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EFFECT OF DRIP IRRIGATION APPLICATION REGIMES AND MULCHING ON SOIL PROPERTIES, GROWTH AND YIELD TRAITS OF TOMATO (*SOLANUM LYCOPERSICUM* L.) VARIETIES

BY

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DECLARATION

Student

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere:

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ABSTRACT

Agriculture in northern Ghana is challenged by drought and erratic rainfall pattern which greatly affects productivity of Tomato. The poor crop yield results in demand shortfall and subsequently importation of tomatoes from neighbouring countries. This research was conducted at the CSIR-SARI, Nyankpala to investigate the effect of drip irrigation application regimes and mulching on soil properties, physiological and yield traits of tomatoes. The experimental design was a split-split plot. Treatments consisted of tomato variety as mainplot factor at two levels (Mongal F1, Pectomech), irrigation regimes as subplot factor at three levels (100 % crop water requirement (ET_c), 75 % ET_c and 50 % ET_c), and quantity of rice straw mulch as sub-subplot factor at three levels (6 t ha^{-1}, 3 t ha^{-1} and 0 t ha^{-1}). Results showed that soil water content, soil pH and soil temperature were significantly improved by the full irrigation regime and 6 t ha^{-1} mulch. The total fruit yield (TFY) was significantly affected by treatments. Mongal F1 produced more TFY that ranged from 9.4 - 12.08 t ha^{-1}. Also, 100 % ET_c produced the highest TFY ranging from 7.24 - 9.56 t ha^{-1}. The 6 t ha^{-1} mulch gave more TFY between 8.54 - 9.42 t ha^{-1} compared to no-mulch treatment. Furthermore, the irrigation water-use efficiency was highest for Mongal F1 and ranged between 2.43 - 3.07 kg m^{-3}. Interaction of Mongal F1 and 50 % ET_c produced 3.88 kg m^{-3}. The crop water stress index showed plant stress condition for 50 % ET_c, followed by 75 % ET_c as well as no-mulch. Also, brix and pH content of fruits were influenced by treatments. Pectomech had more brix content than Mongal F1. Deficit irrigations (50 % and 75 % ET_c) improved brix content compared to full irrigation. Pectomech in combination with 3 t ha^{-1} mulch as well as Pectomech in combination with 50 % ET_c gave highest brix content of 8.16 % and 8.67 % respectively. The CROPGRO -Tomato Model was excellent in simulating soil temperature, canopy height and fresh fruit yield of tomatoes. The adoption of Mongal F1 in combination with deficit irrigation regimes and rice straw mulch would improve water and crop productivity of tomato under water scarce environments.

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DEDICATION

I dedicate this thesis to my wife; Mary Awini and Children (Aaron Awinpang Adombilla, Anne Awintis Adombilla and Addilyn Awinbon Adombilla).

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LIST OF ABBREVIATIONS AND ACRONYMS

AWC	Available Soil Water Content
VVC	Volumetric Soil Water Content
BD	Bulk Density
Ca	Calcium
CEC	Cation Exchange Capacity
CSIR	Council for Scientific and Industrial Research
SARI	Savanna Agricultural Research Institute
DU	Distribution Uniformity
AE	Application Efficiency
CV	Manufacturer’s Coefficient of Variation
UC	Uniformity Coefficient
EU	Emission Coefficient
DI	Deficit Irrigation
SDI	Surface Drip Irrigation System
SSDI	Subsurface Drip Irrigation System
NPV	Nuclear Polyhedrosis Virus
WAE	Weeks after Emergence
WAT	Weeks after Transplanting
EC	Electrical Conductivity
ETc	Crop Water Requirement
FAO	Food and Agricultural Organization
FC	Field Capacity
GDP	Gross Domestic Product
GIR	Gross irrigation requirement
NIR	Net irrigation requirement
K	Potassium
Kc	Crop Coefficient Factor
Kg	Kilogram

MAD	Manageable Allowable Depletion
Mg	Magnesium
MoFA	Ministry of Food and Agriculture
N	Nitrogen
O.C	Organic carbon
P	Phosphorus
pH	Acidity or Alkalinity
PWP	Permanent Wilting Point
RAW	Readily Available Water
TAW	Total Available Water Content
WP/CWP	Crop Water Productivity
DSSAT	Decision Support System for Agrotechnology Transfer
ETo	Reference Evapotranspiration
CWSI	Crop Water Stress Index
IWUE	Irrigation Water Use Efficiency
IPPC	Intergovernmental Panel on Climate Change
WRM	Water Resource Management
FLID	Farmer Led Irrigation Development
IWAD	Integrated Water and Agricultural Development
BFC	Babato Farming Company
GoG	Government of Ghana
GCAP	Ghana Commercial Agriculture Programme
GSS	Ghana Statistical Service
GLSS	Ghana Living Standard Survey
SPAW	Soil Plant Atmosphere and Water Model
SDV	Stem Diameter Variation
TTT	Temperature Time Threshold
TSD	Time Stress Day
VPD	Vapor Pressure Deficit
LAI	Leaf Area Index

ANOVA	Analysis Of Variance
LSC	Leaf Stomatal Conductance
LT	Leaf Canopy Temperature
LCC	Leaf Chlorophyll Concentration
TSS	Fruit Total Soluble Solids
RRMSE	Relative Root Mean Square Error
RMSE	Root Mean Square Error
D	Wollmatt’s Index of Agreement
R^2	Coefficient of Determination
PRD	Partial Root Drying
LDA	Laser Diffraction Analysis
NSKE	Neem Seed Kernel Extract

CHAPTER ONE

INTRODUCTION

1.1 Background

The arid regions of Africa are characterized by climate change effects of increase drought frequencies and severity (Jones and van Vliet, 2018). The major production constraint in agriculture is insufficient water availability caused by rainfall variability (Cook *et al.*, 2012; Sylla *et al.*, 2016). The future projections on weather suggest a severe climate change impact on water availability, indicating increased risk of soil-water stress conditions on plants (Oyerinde *et al.*, 2014; Sylla *et al.*, 2015). Irrigation is key in overcoming climate change related effect on crop production by providing the required amount of water to meet the daily crop needs.

Tomato is extensively cultivated worldwide for its fruits and numerous nutritional benefits (Srinivasan, 2010). The fruit contains vitamin C, provitamins and β-carotene at significant levels and highly rich in lycopene; a powerful antioxidant that helps in the prevention of various forms of cancer (Bratianu and Schwontkowski, 2013; Arah *et al.*, 2015). Tomato is a major vegetable produced and consumed locally in Ghana (Asare-Bediako *et al.*, 2007; Adazabra *et al.*, 2013) and drives both rural and urban economies through the creation of sustainable jobs and alleviates poverty (Asare-Bediako *et al.*, 2007; Sugri *et al.*, 2013). The crop is extensively cultivated in the Savanna agroecological zone of the country under traditional furrow irrigation (Adu-Dapaah and Oppong-Konadu, 2002).

The existing traditional furrow irrigation method used by farmers to grow tomatoes in the zone largely affects the physiological performance of tomato plants. The tendency to apply more or less water to the soil is high under the traditional irrigation method. Drought or less irrigation poses severe soil water stress conditions which is detrimental to the growth and yield of most crops (Gulen *et al*., 2004). On the other hand, over irrigation leads to inefficient use of water (Zheng *et al*., 2015) and increases the risk of nitrate leaching (Popova *et al*., 2005). Therefore, the need to maintain soil water conditions within optimum levels of field capacity using efficient irrigation systems and practices for the best performance of crops. An alternative to the traditional furrow irrigation method is the drip irrigation system which has enormous benefits because water delivery is directed at the root zone of plants and about 95 % efficient (Sharma, 2001; Pedro *et al*., 2007). Several studies have focused on the advantages of drip irrigation over the other methods in cotton (Hussein *et al*., 2011), wheat (Ansari *et al*., 2019), maize (Sandhu *et al*., 2019), tomato (Zhai *et al*., 2010), pepper (Edossa and Emana, 2011) and cucumber (Kirnak and Demirtas, 2006). Drip irrigation reduces water use without significant yield reduction thus, maximising farmers profit (Kirda *et al*., 2005). The irrigation system improves tomato fruit yield (Warner *et al*., 2004; Xu *et al*., 2009), has high water and fertilizer use efficiency (Locascio, 2005; Michael, 2008). Aside the use of efficient irrigation systems such as drip, the practice of deficit irrigation where plants are irrigated with less volume of water below the daily crop water needs at specific stages of growth, have shown significant results in increasing water savings and crop productivity (Costa *et al*., 2007). Shammout *et al*. (2018) assessed deficit irrigation effect on bell pepper yield and water-use efficiency and found that; full (100 %) irrigation gave highest fruit yield whilst the severely stressed irrigation of 60 % gave lowest yield but highest water-use efficiency. However, the practice of deficit irrigation must be done with caution since it can pose soil water stress conditions (Parkash and Singh, 2020), that can be detrimental on the physiological and biochemical processes of the crop (Yuan *et al*., 2016; Sharma *et al*., 2019). Soil water stress conditions can cause the closure of leaf stomata by plants and limit transpiration and eventually reduces stomatal conductance and photosynthesis (Parkash and Singh, 2020). The reduction in photosynthesis activity will result in a drastic decline in yield (Yuan *et al.*, 2016; Sharma *et al.*, 2019). On the other hand, under moderate soil water stress, the efficiency of water-use by plants will increase (Liu *et al.*, 2005; Pazzagli *et al*., 2016). The proper use of crop residue as mulch helps to conserve soil water and maximise irrigation water and nutrient use (Hochmuth *et al.*, 2001; Kirnak *et al*., 2001). Crop residue mulch improves soil infiltration rate (Agyenim-Boateng and Dennis, 2001), regulates root zone soil temperature and increase tomato fruit yield (Pandey *et al*., 2015). The findings of Kirnak *et al.* (2001) revealed that mulching can overcome the effects of deficit irrigation on the growth performance of strawberry notably under arid conditions. The Guinea Savannah of Ghana has abundant crop residue especially rice straw in the dry season immediately after harvesting of rainfed crops. Rice straw residue for example is often consumed by bush fires even though it can be incorporated into the vegetable farming system of irrigated ecologies as surface mulch material.

The different tolerant levels of plants to soil water stress conditions (Liu *et al.*, 2006; Mohawesh, 2018; Singh *et al*., 2019), necessitates an in-depth understanding of the crop's response at different growth stages to deficit irrigation regimes and mulching strategies within the agroecology of the savannah since the environmental condition at the time can influence on how the plants respond to the deficit irrigation (Parkash *et al.*, 2021). The way forward to avert the decline in tomato production and yields in Ghana is to provide the favourable environment needed for the advancement of sustainable technology and agricultural policies in the agricultural sector. Investments targeted at on-farm irrigation development has the tendency to increase overall crop and water productivity, thereby promoting economic growth and providing the necessary pathway to alleviate poverty among smallholder farmers and most Ghanaians.

1.2 Problem Statement and Justification

The agriculture sector is the backbone of Ghana's economy contributing significantly to the Gross Domestic Product (GDP) and with an annual growth rate of 9.4 % in 2017 (MoFA, 2018). However, the sector is faced with complex challenges in coping with the increasing demand for sustainable food production to ensure food security in the country. The situation is exacerbated by the erratic and unpredictable rainfall that creates the uncertainty in agricultural production (Adetola, 2009). The major limiting factor to crop production is the insufficient water available for plant use which is caused by rainfall variability (Cook *et al.*, 2012; Sylla *et al.*, 2016). Despite poor rainfall of the Guinea Savannah Zone of Ghana, production of high value crops such as tomato is done largely under irrigation due to the high water resources potential of the zone (MoFA, 2011). Meanwhile, full attention is yet to be given to the crop regarding the irrigation infrastructure improvements needed to boost production (MoFA, 2011).

Tomato production in Ghana has experienced slow growth of 318,000 tons in 2009 to 420,000 tons in 2019 (MoFA, 2020). The poor performance of most existing irrigation schemes has contributed to the low tomato production (Adongo *et al.*, 2016). Tomato farmers are producing on an average yield of 7.5 t/ha, compared to the estimated annual potential yield of 20 t/ha (MoFA, 2017); thus, giving rise to a yield gap of 50 %. Farmers in the Bontanga Irrigation Scheme of Northern Region are obtaining tomato fruit yields of 2.8 - 5.0 t/ha (Asare-Bediako *et al.*, 2007). Similarly, average yield of 6.2 t/ha and 4.2 t/ha have been recorded by farmers in the Tono and Vea Irrigation Schemes respectively in the Upper East Region of Ghana (Adongo *et al.*, 2016). The current average fruit yield gap of local tomato varieties is a contributory factor to the high importation of fresh tomatoes annually from neighboring countries. The situation could be arrested if smallholder farmers are able to improve their annual yields to 15 t/ha (Robinson and Kolavalli, 2010). The reported yield decline of tomato under irrigated conditions can be attributed largely to the surface irrigation system of furrow irrigation method commonly practiced by farmers for tomato production under irrigation schemes (both formal and informal). The furrow irrigation method though simple in operation, is very complicated in design and management (Burguete *et al.*, 2009) and can pose detrimental conditions to the crop and soil environment. Farmers apply huge volumes of water far above the daily crop water needs during irrigation that leads to inefficient use of water (Zheng *et al.*, 2015). These increases leaching of essential nutrients beyond the rootzone soil (Popova *et al.*, 2005). A study conducted by Sharma *et al.* (2012) on estimating nitrate-nitrogen (NO_3-N) losses within 60 - 200 cm soil depth as influenced by furrow and drip irrigation methods found that, 97.4 to 105.2 mg of NO_3-N was depleted by furrow irrigation method whereas 65.2 to 66.8 mg for drip irrigation method.

Also, the practice of furrow irrigation discourages the use of organic mulches to protect the soil environment despite the abundance of crop residue especially rice straw in the zone. The aforementioned challenges call for improvement of the traditional furrow irrigation method for long term sustainability and an increase in overall irrigation performance of schemes (Sarwar *et al.*, 2001). However, the complicated nature of furrow irrigation system design and management (Burguete *et al.*, 2009), would certainly not allow for easy modifications to be done considering the local environmental conditions pertaining to the zone's irrigated ecologies. That notwithstanding, the sustainability of irrigated agriculture will improve with the introduction of efficient on-farm strategies (Zerihun *et al.*, 2001; Hillel and Vlek, 2005; Khan *et al.*, 2006; Hsiao *et al.*, 2007) to increase soil water availability and ameliorate the high competition for scarce water resources. Efficient irrigation systems such as drip can reduce the amount of water withdrawals from water resources; thereby increase agricultural water productivity (Molden *et al*., 2003). Several stakeholders in the irrigation industry have also advocated for the promotion and adoption of affordable and user-friendly small scale irrigation schemes that are efficient and increases water and crop productivity (Namara *et al.*, 2011). The use of efficient irrigation system such as the drip irrigation system can contribute significantly to achieving the estimated additional 5,600 km^3/year of consumptive green water needed as evapotranspiration by the year 2050 to feed the additional three billion world population and to eradicate malnourishment (Falkenmark and Rockstrom, 2004).

The drip irrigation system reportedly, has enormous benefits over traditional irrigation methods because, water delivery is directed at the root zone of plants with about 95 % efficiency (Sharma, 2001; Pedro *et al*., 2007). Also, the drip irrigation method improves tomato fruit yield by about 50 % (Warner *et al*., 2004; Xu *et al*., 2009); has high water and fertilizer use efficiency of above 60 % (Locascio, 2005; Michael, 2008) and is highly suitable on wide range of soils (Wei *et al*., 2003; Michael, 2008). According to Siag *et al*. (2010), significant gain in cotton yield and increase in water-use efficiency was achieved under drip irrigation system compared to surface irrigation methods. The drip irrigation system combined with proper field management practices brings huge returns on investment. Meanwhile, there are gaps in knowledge on the response of tomatoes to multiple factors of field management strategies in relation to the soil environment. Therefore, there is the need to investigate the interaction effect of deficit irrigation regimes and quantity of crop residue mulch such as rice straw on tomato varieties within the Savannah agro-ecology.

Moreover, the complex interaction of the crop and its environment (soil-plant-atmosphere continuum) require use of crop-water productivity simulating models capable of determining the crop's response to different environmental factors affecting productivity (Greaves *et al.*, 2016; Sekyi-Annan *et al.*, 2017). These models are capable of simulating crop responses to agronomic practices under irrigation systems to inform proper field management decisions. An example is that Abdul-Ganiyu *et al*. (2018) accurately simulated the response of paddy rice to irrigation regimes using Aquacrop model to support decision making and practice. However, the CROPGRO model is very robust in simulation dynamic processes in the soil and crop growth as influenced by multiple agronomic and environmental factors (Jones *et al.*, 2003; Sekyi-Annan *et al.*, 2018). Understanding the nexus is key to agricultural decision making aimed at increasing water and crop productivity of agricultural lands. The need to investigate tomato response to site specific irrigation requirements aimed at improving irrigation scheduling of the crop in the Guinea Savanna Agroecological Zone was emphasized by Sadick *et al.* (2015).

Further, the development of water-stress index (CWSI) is crucial in scheduling irrigation to cater for the water needs of crops without affecting the soil environment. Several researchers have developed model equations to estimate CWSI of crops under different irrigation systems and management strategies for multiple environments to help crop monitoring and irrigation scheduling (Alderfasi and Nielsen, 2001;Testi *et al*., 2008; Lopez- *et al*., 2011;Unlu *et al*., 2011). There is the crucial need to develop CWSI dependent on leaf temperature for high economic value crops such as tomatoes with huge production potential in the zone to maximise water-use and savings.

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of the study was to investigate the effect of drip irrigation application regimes and mulching on soil properties and the physiological performance of two tomato varieties in the upland irrigated ecologies of Guinea Savannah Zone of Ghana.

1.3.2 Specific Objectives

The specific objectives of the study were to:

1. Assess the effect of deficit irrigation application regimes on soil properties, plant growth, fruit yield and fruit quality traits of two tomato varieties under drip irrigation.
2. Assess the effect of rice straw mulch on soil properties, plant growth, fruit yield and fruit quality traits of two tomato varieties under deficit irrigation application regimes.
3. Determine the interactive effect of deficit irrigation application regimes and quantity of rice straw mulch levels on soil properties, plant growth, fruit yield and fruit quality traits of two tomato varieties.
4. Determine water - use efficiency of irrigation (IWUE) and formulate crop water stress index (CWSI) of two tomato varieties as affected by interactive effect of deficit irrigation application regimes and quantity of rice straw mulch under drip irrigation.
5. Model and develop improved irrigation schedule for dry season cultivation of the two tomato varieties under drip irrigation system in the upland ecologies of the Guinea Savannah Zone of Ghana.

1.4 Hypothesis of the Study

To guide the study, the specific objectives were used to formulate the following hypothesis.

Null Hypothesis (Ho):

a. Deficit irrigation application regimes cannot improve soil properties and agronomic performance of tomato varieties.

b. The application of rice straw mulch cannot improve soil properties and agronomic performance of tomato varieties.

c. There will be no interactive effect of deficit irrigation application regimes and quantity of rice straw mulch on soil properties, plant growth and yield components of tomato varieties.

d. The interactive effect of deficit irrigation application regimes and quantity of rice straw mulch lwill not influence the irrigation water - use efficiency (IWUE) and crop water stress index (CWSI) of tomato.

e. No prediction models can be developed and well calibrated to simulate improved irrigation schedule for dry season cultivation of tomato under drip irrigation in the upland ecologies of the Guinea Savannah Zone of Ghana.

Alternate Hypothesis (Ha):

a. Deficit irrigation application regimes will improve soil properties and agronomic performance of tomato varieties.

b. The application of rice straw mulch will improve soil properties and agronomic performance of tomato varieties.

c. There will be high interactive effect of deficit irrigation application regimes and quantity of rice straw mulch on soil properties, plant growth and yield components of tomato varieties.

d. The interactive effect of deficit irrigation application regimes and quantity of rice straw mulch will positively influence the irrigation water - use efficiency (IWUE) and crop water stress index (CWSI) of tomato.

e. Prediction models can be developed and well calibrated to simulate improved irrigation schedule for dry season cultivation of tomato under drip irrigation in the upland ecologies of the Guinea Savannah Zone of Ghana.

1.5 Limitations of the Study

The limitations of the study were:

a. Limited access to primary data such as phenology on the tomato varieties posed challenges in the estimation of crop water requirement and calibration of the CROPGRO - Tomato Model.

b. In the estimation of crop water stress index (CWSI), the 50 % ET_c deficit irrigation regime was considered as the maximum stress and non-transpiring baseline.

c. Soil sensors were not available for installation and continuous monitoring of soil water content at multiple soil depths in each experimental plot. The TDR 150 Soil Misiture Meter was rather used to monitor soil water content at shallow depths which posed challenge in the calibration of the model.

1.6 Structure of the Thesis

This thesis is divided into five (5) chapters. Chapter One introduces the study, pointing out the reasons for the study as well as outlining the study objectives and respective research hypothesis. Chapter Two highlights the background and reviewed literature on the broader practice and principles of irrigation as well as crop response to irrigation and soil amendment strategies with emphasis on deficit irrigation and mulching from global scale to the local situation in Ghana.

Chapter Three describes the study area and provides the technical details on materials and methods that were used to arrive at the results for the outlined objectives. Chapter Four presents detailed results of the study and their discusions in line with the specific objectives. Lastly, Chapter Five summarises the results and draws useful conclusions from the study results as well as highlighting some recommendations for policy and practice.

CHAPTER TWO

LITERATURE REVIEW

2.1 Agricultural Water Resources Potential and Management in sub-Saharan Africa

Water is a natural renewable source and the most valuable of all forms needed for human existence; providing for the various competing needs of man (Yeleliere *et al.*, 2018). The socioeconomic benefits associated with water resource are huge in the recreation, health, agriculture, industry, tourism, irrigation, sanitation, and transport sectors of sub-Saharan African countries (Nsubuga *et al.*, 2014; Owusu *et al.*, 2016; Ngene *et al.*, 2021). Despite the huge presence of water worldwide, there is still lack of access to this valuable resource especially potable water needed for sustainable development (Owusu *et al.*, 2016). Of the 2.5 % fresh water of the world, less than 1 % is accessible in rivers, lakes and underground (FAO, 2003; WRC, 2005). In comparison with other countries, the USA holds about 45 % of the world's total freshwater resources and Asia the second largest with over 28 %. Next is Europe with 16 % and the remaining continents including Africa with 12 % (FAO, 2003).

