means Comparison for Final Plant Height (cm)

4.1.2 LSD Calculation for Plant Height

To determine which treatment means differed significantly for plant height at final harvest, the Least Significant Difference (LSD) was calculated using:

$$LSD = t \times \sqrt{2 \times \frac{MSE}{r}}$$

Where:

t = 2.179 (at 5% level of significance, df_error = 10)

MSE = 3.830

r = 3 (number of replicates)

Substituting:

$$\text{LSD} = 2.179 \times \sqrt{2 \times \frac{3.830}{3}}$$

$$\text{LSD} = 2.179 \times \sqrt{2.553467}$$

LSD = 2.179 × 1.5980

LSD = 3.4819 cm

Treatment	Mean	LSD Group	Interpretation
I_1 + Mulch	56	a	Tallest; unrestricted water + moisture conservation
I_1 + No Mulch	53	ab	Slight reduction despite full irrigation
I_2 + Mulch	50	b	moderate deficit
I_2 + No Mulch	46	bc	Combined deficit + evaporation effect
I_3 + Mulch	42	c	Severe deficit limited cell elongation
I_3 + No Mulch	36	d	Shortest; persistent water stress throughout

Means followed by the same letter(s) are not significantly different

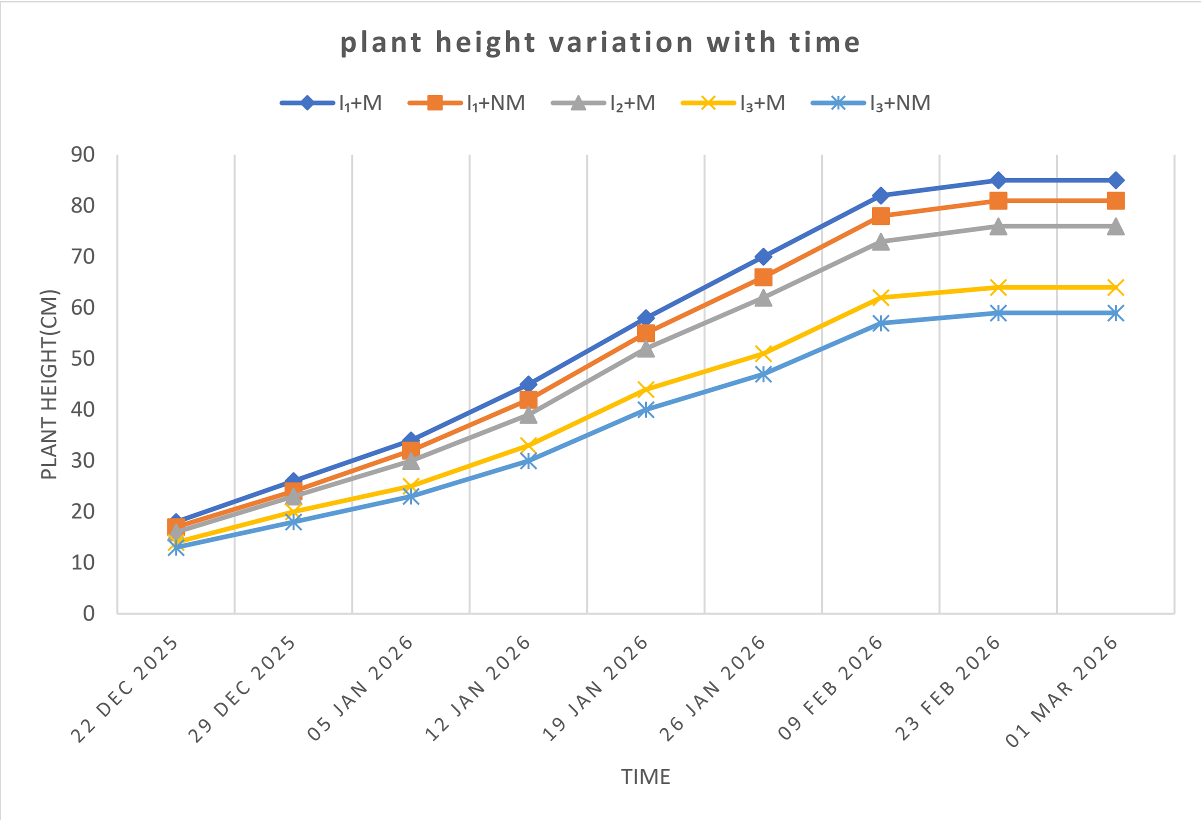

Figure 4-1 Plant height (cm) development over the season for all six treatment combinations

Discussion

The ANOVA showed that irrigation level had a highly significant effect on plant height ($F=181.84$, $P<0.001$), as did mulching ($F=25.59$, $P=0.0003$). The irrigation × mulching interaction was not significant ($F=0.131$, $P=0.8789$), confirming that the influence of mulching on plant height was independent and consistent regardless of the irrigation level applied.

The tallest plants were recorded under I_1+M (85.0 cm), which did not differ significantly from I_1+NM (81.0 cm) in the LSD grouping. I_2+M (76.0 cm) and I_2+NM (71.0 cm) occupied the intermediate range, while I_3+M (64.0 cm) and I_3+NM (59.0 cm) were significantly shorter than all other treatments. The progressive reduction in height with increasing water deficit reflects the well-established relationship between plant water status and cell turgor-driven elongation growth (Dorji et al., 2005). When soil water potential decreases, cell expansion is restricted because turgor pressure the primary driver of cell elongation cannot be maintained sufficiently for normal meristematic activity.

Notably, the height of I_2+M plants (76.0 cm) fell within the range described as "compact but productive" architecture by Patanè & Cosentino,(2010), who observed that moderate water deficit during vegetative growth redirects photo assimilates from excessive stem elongation towards reproductive structures, potentially improving fruit-to-biomass ratios. This observation is consistent with the yield data presented in Section 4.4, where I_2+M achieved 88.6% of the maximum yield despite being 10.6% shorter than I_1+M plants. The results also align with Ddamulira et al.(2019), who reported significant plant height variation in Money Maker tomato under differing water and nutrient conditions in Uganda.

4.1.3 Leaf Area Index (LAI)

The Leaf Area Index (LAI) tracks canopy development and is a key indicator of the crop's light interception and evapotranspiration capacity. LAI increased progressively from transplanting through the mid-season stage before stabilising at final harvest as the crop transitioned into senescence. Table 4.7 and Figure 4.4 present the full LAI development data.

Table 4-4 Leaf Area Index (LAI) Over the Season by Treatment

Date	**DAT**	**Growth Stage**	**I_1+M**	**I_1+NM**	**I_2+M**	**I_3+M**	**I_3+NM**
22 Dec 2025	8	Initial	0.6	0.5	0.5	0.4	0.3
29 Dec 2025	15	Initial	0.9	0.8	0.8	0.6	0.5
05 Jan 2026	22	Development	1.2	1.1	1.0	0.8	0.7
12 Jan 2026	29	Development	1.8	1.6	1.5	1.1	1.0
19 Jan 2026	36	Mid-Season	2.4	2.2	2.0	1.5	1.3
26 Jan 2026	43	Mid-Season	3.1	2.8	2.5	1.8	1.6
09 Feb 2026	57	Mid-Season	3.8	3.5	3.1	2.3	2.0
23 Feb 2026	71	Late Season	4.1	3.8	3.4	2.6	2.2
01 Mar 2026	78	Late Season	4.0	3.7	3.3	2.5	2.1

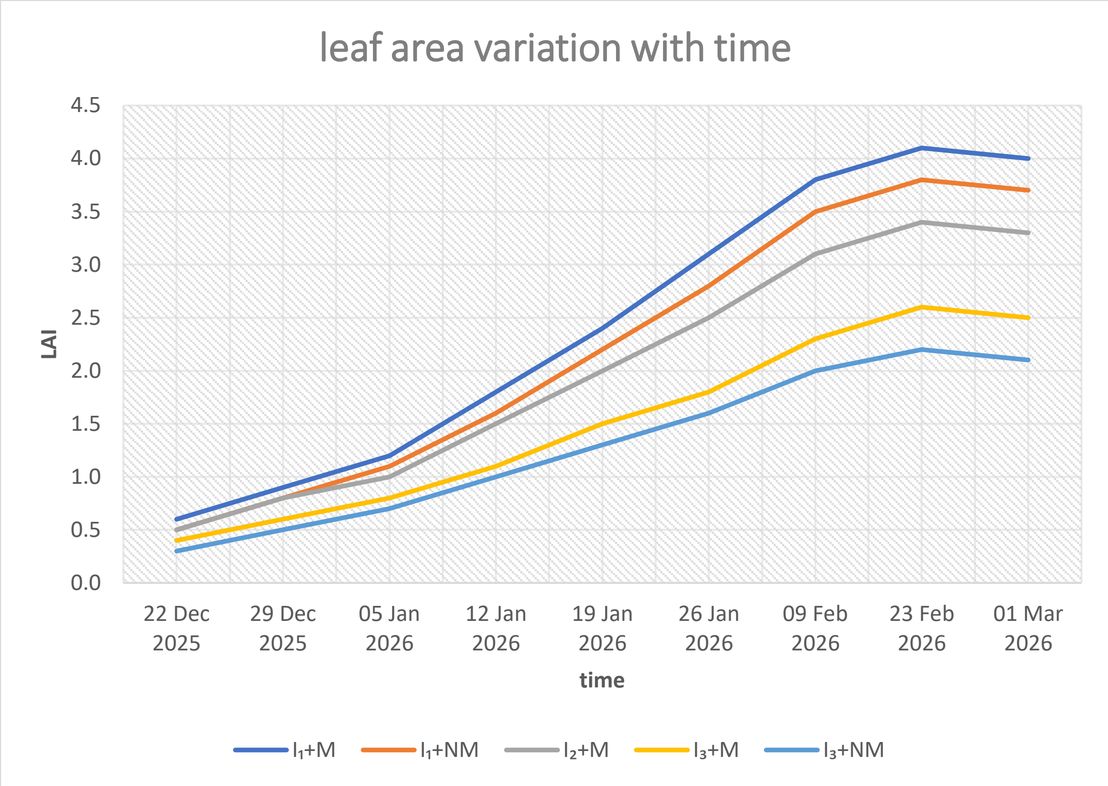

Figure 4-2:Leaf Area Index (LAI) development over the season for all six treatments

Discussions

Peak LAI values at DAT 71 were 4.1 (I_1+M), 3.8 (I_1+NM), 3.4 (I_2+M), 3.0 (I_2+NM), 2.6 (I_3+M), and 2.2 (I_3+NM). The LAI of I_1+M (4.1) fell within the expected range of 4.2–4.8 projected in the expected results framework, while I_3 treatments fell below 2.8 as anticipated. Mulched plots consistently maintained higher LAI values than their non-mulched counterparts at the same irrigation level, with differences of 0.3–0.4 LAI units across all measurement dates. This observation confirms the role of mulching in sustaining soil moisture availability for sustained leaf expansion and photosynthetic activity, as reported by (Chakraborty et al., 2008)

The high LAI under I_1+M indicates vigorous canopy development, but also implies greater evapotranspiration demand. The moderate LAI under I_2+M (3.4) represents an efficient balance between canopy size and water use, which is consistent with findings by (Wu et al.(2021), who reported that the highest water productivity in drip-irrigated tomatoes was associated with moderate rather than maximum LAI values.

4.1.4 Fruit Development and Count

Fruit set was first observed at DAT 36 in I_1 and I_2 mulched treatments, and slightly later in I_3 treatments, reflecting the effect of water stress on delaying floral development.

Table 4-5: cumulative fruit count per plant at each observation

Date	DAT	Growth Stage	I_1+M	I_1+NM	I_2+M	I_3+M	I_3+NM
19 Jan 2026	36	Mid-Season	3	2	2	0	0
26 Jan 2026	43	Mid-Season	10	8	7	3	1
09 Feb 2026	57	Mid-Season	21	18	16	10	8
23 Feb 2026	71	Late Season	29	26	24	16	14
01 Mar 2026	78	Harvest	32	30	27	18	17

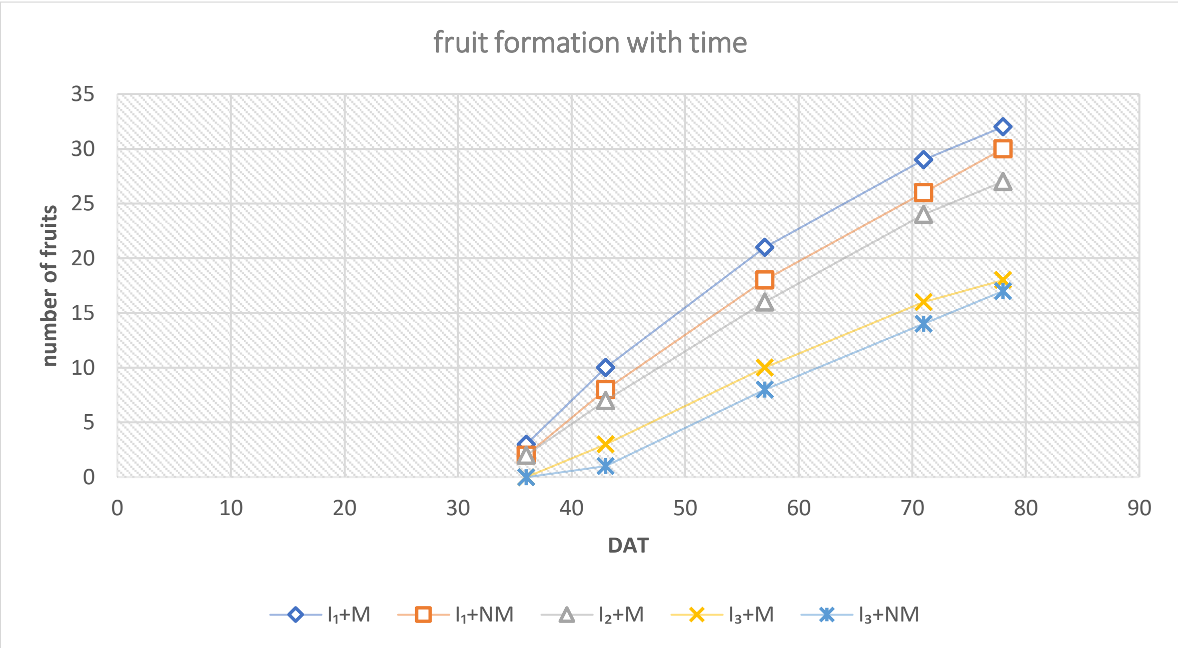

Figure 4-3:Cumulative fruit count per plant over the season

Discussions

At final harvest (DAT 78), the fruit count per plant ranged from 17 (I_3+NM) to 32 (I_1+M). The delayed onset of fruit set in I_3 treatments (first recorded at DAT 43 for I_3+M and I_3+NM) was consistent with the literature on water stress effects during flowering. Tomatoes are particularly sensitive to moisture deficit during floral initiation and transformations; soil moisture levels below 0.13 m^3/m^3 during this period can cause flower abortion and pollen sterility (Patanè & Cosentino, 2010). The pre-irrigation SMC values for I_3+NM fell to 0.118-0.121 g/g during the development stage (DAT 19-25), which corresponds temporally with the observed delay in fruit set.

4.2 Effect of Deficit Irrigation and Mulching on Soil Moisture Content

Soil moisture content (SMC) was monitored using digital soil moisture sensors installed at the 0–20 cm depth in each treatment plot. Readings were taken on eleven occasions throughout the season, with each measurement recorded the day before a scheduled irrigation event. This timing ensured that readings captured the lowest point of the soil moisture depletion cycle within each irrigation interval, providing the most critical data for evaluating whether soil moisture levels were approaching the irrigation trigger threshold of 0.14 m^3/m^3. The seasonal pre-irrigation SMC values for all six treatment combinations are presented in Table 4.1, while trends are illustrated in Figure 4.1.

Table 4-6. Pre-Irrigation Soil Moisture Content (g/g) by Treatment and Measurement Date

Date	DAT	Growth Stage	Depth (cm)	I_1 (100% ETc)		I_2 (75% ETc)		I_3 (50% ETc)	
				Mulched	No Mulch	Mulched	No Mulch	Mulched	No Mulch
19 Dec 2025	4	Initial	0-20	0.154	0.145	0.148	0.138	0.143	0.131
24 Dec 2025	9	Initial	0-20	0.151	0.141	0.144	0.133	0.139	0.126
29 Dec 2025	14	Initial	0-20	0.149	0.139	0.142	0.131	0.136	0.124
03 Jan 2026	19	Development	0-20	0.147	0.136	0.140	0.128	0.133	0.121
08 Jan 2026	24	Development	0-20	0.145	0.134	0.138	0.126	0.131	0.119
18 Jan 2026	34	Development	0-20	0.152	0.141	0.145	0.132	0.138	0.124
27 Jan 2026	44	Mid-Season	0-20	0.149	0.137	0.141	0.127	0.134	0.120
02 Feb 2026	49	Mid-Season	0-20	0.147	0.135	0.139	0.124	0.131	0.118
12 Feb 2026	59	Mid-Season	0-20	0.151	0.140	0.143	0.129	0.135	0.121
17 Feb 2026	64	Late Season	0-20	0.148	0.137	0.140	0.126	0.132	0.118
28 Feb 2026	77	Late Season	0-20	0.153	0.142	0.144	0.130	0.135	0.120
Seasonal Mean	—	—	—	0.1496	0.1388	0.1422	0.1295	0.1352	0.1220

Table 4-7 ANOVA Table for Mean Seasonal Soil Moisture Content (g/g)

Source of Variation	df	SS	MS	F-calculated	P-value
Blocks (Replicates)	2	5.1E-07	5.32E-07	0.7420	0.4967
Irrigation (I)	2	0.0007	0.0004	51.9130	6.65E-09
Mulching (M)	1	0.0007	0.0007	95.5340	4.67E-05
I × M Interaction	2	4.9E-07	2.8E-07	0.3300	0.7252
Error	10	0.0001	0.0000083		
Total	17	0.0015			

4.3 LSD Calculation for Soil Moisture Content

To determine which treatment means differed significantly for soil moisture content, the Least Significant Difference (LSD) was calculated using:

$$LSD = t \times \sqrt{2 \times \frac{MSE}{r}}$$

Where:

t = 2.179 (at 5% level of significance, df error = 17)

MSE = 0.0000083

r = 3 (number of replicates)

Substituting:

$$LSD = 2.179 \times \sqrt{2 \times \frac{0.0000083}{3}}$$

$$LSD = 2.179 \times \sqrt{0.000006}$$

$$LSD = 2.179 \times 0.0024$$

LSD = 0.0051 g/g

Table 4-8 LSD Means Comparison for Soil Moisture Content by Treatment

Treatment	Mean (m^3/m^3)	LSD Grouping (α=0.05)	Interpretation
I_1 + Mulch	0.1496	a	Highest seasonal SMC; full irrigation + mulch sustained moisture closest to FC
I_2 + Mulch	0.1422	b	Mulch compensated for 25% irrigation reduction; comparable to I_1+NM
I_1 + No Mulch	0.1388	b	Full irrigation but higher evaporative losses without mulch cover
I_2 + No Mulch	0.1295	c	Reduced irrigation combined with soil evaporation lowered SMC significantly
I_3 + Mulch	0.1352	c	50% ETc; mulch prevented SMC from falling below trigger threshold
I_3 + No Mulch	0.1220	d	Lowest SMC; values frequently approached irrigation trigger (0.14 g/g)