The water resources of Ghana are categorised into surface and ground water; with patches of reservoirs or impoundments such as dams and dugouts. The foundation of surface based water sources of Ghana emanates from river systems namely, South-Western, Coastal and Volta River systems (GNWP, 2007). The GNWP (2007), stated emphatically that, the Red, White and Black Volta as well as the Oti River constitute the Volta-River system; the Densu, Ayensu, Ochi-Amissah, Tordzie/Aka and Ochi-Nakwa comprise the Coastal-River system; and the Pra-Rivers constitute the South-Western River systems of Ghana. The GNWP (2007) further delineates Ghana's groundwater resources according to three geological formations consisting of 1 %, 45 %

and 54 % for the Mesozoic and Cenozoic sedimentary rocks; the consolidated sedimentary formations; and basement complex (crystalline igneous and metamorphic rocks) respectively.

Ghana has over the years experienced several reservoirs and dams constructed within its entire stretch especially in the middle belt and northern parts for multiple purposes such as irrigation, animal watering and hydroelectricity. An example of man-made lake is the Akosombo which is larger and covers 8500 km^2 area and 148 km^3 water volume capacity (Ghana National Water Policy 2007; WRC, 2015). According to Namara *et al.* (2010), irrigation in Ghana accounts for an estimated 66.4 % of freshwater withdrawals. Despite the huge withdrawals of freshwater for agriculture, recharge by precipitation is declining as well as intensification of frequency of extreme weather events such as drought and flooding; a consequence of increase in temperature due to climate change (Piani *et al*., 2010; Salack *et al*., 2015; Finley, 2016). In addition, there has been variation in seasonal rainfall distribution, amount, intensity, and duration over the years affecting the water resource potential (Finley, 2016). The exponential growth of human population exacerbates the problem, due to the increasing demand for water, which is becoming a limited and scarce resource. The quality of Ghana's water resources has over the years been compromised due to the rapid pollution rate from sources such as the discharge of sewage into water bodies from domestic and industrial activities and the menace of illegal artisanal mining popularly known as 'galamsey' (USAID, 2011). The leaching of pesticides residues and chemical fertilizers from agricultural lands contributes significantly to pollution of groundwater (USAID, 2011). The resultant increase in the cost of treating polluted water for domestic use is experienced due to the heavy metal contaminants (Yeleliere *et al*., 2018). Nonetheless, the polluted water resource can be channeled into off-shore storages, recycled, and reused for various purposes including agriculture

(Nsubuga *et al.*, 2014). The rapid urbanization and population growth, coupled with conflicts over the limited water resources emphasizes the need for effective water management and allocation of water resources (Zhao *et al.*, 2017; Yeleliere *et al.*, 2018).

Agricultural water management entails adequate and timely measures to facilitate the safe delivery and use of water, both in good quality and quantity for sustainable production of livestock, fish, and crops (Chitima and Rutten, 2015; Koppen *et al.,* 2015). Weerasinghe (2020), further defines water resource management (WRM) as the planning, developing and management of water resources by all stakeholders regarding their quality and quantity needs. The sustainable management of water resources is crucial in providing the basic needs of man (Ngene *et al*., 2021). However, the climate change impact on the hydrological system poses a challenge to the development and introduction of adaptation strategies for water resource management (Piani *et al*., 2010; Muerth *et al*., 2013). According to the IPCC (2014) report, the West African region is highly prone to the dangers of climate change and with a low adaptive capacity. Further projections into the future suggest a severe climate change impact on the water resources of the region; indicating increased risk of flooding and water stress conditions for crops (Oyerinde *et al*., 2014; Sylla *et al*., 2015). The increased risk of flooding will certainly lead to changes in river flows (Ardoin-Bardin *et al.*, 2009; Aich *et al.*, 2014; Mbaye *et al.*, 2015). There is urgency in realising the important role irrigation plays in mitigating the negative effect of climate change on agriculture.

2.2 History of Irrigation Development: Pre and Post-Colonial Era

Irrigation development spans several civilizations of the world to overcome food insecurity: by increasing food crop production with the available water resources. The practice of irrigation was common in the early Mesopotamian and Chinese Civilizations during the pre-historic time using simple water diversion structures such as canals to move water from rivers to the field for crop production. In Egypt, archaeological evidence of irrigation points to some 5000 years BC where flat basins of varying sizes were used to direct floodwater to the Nile River basin to produce winter crops (Bazza, 2006). This system was improved and gave rise to basin irrigation, with the use of earthen banks to direct flood water in the region. The poor rainfall and dry climate of the region forced the Egyptians to practice the basin irrigation at peak streamflow of the Nile River. The practice was adapted with slight modifications and used in Mesopotamia around 3000-5000 years BC to the Euphrates and Tigris river basins (Water encyclopedia, 2019). The Chinese joined in during the Neolithic period about 7000 years ago after the emergence of abundant water resources and favorable flat land topography for paddy rice and stock breeding. Later, the Chinese drained excess floodwater from their farmlands by digging canals in the summer and autumn seasons, which were characterised by heavy rains (Bazza, 2006). During the Bronze Age civilization, the Minoans of Crete considered choice of settlement land on their food, defense, and water needs (Angelakıs, 2020), and introduced sophisticated technologies into the development of new plant species and terraced agriculture in the bid to increase food crop production. The eastern Crete region had groves intersected by numerous irrigation and drainage channels with aesthetic value, which were later transferred to the central Greece by the Minyans. Several local factors such as climate, soil type, water availability among other socio-economic and environmental conditions influenced water resources management actions that led to development of technologies such as the terracing agriculture (Lyrintzis and Angelakis, 2006; Angelakis *et al.*, 2013).

There is archaeological evidence of water wells of 10 –15 m depth in the same era within the Palaikastro region (Angelakis *et al.*, 2012). The Meso-Minoan period (ca 2150–1600 BC) in the eastern Crete saw the invention of a simple hand tool ‘shaduf or shadoof’ for lifting water to support irrigation (Yannopoulus *et al.*, 2015). The tool 'shaduf' is in use in Egypt, India, and other countries. The Minoans of Crete constructed water holding structures such as earthen dams to regulate the flow of streams during the second millennium BC. The transition had irrigation practices and systems been modified to meet local conditions. The use of simple – pot irrigation to sophisticated hydraulic structures such as surface and groundwater storage reservoirs and water lifting devices such as traditional pumps were developed in the pre-historic era (Kenoyer, 1991; Paresh, 2009). Despite the quick evolvement of irrigation and drainage over the numerous civilizations recorded pre-and historical era, the increase in irrigated land is slow; though an increase from 184 million hmz in 1970 to 258 million hmz in 1990 and 324 million hmz in 2012 was reported by the FAO (Postel and Last, 1992; Faures, 2002). The poor irrigation infrastructure and collapse of several large-scale irrigation systems of the former Soviet Union and parts of Europe accounted for the slow expansion (Siebert and Doll, 2007). There is a further diminished land area under irrigation of several developed and developing countries of the world attributed to the high cost of modern irrigation systems, soil salinity and depletion of water resources by climate change (Freydank and Siebert, 2008).

The spate irrigation is more than 400 years old and largely practice in East Africa along the Tana River, Marakwet, West Pokot, Baringo and Keiyo districts of Kenya (Ngigi, 2002; Muthigani, 2011). Also, in the mid-90's, the practice of Farmer led irrigation development (FLID) characterized by the manual bucket irrigation method was practiced on the banks of Lake Victoria and the traditional furrow irrigation method used for fodder production in Kenya (Scheltema, 2002). The expansion of traditional irrigation infrastructure to large-scale irrigation schemes in Kenya started when interest in the production of cash crops such as coffee and tea aroused (Ngigi, 2002; Nakawuka *et al*., 2018). Irrigation have improved from the use of traditional methods to the use of the sprinkler irrigation system in the production of horticultural and ornamental plants in Kenya (*Nakawuka et al*., 2018). The gradual shift from the traditional irrigation methods to modern ones, ignited the need for manual to motorised pumps to lift water and create the required pressure needed to run the sprinkler and drip irrigation systems (Nakawuka *et al.*, 2018). The use of groundwater for irrigation through boreholes has widely increased the use of drip irrigation system in East African countries including Kenya to produce high value vegetables, flowers, and fodder for animals (Scheltema, 2002).

Irrigation development in Ghana is driven by the formal and informal sectors (Namara *et al*., 2011). The existence of small-scale irrigation in Ghana, is little over a century ago (Namara *et al*., 2011), to mitigate the low and erratic rainfall patterns and increase crop production (Abric *et al*., 2011). Irrigation development in Ghana transitioned from about 19,000 ha of irrigable lands in the 1980s and almost doubled in 2007 due to increased government commitment to the irrigation sector (Namara *et al.*, 2011). Notably, some peasant farmers in the early 1980s, practiced traditional irrigation in small scale along several flood plains and incorporated good agricultural practices such as crop rotation and manuring (Kyei-Baffour and Ofori, 2006). In 2010, an estimated 185,000 ha irrigable land was reported to be under informal irrigation involving about 500,000 smallholder farmers (Evans *et al*., 2012). According to Dittoh *et al*. (2013), the informal irrigation sector of Ghana is five-times bigger than the formal sector in terms of irrigable area. In 2019, the informal sector's irrigable land alone was 20 times bigger and employs 45 times more people than the formal sector (Balana *et al.*, 2019). The irrigated land area under informal sector could even be more, since the national irrigation statistics usually excludes the farmer-led irrigation investments (Giordano *et al.*, 2012). The traditional or surface irrigation system comprising basin, furrow, and border irrigation methods, is major in Ghana. Traditional irrigation's water withdrawal is from groundwater sources (shallow wells, tube wells and boreholes) and surface water sources (rivers, streams, lakes, and reservoirs). In addition, the use of small motorized pumps to lift water from surface water resources for irrigation purposes is common (Segtub *et al*., 2018), and popular with peri-urban farmers (Namara *et al*., 2011). Dittoh (2020) reported that, the manual irrigation method using watering cans and buckets to draw water from shallow wells is very common amongst peasant farmers as well as the traditional small scale irrigation practice being prominent in the drought prone areas of northern and coastal Savanna Ecological Zones of Ghana. The Volta, Ashanti and Eastern regions are also known for the surface-water-pumping-based irrigation systems (Namara *et al.*, 2010).

The formal irrigation sector of Ghana relies heavily on built irrigation infrastructure notably earthen dams, small reservoirs, and dugouts for multipurpose uses such as domestic, animal watering and to irrigate crops under the forces of gravity. Basin irrigation for rice production is usually within the lowland areas of the irrigation schemes and the upland irrigable areas designated for cereal crops such as maize and vegetables (tomatoes, pepper, onion, and lettuce) under the traditional furrow irrigation method (Kyei-Baffour and Ofori, 2006). There are 22 public irrigation schemes dotted all over the country, but most are under performing (Kyei-Baffour and Ofori, 2006; Dittoh *et al*., 2014; Adongo *et al.*, 2016). The transition from traditional to modern irrigation systems in Ghana has been slow by both peasant and large-scale commercial farmers. The use of improved irrigation systems such as the drip and sprinkler irrigation systems have been introduced by several actors in the irrigation sector. The IWAD through partnership with the Ghana Government (GoG) and other private bodies, established a modern large scale commercial farm in

Yagaba, Mamprugu-Moagduri District of the North – East Region aimed at producing rice under improved basin, cereals under furrow irrigation and centre-pivot system, as well as vegetables under drip irrigation systems (IWAD, 2016; Ayelazuno, 2019). Also, there is a private driven commercial investment of a similar irrigation installation known as the Babator Farming Company (BFC) situated in the Buipe District of the Savanna Region. The BFC is funded by AgDevCo and envisage to establish about 5,740 ha of farmlands and processing hub after completion. The BFC depends solely on the Volta Lake as source of water for pump irrigation to support installed drip, solid-set sprinkler, and pivot irrigation systems. The pivot irrigation system was largely promoted in northern Ghana by the Ghana Commercial Agriculture Project (GCAP). However, most of the center pivots are now abandoned under the harsh weather; yet to receive the needed attention. This could possibly be attributed to the high running cost of the system and lack of expertise needed for its periodic maintenance. Aside the investment, the individual farmers' contribution to small scale irrigation systems such as drip and sprinkler irrigation is enormous and dotted all over the country to produce horticultural and ornamental plants for both local and foreign markets.

2.3 High Value Vegetable Crop Production in Ghana: Relevance and Scope

The production of vegetable crop is crucial in agricultural systems and contributes to food sovereignty as well as generating income and employment (Schreinemachers *et al.*, 2016). The importance of vegetables is enormous and helpful in fighting against numerous diseases (Baidya and Sethy, 2020). The disease curing properties can be an incentive towards strategies aimed at increasing the intake of vegetables (Baidya and Sethy, 2020; Moseley *et al*., 2020). Tomato is high value with more economic benefits and highly produced in terms of cultivated area as well as consumption (FAOSTAT, 2019). According to Asselt *et al*. (2018), tomato emerged as highest (35 %), followed by onions (19 %), chillies (10 %) and carrot the least with 1 % from the 12.8 % food expenditure. The fruit of tomato is consumed either cooked, half-cooked or added in salad (Dhaliwal, 2014; Welbaum, 2015; OECD, 2017). Tomato fruit contains health benefits notably lycopene which helps the body in fighting formation of cancerous cells and related diseases (Bhowmik *et al*., 2012; Ilić *et al*., 2014; Baidya and Sethy, 2020). In addition, the fruits contain vitamins C and A which are immune booster and other trace elements that helps in regulating blood pressure and nerve activity (Bhowmik *et al*., 2012). Tomato production world-wide was 180 million tonnes as of 2019 which was produced on 5 million hectares of land. However, production in Ghana was 395,755 on 92,045 ha of land (FAOSTAT, 2019). Contrastingly, the estimated annual consumption of tomato fruits in Ghana stood around 400,900 tonnes which exceeds the country's domestic supply: hence an indication of deficit. To meet the deficit supply and high demand of tomato and tomato products, Ghana imported 8,753 tonnes of tomato valued at US$1.84 million (FAOSTAT, 2019). Also, 57,971 tonnes of tomato products valued at US$ 47.37 million was imported same year (FAOSTAT, 2019). According to Asselt *et al.* (2018), the Burkina Faso's share in Ghana's market is 89 % though the tomato imports and the values of trade might be higher than official figures reported. Tomato fruit yield in Ghana is low averaging 7.5 t/ha recorded by farmers (MoFA, 2017). Nigerian growers obtained 4 t/ha from 2012–2014, growers in Cameroon attain yields of 13 t/ha, India 21 t/ha, and China as much as 51 t/ha is attained by farmers (FAO, 2017). FAOSTAT (2019) reported declined yields of 4 t/ha in Ghana compared to 10.86 t/ha for Burkina Faso and the 35.93 t/ha globally (FAOSTAT, 2019). There is wide variation in onfarm productivity of vegetable (FAO, 2017). The differences are largely due to tremendous variability in growing conditions and input use. The poor yields could be militated by so many constraints in the production process that consist of biotic and abiotic factors. The perishable nature of tomato fruits poses post-harvest handling challenges affecting productivity. The losses associated to vegetables could be as much as 50 % (Gonzalez *et al.*, 2016) which suggest non-sustainability of current production practices.

The high production and import cost of tomato and its products, dwindles the relevance of tomato in the country (Robinson and Kolavalli, 2010). Despite interventions to revamp tomato processing factories, they remain shut-down due to poor quantity and quality of tomato fruits (Robinson and Kolavalli, 2010). This has resulted in huge potential of the industry in boosting economic growth and job creation (Gonzalez *et al.*, 2016). The consumption of vegetables in Ghana is still relatively small as compared with other African countries like Kenya, though there is rapid expansion. Besides local vegetables, the most important ones are tomatoes, peppers (both sweet and hot chilies), onions and okra with a boom in the market for tomatoes and peppers in recent times (Gonzalez *et al.*, 2016). For countries in the West Coast of Africa, the production of tomato is concentrated under rainfed conditions due to lack of heat-tolerant varieties for dry season production (Ayenan *et al.*, 2021). This seasonality often results in produce shortage during the dry season and prices hikes (Ayenan *et al.*, 2021). On the contrary, farmers experience glut during the rainy season and abandon their fields when prices are so low. Considering the environmental and agronomic requirement of tomato, many parts of Ghana is suitable for tomato production (Melomey *et al.*, 2019).

The challenges can be averted through the comprehensive dedication of efforts and resources so that opportunities for tomato production, improvement in yield, storage, and marketing could be enhanced. Moreover, understanding key drivers in the use of improved tomato varieties will guide interventions seeking to promote new varieties. Vegetable production, processing and marketing offer potential opportunities that can be especially attractive to youth: production requires only small amounts of land, is technology-savvy, and high profits can be obtained in a relatively short period of time.

Furthermore, low levels of mechanisation in vegetable production and the need for careful handling of produce often create a specific demand for female labour. Food safety goals require policymakers to define suitable standards for vegetable production and handling and to put in place systems for monitoring compliance, including regular testing for pesticide residues and pathogens at major markets and public dissemination of the test results. The potential of vegetable production in creating employment and generating income is huge in developing countries (Gonzalez *et al.,* 2016). Also, it provides micronutrients for the body and antioxidants and phytochemicals that may protect people against diseases (Melomey *et al.*, 2019).

2.4 Origin and Classification of Tomato Crop

Numerous debates have surrounded the origin of tomato crop. While some are suggesting the center of origin to be Peru (Preedy and Watson, 2008), others have suggested two centers of origin - the coastal region between the Andes and the ocean (Blanca *et al.*, 2012) and the other from South-Mexico to Guatemala (Bauchet and Mathilde, 2012). Authors; Peralta *et al.* (2005) and Blanca *et al.*, 2012) reported that wild-families of tomato can be found in the Andes from Ecuador, through Peru and to Chile, growing in diverse climatic conditions. Bergougnoux (2014) dates tomatoes to 500 BC in Mexico that was used in cooking by the Aztecs. Evidence has shown that Peru and Mexico are the major regions of tomato domestication (Peralta *et al.*, 2006). Two hypotheses have been expressed for the original site of tomato domestication: one stipulates Peru and the other Mexico. It is, however, presumed that Mexico is probably the site of domestication and Peru is the centre of diversity (Larry *et al.*, 2007). Originally, tomatoes were pea-sized berries, but domestication and plant breeding have resulted in increased fruit sizes (Soyk *et al.*, 2017). Up until the year 2014, Asia has been the largest producer of the vegetable with 51.2 % (FAOSTAT, 2014). In 2015, tomato export grew and summed up to US$ 8.4 billion with Mexico being the highest exporter in dollar value of US$ 1.8 billion comprising 21.6 % of total tomato exports (Workman, 2016).

Taxonomically, the crop belongs to the Solanaceae family. The *Solanum lycopersicum* is the cultivated species, while *Solanum pimpinellifolium* is the closest wild relative of only 0.6 % divergence nucleotide base pairs (Soyk *et al.*, 2017). Norman (1992) stated that, tomato (*S. lycopersicum*) was introduced into the geographical area considered modern day Ghana in the sixteenth century. Despite the large cultivation of tomato, it remains a subsistent farming activity, and its cultivation and trade have contributed immensely to the improvement of livelihoods (Gongolee, 2014). Schippers (2000) reported on the relevance of tomato which is justified by the continuing increase in demand for fresh and processed tomatoes in Ghana. Although tomato production in Ghana is seasonal due to the differences in the rainfall patterns as well as water availability for irrigation, yet the demand for both fresh tomato and tomato products remains year-round. The cultivation of tomato is done under rainfed and irrigated conditions of the agroecologies of Ghana. Tomato is mostly produced in eleven out of the 16 regions in Ghana. These production regions include Upper East, Northern, Savanna, North-East, Upper West, Bono, Ahafo, Ashanti, Eastern, Greater Accra and Volta regions. However, about 80 % of tomato production in Ghana is under irrigation and out of which about 70 % is produced in Upper East Region. Tomato production in the Upper East region is all year-round as compared to Burkina Faso with irrigation playing a key role (Robinson and Kolavalli, 2010).

2.5 Molecular and Morphological Characteristics of Tomato

Morphological characterisation is the first step for the evaluation of genetic diversity and is also important for the preservation and conservation of plant genetic resources (Osei *et al.*, 2014; Figas *et al.*, 2015; Sacco *et al.*, 2015). Local landraces are known for their large fruit size, traditional taste, fleshy texture, and flavour (Ganeva *et al.*, 2014). Due to the continuous natural or artificial selection, the landraces are well acclimatised and adapted to the local agro-environment but are often not suitable due to low productivity, poor disease resistance, and lack of uniform fruit quality and morphometric attributes (Fess *et al.*, 2011). Morphological characters have for a long time remained the means of studying genetic variations in plant species. Morphological data are affected by ecological interactions; thus, explanations must be made with suitable replication.

Grozeva *et al.* (2020) carried out an experiment on the characterization of tomato accessions for morphological, agronomic, fruit quality and virus resistant traits. They found out that, on the fruit shape, most accessions were flattened to rounded, few accessions were of heart-shape and pear-shape. The most common exterior color of mature fruit that was observed was red, followed by pink, orange, yellow, brown, green and orange-red. Based on fruit size, accessions ranging from very large, large, medium, small, and very small were characterised. Several studies have also shown rich diversity across the morphological characteristics of tomato and descriptors displayed large variations in fruit shape, size, productivity, yield components, and fruit quality (Mavromatis *et al.*, 2013; Omar *et al.*, 2019; Salim *et al.*, 2020). Nankar *et al.* (2020) stated that, there are considerable agro-morphological variations and fruit quality (Mavromatis *et al.*, 2013; Sumalan *et al.*, 2020) to characterize the tomato collections. Also, variability reported for morphometric traits of fruit shape, size, and color indicates that tomato producers prefer fruits of peculiar fruit types, and this information could be used as a base for the development of varieties that has desirable features for any targeted market segment (Nankar *et al.*, 2020; Sumalan *et al.*, 2020). Tomatoes can be classified as determinate, semi-determinate and indeterminate (Steduto *et al.*, 2012).