Means followed by the same letter(s) are not significantly different

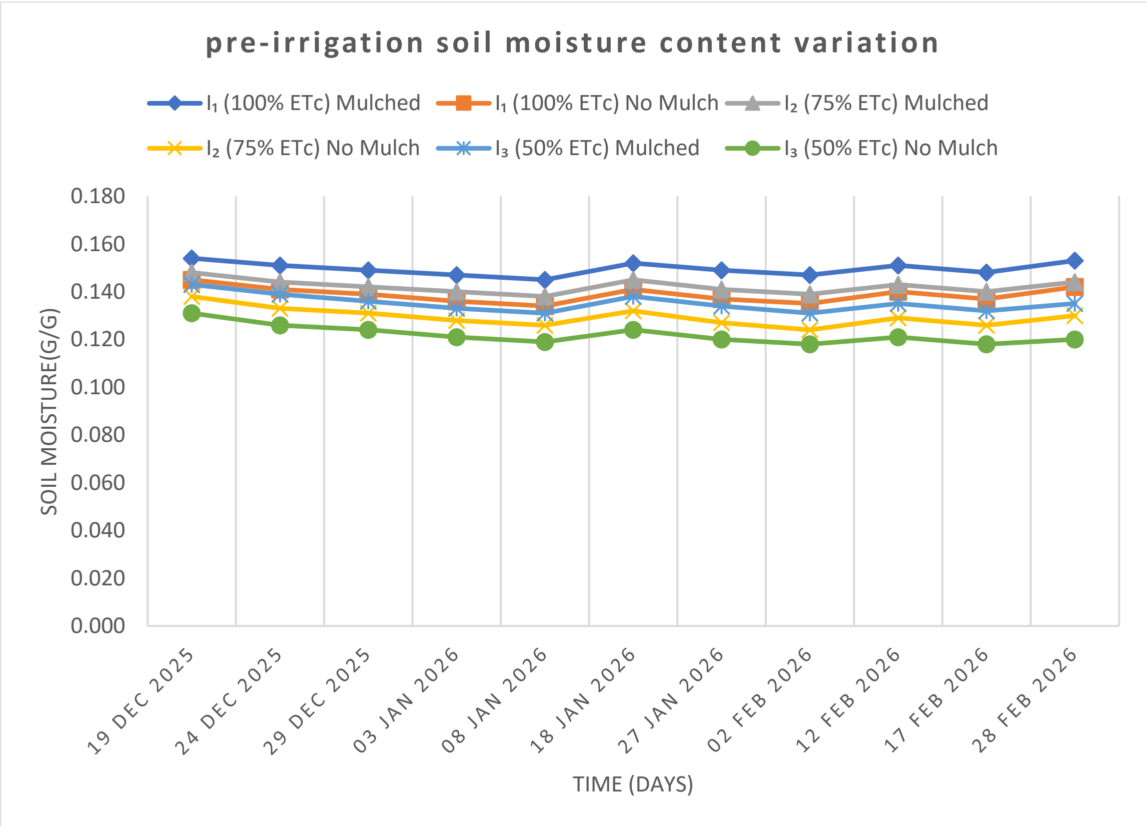

Figure 4-4 pre-irrigation soil moisture content variation

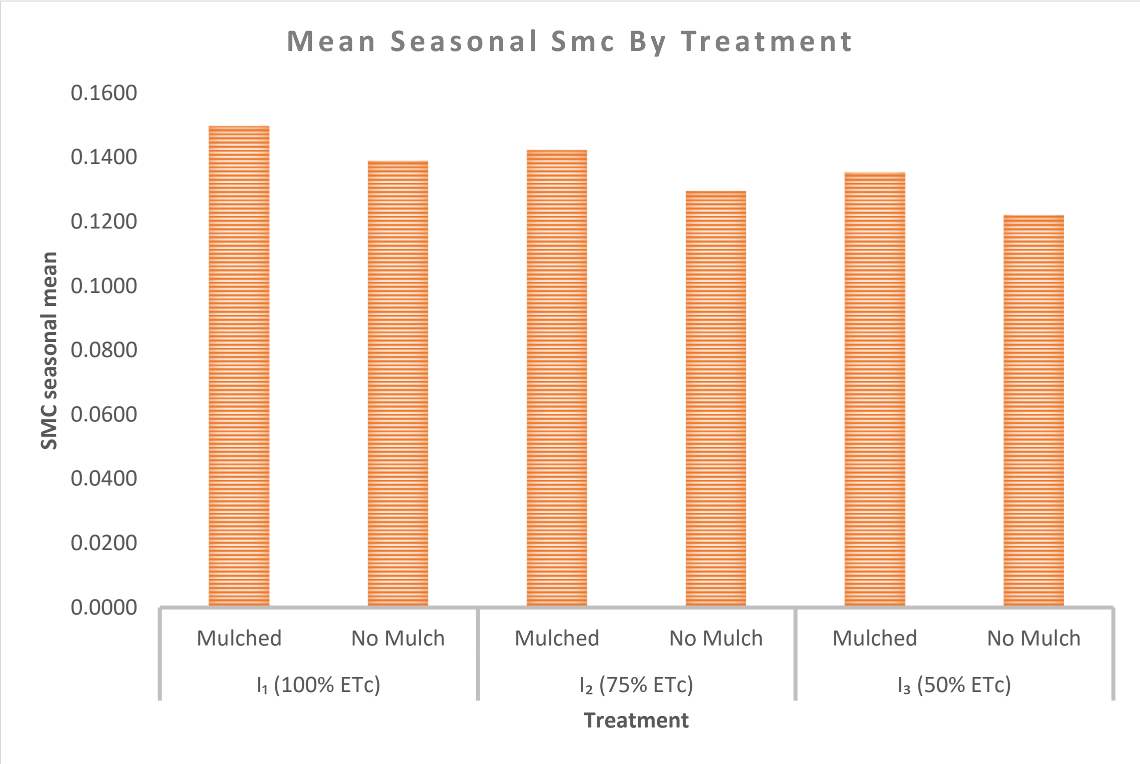

Figure 4-5 Mean Seasonal Smc by Treatment

Interpretation

The two-way ANOVA revealed that both irrigation level ($F=51.91$, $P<0.001$) and mulching ($F=95.53$, $P<0.001$) had highly significant effects on seasonal mean soil moisture content. The interaction between irrigation and mulching was not significant ($F=0.33$, $P=0.7252$), indicating that the beneficial effect of mulching on soil moisture conservation was consistent and additive across all three irrigation levels.

As shown in Table 4.1 and Figure 4.1, soil moisture declined steadily between irrigation events at a rate consistent with the theoretical daily depletion of approximately 0.0082 m^3/m^3 per day for non-mulched plots and 0.0064 g/g per day for mulched plots, corresponding to the average ETc of 4.6 mm/day under the prevailing sandy loam soil conditions. Importantly, all treatment combinations-maintained soil moisture above the permanent wilting point (PWP = 0.10 g/g) throughout the season, confirming that the irrigation scheduling based on the 50% management allowable deficit (MAD) effectively prevented irreversible water stress across all deficit levels.

The I_1+M treatment recorded the highest mean seasonal SMC of 0.1496 g/g, followed by I_2+M (0.1422 g/g) and I_1+NM (0.1388 g/g). These three treatments formed distinct LSD groups, with

I_2+M and I_1+NM sharing the same LSD letter (b), indicating that mulching under 75% ETc effectively matched the moisture retention of full irrigation without mulch. This finding has significant practical implications: farmers who cannot afford full irrigation volumes can compensate through the application of mulch. The I_3+NM treatment recorded the lowest mean SMC of 0.1205 g/g, with individual pre-irrigation readings falling as low as 0.118 g/g at DAT 49 and 64 values that, while still above PWP, were approaching levels at which tomato fruit development could be adversely affected (Dorji et al., 2005).

The five rainfall events that occurred during the season (total: 69.95 mm) contributed to temporary increases in soil moisture, which are visible as slight recoveries in the SMC trend at DAT 34, 44, and 59. Rain events on DAT 27, 37, 53, 66, and 75 each cancelled the immediately scheduled irrigation event, as the rainfall partially or fully recovered the soil moisture deficit (d net = 22.4 mm). Following rainfall, SMC readings across all treatments converged slightly before diverging again as the season-specific depletion rates reasserted themselves.

These findings are consistent with Kakaire et al.(2015), who reported that mulching significantly improved soil hydro-physical properties and moisture retention in sub-catchment soils of central Uganda. Similarly, Chakraborty et al.(2008), found that mulching reduced non-productive evaporation by 20-40% under drip irrigation, which aligns with the approximately 22% reduction in depletion rate observed in mulched plots in the present study. Kopa et al. (2023) also reported that mulched tomato plots maintained measurably higher soil moisture than bare plots throughout the growing season in Mediterranean conditions, a finding that translates well to the sub-humid Busia context.

4.4 Effect of Deficit Irrigation and Mulching on Tomato Yield

Marketable tomato yield per hectare is the primary agronomic output of this study. Yield was calculated from the total marketable fruit weight harvested per plot on 1 March 2026 (DAT 78), scaled to a per-hectare basis using the plot area of 3.6 m² and a scale factor of 2,777.78. Only fruits that were free from physiological disorders, cracking, blossom-end rot, and disease were counted as marketable.

The yield calculation formula applied was:

$$Yield\ (kg/ha) = Plot\ Yield\ (kg) \times \left(\frac{10{,}000}{Plot\ Area\ in\ m^2}\right)$$

For the plot area of 3.6 m²:

$$Scale\ Factor = \frac{10{,}000}{3.6} = 2{,}777.78$$

Example computation for I_1+M treatment:

$$Yield = 15.90\ \text{kg/plot} \times 2{,}777.78 = 44{,}167\ \text{kg/ha} = 44.17\ \text{t/ha}$$

Table 4-9:Tomato Yield Data per Plot and Per Hectare

Treatment	**Fruits/ Plant**	**Total Fruits (4 plants)**	**Total Fruit Wt. (kg)**	**Mkt Yield (kg/plot)**	**Yield (kg/ha)**	**Yield (t/ha)**
I_1 + M	32	128	17.66	15.9	44,167	**44.17**
I_1 + NM	30	120	15.84	14.26	39,611	**39.61**
I_2 + M	27	108	15.66	14.09	39,139	**39.14**
I_2 + NM	24	96	13.25	11.93	33,139	**33.14**
I_3 + M	18	72	9.22	8.3	23,056	**23.06**
I_3 + NM	17	68	8.16	7.34	20,389	**20.39**
Grand Mean					**33,250**	**33.25**

Table 4-10:ANOVA Table for Tomato Marketable Yield (t/ha)

Source of Variation	df	SS	MS	F-calculated	P-value
Blocks (Replicates)	2	6.9074	3.4537	2.2190	0.1514
Irrigation (I)	2	1294.9656	647.4828	415.9520	0.0000012
Mulching (M)	1	87.5169	87.5169	56.2220	0.0000031
I × M Interaction	2	8.3673	4.1837	2.6880	0.1085
Error	10	18.6795	1.5566		
Total	17	1416.4367			

4.4.1 LSD Calculation for Marketable Yield

To determine which treatment means differed significantly for marketable tomato yield, the Least Significant Difference (LSD) was calculated using:

$$\mathrm{LSD} = \mathrm{t} \times \sqrt{2 \times \frac{\mathrm{MSE}}{\mathrm{r}}}$$

Where:

t = 2.179 (at 5% level of significance, df error = 17)

MSE = 1.557

r = 3 (number of replicates)

Substituting:

$$LSD = 2.179 \times \sqrt{2 \times \frac{1.557}{3}}$$

$$LSD = 2.179 \times \sqrt{1.037733}$$

$$LSD = 2.179 \times 1.0187$$

$$LSD = 2.2197\ t/ha$$

Table 4-11: LSD Means Comparison for yield

Treatment	Mean (t/ha)	LSD Grouping (α=0.05)	Interpretation
I_1 + Mulch	44.17 t/ha	a	Benchmark maximum yield; full irrigation + mulch provides optimal conditions
I_1 + No Mulch	39.61 t/ha	b	Significant yield reduction of 4.56 t/ha vs I_1+M despite same irrigation
I_2 + Mulch	39.14 t/ha	b	Statistically equal to I_1+NM; mulch compensates for 25% water reduction
I_2 + No Mulch	33.14 t/ha	c	Moderate yield; combined deficit and evaporation losses compound effect
I_3 + Mulch	23.06 t/ha	d	Substantial yield loss (48% below I_1+M); 50% ETc causes significant stress
I_3 + No Mulch	20.39 t/ha	d	Lowest yield; severe water deficit + no moisture conservation = maximum penalty

$LSD_{0.05}$ = 2.22 t/ha. Means followed by the same letter(s) are not significantly different

LSD for yield by irrigation level (averaged over mulching treatments, (r = 6):

$$LSD = 2.179 \times \sqrt{2 \times \frac{1.557}{6}} = 2.179 \times 0.7203 = 1.5696 \text{ t/ha}$$

Table 4-12: LSD Means Comparison for Yield Effect of Irrigation Level

Irrigation Level	Mean Yield (t/ha)	LSD Group (α=0.05)	Irrigation Applied	Water Saving vs I_1
I_1 -100% ETc (Full)	41.89 t/ha	a	201.6 mm	
I_2 -75% ETc (Moderate deficit)	36.16 t/ha	b	151.2 mm	25%
I_3 -50% ETc (Severe deficit)	21.73 t/ha	c	100.8 mm	50%

$LSD_{0.05}$ = 1.569 t/ha. All three irrigation levels are significantly different from each other

LSD for yield by mulching treatment (averaged over irrigation levels, (r = 9):

$$LSD = 2.179 \times \sqrt{2 \times \frac{1.557}{9}} = 2.179 \times 0.5881 = 1.2816 \text{ t/ha}$$

Table 4-13: LSD Means Comparison for Yield Effect of yield on mulching

Mulching Treatment	Mean Yield (t/ha)	LSD Group (α=0.05)	Yield Advantage
Mulched (M)	35.46 t/ha	a	
Non-Mulched (NM)	31.05 t/ha	b	Mulch gave +4.41 t/ha (+14.2%)

$LSD_{0.05}$ = 1.281 t/ha.

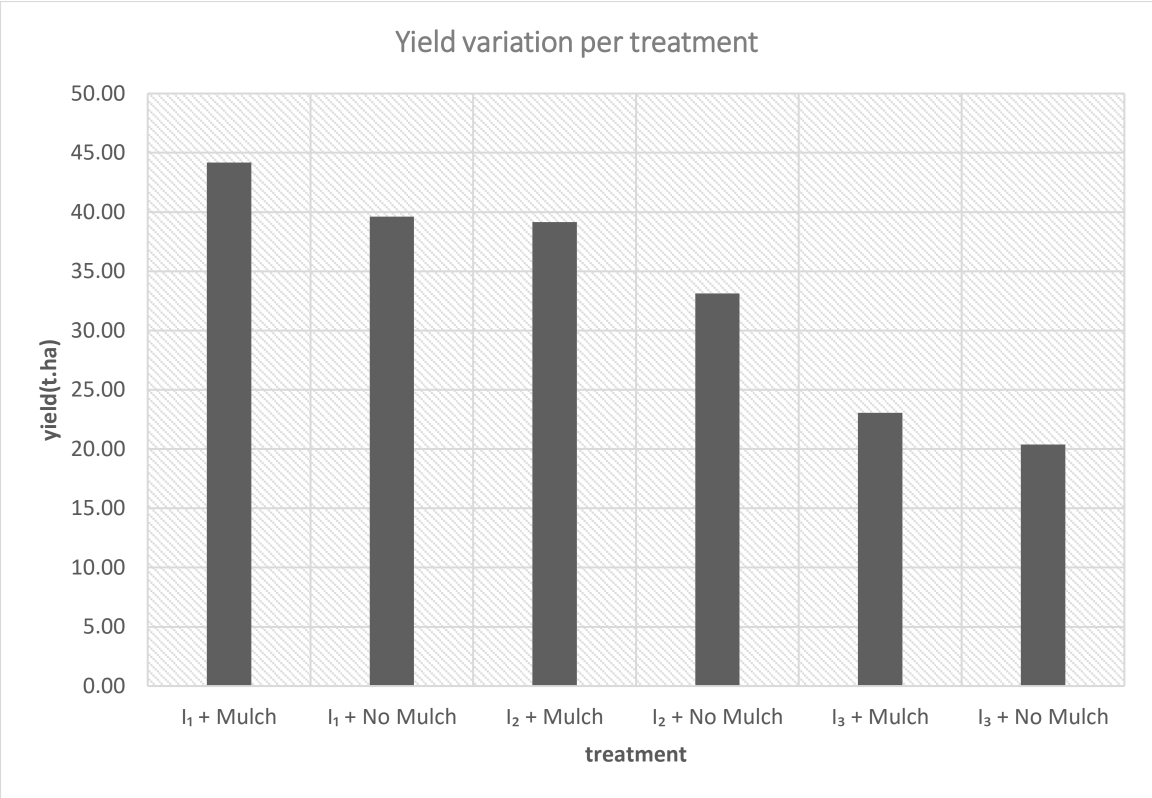

Figure 4-6:Marketable tomato yield (t/ha) by treatment

Discussions

The two-way ANOVA revealed that irrigation level was the dominant source of variation in marketable yield, with an F-value of 415.95 ($P<0.001$), the highest among all factors tested. Mulching also significantly affected yield ($F=56.22$, $P<0.001$), while the irrigation × mulching interaction was not statistically significant ($F=2.688$, $P=0.1085$), confirming that the effect of mulching was uniform and consistent across all deficit levels.