2.6 The Agronomy of Tomato Crop

The demands for tomatoes in both domestic and international markets have led to an increasing cultivated area for the crop. To support growers in producing healthy and quality tomato fruits for diverse users, this review presents an overview on the agronomic requirements of tomatoes regarding climate, suitable soil type, crop varieties, nutrient requirements, pests and diseases control, irrigation, and mulching requirements. The cultivation techniques are reviewed to provide a general understanding of what other researchers have done in their various locations in developing site specific field practices.

2.6.1 Climatic Requirements

Tomato requires temperature of 20 - 25 °C but 21 - 24°C to attain excellent quality red color (Sawant, 2018). Temperatures above 43 °C produce intense heat that scorches plant leaves and causes flowers to abort and small fruits to drop, whereas less than 13 °C and greater than 35 °C decreases the fruits and the red color production ratio. Shankara *et al*. (2005) stated that, tomato requires a relatively cool, dry climate for high yield and premium quality but can adapt to various climatic conditions. The tomato plants can survive a wide range of temperatures, but plant tissues are damaged below 10 °C and above 38 °C (Sawant, 2018). In addition, tomatoes are day-length neutral plants (Nuruddin, 2001). Light intensity of 400 - 500 $\mu mol.m^{-2}s^{-1}$ is optimal for growth and development. High light intensity may cause fruit cracking, sunscald, and green shoulders (Ha, 2015). Fruit formation will be influenced when unfavourable weather events persist during flowering due to low pollen production.

2.6.2 Soil Requirements

Tomato grows very well on a wide range of soils, but most preferred is deep and well-drained soils with good drainage ability, water holding capacity and free of salt (Ha, 2015). Sandy loam to medium black soils is most suitable for tomato cultivation. Soil pH between 6 and 7 with excellent drainage property is highly recommended (Sawant, 2018). Soil pH below 5.5 results in plant disorders such as blossom-end-rot in some varieties, soil magnesium and molybdenum unavailability to the plants and above 6.5; zinc, manganese and iron become deficient in the plant (Ha, 2015).

2.6.3 Tomato Varieties

The selection of varieties depends on local site conditions and the objective of cultivation. Landraces and improved (or commercial) varieties can be distinguished. The criteria for selection are based on certain features such as type of fruit, shape of plant, vitality and resistance to pests and diseases, but also on factors related to climate and management. Farmers select varieties that perform best under their local conditions. In India, some improved varieties have been recorded by Sawant (2018) to include but not limited to: Pusa- 120, Pusa Ruby, Pusa shital, HS101, HS110, HS102, Pusa Early Dwarf, Arka Ahuti, Arka Meghali, Hisar Lalit, Hisar Anmol, Co-1, CO 2, CO 3, S-12, PKM 1, Pant Bahar, and Solan Gola among others. Hybrids included Pusa Hybrid 1, Pusa Hybrid 2, Pusa Hybrid 3, Arka Vishal, Arka Vardan, COTH 1 Hybrid Tomato, MTH 4, Naveen, Avinash 2 and Gulmohar.

In Kenya, field type varieties include but not limited to Assila, Rwambo, Eden, Firenze, DRD 8551, Bravo F1, Rambo, Kilele F1, Shanty, Tropicana, Monica F1, Nouvelle, Bigwa, Nuru F1, Faulu F1, Mavuno F1 while greenhouse varieties include Anna F1, Chonto F1, Eva, Nominneta

F1, Corrazon, Eden F1, Tylka F1, Kilele F1, Prosatar, Little, Libra, Chonto (Madumadu *et al.*, 2004).

In Ghana, several tomato varieties exist and suitable for rainfed and irrigated ecologies that includes; Pectomech, Tropimech, Wosowoso and Power Rano (Clottey *et al.*, 2009; Adubofuor *et al.*, 2010; Robinson *et al.*, 2010). The Department of Agriculture (DoA) also promoted the Rio Grande, Cac J. and Laurano 70 cultivars in addition to the already existing ones (Puozaa, 2015). Also hybrids such as Mongal F1 have been promoted and shown to be high yielding (Ochar *et al.*, 2019). Tomato varieties cultivated in a traditional way have adapted to local environments and developed resistance to diseases than the hybrid tomatoes that are currently cultivated (Carbonell *et al.*, 2018).

2.6.4 Nutrient Requirements

The rapid growth of Tomato necessitates recommended nutrient requirements. For instance, 1 ton of fruits can be produced from 1.36 - 3.63 kg N; 0.23 - 1.36 kg P_2O_5; 2.27 - 5.45 kg K_2O (Ha, 2015). The application of organic fertilizer such as farmyard or animal manure is good in providing the needed plant nutrients and improving the structure of soils especially sandy soils. Sawant (2018) indicated that, at the time of land preparation, decomposed farmyard manure could be broadcasted and thoroughly mixed well at the rate of 20 to 25 t/ha in the soil. A basal fertilizer dose application should then follow with 60 kg of Nitrogen, 80 kg of Phosphorus and 60 kg of Potash per hectare. After 30 to 45 days of planting, 30 kg/ha nitrogen should then be applied.

Tuandike (2018) recommended that for a yield of 40 t/ha, 96 kg of Nitrogen, 144 kg of K_2O, 68 Kg of calcium, 24 kg of Sulphur, 24 kg of Magnesium and 16 kg of P_20_5 should be split applied at 2 and 3 weeks after transplanting. Potassium nitrate could also be applied at a rate of 100 kg/ha 4 to 5 weeks after transplanting and 100 kg/ha of Sulphate of ammonia as top dressing in splits at 6 to 8 weeks after transplanting.

2.6.5 Irrigation Requirements

The type of irrigation used in tomato fields depends on the water resources in a growing area. In some regions in the USA, where water is plentiful, furrow or seepage irrigation is used. In other areas like California, where water is scarce, drip irrigation is used exclusively because of the efficient use of water. Regardless of region, overhead sprinklers are routinely used to help establish new tomato transplants. Tomatoes require a constant supply of soil moisture during the entire growing season. In field situations, tomatoes require 2000 – 6600 m^3/ha of water per season to produce a high yielding crop. In the greenhouse, each plant uses around 1- 2 litres of water every day which is equivalent to around 10,000 m^3/ha per year (Yara, 2019). Excess water, will however, lead to root death in anaerobic soil conditions, as well as delayed, less prolific flowering and fruit set. Too much water after fruit set induces several fruit disorders, most notably cracking. Flowering is also adversely affected under conditions of low moisture stress. Blossom end rot (BER) also becomes a problem due to low water uptake leading to a low calcium uptake and distribution. It is common practice in processing tomato crops to cease irrigation 2 to 4 weeks prior to harvest to maximize dry matter contents in the fruit and minimize soil compaction during harvest (Yara, 2019).

2.6.6 Pests and Diseases Control

The major pests in tomato production are aphids, grasshoppers, whiteflies, crickets, leaf miners, beetles, mites, and caterpillars. Control is with the application of potassic soap solution (Alata samina) at 5 g/L, insecticidal soaps, or recommended insecticides (MoFA, 2013). Also, crop rotation can assist in breaking life cycles of insects and pests. However, control of tomato pests requires careful monitoring and integration of cultural practices and biological control (Jones *et al.*, 2014). A wide range of biological pesticides are available to keep pests below the thresh hold level. Trap crops are also effective in controlling pests. An example is the eradication of Fruit Borer by raising marigold in adjoining plot to divert the attention of the fruit borer. In case eggs of the insect are found on the leaves of the plant, trichocard can be applied (Kaur *et al.*, 2019). Among the alternatives, biological control of pests is one of the important means for checking pest problems in tomato. Neem based pesticides like neem cake, neem seed kernel extract (NSKE), neem leaf extract, neem oil etc., act as a repellent and antifeedent and its oil is effective against fruit borer (Jones *et al.*, 2014). Tomatoes are susceptible to diseases such as bacterial wilt, nematode build up in soils, viral diseases, and bacterial diseases (Abrahamian *et al.*, 2019). Despite agronomic practices, diseases usually occur, presenting one of the greatest challenges to organic tomato growers. The degree of occurrence is largely dependent on environmental conditions (Abrahamian *et al.*, 2019).

2.6.7 Mulching Requirement

Mulch material is required to protect the soil surface from harsh weather conditions such as high temperature, heavy rains and wind speed as well as suppress the growth of weeds on farmlands. Mulching helps to conserve moisture and reduces soil temperature which is ideal for the determinate tomato varieties in maintaining fruit quality. Mulching can be done with organic materials or with inorganic materials such as plastic films (Ramakrishna *et al.*, 2006; Kassahun, 2017). Organic mulches should be applied to the soil surface or incorporated into the soil. Wang *et al.* (2016) stated that, the choice of mulching material depends on the climate, the cost-benefit ratio, and the crop to be grown. Organic mulches directly impact the microclimate near the plant and can affect on plant physiological metabolism (Kader *et al.*, 2017). Beneficial effects of soil mulching have been reported for several crops, including tomato (Kosterna, 2014), potato (Zhao *et al.*, 2014), blueberry (Munner *et al.*, 2019), strawberry (Deschamps *et al.*, 2019), and maize (Wang *et al.*, 2019). Gudugi *et al.* (2012) reported significant gain in fruit yield with rice straw applied at the rate of 5 t/ha. The rice straw significantly increased fruit yield to about two times more than those without mulch. Ertek *et al.* (2004) also revealed that mulching tomato plants using organic materials that is rice straw, green leaves, and coconut fronds at 10 to 20 t/ha gave better fruit yield and significantly decrease soil temperature to 27.5 ⁰ C two weeks after transplanting.

2.7 Irrigation: Definition

Irrigation refers to the artificial application of water to plants to satisfy their daily water requirement (Ali, 2010). Suplementary irrigation is practiced in the raining season whereas total irrigation is done in the dry season in the absence of rains to provide the required soil moisture needed to support the optimum growth of plants. According to Yahaya *et al.* (2012), irrigation water is applied to the soil mainly to support crop production and maintenance of landscapes in dry areas and during periods of drought. According to Finley (2016), irrigation is driven mainly by human or animal power in small farms and by mechanical power in commercial farms. In fact, the methods through which water is applied to the root zone of crops range from simple hand watering to flood and furrow and to sprinkler and drip. In most developing countries, gravity-driven surface methods of irrigation such as flood and furrow have mainly been practiced. However, due to the large water losses associated with these methods, more efficient methods including sprinkler and drip are increasingly being adopted.

2.8 Classification of Irrigation Systems

The classification of irrigation systems can be done according to the level of sophistication involved in operating the system; thus, system monitoring, scheduling, and control of hydraulic structures. The type of setup has the tendency to influence the quantity of irrigation water applied, thereby contributing positively or negatively to water savings and overall delivery efficiencies that will certainly impact the soil and plant environment. Against this backdrop, irrigation systems can be broadly categorised into traditional and modern irrigation systems depending on the nature of water distribution and application systems (Abioye *et al.*, 2020). In other words, the traditional irrigation system is known as the surface irrigation system comprising; furrow, basin and boarder strip irrigation systems, whilst the modern irrigation systems are classified as sprinkler irrigation, micro irrigation and drip irrigation systems (Waller and Yitayew, 2016). The Natural Resources Conservation Service (NRCS): *National Engineering Handbook* (NEH) describes the four major irrigation methods as: surface, sprinkler, micro, and subsurface irrigation. The selection and consideration of a particular irrigation system is dependent on several factors that include soil type and characteristics, crop type, economics, water quality, and management considerations.

2.8.1 Traditional surface irrigation system

In traditional surface irrigation, water is distributed under the force of gravity from higher to lower elevations on the soil surface without any mechanical structure or control action (Ghodake and Mulani, 2016). Traditional surface irrigation methods can be classified as; furrow, basin and border irrigation (Abioye *et al.*, 2020). Moreover, the traditional watering - can and bucket irrigation method is common among some peasant farmers especially women and children in Ghana. The traditional surface irrigation methods are the oldest and most practiced in the world. In the USA, surface irrigation is largely practiced due to its long existence, and native communities have traditionally irrigated their fields for hundreds, possibly thousands of years (Waller and Yitayew, 2016). The practice of traditional irrigation has contributed to the slow adoption of modern irrigation methods by farmers in Ghana. The slow adoption is exacerbated by the numerous uncertainties associated with use of modern irrigation systems.

However, the surface irrigation method is characterised by the use of excessive water for irrigation that results in high water losses from runoff, deep percolation and evaporation (Tagar *et al.*, 2012; Gillies, 2017). The practice of over irrigation poses salinity and waterlogging challenges on agricultural lands and leaching of essential plant nutrients out of the rootzone, leading to poor crop yields and inefficient irrigation (Ishfaq, 2002; Adamala *et al.*, 2014). The efficiency of surface irrigation can be improved through proper land leveling (Zhang *et al.*, 2004). However, farmers are challenged by the availability and affordability of machinery for proper land leveling in Ghana. Further, the installation of modern water control and monitoring structures coupled with water recycle and reuse system downstream of the farm, will help improve farm level efficiency of the traditional surface irrigation method (Koech *et al.*, 2010).

2.8.2 Modern Irrigation Systems

The modern irrigation systems are pressurized to move water from a source/reservoir to the field for plant use through a network of interconnected pipes and hydraulic control structures. The modern irrigation methods are efficient in water delivery to plants and save high volumes of water compared to the traditional irrigation methods. The modern irrigation systems are classified as; micro irrigation, drip irrigation, sprinkler irrigation and subsurface (capillary) irrigation methods (Waller and Yitayew, 2016; Abioye *et al.*, 2020).

2.8.2.1 Subsurface Irrigation System

Subsurface irrigation method supplies water to the plant's rootzone in the soil by the upward movement of water (capillary action) through the soil profile from a controlled water table zone (Waller and Yitayew, 2016). The subsurface irrigation system uses capillary mediums such as mats, ebbs, wicks, porous ceramics, and flows buried in the rootzone of the plants (Wesonga *et al.*, 2014; Cai *et al.*, 2017; Semananda *et al.*, 2018). Aside the use of simple capillary mediums reiterated above, Rahman *et al.* (2019) suggested that water could me moved gradually from the supply tank to the plant's rootzone through a vertical and horizontally placed fibrous capillary interface. To maximise water savings and increase crop yield, the horizontal capillary interface is preferred (Ohaba *et al.*, 2015; Ferrarezi, 2016; Li *et al.*, 2018; Kamal *et al.*, 2019).

Despite the numerous reported benefits associated with the subsurface irrigation system, the capillary action of upward water movement in the soil can introduce and accumulate salts in the plant's rootzone, thereby increasing soil salinity and eventually affecting the performance of the crop (Fujimaki *et al.*, 2018).

2.8.2.2 Sprinkler Irrigation System

Sprinkler irrigation systems mimick the application of water to plants in a form of rain (Abioye *et al.*, 2020). The application of water is overhead the plant canopy through an interconnected network of pipes and spray heads operated under medium to high pressure. Sprinkler irrigation system can be classified as; center pivot, stand-alone, linear, and lateral-move sprinklers. The USA has 46 % of irrigated lands under sprinkler irrigation, of which 75 % is irrigated under the center pivot irrigation system. The advantage of sprinkler irrigation systems over surface irrigation systems is the no restrictions of land leveling or grading on uniformity, even on steep slopes. Further, the system's application uniformity is not affected by variations in soil properties so long as there is no runoff or ponding of soils (Waller and Yitayew, 2016). Sprinklers such as the center pivots and lateral moves, have broader irrigation coverage and capable of irrigating larger areas of farmlands (Evans and King, 2012). However, this irrigation system is challenged with the high cost of operation and accessories. Also, the effect of evaporation and wind drift on water droplets associated with the use of sprinklers is high in arid regions characterized by high temperatures and wind speeds (Zhao *et al.*, 2009; Xingye *et al.*, 2018). The sprinkler irrigation systems require periodic maintenance of hydraulic flow and control structures and regular checks for system leakages which might affect the efficiencies of the system.

2.8.2.3 Drip Irrigation System

The surface-drip irrigation applies the right amount of water directly to the root zone of plants in a controlled manner to meet the crop's water needs (Plusquellec, 2009; Reinders *et al.*, 2012). The application of water in drip irrigation system is done through flexible tubes (driplines) and emitters in a more frequent manner than for surface and sprinkler irrigation systems.

The practice where driplines containing emitters or drippers are placed on the soil surface around the plant to deliver water to the roots is referred to as surface drip irrigation system (SDI). However, the system is referred to as subsurface drip irrigation when driplines are buried in the soil within the rootzone depth of plants to deliver water to the roots system of plants. Drip irrigation is widely adopted and popular in the world due to emerging water scarcity which is exacerbated by the climate change, and the need to achieve a minimum environmental impact of agricultural drainage and runoff associated with the use of traditional irrigation systems (Bloomer *et al.*, 2013). Water losses in drip irrigation is reduced drastically due to the absence of wind drift and evaporation effect on water droplets (Ahadi *et al.*, 2013; Bhalage *et al.*, 2015; Pramanik *et al.*, 2016). The system provides the precise amount of nutrients to plants uniformly through a fertigation system and reduces nutrient losses drastically to the barest minimum (Roma and Arun, 2014; Elasbah *et al.*, 2019; Arshad, 2020). Further, drip irrigation system maintains a relatively constant level of moisture in the root zone for plant use due to the increased frequency of irrigations and increases production and yields of many crops especially vegetables (Xu *et al.*, 2009; Bloomer *et al*., 2013). The drip irrigation system has a high irrigation efficiency of about 95 % (Pedro *et al*., 2007; Reinders *et al*., 2012), resulting in an improved water and fertilizer use efficiency by crops (Locascio, 2005; Michael, 2008; Roma and Arun, 2014). Several studies have been conducted on drip irrigation in combination with field management practices on vegetables especially pepper. Pandey *et al*. (2013) conducted a study on the effect of drip irrigation, spacing and nitrogen fertigation on the productivity of chilli (*Capsicum annuum* L.). Asif *et al*. (2016) investigated the impact of drip and furrow irrigation methods on yield, water productivity and fertilizer use efficiency of sweet pepper (*Capsicum annuum* L.) grown under plastic tunnel. Gadissa and Chemeda (2009) assessed drip irrigation and planting methods and their effect on green pepper (*Capsicum annuum* L.) in Bako, Ethiopia. Debbarma *et al*. (2019) studied the response of bell pepper (*Capsicum annuum* L. *var grossum*) to drip irrigation levels and black plastic mulch under naturally ventilated polyhouse.

Comparatively, the subsurface drip irrigation (SSDI) has numerous benefits over the surface drip irrigation (SDI) (Singh and Rajput, 2007). The benefits of SSDI system include lowering the canopy humidity of crops leading to less diseases and weeds infestation (Camp and Lamm, 2003), improved vegetable yield and quality of produce (Arshad, 2020). In addition, there is reduced nutrient and pesticide leaching into groundwater (Najafi *et al*., 2007) and contributes significantly to high agricultural water savings (Bloomer *et al*., 2013).

Despite the numerous benefits of the drip irrigation system to the soil, water and crop environments, it is challenged by the following (Waller and Yitayew, 2016; Arshad, 2020).

a. Clogging of emitters and preventing the uniformity of water flow into the plant's root system.
b. Regular maintenance is required to overcome leakages in the system.

c. High installation cost.
d. High level of expertise required in the design and maintenance of the system.
e. Wear and tear of components such as pipes due to the high exposure to sunlight.
f. Damage of driplines and related components by rodents and during farm operations.

2.8.2.3.1 Drip Irrigation System: Components

The drip system consists of three main components namely, water source and pump unit, filtration unit and the network of pipes (Arshad, 2020). The source of water for irrigation could be groundwater (borehole, open shallow well) or surface water (river, stream, canal, or overhead tank). For overhead tank installations, a pump may not be required since water can flow under the force of gravity to the irrigable area. Boreholes and wells will require a submersible pump to lift water to desirable head for irrigation purposes. However, centrifugal pumps are needed to lift water from rivers, streams, and other surface water bodies to the field for irrigation. The water yield of groundwater sources is required in the selection of a suitable pump with the desired pressure for drip irrigation installations. Preferably, operating pressure of 1.5 – 2.0 kg/cm^2 is required for drip irrigation (Bucks *et al.*, 1981).

The filtration unit consists of pressure gauge, primary filter, venturi/fertilizer injector, fertigation tank and water-flow meter. Water for irrigation passes through an array of primary and secondary filters to improve quality by removing sediments to avoid clogging of emitters. The types of filters include hydro-cyclone filters, sand/media filters, and screen/disc filters. The suitability and number of filters depends on the quality of water and the level of impurities found in the water source (Arshad *et al.*, 2017).

The pipes are sized and arranged in a network to deliver the required volumes of water to the different segments of the installation for plants use. The pipes consist of mainlines, submain lines, and laterals/driplines containing drippers/emitters. The length and diameter of pipes in the network is dependent on design, land-topography and the crop water requirement which provides basis for the selection of emitters (Arbat *et al*., 2010). Figure 2.1 depicts a schematic layout of pressurized drip irrigation according to Bloomer *et al.* (2013).