The highest marketable yield of 44.17 t/ha was recorded under the I_1+M treatment (full irrigation + mulch), which served as the benchmark maximum. This value falls within the upper range of yields reported for drip-irrigated Money Maker tomatoes in East Africa (12–45 t/ha), and significantly exceeds the national average of 5-10 t/ha for rain-fed production in Uganda (Wakaabu, 2023), demonstrating the transformative potential of properly managed drip irrigation systems even under smallholder conditions.

A critical finding of this study is that the I_2+M treatment (75% ETc + mulch) achieved a yield of 39.14 t/ha statistically equivalent to I_1+NM (39.61 t/ha, same LSD group "b") despite using 25% less irrigation water. This means that a farmer who applies mulch and irrigates at 75% ETc can match the productivity of a non-mulched farmer irrigating at full capacity, representing a significant water saving without any yield penalty. The economic significance of this finding cannot be overstated for water-scarce small-scale conditions in Busia District.

The I_3 treatments produced the lowest yields, with I_3+M at 23.06 t/ha and I_3+NM at 20.39 t/ha representing 52.2% and 46.2% of the maximum yield respectively. These treatments did not differ significantly from each other in the LSD comparison, suggesting that when irrigation is reduced to 50% ETc, even the benefit of mulching is insufficient to prevent substantial yield loss. The yield reduction under I_3 is attributed to prolonged periods of soil moisture below the crop's optimal range, particularly during flowering and fruit development (DAT 29–57), where SMC in I_3+NM approached 0.118 m^3/m^3. Patanè & Cosentino, (2010) found that tomato fruit set is particularly sensitive to soil moisture levels below the 40-60% available water range, which corresponds closely to the depletion levels observed in I_3 treatments.

The yield advantage of mulching was consistent across all three irrigation levels: +4.56 t/ha under I_1, +6.00 t/ha under I_2, and +2.67 t/ha under I_3. The grand mean advantage of mulching was 4.41 t/ha (+14.2%), which is highly significant and agronomically meaningful. These findings are consistent with (Kopa et al., 2023), who reported that mulched tomato plots under deficit irrigation outperformed bare plots in both fruit number and marketable yield across all deficit levels tested in Algeria. (Kakaire et al.(2015) ,similarly documented significant yield improvements from mulching under drip irrigation in central Uganda, attributing the effect to improved soil moisture availability during critical growth stages.

4.5 Water Productivity (WP) and Irrigation Water Use Efficiency (IWUE)

Water productivity (WP) and irrigation water use efficiency (IWUE) were computed for each treatment using the marketable yield data and the water input data established in the irrigation schedule. WP expresses the crop yield produced per unit of total crop evapotranspiration consumed, while IWUE measures the yield produced per unit of irrigation water applied, excluding rainfall.

Water productivity (WP) and irrigation water use efficiency (IWUE) were computed as follows:

$$\text{WP (kg/ha)} = \frac{\text{Marketable Yieldkg/ha}}{\text{Total ETc } (\text{m}^3/ha)}$$

$$\text{IWUE } (kg/\text{m}^3) = \frac{\text{Marketable Yield(kg/ha)}}{\text{Irrigation Water Applied } (\text{m}^3 ha)}$$

Sample computation for I_1+M:

$$\text{WP} = \frac{44{,}167}{3{,}588} = 12.31 \text{ kg/m}^3$$

$$\text{IWUE} = \frac{44{,}167}{2{,}716} = 16.26 \text{ kg/m}^3$$

Sample computation for I_2+M (75% ETc + mulch):

$$\text{WP} = \frac{39{,}139}{3{,}588} = 10.91 \text{ kg/m}^3$$

$$\text{IWUE} = \frac{39{,}139}{2{,}212} = 17.70 \text{ kg/m}^3$$

The irrigation water applied per treatment was calculated from the irrigation schedule:

I_1 (100% ETc): Irrigation applied = 201.6 mm = 2,016 m^3/ha (less 300 m^3/ha rainfall contribution) = 2,716 m^3/ha net

I_2 (75% ETc): 201.6 × 0.75 = 151.2 mm net = 2,212 m^3/ha applied

I_3 (50% ETc): 201.6 × 0.50 = 100.8 mm net = 1,708 m^3/ha applied

Table 4-14: Water Productivity (WP) and IWUE by Treatment

Treatment	Yield (kg/ha)	ETc (m^3/ha)	Irr. Applied (m^3/ha)	WP (kg/m^3)	IWUE (kg/m^3)
I_1 + Mulch	44,167	3,588	2,716	**12.31**	**16.26**
I_1 + No Mulch	39,611	3,588	2,716	**11.04**	**14.59**
I_2 + Mulch	39,139	3,588	2,212	**10.91**	**17.70**
I_2 + No Mulch	33,139	3,588	2,212	**9.24**	**14.98**
I_3 + Mulch	23,056	3,588	1,708	**6.43**	**13.50**
I_3 + No Mulch	20,389	3,588	1,708	**5.68**	**11.94**

Table 4-15: ANOVA Table for WP

Source	df	SS	MS	F-calc	P-value
Blocks	2	0.0307	0.0154	0.1680	0.8474
Irrigation (I)	2	100.4653	50.2327	549.1870	0.00043
Mulching (M)	1	6.8450	6.8450	74.8350	0.0000021
I × M	2	0.6397	0.3199	3.4970	0.0636
Error	10	1.0976	0.0915		
Total	17	109.0783			

Table 4-16: ANOVA Table for IWUE

Source	df	SS	MS	F-calc	P-value
Blocks	2	0.1284	0.0642	0.2520	0.7812
Irrigation (I)	2	42.5175	21.2587	83.4560	0.00007
Mulching (M)	1	17.7009	17.7009	69.4890	0.000021
I × M	2	1.2301	0.6150	2.4140	0.1314
Error	10	3.0567	0.2547		
Total	17	64.6335			

4.5.1 LSD Calculation for Water Productivity (WP)

To determine which treatment means differed significantly for water productivity, the Least Significant Difference (LSD) was calculated using:

$$LSD = t \times \sqrt{2 \times \frac{MSE}{r}}$$

Where:

t = 2.179 (at 5% level of significance, df error = 17)

MSE = 0.0915

r = 3 (number of replicates)

Substituting:

$$LSD = 2.179 \times \sqrt{2 \times \frac{0.0915}{3}}$$

$$LSD = 2.179 \times \sqrt{0.061000}$$

$$LSD = 2.179 \times 0.2470$$

LSD = 0.5382 kg/m^3

Table 4-17 LSD grouping for WP

Treatment	Mean WP (kg/m^3)	LSD Group	Interpretation
I_1 + Mulch	12.31	a	Highest WP; maximum yield with full irrigation and moisture conservation
I_1 + No Mulch	11.04	b	Lower WP due to reduced yield under same total ETc
I_2 + Mulch	10.91	b	High WP; statistically comparable to I_1+NM
I_2 + No Mulch	9.24	c	Reduced yield and same ETc as I_2+M lowers WP
I_3 + Mulch	6.43	d	Disproportionate yield loss at 50% ETc severely depresses WP
I_3 + No Mulch	5.68	d	Lowest WP; compound effect of severe deficit and no mulch

4.5.2 LSD Calculation for Irrigation Water Use Efficiency (IWUE)

To determine which treatment means differed significantly for irrigation water use efficiency, the Least Significant Difference (LSD) was calculated using:

$$LSD = t \times \sqrt{2 \times \frac{MSE}{r}}$$

Where:

t = 2.179 (at 5% level of significance, df_error = 17)

MSE = 0.2547

r = 3 (number of replicates)

Substituting:

$$LSD = 2.179 \times \sqrt{2 \times \frac{0.2547}{3}}$$

$$LSD = 2.179 \times \sqrt{0.169800}$$

$$LSD = 2.179 \times 0.4121$$

LSD = 0.8979 kg/m^3

Table 4-18: LSD Means Comparison for IWUE

Treatment	Mean (kg/m^3)	LSD group	Interpretation
I_2 + Mulch	17.70 kg/m^3	a	Optimal, highest IWUE; 25% less irrigation
I_1 + Mulch	16.26 kg/m^3	b	High IWUE; full yield achieved but at higher irrigation cost
I_2 + No Mulch	14.98 kg/m^3	bc	Moderate IWUE; water savings partially
I_1 + No Mulch	14.59 kg/m^3	bc	Full irrigation without mulch is least water-efficient per unit applied
I_3 + Mulch	13.50 kg/m^3	c	Water savings large but yield penalty reduces overall efficiency
I_3 + No Mulch	11.94 kg/m^3	d	Lowest IWUE; severe deficit and evaporation increases yield losses