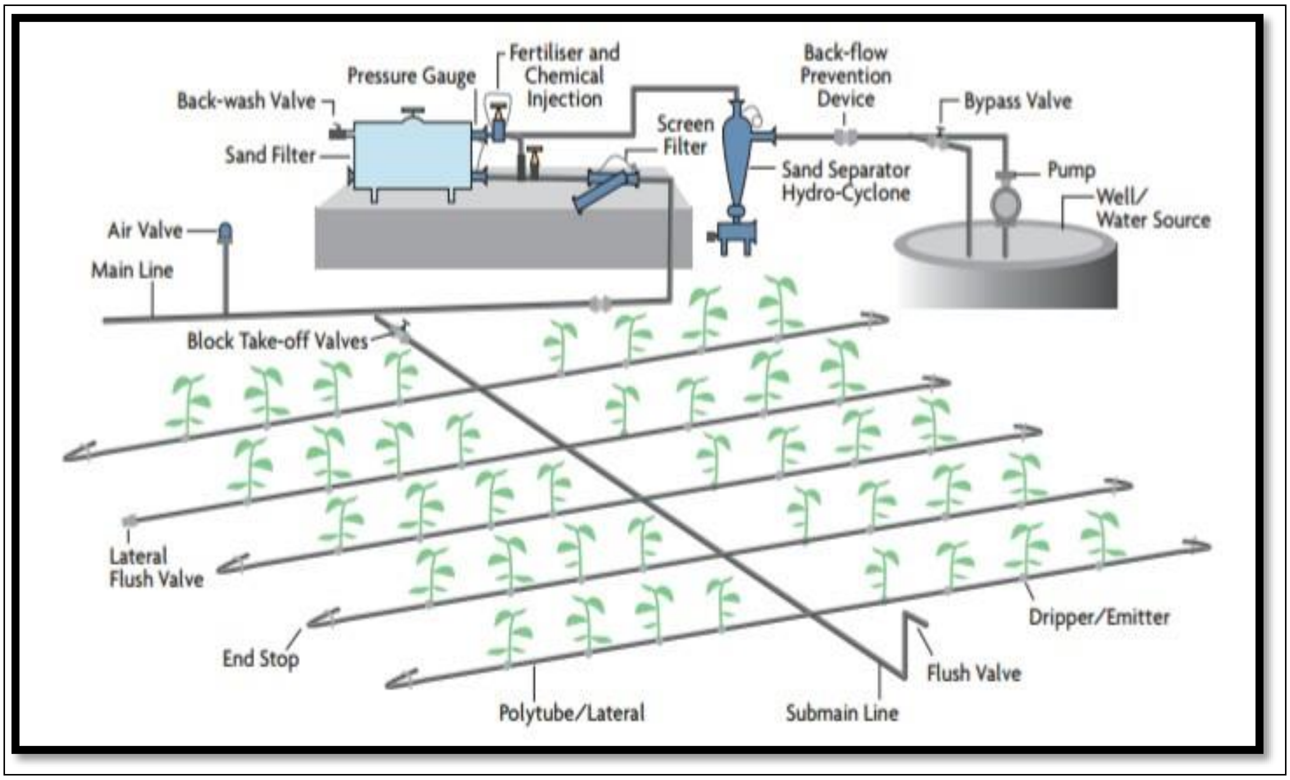

Figure 2.1: Schematic Layout of a Pressurised Drip System. Adopted from Bloomer *et al.* (2013).

2.9 Performance of Drip Irrigation System

The evaluation of drip setup after design and installation is necessary to ascertain the systems performance to accrue to numerous benefits associated to this method of irrigation (Zamaniyan *et al*., 2014). According to Ali (2010), an irrigation system's performance evaluation is the systematic physical analysis of existing system based on standard performance indicators measured under field conditions in comparison to an ideal and well-designed irrigation system. This diagnostic helps in the identification of system design challenges for improvements where possible. The standard and acceptable performance indicators widely used for drip irrigation performance testing are application efficiency (AE), distribution uniformity (DU), uniformity coefficient (UC), emission uniformity (EU), manufacturer's coefficient of variation (CV). According to Ali (2010), statistical uniformity and distribution uniformity are the most preferred indicators for drip irrigation system's performance evaluation. However, this review would place emphasis on performance indicators of manufacturer's coefficient of variation (CV), distribution uniformity (DU), emission uniformity (EU) and application efficiency (AE).

2.9.1 Distribution Uniformity (DU)

Distribution uniformity represents the degree of uniform water application on an entire field (Tagar *et al.*, 2012). DU of the low quarter (DU_{lq}) is commonly referred to as emission uniformity (Merriam and Keller, 1978; Ali, 2010). When measured under field conditions, the DU_{lq} gives an indication of the percentage of the field that is under irrigated or over irrigated (Reinders *et al.*, 2012). Value of DU above 70 % is considered as acceptable (Jamrey and Nigam, 2018). However, this present study considered acceptable DU values above 80 % (Merriam and Keller, 1978) for more accuracy.

$$DU\ (\%) = \frac{Average\ lower\ quarter\ depth\ of\ water\ caught}{Average\ depth\ of\ water\ caught}\ x\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 2.1.}$$

The performance of an irrigation system operated over a year can be evaluated comparing the measured distribution uniformity (DU) values to the classification (Table 2.1) developed by Merriam and Keller, (1978). Performance evaluation on drip irrigation system under naturally ventilated polyhouse (NVPH) and environmentally controlled polyhouse (ECPH) conducted by Arya *et al.* (2017), reported distribution efficiency values of 93.63 % and 93.46 % for drip irrigation system under NVPH and 95.70 % and 95.38 % for drip irrigation system under ECPH during 2013-2014 and 2014-2015 cropping seasons. The results showed that, both systems were excellent, and water was uniformly distributed to meet the crops water requirement.

Table 2.1: Irrigation System Classification for Distribution Uniformity (DU)

DU_{lq} value	Classification
> 90 %	Excellent
90 – 80 %	Good
80 – 70 %	Fair (Acceptable)
< 70 %	Poor (Unacceptable)

Source: (Merriam and Keller, 1978)

2.9.2 Manufacturer's Coefficient of Variation (CV)

The coefficient of variation represents the ratio of the standard deviation to the mean of the emitter discharges operating under the same conditions of pressure and temperature (Tagar *et al.*, 2012; Smajstrla, 2018; Sarker *et al.*, 2019). The manufacturing processes of emitters including design, production materials, and precision accounts for the variations of flow in emitters (Reinders *et al.*, 2012). The ASAE (2002), formulated an equation 2.2 to calculate the coefficient of variation.

$$Cv\ (\%) = \frac{\sigma}{qav} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 2.2}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(qi - qav)^2}{n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 2.3}$$

Where:

Cv - Coefficient of variation

σ - Standard deviation

qav - Average flow of emitters

n - Number of emitters.

A standardized classification criterion for coefficient of variation as an indicator in the evaluation of irrigation systems' performance was developed by Zamaniyan *et al.* (2014) and presented in Table 2.2. Performance evaluation of a drip irrigation system in India conducted by Selvaperumal *et al.* (2019), reported coefficient of variation (CV) value of 2.07 % depicting an excellent system of uniform water delivery rate by emitters. However, coefficient of variation of 38.2 % for micro irrigation system evaluated in India by Zamaniyan *et al.* (2014), is unacceptable and requires system improvement.

Table 2.2: Criteria for Coefficient of Variation (CV) Classification

CV value	Classification
< 5 %	Excellent
5 – 10 %	Good
10 – 15 %	Acceptable
15 – 20 %	Poor
> 20 %	Unacceptable

Source: (Zamaniyan et al., 2014)

2.9.3 Emission Uniformity (EU)

Emission uniformity depicts a measure of the variation in emitter discharge rate for an entire field system. It is the ratio of average discharge in the quarter of the field receiving less water to the average discharge at the system level (Tagar *et al.*, 2012). Emission uniformity is synonymous to DU in predicting the emitter flow variations along a lateral line. EU is largely influenced by variations in pressure head and the individual emitters' manufacturer's coefficient of variation (Khairy *et al.*, 2016). The fastest way to determine uniformity in water delivery is the indicator EU (Al-Ghobari, 2007). Keller and Bliesner (1990), proposed the formular for the estimation of emission uniformity as,

$$EU(\%) = 100\left[1.0 - 1.27\,\frac{Cv}{n^{0.5}}\right]\frac{qm}{qa} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. 2.4}$$

Where:

EU - Emission uniformity

qm - Minimum discharge

qa - Average discharge

n - Number of emitters

Cv - Coefficient of variation

Al-Ghobari (2007), developed a classification criterion for emission uniformity and is adopted in performance evaluation of drip systems (Table 2.3). Emission uniformity of 52.8 % for micro irrigation system evaluated in India by Zamaniyan *et al*. (2014), is unacceptable and requires system improvement.

Table 2.3: Classification of Emission Uniformity (EU)

Emitter Discharge Variation (q_{var})	**Classification**
≤ 10 %	Desirable
10 – 20 %	Acceptable
> 20	Unacceptable

Source: (Al-Ghobari 2007)

2.9.4 Application Efficiency (AE)

Application efficiency of drip irrigation is a measure of how much water is stored in the root zone to the amount of irrigation water applied (Purohit *et al.*, 2017). This definition represents a fully irrigated rootzone. The application efficiency of the drip irrigation system is most often higher than that of sprinkler and traditional furrow irrigation systems. The irrigation scheduling needs, and irrigation run is dependent on the application efficiency and can be expressed using equation 2.5.

$$Ea\ (\%) = 100\left(\frac{Qmin.}{Qavg.}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots \text{Eqn. 2.5}$$

Where:

Ea - Application efficiency

Q_{min} - Minimum emitter discharge

Q_{avg} - Average emitter discharge

2.10 Soil – Water-Plant Nexus

The relationship between soil, water and plants is relevant in the management and planning of irrigation systems. The nexus depicts several physical, hydraulic, and chemical processes influencing the behavior of water in the soil system and movement through the plants' root system. The nexus defines and consist of soil properties that include infiltration rate, soil texture, soil bulk density, field capacity moisture content, moisture content at wilting point, readily available soil water and total available water content.

2.10.1 Soil Texture

Soil texture is the relative proportion of the various soil constituents in a soil medium. It is an indicative of the water holding capacity of soils and varies greatly with the different soils. The combination of sieving and sedimentation techniques are used in particle size analysis for texture determination, but mainly performed now with an areometer or a pipette apparatus (Smith and Mullins, 1991). The commonly used international standard is the sieve-pipette method (Gee and Bauder, 1986; ISO 11277, 2009). The method determines the relative mass of sand, silt and clay fractions which is then classified using a standard nomenclature as the USDA textural triangle (Waller and Yitayew, 2016). There are modern and improved methods of texture determination, such as the laser-diffraction analysis (LDA). The laser method was used by Buurman *et al.* (2004) for stratigraphy analysis of European volcanic soils. However, the LDA has infractions since proportions of silt, sand and clay varied from that analysed by the pipette method. The Soil Plant Atmosphere Water (SPAW) Model can be used to determine the soil texture if the fractions of sand, silt and clay are analysed in the laboratory.

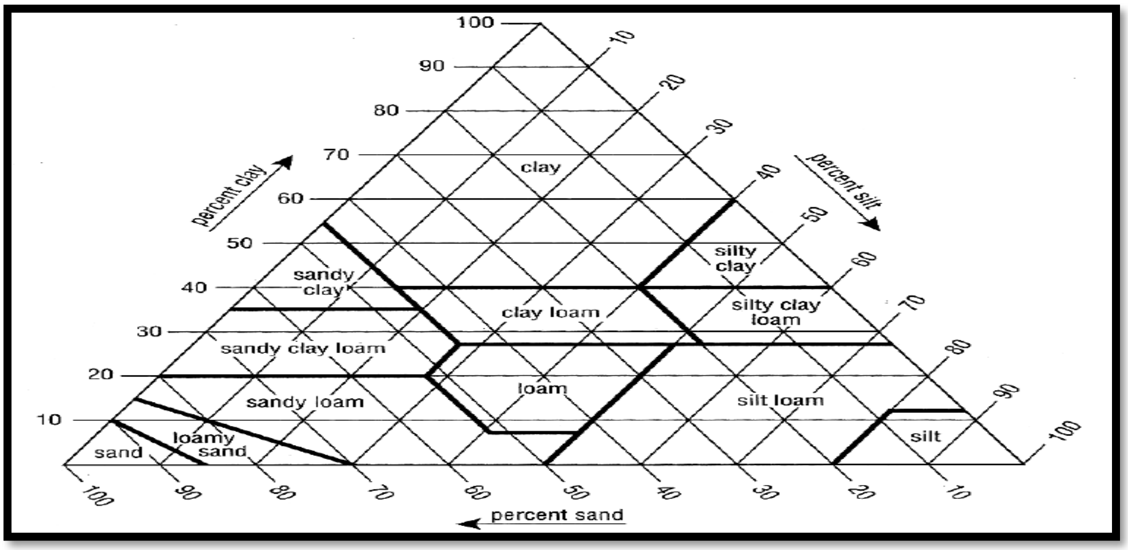

Figure 2.2: USDA Soil Textural Triangle (Credit NRCS, National Agronomy Manual. Part 504)

2.10.2 Soil Infiltration Rate

Soil infiltration is the process of downward water movement from the soil surface to the unsaturated zone and a major component in the water cycle, irrigation design and estimation of overland flow (Lili *et al.*, 2008; Ali, 2010; Mao *et al.*, 2016; Liu *et al.*, 2019). Infiltration recharges ground water (Ferguson, 2017). The soil infiltration rate and the cumulative infiltration are related by Eqn. (2.6) (Wang, 1992; Zhan and Ye, 2000).

$$i = \frac{dI}{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. } 2.6$$

Where:

i - Infiltration rate, mm/h

t - Time, h

I - Cumulative infiltration, mm

The Kostiakov equation is a popular empirical model used to develop infiltration curve over time by fitting infiltration data from field measurements (Waller and Yitayew, 2016). The Kostiakov equation is represented by equation 2.7.

$$i = Kt^{a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \text{Eqn. } 2.7$$

Where:

i - Depth of infiltration, mm

t - Time, hr

k and a - Empirical constants

The Kostiakov's equation is an exponential one and the coefficients can be calculated by taking the natural log of both sides of Eqn. 2.8 and inserting two measured infiltration depths and times; thus two equations and two unknowns (Waller and Yitayew, 2016). The infiltration logarithm is usually linear and fits the slope's equation of a line in Eq. 2.9.

$$In(i) = \text{aln(t)} + In(k) \quad (y = mx + b) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \text{Eqn. } 2.8$$

$$y = mx + b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn. } 2.9$$

Rainfall or irrigation water exceeding the infiltration capacity of soils lead to overland flow and subsequently erosion of the topsoil. Meanwhile, the infiltration capacity of soil is proportional to the inflow rate of water, provided the rainfall or irrigation water supplied is lower than soil infiltration capacity (Mao *et al*., 2011). The infiltration of water through a dry soil is initially high due to the increase in matrix potential gradient of the soil, which eventually decreases over time until a steady state or final infiltration rate is attained (Lili *et al*., 2008). Water infiltrating the soil at a given time is dependent on a plethora of factors that include soil constituents, structure, soil permeability, antecedent water content, intensity of water supply, soil texture, land topography, and soil conditions (Lei *et al*., 2006; Lili *et al*., 2008; Ebel and Moody, 2013; Liu *et al*., 2019).

Soil surfaces with crusty or hard pan formations reduces infiltration rates but rather increases runoff of rainfall (Fischer *et al*., 2014). The numerous factors affecting soil infiltration rate influences the choice of field method of determination (Liu *et al*., 2019).

There are several traditional methods developed by researchers for the determination of soil infiltration rates, such as; the modified double-ring or Mariotte-double ring method (Bobe, 2004), rainfall simulation method (Bouwer, 1986; Viessman and Lewis, 1995), the disc permeameter method (Lei *et al*., 2006); double ring infiltrometer method (Singer and Blackard, 1982), modified rainfall simulation (Peterson and Bubenzer, 1986; Wang and Zhang, 1991). Other methods include the runoff-on-out method (Tricker, 1976) and the linear source method (Mao *et al.*, 2008). The various methods have their own strengths and weaknesses, hence the needed attention during testing of soil infiltration rates (Liu *et al*., 2019). Most field methods are very limited and poorly respond to low conductivity soils due to the short duration of steady-state experiments and the high volumes of water required (Cheng *et al*., 2011). The challenges of most traditional methods can be overcome by the point source method (Liu *et al*., 2019), used for soil infiltration measurements in-situ (Lubana and Narda, 2001; Mao *et al*., 2016). Mao (2016) reported high accuracy of measurements for the point source method when compared with the linear source methods with an error of less than 2.5 %.

2.10.3 The Total Available Soil Water and its Upper and Lower Limits

Total Available Soil Water is water held in soil pores and can be easily accessed by plants for optimum performance and development. However, not all the TAW is available to the plant and a threshold is defined based on adequate knowledge on manageable allowable depletion. In other words, it represents water content between field capacity and permanent wilting point of the soil (Ali, 2010). Field capacity (FC) water content refers to how much water is remaining in the soil after internal drainage from a rainfall or irrigation event has been allowed to freely drain away under the force of gravity. FC depicts the upper limit of soil available water content. In terms of water potential, field capacity water content is generally described as soil water content at – 33 kPa or – 1/3 bar (Ali, 2010). Irrigation is aimed at bringing soil moisture back to field capacity water content to minimise water losses and prevent water stress in crops. However, the tendency to irrigate slightly above or below field capacity is high due to the difficulty in predicting ideal condition of the upper limit under field irrigation conditions. There are comfortable limits of soil moisture depletions that would not affect the performance of crops and must be considered when taking irrigation decisions on individual crops.

The permanent wilting point of soil is the lower limit of soil available water content in each soil. At permanent wilting point, plants can no longer take up moisture due to the stronger forces holding moisture to soil particles. Under this condition, plants will wilt and die due to water stress. In terms of water potential, water content at permanent wilting point is expressed at – 15000 kPa or – 15 bars (Ali, 2010). Irrigation of crops would have to be above this point and towards field capacity of the soil. Most plants will wilt and die under severe soil water stress condition. Permanent wilting point is determined in the laboratory using the membrane apparatus.

2.11 Crop Water Requirements

Crop water requirement denotes the quantity of water needed by a given crop from its sowing to harvest (Reddy, 2010). According to Ali (2010), it is the amount of water needed to compensate the evapotranspiration loss from the crop field. Savva and Frenken (2002), defined crop water requirement as the depth of water required to meet the water loss through evapotranspiration of disease-free crop, growing in large fields under non-restricting soil conditions that includes inadequate soil water and fertility, and achieving full production potential under the given growing environment. Generally, the term crop evapotranspiration is often used to refer to a crop's water requirement. The determination of the crop's water requirement is relevant for proper design and sizing of irrigation systems. Crop water requirement helps irrigators to keep soil water within optimum conditions for plant growth. The water requirements of crops vary significantly across and within species even under different growth condition such as climate, soil type, method of cultivation and effective rain (Reddy, 2010). Even under the same field management and climatic conditions, a given crop requires different amounts of water at different stages in its growth cycle. The crop water requirement is usually low at the initial stage of crop development due to less canopy cover but increases as the crop develops up till maturity after which it declines gradually up till the last day of harvest. Several soil, climatic and crop factors influence the water requirements of crops. They include soil infiltration capacity, antecedent soil moisture, land topography, crop type and cultivar, leaf area, crop growth stage, root development, mean temperature, rainfall, humidity, wind speed and sunshine hours (Finley, 2016).

There are several direct and indirect approaches in measuring and estimating the Crop water requirements (Finley, 2016). It is worth mentioning that the direct measurement procedures of crop water requirements such as the lysimeter method are burdensome, time-consuming, and complicated. Computer programmes such as the FAO-CROPWAT Model have been developed to help ease the burden and improve accuracy the estimation of crop water requirements (Smith, 1992).

According to Finley (2016), the indirect method involves three steps.

1. Determination of reference evapotranspiration (ET_o)
2. Determination of crop coefficient (K_c)

3. Calculation of crop water requirement (ET_c)

2.11.1 Methods of Determination of Evapotranspiration (ET_o)

Reference evapotranspiration is the evapotranspiration rate of a theoretical reference crop with idealised characteristics including uniform height, extensive leaf coverage shading the bare soil, optimal water and nutrient conditions and vigorous growth (Allen *et al*., 1998). It is determined based on a range of specific local climate variables (Finley, 2016). ET_o can be estimated using several methods.

a. Pan evaporation method
b. Radiation method
c. Modified Penman-Monteith method
d. Blaney-Criddle method

However, the FAO-Modified Penman-Monteith method is the most preferred and widely used method due to its high level of accuracy in estimating ET_o (Allen *et al*., 1998). The method has been incorporated into computer based models such as the AQUACROP and CROPWAT models to increase the accuracy (Allen *et al*., 1998). The Modified Penman-Monteith method is based on equation 2.10.

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . \dots . \dots . Eqn.\ 2.10$$

Where:

ET_o - Reference evapotranspiration (mm/day)

R_n - Net radiation at the crop surface (MJ/m^2/day)

G – Soil heat flux density (MJ/m^2/day)

T – Air temperature at 2 m height (°C)

u_2 – Wind speed at 2 m height (m/s)

e_s – Saturation vapour pressure (kPa)

e_a – Actual vapour pressure (kPa)

Δ – Slope vapour pressure curve (kPa/°C)

γ – Psychrometric constant (kPa/°C)

2.11.2 Determination and Adjustment of the Crop Coefficient (K_c)

The K_c is a unitless value that relates the evapotranspiration of a given crop to that of the reference crop based on their differences in size, canopy resistance, albedo, and ground cover (Finley, 2016). The values of the K_c of different crops vary at each growth stage of the crop's development due to changes in the crop's water requirement and canopy expansion rate throughout its growth cycle. The K_c values of crop is lowest at the initial stage and highest at the mid-season stage. However, it ascends towards the crop development stage and declines towards the late season stages of growth. The K_c values can be obtained from the FAO Module 4 (Savva and Frenken, 2002) and applicable to all crops. However, adjusted Kc is required where possible to meet the local site conditions due to the influence of weather on coefficient (Annandale and Stockle, 1994).

2.11.2.1 Adjustment of Kc for Initial Stage

The table values obtained from the FAO Module 4 presents the interactive evaporation and transpiration over time steps which represents wetting frequency for crops growing under standard conditions. The variations in the wetting frequencies from irrigation or rain called for the adjustment of Kc for the initial stage. For more accurate Kc initial, a consideration of the interval of wetting events, the magnitude of wetting events and the atmospheric evaporative power relevant (Savva and Frenken, 2002). The figures (2.3 and 2.4) provide an estimation method of Kc initial.

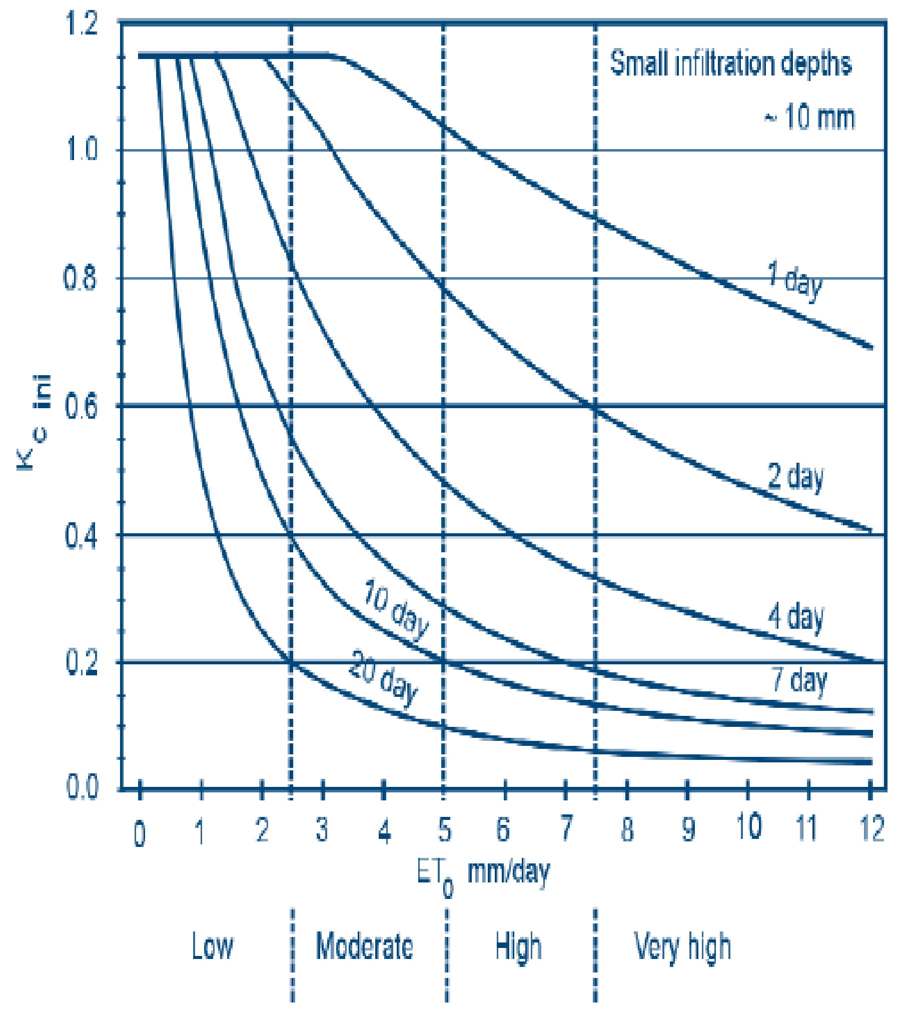

Figure 2.3: Average Kc initial for levels of ETo and irrigation intervals or rain events during the initial growth stage of crop under 3-10 mm wetting events for soil types (Allen *et al.*, 1998).

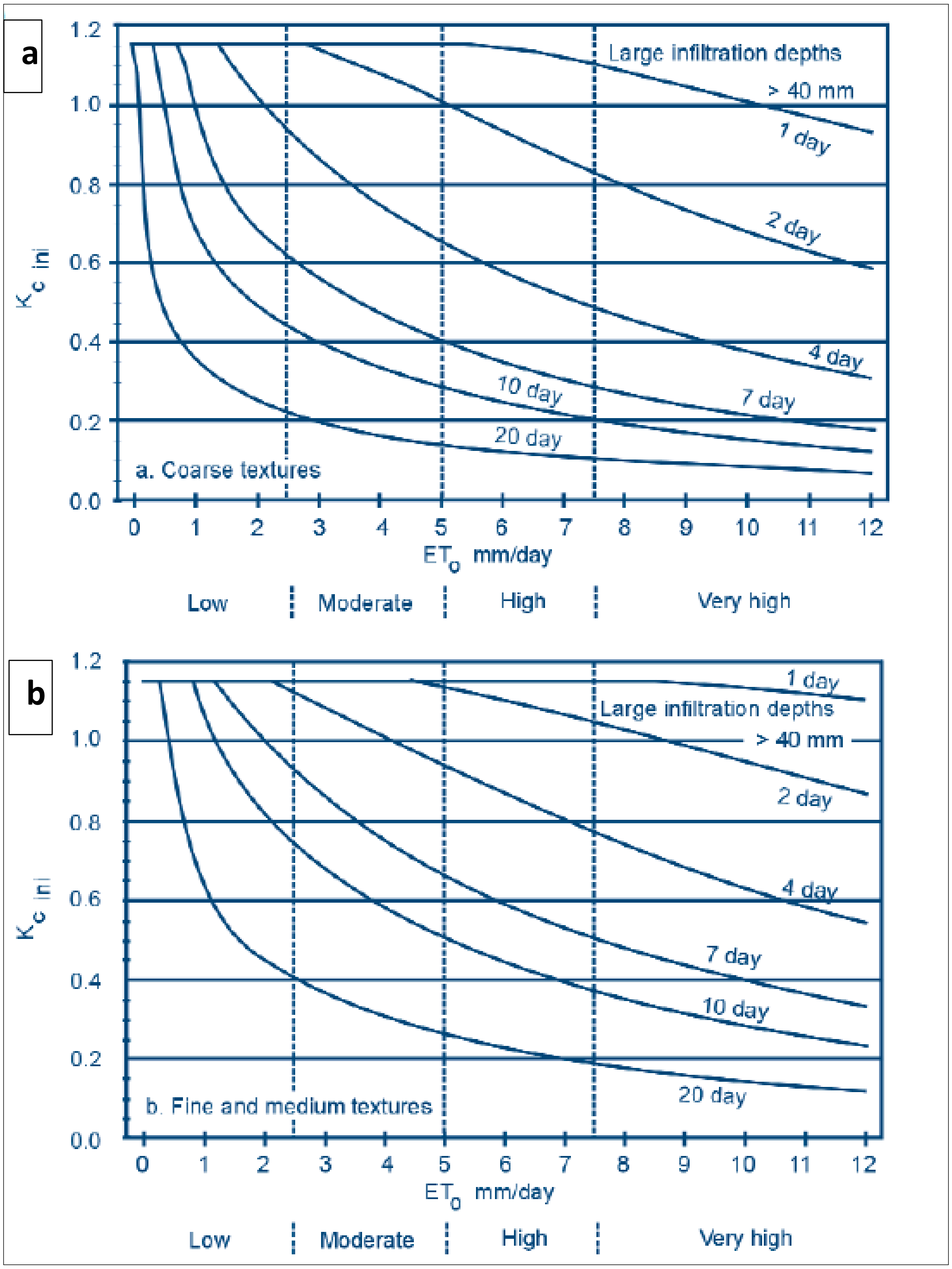

Figure 2.4: Average Kc initial for levels of ETo and irrigation intervals or rain events greater than or equal to 40 mm per event during the initial growth stage of the crop for (a) coarse textured soils; (b) medium and fine textured soils (Allen *et al*., 1998).

2.11.2.2 Adjustment of Kc for Mid and Late Season

The table values obtained from the FAO Module 4 represents Kc's for sub-humid climates with mean relative humidity of 45% in the day and presenting moderate wind speeds with a mean of 2 m/sec. Therefore, the need to adjust and modify the tabular Kc values to meet the different climate of location conditions (Savva and Frenken, 2002). Figure (2.5) assists in the adjustment of Kc for the various climate.

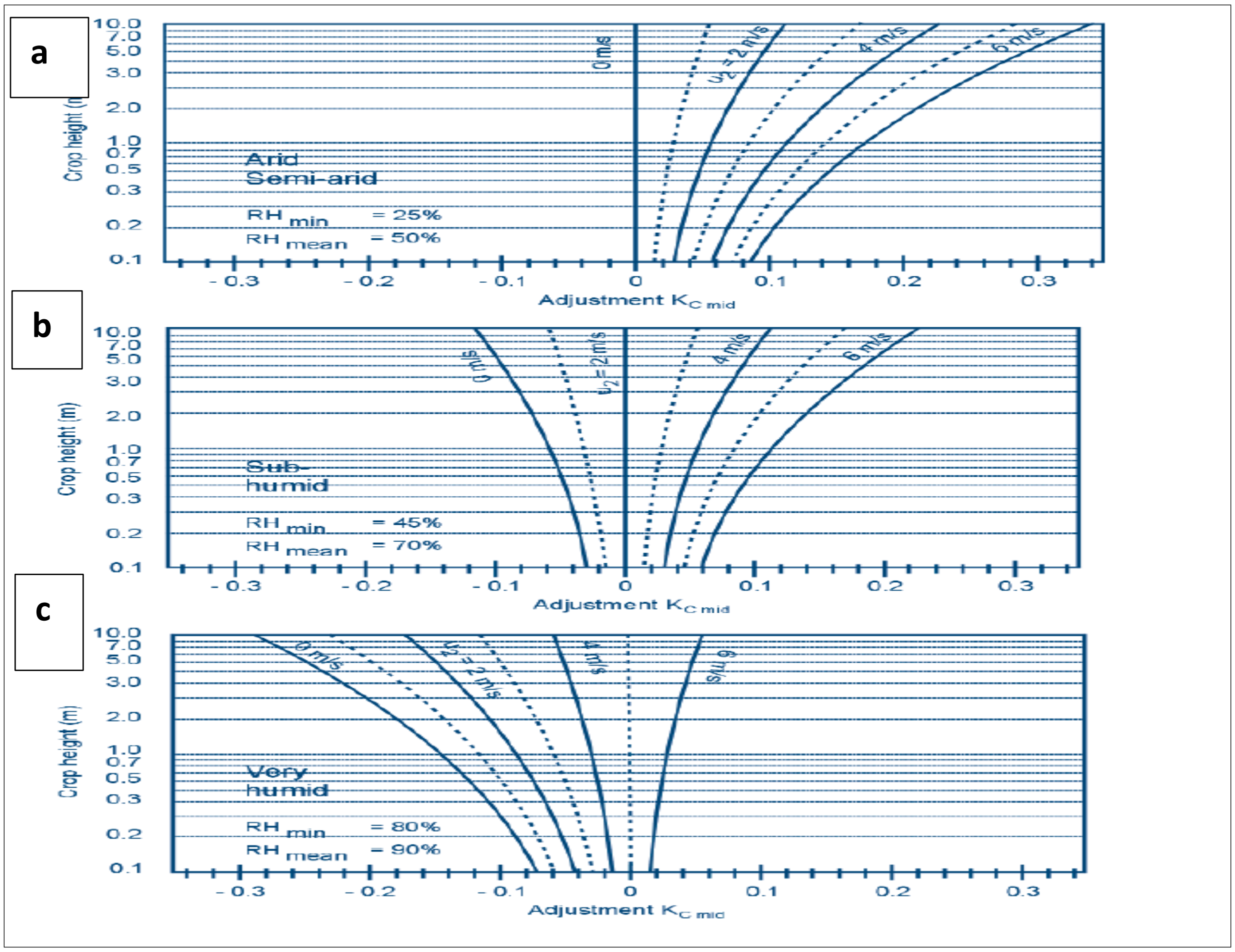

Figure 2.5: Additive Adjustment of Kc mid table values for different crop heights and mean daily wind speeds (u_2) for humidity conditions (Allen *et al.*, 1998).

2.11.2.3 Adjustment of Kc for the Late or End Season

The climate conditions of arid regions characterised by high wind speed will certainly have high kc values for the late season stage than humid conditions of lower wind speed (Savva and Frenken, 2002). Under certain circumstances of RH (45 %) and u_2 (2 m/s), equation 2.11 can be used:

$$Kc\ end = Kc\ end\ (Tv) + [0.04\ (u2 - 2) - 0.004\ (RHmin - 45)]\ \times \left[\frac{h}{3}\right]^{0.3} \ldots\ldots\ldots.Eqn.2.11$$

Where:

Tv - Table value for Kc end for the crop read from FAO Module 4

*u*2 - Mean value for daily wind speed at 2 m height over grass during late season growth stage

RHmin - Mean value for daily minimum relative humidity during the late season stage (%)

h - Mean plant height during the late season stage (m)

2.12 Irrigation Requirement of Field Crops

The present and future, hold new challenges emanating from the field of irrigated agriculture and requires the refinement of management principles and innovative designs. Several emphases have been centered on irrigation project design rather than consented efforts on the many users competing for the limited water supplies, the hazard of water quality degradation through excess irrigation and narrow economic margins. These challenges could be better improved when accurate predictions in consideration of changes in weather are made on irrigation requirements of field crops. Koech and Langat (2018) in their review of irrigation water use defined irrigation water requirement as the quantity or depth of irrigation water in addition to precipitation needed to produce the desired crop yield and quantity while maintaining acceptable salt balance in the rootzone of soils. Several factors such as the prevailing local climatic conditions at the time, crop growth stage, soil properties and condition, and the extent of root development influence the irrigation schedule. It is relevant to consider the field water balance in the determination and application of water because the evapotranspiration is satisfied by rootzone soil water (FAO, 2012).

The successful production of field crops is affected by many biotic and abiotic factors varying from one location to another. However, some of the factors can be controlled or modified through the application of various field management and cultural practices. The quality of soil can be improved by applying soil management practices such as organic manure, inorganic fertilizers, and minimum to zero soil tillage. The adoption of *insitu* soil conservation, irrigation and drainage strategies would improve the soil environment and holding enough water for plant use. To monitor the negative trends which could adversely affect the stability and quality of production, it is important to monitor and analyse all parameters in the process of producing crops (Popović *et al*., 2019). USDA (2009) reported that, water withdrawals for crop production accounts for 79 % of the total water withdrawals in Southwestern part of United States of America. However, as low as 30 % in West Africa was reported by FAO (2012). The report cited irrigation water withdrawals exceeding the net irrigation water requirement of field crops due to the high losses encountered in water distribution from its source to the crops. Accounting for evapotranspiration requirement is relevant in improving crop and water productivity on agricultural lands, considering the high ETo rates resulting from warming of the climates of the world (Dettinger *et al*., 2015).

2.13 Water - Use Efficiency

Irrigated agriculture is the largest consumer of agricultural water and the greatest contributor to water losses in agriculture. However, as water is becoming increasingly scarce in quantity and quality due to competing uses; improving the efficiency of irrigation water-use is crucial in maintaining adequate water levels in rivers and lakes to sustain ecosystems diversity while meeting demands of industry (Sharma *et al*., 2015). Hatfield and Dold (2019) defines water use efficiency as the ratio of total biomass or grain yield to water supply or evapotranspiration or transpiration on a daily or seasonal basis. Evans *et al*. (2008) reiterates the need to maximize crop yields per unit water consumed rather than maximizing yield per unit of land area. Following this context, irrigation management should entail the use of limited water resources in this era of climate change to produce crops with higher yields. In the field of irrigation science, Irmak *et al.* (2011) stated that, the term water (irrigation) use efficiency depicts how successfully water is conveyed to crops and indicating the amount of water losses at the plot, farm, command, or system level.

Several researchers have put in efforts to improve crop water productivity as a strategy for sustainably crop production and efficient management of scarce water resources. Water-use efficiency can be improved drastically by reducing losses associated with deep percolation, evaporation, and runoff. Asenso (2011) further added that, the choice of irrigation method, crop and soil type, irrigation time and amount are very relevant in achieving high water-use efficiency on agriculture lands. Research have shown that the efficiency of irrigation water-use reduced drastically when irrigation depth was increased (Molden and Oweis, 2007; Tadesse *et al.*, 2017; Mubarak and Hamdan, 2018; Ragab *et al.*, 2019). According to Shen *et al*. (2012), the use of straw mulch could effectively improve water-use efficiency of crops.

Walters and Jha, (2016) reported on the significance of drip irrigation method in increasing water-use efficiency of vegetables growing under water scarce environments. Also, Debbarma *et al*. (2019), reported higher gains in water-use efficiency under drip irrigation in combination with either plastic or no plastic mulch. In a comparative study on drip and furrow irrigation methods, drip irrigation gave higher relative water use efficiency (47 %) and higher water productivity (59 %) over furrow irrigation (Asif *et al*., 2016). The authors further reported high water savings of 53.5 % of water applied under the furrow irrigation method. Drip irrigation provides uniform and precise water amount, increase yields, reduce evapotranspiration (ET) and deep percolation (Irmak *et al.*, 2011). However, surface irrigation (traditional furrow) is largely used by farmers for the cultivation of tomatoes in large areas of production leading to wastage of water (Chen *et al.*, 2013). To cope with the scarcity of water which is the primary constraint for high crop yields in many areas, the water-use efficiency of management strategies on field crops for various areas in Africa should be careful studied.

Despite the several research work and reportage on water-use efficiency, other views have emerged and originates confusion on the terminologies of water-use efficiency and water productivity. Evans *et al.* (2008), have criticized the definition of water-use efficiency and stated it as ratio of crop product to water used by the crop. The authors stated that, water use efficiency is a biological response ratio rather than an efficiency term. According to Basso and Ritchie (2018), the productivity of Maize (*Zea mays* L.) can be increased without any change in water-use rate and would result in an increase in water-use efficiency. To overcome the confusion, Fairweather *et al*. (2003) suggested water-use efficiency could be expressed as an index of water use since it defines the output from a system such as yield or economic return on crop evapotranspiration. The authors further proposed the following equations to express crop water use index, irrigation water index and irrigation economic water use index.

1. Crop water-use index = $\frac{\text{yield}}{\text{evapotranspiration}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .. Eqn. 2.12$

2. Irrigation water-use index = $\frac{\text{yield}}{\text{irrigation water applied}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots ... Eqn. 2.13$

3. Economic water-use index = $\frac{\text{gross return (\$)}}{\text{irrigation water delivered to the field (m}^3)} \dots \dots \dots \dots \dots \dots \dots \dots Eqn. 2.14$

2.14 Economic Water Productivity

The term crop water productivity is most often given in terms of mass of produce, or monetary value, per unit of water. Depending on how the terms in the numerator and denominator are expressed, water productivity can be expressed in general physical or economic terms. Abdul-Ganiyu *et al.* (2015) expresses economic water productivity as the net economic value of crops to the amount of water consumed in producing the crop. The authors (Abdul-Ganiyu *et al.*, 2015) identified a challenge of sensitivity of economic water productivity to variation in market prices over time.

The increase water scarcity requires enhanced productivity measures to sustain the desired agricultural production levels. Seckler *et al.* (1998) expressed water productivity in physical terms as "quantity of product divided by the amount of water depleted, in combined physical and economic terms as gross or net present value of the crop divided by the amount of water diverted or depleted and finally in economic terms as gross or net present value of the product divided by the value of the water diverted or depleted". Vorosmarty *et al.* (2010) expressed that communities around the world must make the best use of limited water resources. This can be achieved by adopting proven agronomic and water management practices to improve water productivity. Other than direct benefits accrued in terms of improved yield and water savings, there are several indirect benefits of improved water productivity.

Water productivity has been given different definitions by different authors, often according to the scale of the plant, plot of land or watershed they were investigating or the purpose of their study. In a review conducted by Rashidi and Gholami (2008), the range of Crop Water Productivity (CWP) for tomato was very large (2.58 – 11.88 kg m^{-3}). In an experiment conducted by Kumar and Mali (2009), drip irrigation was effective than furrow in water and labor saving as well as productivity. Scientific management of irrigation water provides the insurance against weather induced fluctuation in total production. This is the only way in which we can make our agriculture competitive and profitable.

2.15 Irrigation Scheduling

Irrigation scheduling is the practice of using some method to decide when to apply irrigation water and knowing how much water to apply. Irrigation scheduling ensures that water is timely and adequately applied to the soil for use by the crop. It is a planning and decision-making activity that the irrigator or farmer is involved in before and during the crop growing season. Irrigation scheduling has been described as the primary tool to improve water use efficiency, increase crop yields, increase the availability of water resources, and provoke a positive effect on the quality of soil and groundwater. However, factors such as the evaporative demand of plants and soil characteristic of the irrigable field is relevant to achieve the desired output of irrigation scheduling. In regions of semi-arid and arid, characterised by water scarcity and unavailability for agriculture, proper irrigation scheduling approaches are relevant to improve water and crop productivity. The practice of determining irrigation timing and amount traditionally involves selecting a desired allowable soil water depletion of total soil water available to represent the readily available for the given crop. The correct measurement or estimate of the daily ET_c is necessary in order to monitor daily soil water depletion in the rootzone using the water-balance approach and to arrive at irrigation intervals thereby answering the question of when to irrigate. Therefore, when irrigation scheduling is supported by correct ET_c estimates, irrigation systems can be operated to provide the appropriate crop water requirement and attain high water application efficiencies with little leaching (Zayzay, 2015). According to Zayzay (2015), several factors such as local climate, plant physical condition, soil fertility and biological status will influence the response of plants to irrigation. The penetration of plant root system within the soil without restrictions will improve soil water uptake by the plant thereby increasing crop yield. However, soil factors such as soil compaction, texture, structure, organic matters, bulk density, salinity, sodicity, acidity and drainage porosity can negatively or positively affect the distribution of plant rooting system.

The water balance method can be used for real-time irrigation scheduling and can be linked to the climatic forecast to assess the agricultural drought. However, factors of the soil-crop-atmosphere that affects soil water availability must be considered in the scheduling process (Huffman *et al.*, 2013).

Grabow *et al.* (2013) stated that, water found in plant tissues supports photosynthesis; regulates temperature and for cell development as well as transports nutrients throughout the plant to support growth. The questions of when and how much water are relevant in irrigation scheduling decisions (Vellidis *et al.*, 2016). Grabow *et al.* (2013) highlighted four types of irrigation scheduling approaches among those that have been proposed. These include, soil-water-balance (WB) and evapotranspiration (ET), plant water status, soil water status and simulation model output (Grabow *et al.*, 2013).

2.15.1 Evapotranspiration (ET) and Soil Water Balance (WB)

The irrigation scheduling method of ET and WB is widely used whereby the consumptive water-use (ET_c), is first derived (Allen *et al.*, 1998). Irrigation is scheduled when the amount of water depletion in the rootzone soil exceeds that which is readily available to plants (RAW) (Huffman *et al.*, 2013).

$RAW = MAD. (\theta_{fc} - \theta_{pwp}). RZD$..Eqn. 2.15

Where:

RZD - Rootzone soil depth

MAD - Manageable depletion

θ_{fc} - Soil-water content at field capacity

θ_{pwp} - Soil-water content at the permanent wilting point.