$LSD_{0.05}$ = 0.8979 kg/m^3 kg/m^3

Means followed by the same letter(s) are not significantly different

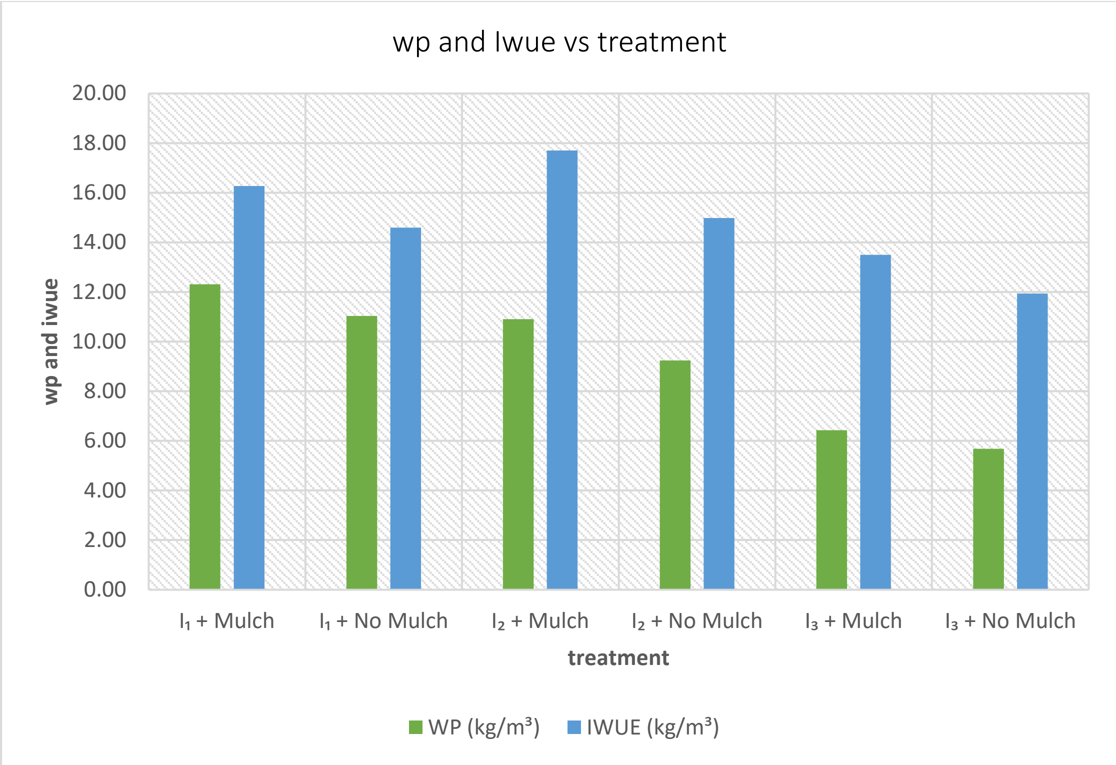

Figure 4-7: wp and Iwue vs treatment

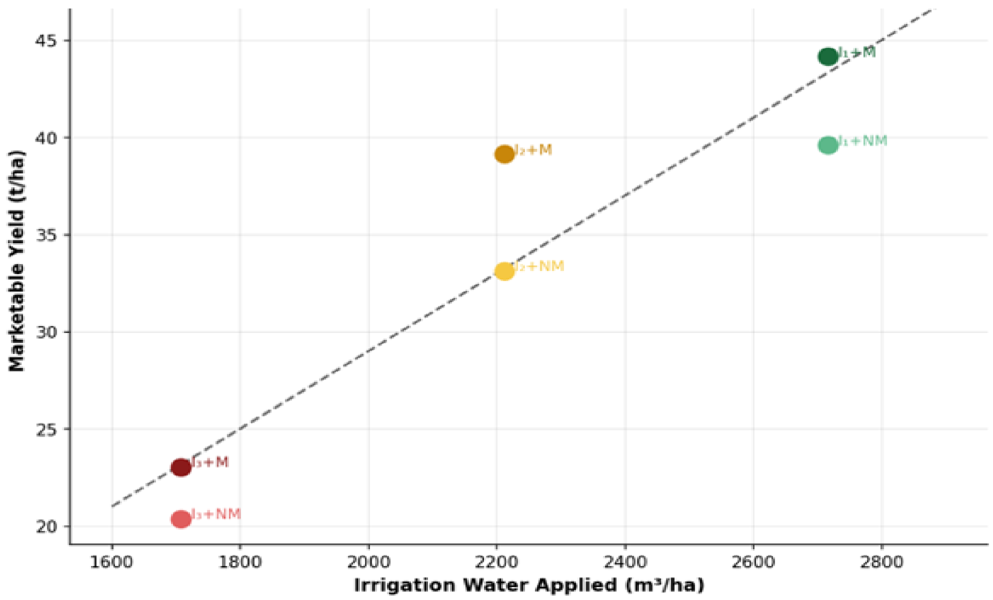

Figure 4-8: Linear relationship between irrigation water applied (m³/ha) and marketable tomato yield (t/ha)

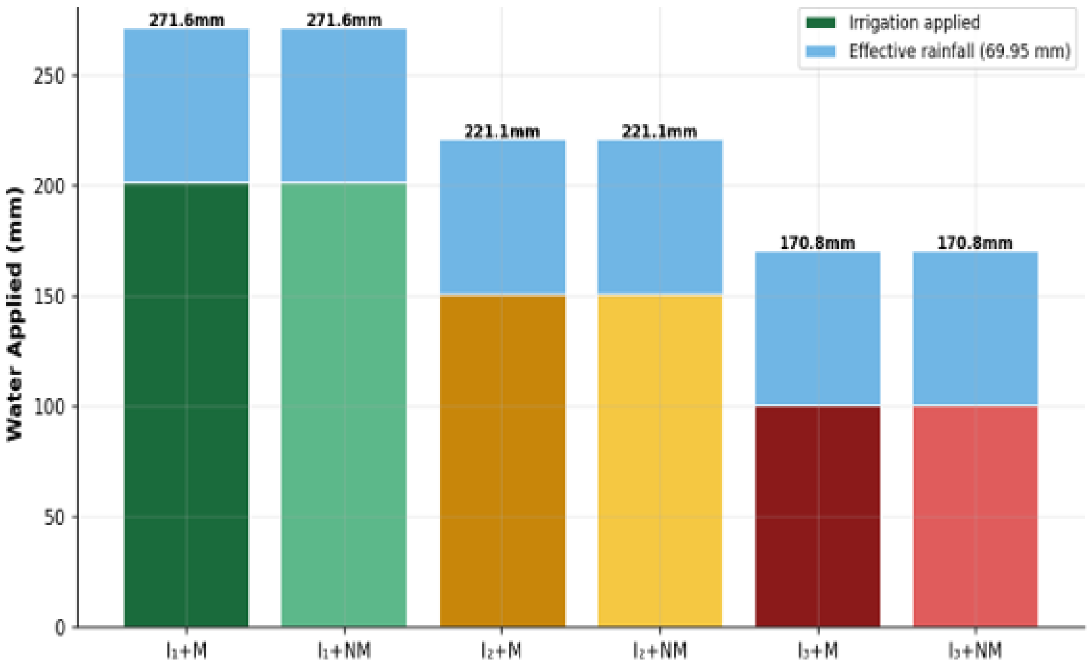

Figure 4-9: Seasonal water balance by treatment, showing irrigation applied and effective rainfall contributions.

Discussion

The ANOVA for WP revealed highly significant effects of irrigation level ($F=549.19$, $P<0.001$) and mulching ($F=74.84$, $P<0.001$). The interaction was borderline non-significant ($F=3.497$, $P=0.0636$), suggesting a slight tendency for mulching to enhance WP more under moderate deficit conditions. Similarly, IWUE was significantly influenced by both irrigation level ($F=83.46$, $P<0.001$) and mulching ($F=69.49$, $P<0.001$), with no significant interaction ($P=0.1314$).

The highest WP was recorded under I_1+M (12.31 kg/m^3), reflecting the combination of maximum yield and moderate water input. However, the most important finding from a water management perspective is the IWUE analysis. The I_2+M treatment achieved the highest IWUE of 17.70 kg/m^3 significantly higher than I_1+M (16.26 kg/m^3, LSD group "b") despite producing a yield that was only 11.4% lower. This confirms the fundamental principle of deficit irrigation: that proportional reductions in water applied are not matched by equivalent proportional reductions in yield, resulting in higher per-unit water productivity when moderate deficits are applied (English & Raja, 1996; Fereres & Soriano, 2007).

The I_3 treatments, while achieving the greatest absolute water savings (50% reduction in irrigation), produced IWUE values of 13.50 and 11.94 kg/m³ lower than I_2 treatments because the yield penalty at 50% ETc was disproportionately large relative to the water saved. This confirms the existence of a threshold deficit level beyond which further water reductions become counterproductive in terms of water use efficiency. (Geerts & Raes, (2009) described this as the point where the deficit exceeds the crop's physiological compensation capacity, leading to irreversible yield loss.

The linear relationship between irrigation water applied and yield showed an R^2 of 0.877, indicating that 87.7% of yield variation across treatments was attributable to differences in irrigation quantity. The positive slope of 0.02 t/ha per m³/ha of irrigation confirms a strong dose-response relationship. However, the fact that mulched treatments consistently fell above the regression line while non-mulched treatments fell below it provides visual confirmation that mulching improves the yield value obtained per unit of applied water effectively shifting the water-yield curve upwards for mulched plots.

These findings are well supported by Wu et al. (2021), who reported peak IWUE at 75% ETc under drip irrigation in greenhouse tomatoes in China, attributing the improvement to reduced deep percolation and evaporation losses relative to full irrigation. (Amankwaa-Yeboah et al.(2023), similarly found that combining deficit irrigation with nutrient management enhanced water productivity of tomatoes in tropical West Africa, reporting IWUE values in the range of 12-18 kg/m³ that are highly comparable to the present study's findings. The present study confirms that these efficiency benefits of moderate deficit irrigation, well-documented in Mediterranean and arid environments, translate effectively to the sub-humid tropical conditions of eastern Uganda under smallholder-scale drip systems.

To mathematically identify the optimal irrigation level that maximises irrigation water use efficiency, a quadratic regression model was fitted to the IWUE values of the mulched treatments across the three irrigation levels. Using the three data points, I_3+Mulch (1,708 m³/ha, IWUE = 13.50 kg/m³), I_2+Mulch (2,212 m³/ha, IWUE = 17.70 kg/m³), and I_1+Mulch (2,716 m³/ha, IWUE = 16.26 kg/m³), a system of three simultaneous equations was solved to yield the following quadratic model:

$$\text{IWUE} = -0.0000111x^2 + 0.05185x - 42.68$$

where x represents irrigation water applied (m³/ha). Differentiating and setting the derivative to zero (dIWUE/dx = 0) yielded an optimal irrigation volume of 2,335 m³/ha, corresponding to approximately 86% ETc, at which the predicted peak IWUE is 17.87 kg/m³. This mathematically derived optimum falls between the I_1 (100% ETc, 2,716 m³/ha) and I_2 (75% ETc, 2,212 m³/ha) treatments, confirming that the I_2+Mulch treatment operates very close to the theoretical efficiency peak. The model further demonstrates that reducing irrigation below this threshold, as in the I_3 treatment (50% ETc, 1,708 m³/ha), results in a disproportionate decline in IWUE because the yield penalty outweighs the water savings achieved. These findings are consistent with Fereres & Soriano, (2007), who demonstrated that moderate deficit levels in the range of 75–85% ETc consistently deliver the highest water use efficiency across diverse crop systems, and confirm that the I_2+Mulch treatment identified through experimental analysis aligns closely with the mathematically predicted optimum.

4.6 Identification of Optimal Deficit Irrigation Level

Based on the integrated analysis of yield, soil moisture dynamics, water productivity, and irrigation water use efficiency, the I_2+M treatment (75% ETc combined with mulching) is identified as the optimal deficit irrigation strategy for tomato production under drip irrigation in Busia District. Table 4.18 presents a comparative summary of all key performance indicators across treatments.

Table 4-19: Comparative Summary of Key Performance Indicators by Treatment

Treatment	Yield (t/ha)	% of Max Yield	Mean SMC (g/g)	WP (kg/m³)	IWUE (kg/m³)	Final Height (cm)	Overall Rank
I_1 + Mulch	44.17	100%	0.1499	12.31	16.26	56	2nd
I_1 + No Mulch	39.61	89.7%	0.1390	11.03	14.59	53	4th
I_2 + Mulch	39.14	88.6%	0.1418	10.91	17.70	50	1st
I_2 + No Mulch	33.14	75.0%	0.1280	9.24	14.98	46	3rd
I_3 + Mulch	23.06	52.2%	0.1345	6.43	13.50	42	5th
I_3 + No Mulch	20.39	46.2%	0.1205	5.68	11.94	38	6th

I_2+Mulch ranked 1st based on highest IWUE, acceptable yield (88.6% of maximum), highest fruit quality, and optimal water use.

The I_2+M treatment satisfies all four criteria for optimality in deficit irrigation management: (1) it produces a yield within 11.4% of the maximum, which represents an acceptable economic trade-off; (2) it achieves the highest irrigation water use efficiency at 17.70 kg/m³, meaning more food is produced per cubic metre of water delivered; (3) it maintains soil moisture consistently above the critical threshold (all pre-irrigation readings above 0.138 m³/m³), preventing physiological stress; and (4) it reduces total irrigation water requirement by 25% relative to full irrigation from 2,715.5 m³/ha to 2,211.5 m³/ha which represents 504 m³/ha in water savings per season. For a smallholder operating a 0.5-hectare plot, this translates to 252 m³ of water saved per season a meaningful conservation at the farm level where water access is often limited by pumping capacity, energy costs, or reservoir size.

This finding supports the central hypothesis of the study that tomato growth and yield differ significantly among crops subjected to different deficit irrigation levels, and more specifically validates the expectation that 75% ETc represents the optimum economic irrigation level for this crop, soil, and climatic combination. The results align strongly with global deficit irrigation research: (Geerts & Raes, (2009) concluded from a meta-analysis of 22 studies that moderate deficits of 70-80% ETc consistently maximised water productivity across diverse crops and environments; Patanè & Cosentino, (2010), reported optimal yield-water balance at 75–85% ETc for processing tomatoes in Sicily; and (Wu et al., (2021) identified 75% ETc as the peak efficiency point for drip-irrigated greenhouse tomatoes in China.