According to Davis and Dukes (2010), ET-based method relies on accuracy of estimated ET_o and crop coefficient (Kc) for the individual growth stages, an evaluation of soil properties as well as measurement of site specific rainfall. However, the challenge with this method is the accuracy in estimating the various variables outlined. The temporal and spatial variability for a largescale estimate of ET is another challenge stated by DeOreo *et al.* (2016).

The ET and WB methods can be implemented easily using developed computer applications and models. However, most of these applications are limited to just the formulation of irrigation scheduling without considering other factors (Yang *et al.*, 2017). Smart Irrigation apps have been developed to perform irrigation scheduling and operate on smartphone platforms. There is however a gap on the irrigation scheduling applications that are specific to Africa and West Africa to be precise.

2.15.2 Soil-Moisture-Based Irrigation Scheduling

The soil-moisture based method relies on monitored soil water measurements in the rootzone of plants and compares to defined thresholds of soil moisture to trigger irrigations. Migliaccio *et al.* (2010) stated that, monitored soil moisture is measured by instruments that include neutron probes and time domain transmission sensors. The use of Tensiometers to measure soil water tension can be deplored in this method. Tensiometers mimic how much energy a plant needs to apply to take up soil water. The method ensures that the rootzone of plants is constantly irrigated to keep soil water at optimum conditions (Viani, 2016). Several researchers have developed methods of determining irrigation timing based on defined threshold of soil moisture (Zotarelli *et al.*, 2010;

Migliaccio *et al.*, 2010; Haley and Dukes 2012). However, these thresholds are site or location specific and dependant on crop species. Thompson *et al.* (2007) proposed an alternative method for threshold determination using leaf water potential was proposed by. The authors established a linear relationship for soil tension and leaf water potential under various soil water stress conditions. Wang *et al*. (2017) indicated that, irrigation should be intended to bring soil water condition back to field capacity if leaching of excess salts is not considered. Evett *et al.* (2011) stated that, the major weakness of a soil-moisture-based irrigation scheduling is the inaccuracy of sensor measurements.

2.15.3 Plant-Based Irrigation Scheduling

The use of plant indices that reflects the water status in plants is implored for irrigation scheduling. Plant-based irrigation scheduling methods rely on plants response to soil water deficit. The sensitivity of plants to water stress differs among species and growth stages. For ease of practice, plant-based measurements have been developed and proposed for purposes of irrigation scheduling. Padilla-Díaz *et al.* (2016) identified two major categories of plant-based measurements for irrigation scheduling.

(i) Direct measurements of water potential in plant tissues (leaf, xylem, or stem) and taking indirect measurements on variation in stem and fruit diameter, leaf thickness and turgor pressure.

(ii) Based on plant physiology (sap flow, xylem cavitation, stomatal conductance, and thermal sensing).

An efficient plant-based programme should depend on the sensitivity of the measurement in other to adequately assess water stress condition of plants (Bellvert *et al.*, 2016). The use of thermal sensing technology using infrared thermometers and other thermography techniques have provided grounds for canopy temperature (T $°_C$) of plants to be used in irrigation scheduling (Osroosh *et al.*, 2015). The commonly used ones include the crop water stress index (CWSI), temperature-time-threshold (TTT) and temperature stress day (TSD) (Osroosh *et al.*, 2015). Wanjura *et al.* (2006) indicated that, the temperature-time-threshold (TTT) method will trigger irrigation as sson as T°C exceeds crop specific temperature threshold ($T°_{th}$) for greater than a predetermined time (time threshold, t_{th}) within 1 day. The TTT method has been explored by several researchers (O'Shaughnessy and Evett, 2010; DeJonge *et al.*, 2015; Osroosh *et al.*, 2016) and they reported on the potential of the TTT for incorporation into automated irrigation scheduling. However, the method can be inaccurate based on the influence of canopy temperature that is greatly affected by the surrounding ambient temperature (DeJonge *et al.*, 2015). Example, T°C can be high on a hot day even if the crop is well watered. Moreover, DeJonge *et al.* (2015) indicated that, the TTT method considers canopy temperature threshold and the time when the threshold was exceeded without considering the extent to which $T°_{th}$ is exceeded. Moreover, if the peak irrigation depth is inaccurate, it may result in deep percolation losses and trigger response in the plants' system.

The water stress index (CWSI) method by Idso *et al.* (1981) and Jackson *et al.* (1981) schedules irrigation based on the crop's water stress using T°C and atmospheric vapor pressure deficit (VPD). The CWSI is calculated as:

$$CWSI = \frac{(T_c^o - T_a^o) - D_2}{D_1 - D_2} \quad \ldots\ldots\ldots \text{Eqn. 2.16}$$

Where:

D1 - max ($T°_c - T°_a$) of water stressed crop thus maximum stress baseline.

D_2 - min ($T°_c - T°_a$) of well-watered crop thus no-water-stress baseline

$T°_a$ - air temperature

$T°_c$ - canopy temperature.

The value of CWSI is close to zero for well watered crops and closer to 1.0 for severely water stressed crops. The method helps to determine time of irrigation by evaluating CWSI under different irrigation scenarios and the baseline temperature acquired through experiments with fully stressed and non-stressed treatments (Emekli *et al.*, 2007; Gontia and Tiwari, 2008). Threshold of CWSI can be assigned by users to serve and trigger irrigations using thermal-sensed T °C (Idso 1982). However, the accuracy of baselines is the key to this method, especially for D_2 (Idso 1982). O'Shaughnessy *et al.* (2012) proposed CWSI time threshold (CWSI-TT) method to overcome the limitation by strictly measuring the variables of CWSI near noon (mid-day) or soon after noon (12 – 15 hrs) under cloud free conditions.

2.15.4 Model Based Irrigation Scheduling

2.15.4.1 Process-Based Models

For increased precision in irrigation, computer models are founded on experimentation of the crop's physiological processes as well as influence of the entire soil, crop and atmosphere components have been tested (Chen *et al.*, 2019). After careful calibration of models, they can accurately simulate crop responses to variable factors and management scenarios (Ma *et al.*, 2012). However, process-based models are commonly used for irrigation planning but not real-time decision-making.

The CROPWAT model is user-friendly and has been successfully used to calculate the impact of climate change on crop water use (Teklu and Hammer, 2006). The program is used for simulating crop yield response to water and is a decision support system developed by the Land and Water Development Division of the FAO (AQUASTAT, 2009). Its main functions are to calculate reference evapotranspiration, crop water and irrigation requirements to develop irrigation schedules under various management conditions and scheme water supply and to evaluate rainfed production, drought effects and efficiency of irrigation practices. CROPWAT functions using the ET and WB methods together with algorithms to help predict plant resonse to water-stress conditions (Doorenbos and Kassam 1979). The CROPWAT model requires several climatic data (wind speed, relative humidity, temperature, sunshine hours, and rainfall), crop data (planting date, rooting depth at different growth stages, crop coefficient (Kc) curve, the allowable soil moisture depletion level, and the yield response factor-K_y), along with soil data (total available soil water content, initial soil water depletion). The calculations of CROPWAT model are based on FAO-Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam 1979) and No. 56 (Allen *et al.,* 1998). CROPWAT's ability to simulate deficit irrigation was evaluated by Smith *et al.* (2002), whereas Feng *et al.* (2007) and Augustin *et al.* (2015) used it to develop an optimal irrigation schedule. George *et al.* (2000) developed an irrigation scheduling model like CROPWAT while using the nine most used ET_o estimation methods and providing a graphical user interface. In Kenya, the CROPWAT version 8 was used to schedule irrigation required to cater for the water deficit and to reduce water stress (Ks) and to obtain optimal tomato yield (Karaku *et al.*, 2014).

The FAO-AquaCrop model was developed to simulate crop rresponse (attainable crop biomass and harvestable yield) to available water (Raes *et al.*, 2009; Steduto *et al.*, 2009). The model is capable of simulating irrigation through careful calibration to specify time and depth of water application, or by choosing the automatic option to develop a schedule. In the latter case, irrigations are scheduled either at a fixed time interval and depth, or by a fixed percentage of allowable water depletion of the root zone. The model was developed with a view to balance simplicity, robustness, and accuracy and is a more suitable model for researchers and farmers to use than the more complex models available (Abedinpour *et al.*, 2012). The AquaCrop model simulates water-driven plant growth and yield. It is suitable for evaluating the effect of irrigation schedules on crop yield. The model calculates the soil water balance, considering rainfall, irrigation, capillary rise, runoff, evaporation, transpiration, and deep percolation. To simulate plant growth and yield requires climate, soil, crop, and field management characteristics to be specified in the model. Using the AquaCrop model and drawing on a long series of historical climate data, Geerts *et al.* (2010), irrigation schedules can be well optimized to overcome stresses during critical growth stages. Linker and Sylaios (2016) presented an efficient model-based procedure for generating near-optimal irrigation schedules for real-time applications utilizing the AquaCrop model.

The model's precision and quality of calibration will certainly affecet the outcome of irrigation scheduling. For example, Xu *et al.* (2019) found that AquaCrop underestimated soil moisture with a root-mean-square error of 0.15 cm^3 cm^{-3} after calibration, which may affect the irrigation scheduling. Therefore, before applying process-based models in irrigation scheduling, they must be calibrated; thus, historic field measurements are needed.

The Decision Support System for Agro-technology Transfer (DSSAT) is a crop simulation model developed to understand the response of diverse factors on the performance of crops. The model software program has been calibrated and used for several crops in diverse environments. The latest DSSAT Version 4.8 was used in this study. The performance of DSSAT depends on several data base management programs the controls processes in the soil, weather, and crop environments (Hoogenboom *et al.*, 2017). The model also has a program for imputing and managing experimental data, as well as utilities embedded to perform other relevant processes and analysis. The crop model simulates the growth, crop development and yield as a function of the soil-plant-atmosphere dynamics. Furthermore, the DSSAT model simulates applications including field level to regional assessments of the impact of climate variability and climate change. The DSSAT model is embedded with several models to run crop-specific simulations.

The CROPGRO is a robust simulation crop model that predicts growth and development for a variety of crops. Several crops have been added to the CROPGRO Model by researchers and modelers that include tomato (Boote *et al.*, 2012), canola (Deligios *et al*., 2013), mucuna or velvet bean (Hartkamp *et al*., 2002), faba bean (Boote *et al*., 2002), cotton (Boote, 2010) and pigeon pea (Alderman *et al*., 2015). The model relies on daily weather data, information on soil property characteristics from known soil depth, detailed crop genetic and management information, and cultivar characteristics as input data. The simulation is done to allow for comparison between that which is predicted and measured. The measured data depends on the research objectives. The parameters to consider for measurement can include yield and yield components, detailed crop phenology, crop growth analysis, and soil profile measurements such as soil moisture, nitrate, and ammonia, organic carbon, and other information (Hoogenboom *et al.*, 2017). Evaluation statistics is produced to help in the assessment of model's performance to the measured variable.

2.16 Deficit Irrigation

The need to increase food production is of essence to provide for the growing world population (Bouman, 2007). Scheierling and Treguer (2016) stated that, the increase in food production is a necessity amidst changing climate and water shortages. With growing demand of water in developing countries, enhanced agricultural water management is of supreme importance to reduce food insecurity (Giordano *et al.*, 2016). Molden *et al.* (2010) reiterated the need to increase water productivity (WP) under water scarce environments.

In ensuring fair distribution of the limited supplies of water, irrigation technologies and irrigation scheduling strategies can be modified for more-effective and rational uses. Drip and sprinkler irrigation methods are preferable to less efficient traditional surface irrigation methods. It is necessary to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of allocated water. Deficit irrigation is one way of maximizing water use efficiency (WUE) for higher yield gains per unit of irrigation water applied. This means the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. The farmer must have prior knowledge of crop yield responses to deficit irrigation at the different stages of growth.

Deficit irrigation (DI) is an irrigation strategy aimed at improving water productivity. It consists of the cautious and methodical strategy of applying water on an ‘under-irrigation’ rate for crops. In other words, the amount of water applied is lower than that needed to satisfy the full daily crop water requirements. It is well known that reductions in the water applied usually lowers evapotranspiration (ET) and crop growth rates by limiting their principal component of transpiration (T) and, consequently, carbon assimilation. For this reason, it is of great interest to know the maximal reduction in ET compatible with obtaining benefits similar or even higher to those obtained when crop evapotranspiration (ET_c) is fully satisfied. The saved water under DI can be used for other purposes or to irrigate extra units of land to accrue more benefits. The FAO (2011) stated that, the emerging demand for water and unproductive uses are conceivable to widen the gap between water supply and demand. Hence, more attention should be given to the long-term sustainability of agricultural production by improving water productivity. If not, it is hardly impossible to address the food demands of the world population that is expected to surpass 9 billion in the 2050.

Linker *et al.* (2016) stated that, soil moisture stress conditions caused by inadequate water supply is increasing rapidly in sub-Saharan African (SSA). Introducing irrigation technologies that suit local situations can contribute to reducing this problem (Geerts and Raes, 2009). Approaches dealing with improved water productivity such as water-saving irrigation technologies and better soil management practices are considered important (Prosdocimi *et al.*, 2016). Among others, deficit irrigation is a promising option for farmers, who endeavor to improve the output of their limited land and water resources in areas where the available water supply is too low to provide an acceptable yield (Geerts and Raes, 2009). Geerts *et al.* (2010) defined deficit irrigation as a strategy whereby crops are irrigated to meet their daily water needs during critical growth stages, while maintaining irrigations below watering requirement during less drought-sensitive periods. Deficit irrigation is comparatively inexpensive and easy to apply (Geerts and Raes, 2009) and stabilizes crop yield with limited water (Heng *et al.*, 2009). It has been widely studied as an appreciated and viable production approach for a wide range of crops in water-limited regions (Rosin *et al.*, 2017). If the soil fertility is favorable and the crops are applicable for the deficit irrigation strategy, then it will enhance water productivity in comparison with full irrigation (Pereira *et al.*, 2012). Hence, Geerts and Raes (2009), highlighted the following contributions of deficit irrigation.

(i) Reduction in operation and maintenance costs related to desilting and water out-take including the costs of pumping, delivering water or water fees.

(ii) Reduction in overall water demand

(iii) Increase in irrigated areas with the same amount of irrigation water.

(iv) Reduce the decline of land productivity allied with soil erosion, waterlogging, and salinization.

(v) Improve agricultural output, food security, and profitability.

Also, Molden *et al.* (2010) confirmed that improving agricultural water productivity using deficit irrigation is expected to;

(i) Meet rising demands for food from a wealthier, and rapidly growing urbanized population considering limited water.

(ii) Respond to pressures to re-allocate water from agriculture to cities and ensure that water is accessible for ecological uses.

(iii) Contribute to poverty reduction and economic growth.

In developing countries, many of the irrigation strategies are traditional and are based on farmer's local knowledge. This means that farmers often irrigate their fields without any gauging mechanism. Also, there is limited expert advice regarding when, how, and how much water to irrigate (Beyene *et al.*, 2018). Hence, crops are watered more than they require. Most of the farmers irrigate their fields by flooding despite the inefficiencies of the method.

Crop water productivity (WP) is a key term in the evaluation of deficit irrigation strategies and was defined by Geerts and Raes (2009) as the ratio of the mass of marketable yield (Y_a) to the volume of water consumed by the crop (ET_a):

$$WP\ (\mathrm{kg}\, m^{-3}) = \frac{Ya}{ETa} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn. 2.17$$

Where:

Ya - Marketable yield (Kg)

ETa - Volume of water consumed by the crop (seasonal) (m^3).

There are various forms of deficit irrigation, depending on the situation it is implemented. When the water supply cannot be guaranteed or its onsite availability depends on external factors such as droughts or political decisions taken at local or national level, as occurs in many arid zones of the planet, the deficit irrigation is referred to as uncontrolled (Goldhamer *et al.,* 2006). However, when the water supply is continuous, it is possible to apply one of the following deficit irrigation strategies: regulated deficit irrigation (RDI); partial root-zone drying (PRD); or even sustained deficit irrigation (SDI) (Goldhamer *et al.,* 2006). Therefore, water resources should be used with a higher degree of efficiency or productivity. Improvement in agricultural water management is the best way to increase the utilization of limited water resources. Applying efficient water management strategies is critical to increasing water productivity on agricultural lands.

Many vegetable crops have high water requirements, and in most countries, irrigation is necessary for the successful production of vegetable crops. Research has focused on achieving a better understanding of crop physiology and management in arid climatic conditions, with the aim of improving the water efficiency of plants in those regions. Tomatoes are one of the most common and important types of vegetables in the world, and they have high water requirements. Improved irrigation methods can conserve water without compromising yield or quality. Studies on irrigation have shown that tomato is sensitive to water stress (Patanè and Cosentino, 2010). In adequate water application posing soil moisture stress condition as well as nutrient stress will result in reduction in marketable yields and quality. To obtain high yields, seasonal irrigation water requirement of tomatoes should range from 400 to 800 mm with a daily evapotranspiration rate of 4 to 6 mm (Mukherjee *et al.*, 2010). The tomato fruit consist of above 90 % water, therefore reduced irrigation depth especially at sensitive growth stages will result in flower abortions and fruit drops, as well as blossom end rots resulting in a drastic reduction on fruit yield and fruit quality (Tsige *et al.*, 2016). Irrigation water level and scheduling of irrigation application significantly affect tomato yield and fruit quality (Wang *et al.*, 2012).

2.17 The Soil and Plant Environment: Influence of Deficit Irrigation and Mulching Strategies

The application of high irrigation water volumes has the tendency of leaching out essential plant nutrients such as nitrogen from the root zone of the soil medium (Popova *et al.*, 2005). Soil moisture content within the upper limit of field capacity is considered ideal for optimum growth of plants. Irrigation and mulching strategies play a significant role and contributes to the soil water dynamics. In the studies of Lahmod *et al.* (2019), the application of wheat straw on *Trigonella foeunm graecum* L. increased the chlorophyll content of leaves (58.17 SPAD) at the maturity stage when compared to the control of no mulch (38.85 SPAD). In addition, higher Leaf Area Index (LAI) was recorded for frequently irrigated (Cumulative pan evaporation of 50 mm - CPE_{50}) tomato plants than less irrigated plants (CPE_{25}) (Mukherjee *et al.*, 2017). Mohawesh (2018), reiterated on the significant reduction in leaf area of eggplant under deficit irrigation regime of 80 % of the crop evapotranspiration (ET_c) requirement when compared to the control of 100 % ET_c. The leaf expansion rate of crops is largely controlled by leaf temperature changes, status of soil water and atmospheric evaporative demand (Parkash *et al.*, 2021). Leaf expansion rate under soil water stress conditions starts to decline earlier than net photosynthesis of crops (Sharma *et al.*, 2019). However, plants adapt to the impact of soil water stress conditions by reducing their leaf area to conserve the water stored in tissues (Jones, 2004). According to the study by Parkash *et al.* (2021), the leaf area of cucumber reduced by 42 %, 33 % and 7 % in 40 % ET_c, 60 % ET_c and 80 % ET_c respectively when compared to 100 % ET_c.

Also, low stomatal conductance as an indication of plants under soil water stress condition (Parkash and Singh, 2020) and reduces the transpiration requirement of plants (Pask *et al.*, 2012). The major importance of transpiration is to help in regulating the temperature of plants (Cornic and Ghashghaie, 1991); hence a reduction will surely increase leaf temperature. According to Testi *et al.* (2008), the reduction of transpiration rate under soil water stress treatments resulted in relatively higher leaf temperature in the deficit irrigation regimes of 40 % ET_c and 60 % ET_c compared to full irrigation of 100 % ET_c. High leaf temperature of tomato plants will drastically affect certain physiological processes in the plant system (Parkash and Singh, 2020). The variations in environmental conditions surrounding the plant at the time of soil water stresses can be a contributory factor influencing the plant's stomata closure (Medyoun *et al.*, 2021; Parkash *et al.*, 2021) and care is needed in ascertaining the causal effects.

Previous studies show that deficit irrigation can increase water use efficiency (WUE) and improve quality in the tomato plant (Favati *et al.,* 2009; Kuşçu *et al.,* 2014). On the other hand, deficit irrigation practices can result in small size fruits, lower marketable yields, and higher susceptibility to various diseases (Favati *et al.,* 2009). Unlike what has been stated, other researchers have indicated that drip irrigated deficit water supply is the leading approach with the most efficient water use in irrigated agriculture. Numerous studies have been carried out on the advantages of drip irrigation over the other methods in cotton (Hussein *et al.*, 2011), wheat (Ansari *et al.*, 2019), maize (Sandhu *et al.*, 2019), tomato (Zhai *et al.*, 2010), pepper (Edossa and Emana, 2011) and cucumber (Kirnak and Demirtas, 2006). It reduces water-use without significant yield reduction thus maximizing farmers profit (Kirda *et al.*, 2005). Also, Shammout *et al*. (2018) assessed deficit irrigation effect on bell pepper yield and water- use efficiency and found that; full (100 %) irrigation gave highest fruit yield whilst the severely stressed irrigation of 60 % gave lowest yield, but highest water-use efficiency. Contrary, drip irrigation level of 80 % ET_c gave highest fruit yield (89.1 kg ha^{-1}) in study conducted by Debbarma *et al.* (2019) to quantify the response of bell pepper to drip irrigation levels and black plastic mulch under naturally ventilated polyhouse in Tarai region of Uttarakhand, India. Multi-season evaluation of deficit irrigation regimes on tomatoes by Regab *et al.* (2019) revealed that flower and fruit number was significantly lower in soil water stress treatment of 55 % ET_c when compared with the full irrigated treatment. Irrigation plays a significant role in tomato production notably under water-scarce areas (Steduto *et al.*, 2012). The water depand for tomato plants is high throughout the growing stages (Patane *et al.*, 2011). However, the application of excess irrigation saturates the rootzone soil that results in death of roots, poor flowering and fruit quality (Tsige *et al.*, 2016).

Diaz-Perez (2009) stretched the irrigation levels to above full crop water requirement in a study to assess effects of drip irrigation from 33 to 166 % of ET_c on growth and yield of bell pepper. They found that, marketable yield of pepper had reduced drastically under severe soil water stress condition (33 % ET_c) and under over irrigated condition of 166 % ET_c. Results further revealed that, more chlorosis were seen in plants under irrigated at high irrigation levels compared to plants irrigated at medium levels. In a similar stretched irrigation regime (60, 80, 100, 120 and 140 % ET_c) studies by De Souza *et al.* (2019) on pepper, the highest applied water levels significantly increased fruit number, fruit weight and fruit yield. The application of full irrigation regime on onion also yielded 19 t/ha compared to 7 t/ha obtained by the deficit irrigation regime (Mubarak and Hamdan, 2018)

Several studies on the interaction of irrigation regimes at deficit levels and mulching have been reported for the agroecologies of the world including Africa. Research on the use of plastic materials as mulch have been extensively reported by Asian and American based researchers but limited in Africa. In as much as optimum irrigation boosts tomato fruit yield (Patane *et al*., 2011; Kumar, 2012), several studies highlights the importance of mulches in improving and protecting the soil environment. Kirnak *et al.* (2001) reported on the huge potential of mulches in mitigating the negative effects of deficit irrigation on the growth of plants. The use of drip together with plastic mulch has recorded excellent outcome on optimum growth and production of tomato (Wang *et al*., 2018). Ahmad *et al.* (2011) in their comparative study on mulching using sugarcane straw, rice straw and wheat straw and no mulching as control on chilli pepper reported significant gains in fruit weight for mulched plots than the un-mulched plots. Also, an increase in fruit yield of tomato (20.7 to 29.8 %) was reported by Kamal and Shashi (2012) for the temperate region of Uttarakhand.

The use of black plastic mulch increased Okro yields significantly by 30 % over no mulch treatments (Patel *et al*., 2009). Further, the benefit associated with the use of black plastic mulch was reported by Berihun (2011) with fruit yield of 55.32 t/ha and 70.85 t/ha for two seasons. However, according to Biswas *et al*. (2015), the use of mulches with drip is relevant for water savings and improving tomato fruit yield. The authors reported tomato fruit yield of 79.49 t/ha and 81.12 t/ha for rice straw and polyethylene mulch, respectively in contrast to yields from un-mulched plots and concluded that, 50 % water was saved under the drip irrigation and increased fruit yield by 25 – 27 %. The combined influence of deficit irrigation and straw mulch levels on onion bulb yield was significant with the highest total yield of 34.71 t/ha obtained by 100 % ET_c and 6 t/ha straw mulch, next by 80 % ET_c and 6 t/ha straw mulch with 32.52 t/ha (Kebede, 2019). The total bulb yield of 21.10 t/ha was obtained by 60 % ET_c with no mulch according to Kebede, (2019). Osei-Bonsu and Asibuo, (2013) and Kassahun, (2017) also reported significant yield increase amounting to 100 % for management strategies compared to the lowest yield by the unmulched.

In a study by Igbadun *et al*. (2012), onion bulb yield was reduced by 50 % for 25 % $ET_{c,}$ and 16 – 23 % for 50 % ET_c. However, 75 % ET_c treatment did not significantly reduce yield in contrast to 100 % ET_c. Also, mulching treatment recorded 12 – 15 % yield increase compared to non-mulched conditions. The evidence on the benefits of mulching was more pronounced by Malik *et al*. (2018) in their studies on sugar beet in areas of limited water supply. The authors reported an increase from 11.96 to 19.45 % root yield for mulched treatments compared to no mulch treatments. Also, mulches enhanced water productivity (Malik *et al*., 2018). In strawberry production, mulches improved growth traits and fruit quality (Fan *et al*., 2012).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

The study was conducted at the experimental field of CSIR-Savannah Agricultural Research Institute (SARI), Nyankpala, Tamale situated in the Northern Region of Ghana. The coordinates of the field are: N09˚23.309’, W001˚00.131’ and altitude of 176 m above sea level (Figure 3.1). The vegetation of the experimental site is typically of Guinea Savannah and characterized by grassland with interspersed trees. Common tree species found in the area are of economic value. They include *Azadiracta indica* (Neem), *Parkia biglobosa* (Dawadawa) and *Vitellaria paradoxa* (Shea). The soils of the zone are generally well drained sandy loam with flat topography. The climate of the area is warm and semi-arid with unimodal annual rainfall of 800 – 1300 mm (Kombiok *et al.*, 2005; Abdul-Ganiyu *et al.*, 2018, Awuni *et al.*, 2020). In a normal year, the raining season of the zone starts from May and ends in October giving way to onset of the dry season. The remaining prolonged months (November – April) defines the dry season within which irrigation is fully practiced in the agro-ecology. Temperature is consistently high, averaging an annual range of 29 to 39 ˚C and an estimated reference evapotranspiration (ET_o) above 1,600 mm/y (Abdul-Ganiyu, 2011; Abdul-Ganiyu *et al.*, 2018). The soil of the experimental site is characterised by the Nyankpala series which is largely classified under Plinthic Acrisols (Adu, 1962).

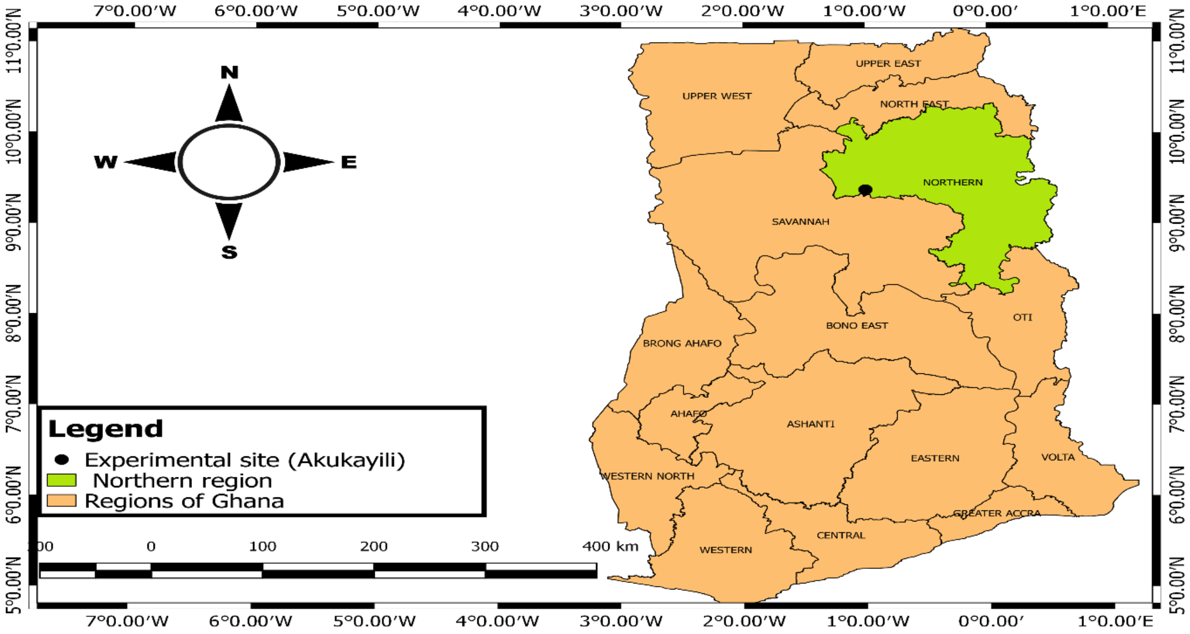

Figure 3.1: Map of Ghana showing the location of experimental site in the Northern Region

3.2 Soil Characterization of the Experimental Site

3.2.1 Soil Sampling Procedure

The composite random sampling method was conducted prior to tillage for the extraction of soil samples using the soil auger diagonally through the soil profile, i.e., at 0 – 20, 21 - 40 and 41 – 60 cm soil depths over the experimental area. Soil samples totaling ten for each of the soil depths was considered in a diagonal pattern in each block and later combined as composite sample. The composite soil samples that emanated from the 0 - 20, 21 - 40 and 41 - 60 cm soil depths were put into sampling bags, labelled, and transported to the soil chemistry laboratory of the CSIR-SARI for the determination of chemical and physical properties. Also, soil samples within the respective depths were extracted using core samplers and transported to the laboratory for the determination of soil bulk density.

3.2.2 Laboratory determination of Soil Chemical Properties

Soil samples within the augered depths were analysed for macronutrients that included Ammonium Nitrogen (NH4-N), Nitrate Nitrogen (NO_3^-N) content by Kjeldahl method (Novozamsky *et al*., 1983), Soil salinity and pH (Schofield and Taylor, 1955), Organic carbon (OC) and Organic Matter (OM) content (Nelson and Sommers, 1996). Cation Exchange Capacity (CEC) and Potassium (K) was tested using flame photometer method (Toth and Prince, 1949) and Phosphorus (P) (Bray and Kurtz, 1945). Also, Calcium (Ca) and Magnesium (Mg) was tested using the Atomic Absorption Spectrophotometer (AAS) (Motsara and Roy, 2008; Ogundare *et al*., 2015; Peters, 2018).

3.2.3 Laboratory determination of Soil Physical and Hydraulic Properties

Physical and hydraulic properties of the soil was determined in the laboratory at the University for Development Studies, Nyankpala. The Pedo-transfer function of the Soil-Plant-Atmosphere-Water (SPAW) - Hydrology model was further used for the determination of field capacity, total porosity, permanent wilting point, available water content and saturated hydraulic conductivity (Ksat) of each soil horizon (Saxton *et al.*, 2006; Raes *et al*., 2012) and compared to the laboratory results for accuracy.

3.2.3.1 Determination of Soil Bulk Density

The bulk density of soils was determined from undisturbed soil samples within the identified depths (0 - 20, 21 - 40 and 41 - 60 cm) using the gravimetric method. Soil samples were extracted using core ring samplers carefully hammered into the soil within respective depths and dugout with open ends carefully trimmed to take the shape of the core cylinder. The core is covered with a lid to protect soil in the ring and transported to the laboratory of the CSIR-SARI for the determination of bulk density. Soil samples were put in an oven and dried at 105 °C to a constant weight and reweighed to attain the final weight of samples for the determination of bulk density following proposed method by Hillel (2004). The weight of an empty core sampler is taken and subtracted from the final weight of the dry soil.

$$\text{Bulk density (BD)} = \frac{Weight\ of\ oven\ dry\ soil\ (g)}{Total\ volume\ of\ the\ soil\ (cm^3)} \text{..........Eqn. 3.1}$$

The volume of soil takes the volume of the core rings as 100 cm^3.

3.2.3.2 Determination of Field Capacity of the Soil

The field capacity of soil depicts the upper limit of soil available water (TAW). The soil samples in core samplers was immersed in distilled water for 24 – 48 hours to attain soil saturation and field capacity translating -0.33 bar pressures is determined using the Richards pressure chamber following standard operating procedures (Shaykewich, 1965).

3.2.3.3 Determination of Permanent Wilting Point of the Soil

The permanent wilting point of soil is the lower limit of soil available water (TAW) at which point plants suffer soil moisture stress conditions (Judy, 2004). At permanent wilting point, soil water is strongly held between soil particles by tension forces equivalent to 15 bar pressure. The membrane apparatus is used in the determination of permanent wilting point of soils where a tension of 15 bar is applied to the saturated soil sample. The soil samples on reaching equilibrium after immersed in water, was weighed (W_1) and dried in an oven and then re-weighed (W_2). The weight difference thus; initials weight (W_1) and final weight (W_2) divided by the soil volume represents the permanent wilting point of the soil (Shaykewich, 1965).

3.2.4 Determination of the Soil Infiltration Rate

The infiltration rate of soils defines the vertical movement of water from the soil surface into the unsaturated zone of the soil per unit time. The soil infiltration rate of the experimental field was determined using the minidisc infiltrometer (Decagon Device, Inc. 2016). The device has a lower and upper chamber that is filled water prior to conducting the test. The suction rate of water is controlled using the top chamber. The bottom chamber is calibrated and transparent for easy reading of water level. The porous steel disk at the closed end prevents leakage of water. The suction control tube is left at 2 cm for most soils. The infiltration process starts as soon as the porous stainless-steel disc is placed on a smooth, undisturbed soil surface with a gradual reduction in the level of water contained in the lower chamber. The volume of water in the chamber is recorded against the drop per unit time intervals. The data generated from the test was entered into a Decagon spreadsheet (http:/www.decagon.com/macro) for the related cumulative infiltration graphs and value for the soil infiltration rate.

3.2.5 Estimation of Total Available Water (TAW) Content of the Soil

The TAW within the plants' root zone soil is the difference in soil water content at field capacity and permanent wilting point. TAW was computed following the equation 3.2 (Doorenbos and Pruitt, 1977).

$$TAW = Zr\ (\theta FC - \theta WP) \quad \text{.......Eqn. 3.2.}$$

Where:

Zr - Efective rooting depth derived (assumed 30 cm under drip irrigation),

θFC – Field capacity water content

WP - Soil water measured at wilting point

3.2.6 Estimation of Readily Available Water (RAW) Content of the Soil

RAW depicts fraction of TAW that is always available to the plants. RAW was calculated using the equation proposed by Allen *et al.* (1998); Benjamin *et al.* (2014) as;

$$RAW = P\ (\theta FC - \theta WP) \times Zr \quad \text{.......Eqn. 3.3}$$

Where:

P - Fraction of soil available water content that can be depleted from the root zone before moisture stress and derived from FAO-tables. P varies for all crops and growth stages with values reported by the FAO Irrigation and Drainage Paper No. 56 (Allen *et al*., 1998).

Zr - Effective rooting depth

θFC - Soil water content at field capacity

WP - Soil water content at wilting point

3.2.7 Calculation of Crop Water Requirement (ETc) of Tomato

The daily crop evapotranspiration (ET_c) rate of tomatoes under standard growing conditions was estimated using the FAO CROPWAT Model following the equation according to Doorenboos and Pruitt (1977). Reference Evapotranspiration (ET_o) was estimated using the ET_o Calculator according to the Modified Penman Montieth equation (Allen *et al*., 1998) imbedded in CROPWAT Model with 47 years averaged historical climatic data sourced from the local weather station located at CSIR-Savanna Agricultural Research Institute (SARI). The input climatic data to estimate ET_o included altitude, latitude, and longitude of weather station, monthly average maximum, and minimum air temperature (^oC), air humidity (%), sunshine hours/solar radiation and wind speed at 2 m above the ground. The single crop coefficient (Kc) values of tomato at the different growth stages were obtained and adjusted to meet local conditions following standard procedures outlined in the FAO Irrigation and Drainage Paper No. 56. There exist fluctuations of crop coefficient with weather, crop height and stomata conductance (Annandale and Stockle (1994), therefore adjustment is significant. The K_c's for the growth stages are represented as decadal values except for initial and mid-season stages. The values used for the determination of crop water requirement for tomato are (1) Initial stage = 0.90; (2) Development stage = 0.94 (Ist Decade), 1.00 = (2nd decade), 1.06 (3rd decade); (3) Mid-season growth stage = 1.11 and (4) Late-season growth stage = 1.01 (1st decade), 0.83 (2nd decade). The crop water requirement of tomato estimated by the FAO-CROPWAT used the method by Doorenboos and Pruitt (1977).

$ET_c = K_c \times ET_o$……………………………………………………………………Eqn. 3.4

Where:

K_c - Crop coefficient for the different growth stages.

ET_o - Reference evapotranspiration (mm).

Adjustment of estimated ET_c is necessary for drip irrigation system with considerations on the percentage of ground cover which further reduces evaporation losses of water. Keller and Bliesner (1990) developed equations to help adjust the ET_c with known ground cover (P_d) which was assumed as 95 % due to the presence of mulch material.

$Td = Ud\ X\ [0.1\ (Pd)\ 0.5]$………………………………………………………… Eqn. 3.5

Where:

Td - Localized or adjusted ET_c (Adj. ET_c.) (mm)

Ud - Conventionally estimated peak ET_{crop} (mm)

Pd - Percentage observed ground cover (%)

3.2.8 Calculation of Net Irrigation Requirement (NIR)

Net irrigation requirement (NIR) is the amount of irrigation water required to bring soil moisture to field capacity. NIR does not include losses that are occurring in the process of water application and was determined using the empirical approach formulated by Savva and Frenken (2002) as;

NIR (mm) = $ET_c - (Pe + Ge + Wb) + LR$ mm……………………………………………Eqn. 3.6

Where:

ET_c - Evapotranspiration (mm)

Pe - Effective rainfall (mm)

Ge - Ground water contribution of water (mm)

Wb - Water stored in the soil at the beginning of each period (mm)

LR - Leaching requirement (mm)

However, for purposes of this study, the net irrigation requirements (NIR) equal the daily ET_c because rainfall, groundwater contribution of moisture to the rootzone, and leaching requirements were assumed to be zero.

3.2.9 Calculation of Gross Irrigation Requirement (GIR)

Gross irrigation requirement (GIR) is the total irrigation water applied and incorporates the losses resulting from the conveyance and application of water to fields. The equation proposed by (Savva and Frenken, 2002) was used in the determination of GIR.

$$GIR\ (mm) = \frac{NIR}{AE} \quad \text{Eqn. 3.7}$$

Where:

AE - Irrigation application efficiency (%). The irrigation application efficiency of 95 % was adopted for this present study. According to Coolong (2016), application efficiency of 90 – 95 % is recommended for the drip irrigation efficiency because water delivery is targeted at the plant roots system.

NIR - Net irrigation requirement (mm)

3.2.10 Performing Irrigation Scheduling

Irrigation scheduling is knowing when and how much irrigation water to apply to a field. Under this study, irrigation scheduling was done according to the soil moisture regime approach; in which the soil is periodically monitored for percent depletion of total available water content (TAW) and refilled back to field capacity through irrigation. The empirical approach for the estimation of the percent depletion of TAW was proposed by (Waller and Yitayew, 2016) as;

Percent soil moisture depletion (%) = $\frac{\text{FC}-\text{M}}{\text{FC}-\text{PWP}}\ x\ 100$..Eqn. 3.8

Where:

FC - Field capacity of the soil (%).

PWP - Permanent wilting point of the soil (%).

M – Soil moisture before irrigation (%).

3.2.11 Estimation of Irrigation Interval

Irrigation interval was estimated as the ratio of readily available soil water (RAW) content to the net irrigation requirement (NIR) which equals the daily ET_c.

3.2.12 Estimation of Irrigation Duration

The duration of irrigation denotes the start and end time during irrigation events. This is dependent on the gross irrigation requirement and the emitter discharge**.** The irrigation duration according to Waller and Yitayew (2016) can be estimated following the empirical method in equation 3.9.

$ID\ =\ \frac{GIR}{Q}$ ....Eqn. 3.9

Where:

ID - Irrigation duration (hours)

GIR - Gross irrigation water requirement (mm)

Q - Emitter discharge (l/h)

3.3 Experimental Phase

3.3.1 Experimental Design and Treatments

The experiment was conducted under irrigated conditions within the dry cropping season over two years (November 2020 – April 2021, November 2021 – April 2022). The experimental design was split-splitplot arranged in Randomized Complete Block Design (RCBD) with each experimental unit replicated four times. Treatments consisted of Tomato varieties as mainplot factor at two levels (Mongal F1 and Pectomech); drip irrigation application regimes as subplot factor at three levels (100 % crop evapotranspiration (ET_c) – daily watering, 75 % ET_c – watering at 2 days interval and 50 % ET_c – watering at 3 days interval); and quantities of rice straw mulch as sub-subplot factor at three levels (6 t/ha, 3 t/ha and 0 t/ha) (Table 3.1). Experimental treatments were randomly assigned to the experimental units and replications. The randomization plan for treatments was generated using the Genstat statistical package/software. The imposition of irrigation regime treatment started two weeks after transplanting (WAT) to allow for proper seedling establishment.

Table 3.1: Treatment Structure for the experiment following split-split plot design

Tomato Varieties	Deficit Irrigation Regimes	Quantity of Rice Straw Mulch
1. Pectomech VF	1. 100 % ETc	1. 6 t/ha
2. Mongal F1 Hybrid	2. 75 % ETc	2. 3 t/ha
	3. 50 % ETc	3. 0 t/ha

ET_c=Estimated crop water requirement of tomato, t/ha=Tonnes per hectare, Kg=Kilograms

3.3.2 Field Layout

The field layout was done according to the split splitplot design (Figure 3.2). The desired area and plot sizes of 3 rows of 4.5 m in length (8.1 m^2) area was marked and laid-out using measuring tape and wooden pegs following the trapezoidal rule for accurate field layout and uniform angles. Alleys of 1 m width were made to separate experimental units, blocks, and replications for easy movement of personnel and equipment while preventing the lateral movement of water into adjacent plots.