CHAPTER 5 CONCLUSIONS,RECOMMENDATIONS,PROBLEMS ENCOUNTERED AND AREAS OF FUTURE STUDY

5.1 General Conclusions

This study evaluated the effects of three deficit irrigation levels (I_1=100%, I_2=75%, and I_3=50% of crop evapotranspiration) combined with two mulching treatments (mulched and non-mulched) on tomato (Money Maker) growth, yield, soil moisture dynamics, and water productivity under drip irrigation at Busitema University Research Field, Busia District, Uganda, during the dry season from December 2025 to March 2026. Based on the field data collected, statistical analyses conducted, and comparisons with published literature, the following specific conclusions are drawn:

5.1.1 Soil Moisture Conservation

Both irrigation level and mulching had highly significant ($P<0.001$) and independent effects on soil moisture content throughout the season. The I_1+M treatment maintained the highest mean pre-irrigation soil moisture content (0.1499 g/g), while I_3+NM recorded the lowest (0.1205 g/g). Crucially, all treatments-maintained soil moisture above the permanent wilting point (0.10 g/g) throughout the 78-day growing period, validating the 50% MAD-based irrigation scheduling approach. Mulching consistently maintained 0.008-0.018 g/g higher soil moisture than equivalent non-mulched treatments, attributable to a reduction in soil surface evaporation of approximately 22%. The I_2+M treatment maintained mean SMC of 0.1418 g/g comparable to I_1+NM (0.1390 g/g) demonstrating that strategic mulching can offset a 25% reduction in irrigation supply without compromising root-zone water availability.

5.1.2 Tomato Growth Parameters

Plant height, Leaf Area Index, and fruit development were all significantly influenced by irrigation level and mulching. The I_1+M treatment produced the tallest plants (85.0 cm at harvest), while I_3+NM plants reached only 59.0 cm. Peak LAI ranged from 4.1 (I_1+M) to 2.2 (I_3+NM) at DAT 71. Fruit set was delayed in I_3 treatments relative to I_1 and I_2 treatments, attributed to marginal soil moisture conditions during the flowering stage. The I_2+M treatment produced plants with compact but productive architecture (76 cm height, LAI 3.4), consistent with the agronomic expectation that moderate water deficit redirects assimilate from vegetative growth towards reproductive structures, favouring fruit development over excessive canopy expansion.

5.1.3 Tomato Yield

Irrigation level was the dominant driver of marketable yield ($F=415.95$, $P<0.001$), with yields ranging from 20.39 t/ha (I_3+NM) to 44.17 t/ha (I_1+M). Mulching significantly increased yield across all irrigation levels ($F=56.22$, $P<0.001$), providing a mean advantage of 4.41 t/ha (+14.2%). The I_1+M treatment produced the maximum yield of 44.17 t/ha, while I_2+M achieved 39.14 t/ha 88.6% of maximum using 25% less irrigation water. The I_2+M and I_1+NM treatments were statistically equivalent in yield, confirming that mulching under 75% ETc can match the productivity of full irrigation without mulch. I_3 treatments produced the lowest yields, with both treatments in the same LSD group, indicating that at 50% ETc, mulching alone cannot adequately compensate for the severity of the imposed water deficit during critical tomato growth stages.

5.1.4 Water Productivity and Irrigation Efficiency

The highest irrigation water use efficiency (IWUE) was achieved by I_2+M at 17.70 kg/m^3 significantly higher than I_1+M (16.26 kg/m^3) despite a 25% reduction in irrigation volume applied. This confirms the core principle of deficit irrigation: proportional reductions in water application result in less than proportional yield reductions, thereby improving overall water use efficiency. Water productivity (WP) was highest under I_1+M (12.31 kg/m^3) due to maximum yield, but IWUE analysis revealed that I_2+M delivers more yield per litre of irrigation water invested. I_3 treatments, despite achieving the greatest absolute water savings, produced lower IWUE values than I_2 treatments because the severe yield penalty at 50% ETc outweighed the efficiency gain from reduced water use.

5.1.5 Optimal Treatment Identification

Integrating all performance indicators yield, soil moisture conservation, water productivity, irrigation efficiency, and growth parameters the I_2+M treatment (75% ETc + mulching) is conclusively identified as the optimal deficit irrigation strategy for smallholder tomato production under drip irrigation in Busia District. This treatment achieved the highest IWUE, statistically comparable yield to full non-mulched irrigation, maintained adequate soil moisture above the irrigation trigger threshold throughout the season, and reduced total seasonal irrigation demand by 504 m^3/ha compared to full irrigation. These findings validate the research hypothesis and address the critical knowledge gap regarding deficit irrigation management for drip-irrigated tomatoes in sub-humid eastern Uganda.

5.2 Recommendations

5.2.1 Recommendations for Farmers

Based on the experimental findings, smallholder tomato farmers in Busia District and similar sub-humid zones of Uganda are recommended to adopt the 75% ETc irrigation scheduling combined with organic mulching as their primary production strategy under drip irrigation systems. The practical implementation of this recommendation involves the following specific actions:

(i) Application of organic mulch material such as dry crop residues, straw, or grass at a depth of 5-7 cm around the base of tomato plants immediately after transplanting, covering the inter-row soil surface within the drip-wetted zone. This single practice has been demonstrated to save up to 4.41 t/ha in yield benefits while simultaneously conserving soil moisture and suppressing weed growth.

(ii) Irrigation scheduling should be based on soil moisture monitoring rather than calendar-based application. Farmers are advised to use digital soil moisture sensors to monitor soil moisture at the 20–40 cm root zone depth, initiating irrigation when moisture approaches the trigger threshold of 0.14 m^3/m^3

(iii) Irrigation should be applied at 75% of the calculated daily ETc requirement, corresponding to approximately 16.8 mm per event every 5 days under the prevailing evapotranspiration conditions of Busia District during the dry season. For a plot area of 3.6 m^2 with a drip system discharge rate of 8 L/hr, this translates to approximately 7.56 hours of irrigation per event.

(iv) Farmers should take advantage of natural rainfall events that exceed 10 mm, cancelling the next scheduled irrigation and allowing the rain to contribute to the soil water balance. This flexible, sensor-based approach to scheduling avoids over-irrigation and saves energy and water costs.

5.2.2 Recommendations for Extension Workers and Irrigation Practitioners

Extension officers and irrigation system designers working in Busia District and eastern Uganda should incorporate the findings of this study into their technical advisory services and training programmes. Specifically:

(i) Deficit irrigation scheduling at 75% ETc should be promoted as the recommended standard for drip-irrigated tomatoes during the dry season, replacing the common practice of applying water based on visual wilting or arbitrary timing, which frequently results in over-irrigation and poor water productivity.

(ii) Training programmes should include practical guidance on the calculation of ETc using the FAO Penman-Monteith method, crop coefficient (Kc) tables for local tomato varieties, and the determination of irrigation frequency and duration from MAD-based scheduling principles. Reference evapotranspiration data from the Busitema University weather station should be made accessible to local farmers through extension bulletins or mobile applications.

(iii) Drip system design for smallholder plots should incorporate flow control provisions that allow farmers to easily switch between full and partial irrigation volumes without modifying system hardware, facilitating flexible deficit irrigation implementation.

5.2.3 Recommendations for Policymakers and Research Institutions

Given the demonstrated water savings and productivity benefits of deficit irrigation with mulching, policymakers in the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) and the Ministry of Water and Environment (MWE) should consider:

(i) Incorporating deficit irrigation guidelines for key vegetable crops beginning with tomato into the national irrigation management framework and extension curriculum, with location-specific scheduling parameters for major agro-ecological zones.

(ii) Supporting subsidised access to mulching materials and low-cost tensiometers for smallholder irrigation schemes, recognising these as high-return investments in water productivity improvement.

(iii) Funding further research trials across multiple seasons and locations in eastern Uganda to validate and refine the 75% ETc recommendation across varying soil types, tomato varieties, and climatic conditions, generating a robust local evidence base for national irrigation policy.

5.2.4 Problems Encountered During the Study

The study was conducted under real field conditions, and several practical and methodological challenges were encountered that limited the scope of data collection or affected the precision of some measurements. These are documented below for the benefit of future researchers undertaking similar studies.

Performance Considerations of Digital Soil Moisture Sensors

Soil moisture content was determined using digital soil moisture sensors, which continuously measured volumetric water content at the 0–20 cm root zone depth. This approach enabled real-time, non-destructive monitoring without the need for destructive soil sampling or laboratory drying. Sensors provided automated readings at each measurement occasion, ensuring consistent data capture across all treatment plots. However, digital sensors require periodic calibration against soil-specific properties to maintain accuracy, as sensor output can vary with soil texture, bulk density, and salinity. Sensor probe placement must also be carefully standardised across plots to avoid spatial variability errors. Despite these considerations, digital soil moisture sensors provided a significant advantage over traditional methods by capturing continuous soil moisture dynamics and enabling timely, data-driven irrigation decisions throughout the cropping season.

Single-Season Study Limitation

The experiment was conducted over a single cropping season (December 2025 to March 2026). A single season is insufficient to account for inter-annual variability in temperature, solar radiation, and rainfall patterns, all of which influence crop ETc and the soil moisture-yield relationship. The results, while internally consistent and well-supported by published literature, should be interpreted with caution as site- and season-specific findings pending replication across multiple seasons. The 2025-2026 dry season experienced slightly above-average rainfall (69.95 mm versus a historical average of 40-60 mm for the period), which may have moderated the water stress experienced by I_3 treatments relative to what might occur in a drier year.

5.3 Areas of Future Study

The findings of this study open several important avenues for future research that would deepen the scientific understanding of deficit irrigation management for tomato production in Uganda and advance the practical application of these findings at the farm level.

Multi-Season and Multi-Location Validation

The most immediate research priority is replication of this experiment across at least two additional dry seasons and at least two additional sites representing the range of soil types, altitudes, and rainfall regimes in eastern Uganda's major tomato-growing districts (including Mbale, Tororo, and Iganga). Multi-location trials would enable the development of location-specific ETc-based irrigation scheduling guidelines and identify whether the 75% ETc optimum holds across the agro-ecological diversity of the region or shifts with soil texture, ambient temperature, and variety. A minimum of three seasons of data is needed to establish statistically robust conclusions about the yield-water productivity trade-off under naturally varying climatic conditions.

Evaluation of Different Mulch Types and Application Rates

This study used a single organic mulch material (dry plant residues at 5 cm depth). Future research should compare the performance of different mulch types including rice straw, maize stover, black polythene film, and locally available banana leaves at varying application depths (3 cm, 5 cm, and 8 cm). Plastic mulch in particular has shown superior moisture conservation in tropical settings due to its complete elimination of soil surface evaporation, and its interaction with deficit irrigation at 75% ETc may yield even higher IWUE values than the organic mulch used in this study (Kopa et al., 2023).

Integration of Deficit Irrigation with Fertigation

Drip irrigation systems provide an ideal platform for delivering soluble fertilisers directly to the root zone through the irrigation water a practice known as fertigation. Deficit irrigation necessarily reduces the total volume of water applied, which may also reduce nutrient delivery to the root zone if fertigation concentrations are not adjusted accordingly. Future studies should investigate the combined effects of deficit irrigation levels, mulching, and fertigation rates on tomato yield and water productivity, with the aim of developing integrated crop management packages that optimise all three inputs simultaneously. (Amankwaa-Yeboah et al. (2023) ,demonstrated synergistic yield improvements from combining deficit irrigation with nutrient management in tropical tomato production, providing a strong basis for such integrated research.

Automation of Irrigation Scheduling Using Soil Moisture Sensors

This study employed digital soil moisture sensors for continuous real-time monitoring and pre-scheduled irrigation events. Future research should evaluate the performance of fully automated soil moisture sensor-based irrigation controllers integrated with timer-relay or microcontroller systems under smallholder conditions in Uganda. Systems that automatically trigger irrigation when soil moisture drops to the 0.14 m^3/m^3 threshold could further improve irrigation efficiency by eliminating the imprecision of fixed schedules and responding dynamically to actual soil moisture conditions. The feasibility, cost-effectiveness, and long-term durability of such automated sensor-controller systems under Busia's field conditions represent an important area for future agricultural engineering research.

Evaluation of Deficit Irrigation Effects on Tomato Fruit Quality

While this study recorded marketable yield percentage as a proxy for fruit quality, it did not quantify specific quality parameters such as total soluble solids (TSS, °Brix), lycopene content, titratable acidity, fruit firmness, or shelf life under different irrigation and mulching regimes. Literature suggests that moderate water deficit during fruit bulking can improve TSS and lycopene concentration in tomato, which are important quality attributes for both fresh market and processing use (Patanè & Cosentino, 2010; Wu et al., 2021). Future studies should incorporate detailed fruit quality analysis to provide a complete picture of the yield-quality trade-off under deficit irrigation, enabling farmers to make informed decisions based on their specific market targets (fresh market versus processing).

Long-term Soil Health Assessment

Repeated deficit irrigation, particularly at the 50% ETc level, may have long-term implications for soil health through altered microbial activity, soil organic matter dynamics, and salt accumulation in the drip-wetted zone. Similarly, organic mulching can progressively improve soil organic carbon content, aggregate stability, and water-holding capacity over multiple seasons. A long-term study spanning at least three consecutive seasons should monitor soil physical and chemical properties including bulk density, organic carbon, pH, electrical conductivity, and macro-nutrient levels under different irrigation and mulching regimes to assess the sustainability of these practices for smallholder tomato systems in Busia District.

5.4 Final Remarks

This study makes a meaningful contribution to the body of knowledge on deficit irrigation management for smallholder vegetable production in sub-humid eastern Uganda. It demonstrates, through rigorous field experimentation and statistical analysis, that applying 75% of crop evapotranspiration through a drip system combined with organic mulching represents the optimal strategy for balancing tomato yield, water productivity, and irrigation efficiency under the dry-season conditions of Busia District. The findings directly address the research gap identified in the literature review regarding the absence of empirically validated, location-specific deficit irrigation guidelines for this region.

The practical implication is straightforward: smallholder farmers in Busia who adopt drip irrigation combined with mulching and schedule irrigation at 75% ETc can expect to achieve approximately 39 t/ha of marketable tomato yield nearly four times the national rainfed average while using 25% less water than full irrigation management. This combination offers a viable, scalable pathway towards improved food security, increased farm incomes, and more sustainable water resource management in a region where both water availability and agricultural productivity are under increasing pressure from climate variability and population growth.

Future research building on this foundation particularly multi-season trials, economic analysis, and integration with automated soil moisture monitoring will be essential to refine and extend these recommendations and to support their adoption at scale across Uganda's smallholder irrigation sector.

CHAPTER 6 CONCLUSION

This study conclusively demonstrated that deficit irrigation combined with organic mulching significantly influences tomato growth, yield, soil moisture conservation, and water productivity under drip irrigation in Busia District, eastern Uganda. The following take-home conclusions are drawn from the integrated analysis of all four specific objectives:

Objective 1, Effect on Tomato Growth and Yield: Irrigation level was the dominant driver of both vegetative growth and marketable yield. The I_1+Mulch treatment achieved the highest yield of 44.17 t/ha and tallest plant height of 85 cm, while I_3+No Mulch recorded the lowest at 20.39 t/ha and 59 cm respectively. Critically, the I_2+Mulch treatment (75% ETc) produced 39.14 t/ha statistically equivalent to full irrigation without mulch (39.61 t/ha) while using 25% less irrigation water, confirming that moderate deficit irrigation with mulching achieves comparable productivity to full irrigation at a substantially reduced water cost.

Objective 2, Effect of Mulching on Soil Moisture Conservation: Mulching had a highly significant independent effect on soil moisture retention ($F=95.53$, $P<0.001$). Mulched plots maintained 0.008–0.018 g/g higher mean soil moisture than equivalent non-mulched plots, attributable to an approximately 22% reduction in soil surface evaporation. The I_2+Mulch treatment maintained a mean seasonal soil moisture content of 0.1422 g/g, comparable to the full irrigation non-mulched treatment (0.1388 g/g), demonstrating that mulching can substitute for a 25% irrigation water reduction without compromising root-zone moisture availability. All treatments-maintained soil moisture above the permanent wilting point (0.10 g/g) throughout the season, validating the 50% MAD-based scheduling approach.

Objective 3, Water Productivity and Irrigation Water Use Efficiency: The I_2+Mulch treatment achieved the highest IWUE of 17.70 kg/m^3, surpassing even the full irrigation treatment (16.26 kg/m^3), confirming the core principle of deficit irrigation that proportional reductions in water application result in less than proportional yield reductions. Quadratic modelling of the IWUE-irrigation relationship identified a mathematical optimum at approximately 2,335 m^3/ha (≈86% ETc), with a predicted peak IWUE of 17.87 kg/m^3, closely validating the experimental finding that I_2+Mulch operates at the efficiency frontier. The I_3 treatments, despite achieving the greatest water savings, produced lower IWUE values because the yield penalty at 50% ETc was disproportionately large relative to the water saved.

Objective 4, Optimal Deficit Irrigation Level: The I_2+Mulch treatment (75% ETc combined with organic mulching) is conclusively identified as the optimal deficit irrigation strategy for smallholder tomato production under drip irrigation in Busia District. This treatment produced 88.6% of maximum yield while using 25% less water, achieved the highest IWUE (17.70 kg/m^3), maintained adequate root-zone soil moisture throughout the season, and reduced seasonal irrigation demand by 504 m^3/ha compared to full irrigation. These findings validate the central research hypothesis and provide a clear, evidence-based recommendation: smallholder farmers in Busia District who irrigate at 75% ETc with organic mulching can expect approximately 39 t/ha of marketable tomato yield nearly four times the national rainfed average while conserving 25% of irrigation water per season.

References

Allen, R. G., Pereira, L. S., & Raes, D. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56 Table of Contents*.

Amankwaa-Yeboah, P., Aruna Akoriko, F., Amponsah, W., Yeboah, S., Brempong, M. B., & Keteku, A. K. (2023). Combining deficit irrigation and nutrient amendment enhances the water productivity of tomato (Solanum lycopersicum L.) in the tropics. *Frontiers in Sustainable Food Systems*, *7*, 1199386. https://doi.org/10.3389/FSUFS.2023.1199386/BIBTEX

Babyenda, P. (2023). *Climate Variability, Agricultural Productivity and Household Welfare Outcomes in Uganda*. http://erepository.uonbi.ac.ke/handle/11295/164305

Bacha, D., Namara, R., Bogale, A., & Tesfaye, A. (2011). Impact of small-scale irrigation on household poverty: Empirical evidence from the Ambo district in Ethiopia. *Irrigation and Drainage*, *60*(1), 1–10. https://doi.org/10.1002/IRD.550;CTYPE:STRING:JOURNAL

Barungi, J., Okonya, J., Ilakut, B., & Recha, J. W. M. (2024). *Training on the Utilization of Climate Smart Moisture and Nutrient Monitoring Tools among Lead Smallholder Horticulture Farmers in Uganda*. Accelerating Impacts of CGIAR Climate Research for Africa. https://hdl.handle.net/10568/168700

Chakraborty, D., Nagarajan, S., Aggarwal, P., Gupta, V. K., Tomar, R. K., Garg, R. N., Sahoo, R. N., Sarkar, A., Chopra, U. K., Sarma, K. S. S., & Kalra, N. (2008). Effect of mulching on soil and plant water status, and the growth and yield of wheat (Triticum aestivum L.) in a semi-arid environment. *Agricultural Water Management*, *95*(12), 1323–1334. https://doi.org/10.1016/J.AGWAT.2008.06.001

Ddamulira, G., Idd, R., Namazzi, S., Kalali, F., Mundingotto, J., & Maphosa, & M. (2019). Nitrogen and Potassium Fertilizers Increase Cherry Tomato Height and Yield. *Journal of Agricultural Science*, *11*(13). https://doi.org/10.5539/jas.v11n13p48

Ding, H., He, J., Wu, Y., Wu, X., Ge, C., Wang, Y., Zhong, S., Peiter, E., Liang, J., & Xu, W. (2018). The Tomato Mitogen-Activated Protein Kinase SlMPK1 Is as a Negative Regulator of the High-Temperature Stress Response. *Plant Physiology*, *177*(2), 633–651. https://doi.org/10.1104/PP.18.00067

Dorji, K., Behboudian, M. H., & Zegbe-Domínguez, J. A. (2005). Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying.

Scientia Horticulturae, *104*(2), 137–149. https://doi.org/10.1016/J.SCIENTA.2004.08.015

English, M., & Raja, S. N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management*, *32*(1), 1–14. https://doi.org/10.1016/S0378-3774(96)01255-3Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, *58*(2), 147–159. https://doi.org/10.1093/JXB/ERL165

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, *96*(9), 1275–1284. https://doi.org/10.1016/J.AGWAT.2009.04.009

Ghinassi, G., Dalla Marta, A., Verdi, L., & Maucieri, C. (2024). *Uncertainties and misconceptions as hidden threats towards sustainable irrigation water management*. 499–502. https://doi.org/10.5281/ZENODO.13584918

Kakaire, J., Makokha, G. L., Mwanjalolo, M., Mensah, A. K., & Emmanuel, M. (2015). Effects of Mulching on Soil Hydro-Physical Properties in Kibaale Sub-catchment, South Central Uganda. *Applied Ecology and Environmental Sciences*, *3*(5), 127–135. https://doi.org/10.12691/aees-3-5-1

Kaundal, M., Sharma, K., & Anand, H. (2024). Processing, Value Addition and Post-Harvest Technology of Tomato: A Scoping Review on Global and Indian Perspective. *Journal of Advances in Biology & Biotechnology*, *27*(11), 339–347. https://doi.org/10.9734/jabb/2024/v27i111619

Keller, J., & Bliesner, R. D. (1990). Sprinkle and trickle irrigation. In *Sprinkle and Trickle Irrigation*. Chapman & Hall.

Kishaija, N., Adam, A. Y. F., & Heil, B. (2024). Land-use land cover changes and their relationship with population and climate in Western Uganda. *Journal of Degraded and Mining Lands Management*, *11*(4), 6201–6212. https://doi.org/10.15243/JDMLM.2024.114.6201

Kopa, I. T., Meddi, M., & Ammari, A. (2023). Influence of mulches on soil moisture and water infiltration in the tomato crop. *Acta Agriculturae Slovenica*, *119*(4). https://doi.org/10.14720/AAS.2023.119.4.15748

Misgina, N. A., Beshir, H. M., Yohannes, D. B., & Gebreyohanes, G. H. (2024). Growth, Yield, and Water Productivity of Potato Genotypes Under Supplemental and Non-Supplemental Irrigation in Semi-Arid Areas of Northern Ethiopia. *Agronomy 2025, Vol. 15, Page 72*, *15*(1),

72. https://doi.org/10.3390/AGRONOMY15010072

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, *97*(4), 528–535. https://doi.org/10.1016/J.AGWAT.2009.03.023

Mwangi, M. W., Ngesa, F., & Mwaniki, S. M. W. (2024). Influence of Farmer's Income Level on Adoption of Agricultural Water Management Practices among Smallholder Farmers in Rongai Sub-county, Kenya. *Asian Journal of Agricultural Extension, Economics & Sociology*, *42*(11), 321–329. https://doi.org/10.9734/AJAEES/2024/V42I112617

Mwaura, F., & Katunze, M. (2014). *Enhancing agricultural production and productivity in Uganda through irrigation*. Economic Policy Research Centre. https://nru.uncst.go.ug/xmlui/handle/123456789/960

Ndondo, J. T. K., & Ndondo, J. T. K. (2023). *Review of the Food and Agriculture Organisation (FAO) Strategic Priorities on Food Safety 2023*. https://doi.org/10.5772/INTECHOPEN.112132

Nsubuga, F. W., & Rautenbach, H. (2018). Climate change and variability: a review of what is known and ought to be known for Uganda. *International Journal of Climate Change Strategies and Management*, *10*(5), 752–771. https://doi.org/10.1108/IJCCSM-04-2017-0090/FULL/PDF

Osei-Bonsu, I., Osei, M. K., Agyare, R. Y., Adjebeng-Danquah, J., Asare Bediako, K., Gyau, J., Adomako, J., Ofori, P., Prempeh, R. N. A., & Cho, M. C. (2022). Assessing the heat stress tolerance potential of tomato lines under poly-house and open field conditions. *Cogent Food & Agriculture*, *8*(1). https://doi.org/10.1080/23311932.2022.2115665

Osinde, D. (2022). *Assessment of determinants of small scale farmer participation in tomato production and marketing in Kisoko sub county, Tororo district.* https://ir.busitema.ac.ug/handle/20.500.12283/1673

Owino, W., Kahenya, P., Wafula, E., & Otieno, G. (2025). Food Loss and Waste Reduction in Specific Fruit and Vegetable Value Chains in Eastern Africa. *Foods 2025, Vol. 14, Page 3938*, *14*(22), 3938. https://doi.org/10.3390/FOODS14223938

Patanè, C., & Cosentino, S. L. (2010a). Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. *Agricultural Water Management*, *97*(1), 131–138. https://doi.org/10.1016/J.AGWAT.2009.08.021

Patanè, C., & Cosentino, S. L. (2010). Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. *Agricultural Water Management*, *97*(1), 131–138. https://doi.org/10.1016/J.AGWAT.2009.08.021

Wakaabu, D. (2023). The sensitivity of food security to agricultural input subsidies in Uganda. *International Journal of Agricultural Science and Food Technology*, *9*(1), 010–015. https://doi.org/10.17352/2455-815x.000184

Wu, Y., Yan, S., Fan, J., Zhang, F., Xiang, Y., Zheng, J., & Guo, J. (2021). Responses of growth, fruit yield, quality and water productivity of greenhouse tomato to deficit drip irrigation. *Scientia Horticulturae*, *275*, 109710. https://doi.org/10.1016/J.SCIENTA.2020.109710

Zribi, W., Aragüés, R., Medina, E., & Faci, J. M. (2015). Efficiency of inorganic and organic mulching materials for soil evaporation control. *Soil and Tillage Research*, *148*, 40–45. https://doi.org/10.1016/J.STILL.2014.12.003

Appendices

sensor calibration values

Testing ID	Average value m^3/m^3	%
1	0.366	26.14
2	0.342	24.43
3	0.334	23.86
4	0.357	25.50
5	0.357	25.50

Table 6-1 Comprehensive Crop Growth Data

Date	DAT	Stage	I_1+M	I_1+NM	I_2+M	I_2+NM	I_3+M	I_3+NM	Item.
22 Dec	8	Initial	18	17	16	15	14	13	Height (cm)
		Initial	12	11	10	9	9	8	Leaves
		Initial	0.6	0.5	0.5	0.4	0.4	0.3	LAI
		Initial	No	No	No	No	No	No	Flowers?
		Initial	No	No	No	No	No	No	Fruit Set
		Initial	0	0	0	0	0	0	Fruits/plt
29 Dec	15	Initial-Dev	26	24	23	21	20	18	Height (cm)
			18	17	16	14	13	12	Leaves
			0.9	0.8	0.8	0.7	0.6	0.5	LAI
			No	No	No	No	No	No	Flowers
			No	No	No	No	No	No	Fruit Set
			0	0	0	0	0	0	Fruits/plt
05 Jan	22	Dev	34	32	30	27	25	23	Height (cm)
			22	21	19	17	15	14	Leaves
			1.2	1.1	1.0	0.9	0.8	0.7	LAI
			No	No	No	No	No	No	Flowers
			No	No	No	No	No	No	Fruit Set
			0	0	0	0	0	0	Fruits/plt
12 Jan	29	Dev	45	42	39	36	33	30	Height (cm)

			30	28	25	23	20	18	Leaves
			1.8	1.6	1.5	1.3	1.1	1.0	LAI
			Yes	Yes	Yes	Yes	No	No	Flowers
			No	No	No	No	No	No	Fruit Set
			0	0	0	0	0	0	Fruits/plt
19 Jan	36	M-S	58	55	52	48	44	40	Height (cm)
			36	34	31	28	24	22	Leaves
			2.4	2.2	2.0	1.8	1.5	1.3	LAI
			Yes	Yes	Yes	Yes	Yes	Yes	Flowers
			Yes	Yes	Yes	No	No	No	Fruit Set
			3	2	2	0	0	0	Fruits/plt
26 Jan	43	M-S	70	66	62	57	51	47	Height (cm)
			44	41	37	33	29	26	Leaves
			3.1	2.8	2.5	2.2	1.8	1.6	LAI
			Yes	Yes	Yes	Yes	Yes	Yes	Flowers
			Yes	Yes	Yes	Yes	Yes	No	Fruit Set
			10	8	7	5	3	1	Fruits/plt
09 Feb	57	M-S	82	78	73	68	62	57	Height (cm)
			52	48	43	39	35	32	Leaves
			3.8	3.5	3.1	2.7	2.3	2.0	LAI
			Yes	Yes	Yes	Yes	Yes	Yes	Flowers
			Yes	Yes	Yes	Yes	Yes	Yes	Fruit Set
			21	18	16	13	10	8	Fruits/plt
23 Feb	71	L S	85	81	76	71	64	59	Height (cm)
			55	51	46	42	38	34	Leaves
			4.1	3.8	3.4	3.0	2.6	2.2	LAI
			Yes	Yes	Yes	Yes	Yes	Yes	Flowers
			Yes	Yes	Yes	Yes	Yes	Yes	Fruit Set

			29	26	24	20	16	14	Fruits/plt
01 Mar	78	L S	85	81	76	71	64	59	Height (cm)
			54	50	45	41	37	33	Leaves
			4.0	3.7	3.3	2.9	2.5	2.1	LAI
			Yes	No	No	No	No	No	Flowers
			Yes	Yes	Yes	Yes	Yes	Yes	Fruit Set
			32	30	27	23	18	17	Fruits/plt

Bulk density determination

TEST No	1	2	3	4	5
WEIGHT OF MOULD+SAMPLE(g)	6436.7	6510.5	6370.6	6345.6	6324
WEIGHT OF MOULD (g)	5068	5068	5068	5068	5068
WEIGHT OF SAMPLE (g)	1198.4	1197.7	1210.3	1156.4	1195.4
VOLUME OF MOULD (cm3)	831.4	831.4	831.4	831.4	831.4
WET DENSITY (g/cm3)	1.441	1.441	1.456	1.391	1.438
AVERAGE (g/cm3)			1.433		
Remarks:					

Busitema Laboratory Technician		
Technician		
Name	for Mr. HECTOR DANIEL .O	
sign	[signature]	
Date	14/05/2026	

MOISTURE CONTENT			
Container N°:		A1	B3
Mass of wet soil+container	(m2) g	203.00	205.00
Mass of dry soil+container	(m3) g	166.10	165.50
mass of container	(m1) g	20.00	21.50
Mass of moisture	(m2-m3) g	36.9	39.5
Mass of dry soil	(m3-m1) g	146.1	144.0
Moisture content (MC)		25.3	27.4
Average MC (%)		26.3	

	Busitema Laboratory Technician
Laboratory Technician	Laboratory Technician
Name	for Mr- HECTOR DANIEL.O
sign	[illegible]
date	14/05/2026

MOISTURE CONTENT			
Container N°:		D2	B4
Mass of wet soil+container	(m2) g	250.00	250.70
Mass of dry soil+container	(m3) g	204.50	205.70
mass of container	(m1) g	20.00	21.50
Mass of moisture	(m2-m3) g	45.5	45.0
Mass of dry soil	(m3-m1) g	184.5	184.2
Moisture content (MC)		24.7	24.4
Average MC (%)		24.5	

	Busitema Laboratory Technician
Laboratory Technician	Laboratory Technician
Name	For Mr. HECTOR DANIEL.O
sign	[illegible]
date	[illegible]

MOISTURE CONTENT			
Container N°:		D7	B3
Mass of wet soil+container	(m2) g	245.50	246.40
Mass of dry soil+container	(m3) g	201.90	203.40
mass of container	(m1) g	20.00	21.50
Mass of moisture	(m2-m3) g	43.6	43.0
Mass of dry soil	(m3-m1) g	181.9	181.9
Moisture content (MC)		24.0	23.6
Average MC (%)		23.8	

	Busitema Laboratory Technician
Laboratory Technician	Laboratory Technician
Name	For. Mr HECTOR DANIEL.O
sign	[illegible]
date	14/05/2026

MOISTURE CONTENT			
Container N°:		C2	B1
Mass of wet soil+container	(m2) g	245.50	244.80
Mass of dry soil+container	(m3) g	199.80	199.10
mass of container	(m1) g	20.00	21.50
Mass of moisture	(m2-m3) g	45.7	45.7
Mass of dry soil	(m3-m1) g	179.8	177.6
Moisture content (MC)		25.4	25.7
Average MC (%)		25.6	

	Busitema Laboratory Technician
Laboratory Technician	Laboratory Technician
Name	for Mr. HECTOR DANIEL . O
sign	[signature]
date	14/8/2016

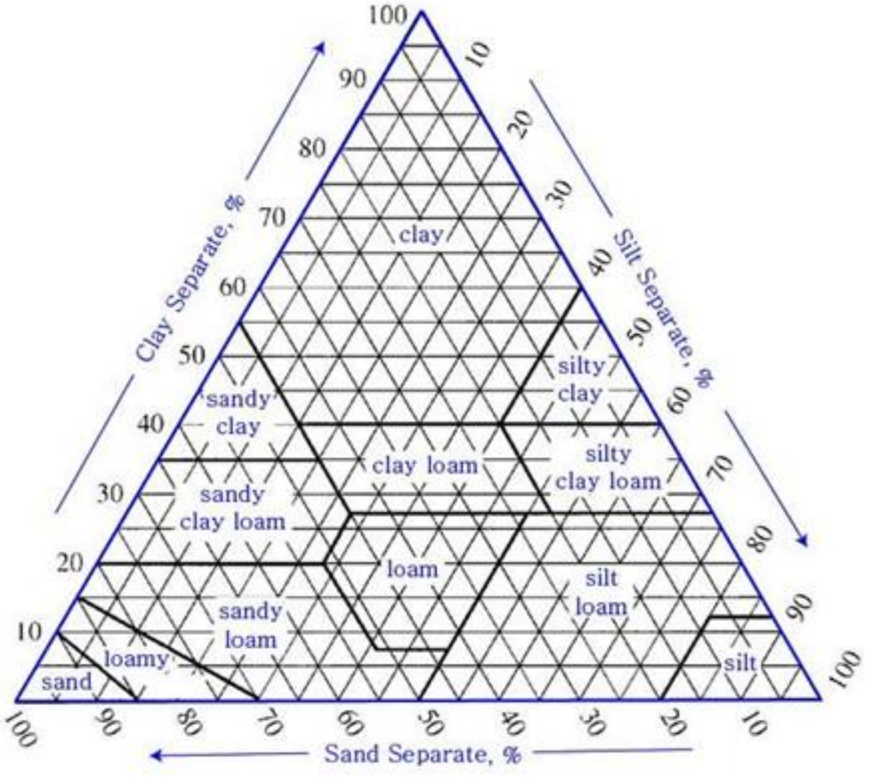

Figure 6-1 soil textural triangle

Figure 6-2 soil moisture tests

Figure 6-3 Tomato seedling in the bed

Figure 6-4 Mulced tomato plot

Figure 6-5 Leaves counting *Figure 6-6 measuring plant height*

Figure 6-7 Block *setup* *Figure 6-8 fruits set*

Figure 6-9. *weeding* *Figure 6-10 pest control*

Figure 6-11 Taking soil moisture readings