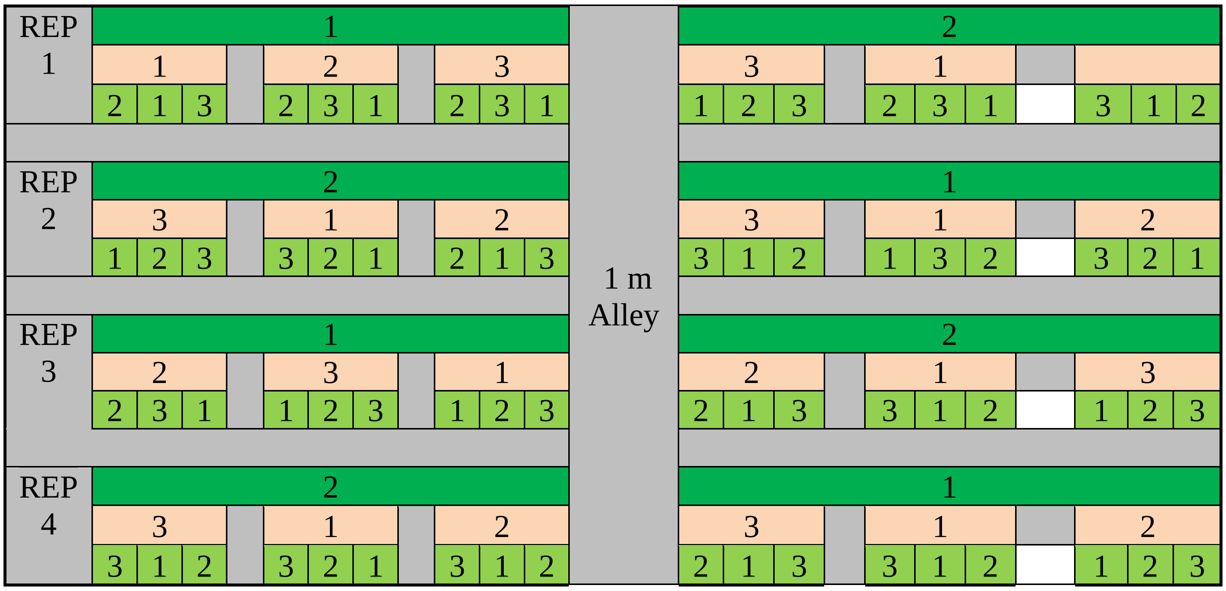

Figure 3.2a: Experimental field layout according to Split-splitplot design

LEGEND FOR FIELD LAYOUT		
MAINPLOTS	VARIETIES	🟩
SUBPLOTS	IRRIGATION REGIMES	🟧
SUB-SUBPLOTS	RICE STRAW MULCH	🟩

Figure 3.2b: Legend for the field layout according to split-splitplot design

3.3.3 Design and Installation of Drip Irrigation System

Plants were irrigated using surface drip irrigation system laid out according to the split-splitplot design (Figure 3.3). The drip irrigation system was designed and constructed to operate at uniform pressure and flow rate to deliver the required volume of water to meet the daily need of the crop. The drip irrigation system had its source of water from 30 m^3 reservoir located next to the experimental field. Petrol pump with the following characteristics (Power; 2.5 Hp, Flow; 100 l/min, Maximum Delivery Head; 16 m) was installed to supply water during irrigations. The control head consisted of filtration system to help remove sediments in the irrigation water to prevent the clogging of emitters; pressure gauges to monitor pressure variations in the system; and control valves to regulate water flow to experimental area. The drip irrigation system was segmented into blocks as subplots to host the irrigation regime treatments. Manifolds were constructed on 30 mm mainlines to connect 25 mm submain lines and fitted with plastic valves to control flow of water into plots. The setup allowed for closure of valves as and when irrigation is not required of certain plots. Drip tapes served as plot rows (3) and of 4.5 m in length. The characteristics of the driptape consisted of; 0.30 m emitter spacing and 1 L/h discharge, 16 mm diameter, 0.20 mm thickness and 1 bar nominal pressure. Each plant was irrigated by one emitter.

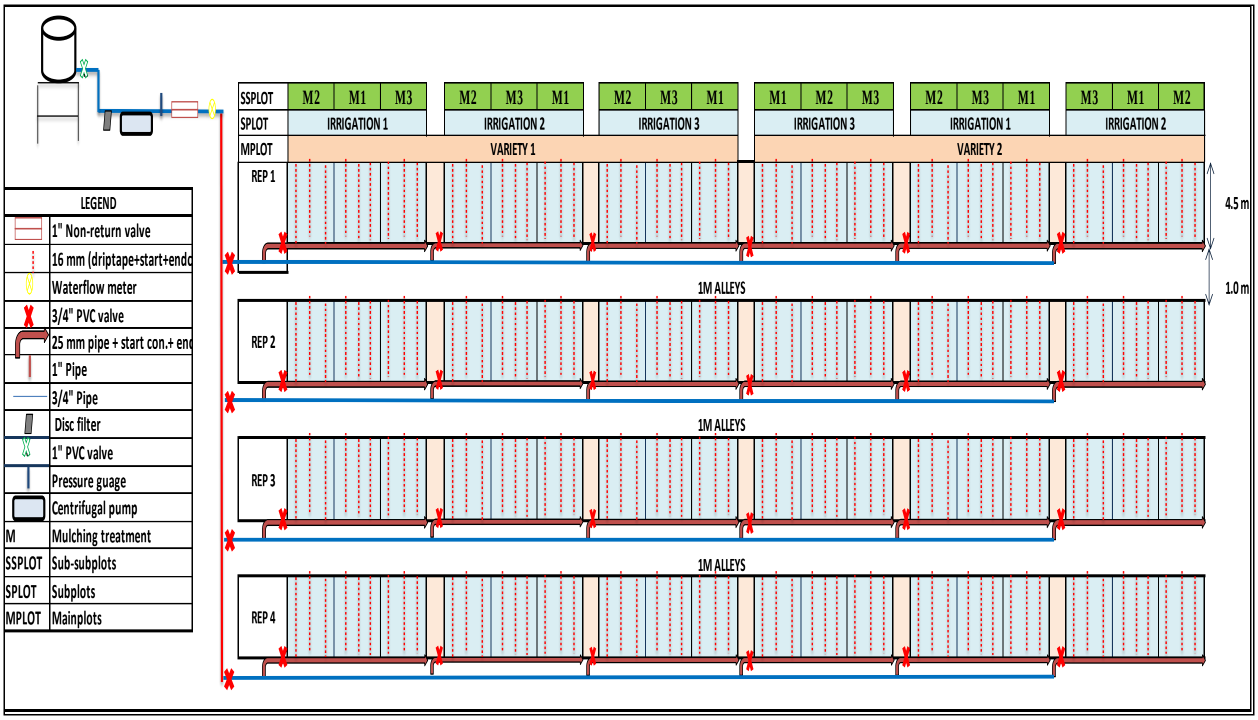

Figure 3.3: Drip Irrigation System Layout following the Split-splitplot design

3.3.4 Performance Evaluation of the Drip Irrigation System

3.3.4.1 Distribution Uniformity Test

The drip performance testing is done to ensure uniform water distribution to the various portions of the experimental field. The experimental fields had irrigations done according to replications; therefore, the need to establish the distribution uniformity of each replicate. There are several performance test indicators for the drip irrigation system, however, the test of distribution uniformity (DU) is most preferred and easy to conduct. In the distribution uniformity test, catch-cans of known volumes were randomly placed beneath selected emitters within replications to collect water per unit time. The water stored in the catch-cans per unit time was measured and recorded. The measured water volumes of each catch-can were sorted from the highest volume to the lowest. The mean value for the low quarter (1/4) was taken as well as the mean values for all the measurements. Distribution uniformity was maintained at acceptable level thus greater than 80 % (Irrigation Evaluation and Maintenance, 2017).

Distribution uniformity was determined using equation 3.10.

$$DU_{lq} = \frac{Q_{25\%}}{Q_n} \times 100 \quad \text{Eqn. 3.10}$$

Where:

$Q_{25\%}$ - Average flow rate of the 25 % of the emitters with the lowest flow rate.

Q_n - Average flow rate of all the sampled emitters.

3.3.4.2 Measurement of Emitter Discharge (l/h)

The emitter discharge rate was measured during the performance of DU test following the procedure used by Bajpai (2014). The volume of water stored in the catch-cans per unit irrigation time during the DU test was used to determine the emitter discharge. The system operating pressure during the test was kept uniform to avoid external influence on the emitter discharge. The selection of emitters was done according to guidelines by Merriam and Keller (1978); where emitters located around the lateral inlets, middle and end of laterals are carefully selected. The test was conducted according to the scheduled irrigation turns following subplots for delivery of water to the 100 % 75 % and 50 % ET_c irrigation regimes.

3.3.4.3 Emitter Flow Variation (EFV)

The flow of water in the lateral of drip irrigation system is affected by several factors that include slope of land, length of lateral and pressure variations. However, the installed drip irrigation system met all the standards; therefore, the need to determine the emitter flow variations in confirming the design. The variation in emitter flow was calculated using the following formula in quation 3.11.

$$q_{var} = \left(\frac{q_{\max} - q_{min}}{q_{max}}\right) \times 100 \quad \text{……………………………………..…..Eqn. 3.11}$$

Where:

qvar - Emitter flow variation along the lateral line

q_{min} - Minimum measured emitter flow rate along the lateral line (l/h)

q_{max} - Maximum measured emitter flow rate along the lateral line (l/h)

3.4 Field Cultural Practices

3.4.1 Planting Materials

Certified seed of Pectomech VF and Mongal F1 tomato varieties was purchased from Agri-seed Ltd, Tamale and used as planting materials for the experiment. The Pectomech VF tomato variety is open pollinated and widely grown variety by farmers in the irrigated ecologies of Ghana and well adapted to the dry season irrigated ecologies and is high yielding. The Mongal F1 is hybrid and high yielding with resistance to leaf blight disease and widely used for most farmers.

3.4.2 Nursery Operations

Nursery beds of 1 x 6 m dimension was marked out using a measuring tape and wooden pegs. The construction of nursery beds was done using hand hoes and the soil heat treated by burning rice straw to kill pathogens. Tomato seed (50 g Mongal F1 and 100 g Pectomech) was sowed in shallow drilled lines of 1-2 cm depth and 20 cm apart and covered with a thin layer of soil. Following sowing, nursery beds were mulched with 2 cm layer of rice straw to enhance uniform seed germination. Nursery beds were irrigated soon after mulching using watering-cans to provide optimum soil water conditions. Seedling emergence at the nursery stared 4-5 days after sowing with Mongal F1 showing more vigor than Pectomech. The poor germination percentage of Pectomech necessitated the use of more seeds (100 g). The mulch material was removed at one week after seedling emergence from the surface and slightly raised to about 1m above the ground with the support of sticks for proper ventilation. Foliar compound NPK (15-15-15) fertilizer was applied 2 weeks after emergence (WAE) at the rate of 10 g/L of water to support the establishment of seedlings. Healthy and high vigor seedlings were pricked-out onto separate seedbed to avoid overcrowding. Seedlings were hardened one week to transplanting by decreasing the shade cover to one day full exposure to sunlight and reducing irrigation.

3.4.3 Land Preparation of the Experimental Area

Total weed killer (Glyphosate herbicide) was applied at the rate of 3.0 l/ha using a Matabi Knapsack sprayer with water rate of 200 l/ha to kill weeds prior to tillage. The entire experimental area was tractor harrowed in the first dry cropping season of 2020; and minimum –zero tillage applied using hand-hoes in the second dry cropping season of 2021. The same field was maintained and used for both seasons. The field was properly leveled using hand-hoes to avoid uneven soil surface and runoff.

3.4.4 Transplanting of Seedlings

Seedlings were ready for transplanting 4 weeks after emergence (WAE) when 4-6 true leaves have developed. Seedlings were carefully and singularly transplanted in the evening of 24th December 2020 and 24th December 2021 following light irrigation to the field. Seedlings were transplanted on the flat and spaced 0.60 x 0.30 m inter and intra-rows respectively.

3.4.5 Mulching

Rice straw was used as mulching material. The application of rice straw mulch was done 1 week after transplanting (WAT). The rice straw was chopped with a cutlass into small pieces of 1-2 cm length and weighed according to treatment requirement as 6 t/ha (4.86 kg/plot), 3 t/ha (2.43 kg/plot) and 0 t/ha (0 kg/plot) using a hanging weighing scale. The measured rice straw was uniformly spread over the soil surface of respective plots. Earth bunds were raised around each plot and smaller sand placed on the rice straw mulch to offer protection from wind spread of mulch material onto other plots. The driplines were totally covered with the rice straw mulch in each plot.

3.4.6 Irrigation

Drip irrigation water was applied daily and uniformly in equal amounts to all plots in the first three weeks after transplanting (WAT). However, the imposition of irrigation regime (100 %, 75 % and 50 % ET_c) treatments started 3WAT and translated to daily (1 day), every 2 days and every 3 days irrigation intervals for regimes respectively. In each of the irrigation events, the percent depletion of total available water (TAW) was estimated from known soil moisture condition before irrigation. The water volume corresponding to the soil moisture depleted was estimated and water applied to bring soil moisture back to field capacity; being the upper limit of TAW.

3.4.7 Fertilizer Management

Organic fertisoil was incorporated into the soil at the rate of 6 t/ha at land preparation prior to transplanting of seedlings. After laying of the driptape as planting rows, each emitter position was identified and surrounding soil carefully dug with a cutlass to depth of 15 cm and diameter of 15 cm. Fertisoil, amounting to a hand-full was applied into the dug holes and mixed with the soil. Irrigation water was applied to facilitate the decomposition of the material. The field was allowed for two weeks before seedlings were transplanted. Fertilizer was applied at the rate of 75 kg N/ha, 40 kg P_2O_5/ha and 40 kg K_2O/ha for the crop in two splits. Basal fertilizer (Yara Mila Grower – 17 % N-10 % P-10 % K-3 % S+0.3 % Zn) was applied two weeks after transplanting by the dibble and burry method. Plants were top dressed 4 weeks after transplanting using (Yara Mila Actyva – 23 % N-10 % P-5 % K-2 % MgO+3 % S+0.3 % Zn). The Adepa Agro Organic Pesticide has an added nutritional benefit and was used as soluble fertilizer to provide the calcium need of plants prior to fruiting.

3.4.8 Crop Protection

The early season insect pests such as aphids and whiteflies were controlled with Tihan (Spirotetramat 75 g l^{-1} and Flubendiamide 100 g l^{-1}) at the rate of 200 ml ha^{-1} and Thunder (Imidacloprid 100 g l^{-1} and Betacyfluthrin 45 g l^{-1}) insecticide at the rate of 200 ml ha^{-1} to control mid to late season insect pests. Diseases associated to fungal and bacterial were controlled using Adepa Agro Organic Pesticide (Ethyl Palmitate, Ethyl Oleate, 9-methyl-Z-10-tetradecen-1-olacetate, 1-Ecosanol, Elcosen-1-ol, cis-9-Trans Squalene) applied at the rate of 100 mls per 15 liters of water. Weeds were controlled manually by hand-picking in plots and hoeing in alleys as soon as they emerge to avoid competition with plants.

3.4.9 Staking

The tomato plants were supported on metallic pegs used as stakes. The metallic pegs were 60 cm in length and with a pointed tip for easy soil penetration. The stem of tomato plants was secured to the stake using nylon twine. Individual plants had a stake to confer support to the stem against wind and the weight of fruits.

3.4.10 Harvesting

The fruits of tomato were harvested at maturity as and when they were fully ripe and colour turned red. Harvesting was done by hand-picking plot-wise to avoid fruit mix-ups during the estimation of yield and related parameters. Fruits were harvested six times in each season.

3.5 Data Collection Phase

Data collection consisted of measurements conducted on the soil, weather, and plants during the evaluation months. The soil physical and chemical conditions affected by the treatment factor levels and their interactions was monitored in-season at different stages of the crop growth. The agronomic characterization of the two varieties with respect to treatment effects was also monitored throughout the growth stages of the crop. Moreover, the various weather variables of the experimental fields were monitored by a weather station installed at the middle of experimental field.

3.5.1 Soil Data Collection Parameters and Proceedures

3.5.1.1 Rootzone Soil Moisture Content (% v/v) Monitoring

The soil moisture content was monitored before and after every irrigation within the root zone of 30 cm depth and started 3 WAT in experimental units. Volumetric soil moisture content was monitored using FieldScout TDR 150 Soil Moisture, Spectrum Technologies, Inc., USA. Ten sample points in the middle row of each plot and around the plant root system was considered and averaged to represent soil moisture content per plot.

3.5.1.2 Rootzone Soil Temperature (˚C) Monitoring

Soil temperature was monitored before every irrigation on the soil surface and within the root zone of 30 cm depth and started 3WAT in experimental units. The surface soil temperature was monitored using FLIR C5 Compact Thermal Infra-red Camera, Teledyne FLIR LLC., USA. Soil temperature measurements were taken during the active hours of 12 – 15 hrs. However, soil temperature within the rootzone was monitored using FieldScout TDR 150 Soil Moisture/Temperature Meter, Spectrum Technologies, Inc., USA. Ten sample points in the middle row of each plot and around the plant root system was considered and averaged to represent soil temperature per plot.

3.5.1.3 Available Nitrogen (N) Content of the Soil

The nitrogen (N) content of the soil within the root zone of 30 cm depth was measured at maturity within each experimental unit. In the middle of each plot, soil was augered to 30 cm depth and soil samples collected into sampling bags and transported to the CSIR-Soil chemistry laboratory for the determination of Nitrate - Nitrogen (NO_3-N) content (Novozamsky *et al*., 1983) of the soil. However, due to high accuracy of the Virtual Irrigation Academy (VIA) Nitrate Test Strip – medium resolution and its low-cost nature, it was used in the determination of Nitrate - Nitrogen (NO_3-N) content in the second irrigated cropping season. Reading was done after 60 seconds on a scale of 0-500 mg/L.

3.5.1.4 Rootzone Soil pH Content

The soil pH within the root zone of 30 cm depth was measured in each experimental unit. In the middle of each plot, soil was augered to 30 cm depth and soil samples collected into sampling bags and transported to the CSIR-Soil chemistry laboratory for the determination of pH using a pH Meter in a solute solution of 1:2.5 (Soil: H_2O ratio) (Schofield and Taylor, 1955). The mixing plate and meter was rinsed thoroughly with distilled water after every round of testing to avoid cross contamination.

3.5.1.5 Rootzone Soil Electrical Conductivity Content (ds/m)

The soil pH within the root zone of 30 cm depth was measured in each experimental plot. In the middle of each plot, soil was augered to 30 cm depth and soil samples collected into sampling bags and transported to the CSIR-Soil chemistry laboratory for the determination of electrical conductivity in a solute solution of 1:2.5 (Soil: H_2O ratio) (Schofield and Taylor, 1955). The mixing plate and meter was rinsed thoroughly with distilled water after every round of testing to avoid cross contamination.

However, in the 2021/22 dry season, soil electrical conductivity (EC) was monitored within the root zone of 30 cm depth and started 3WAT in experimental units. The soil EC measured using FieldScout TDR 150 Soil Moisture/Temperature/EC Meter, Spectrum Technologies, Inc., USA. Ten sample points in the middle row of each plot and around the plant root system was considered for EC measurements and averaged to represent soil EC per plot.

3.5.2 Agronomic Growth Parameters and Data Collection Proceedures on Tomato Plants

3.5.2.1 Measurement of Plant Height (cm)

The measurement of plant height started 4WAT from ten randomly selected and tagged plants within the middle row of experimental units. Plant height was measured from the base of the plant to the apical meristem/tip using a 2 m graduated wooden pole and recorded in centimeters (cm) and averaged to represent plant height per plant/plot.

3.5.2.2 Measurement of Stem Diameter (cm)

The expansion rate of plant stem was monitored throughout the plants growth starting 4WAT from ten randomly selected and tagged plants within the middle row (net plot) of experimental units. Stem diameter was measured on the stem at 2 cm above the soil surface using a digital vernier caliper. Measurements were recorded in centimeters (cm) and averaged to represent stem girth per plant/plot.

3.5.2.3 Measurement of Leaf Area Index (LAI)

The measurement of LAI was done throughout the growing season. It started 3 weeks after transplanting (WAT) in each experimental unit at weekly intervals that lasted 6 times. LAI was measured using AccuPAR Ceptometer LP-80, Decagon Devices, Inc., USA between 12 – 15hrs local time. The device has been widely used for the determination of LAI in most crops (Finzel *et al*., 2012, Francone *et al*., 2014), but with limited use on horticultural crops such as tomato (Mamun *et al*., 2017). The Ceptometer is user-friendly and runs directly on battery with an external Photosynthetic Active Radiation (PAR) sensor to guide its operation. Other main components of the Ceptometer are a probe with 80 imbedded sensors and an integrated microprocessor-driven data logger to access readings. For accuracy of LAI measurements, readings were taken with high PAR values above 800 µmolm^{-2}s^{-1}. The device measures the intercepted light in plant canopies to calculate LAI.

3.5.2.4 Measurement of Leaf Chlorophyll Concentration (LCC) (µmol/m^2)

The non-destructive method of measuring the chlorophyll content of leaves was done throughout the growing season beginning 3 WAT in each experimental unit at weekly intervals that lasted six times. Leaf chlorophyll concentration was measured using a portable device; CCM-200 plus, OPTI-SCIENCES, INC., USA. The device is widely used on a variety of both C_3 and C_4 plants and is fast, reliable, and user-friendly. Measurements were taken between 12 – 15 hrs local time. A total of three leaves were considered per plant for measurements and 10 randomly selected plants in each plot. Leaves considered per plant were randomly selected from the down, mid and top portions of the stem. Chlorophyll readings per plant represented an average of the three leaves and further averages of the 10 randomly selected plants represented that of the experimental unit.

3.5.2.5 Measurement of Leaf Canopy Temperature (˚C)

The leaf canopy temperature of the plants was measured by non-contact approach using the FLIR C5 Compact Thermal Infra-red Camera, Teledyne FLIR LLC., USA. Soil temperature measurements were taken between 12 – 15 hrs local time. Measurements were above the canopy at an angle of 45 ˚ and 30 cm distance targeted at the leaves. Care was taken to avoid the tendency of measuring ground surface temperature. A total of three measurements per plant was considered from 10 randomly selected plants per plot biweekly starting 3 WAT. Temperature readings per plant represented an average of the three per canopy/leaves and further averages of the 10 randomly selected plants represented that of the experimental unit.

3.5.2.6 Measurement of Leaf Stomatal Conductance (mmol/m^{2}s)

The stomatal conductance of leaves was measured using the Steady State Diffusion Porometer Model SC-1, Decagon Devices, Inc., USA. The Leaf Porometer was calibrated in the field to meet local conditions prior to measurements. Abaxial measurements were taken throughout the growing season beginning 3 WAT in each experimental unit at weekly intervals that lasted six times. A total of three leaves were considered per plant for measurements and five randomly selected plants per plot. Leaves considered per plant was randomly selected from the down, mid and top portions of the stem. Leaf stomata conductance readings per plant represented an average of the three leaves and further averages of the 10 randomly selected plants represented that of the experimental unit.

3.5.2.7 Aboveground Biomass Weight (g)

Aboveground biomass weight (stem/shoots, leaves and fruits) was measured at the peak water consumptive stage (8 – 9 WAT) of the crop from three randomly selected plants within the inner border row of experimental units. The shoots/stem was cut using a cutlass at 2 cm above the soil (Anderson, 1988). Aboveground fresh biomass (shoot, leaves and fruit) was separated, weighed, chopped, and then placed inside sampling paper bags for oven-drying at 70 °C (Bohm, 1979). Samples were removed at constant weight and reweighed to represent aboveground biomass weight for shoots, leaves and fruits. The total average weights of shoot, leaves and fruits represents the aboveground biomass per plant/plot.

3.5.3 Agronomic Yield Parameters and Data Collection Procedures on Tomato Plants

3.5.3.1 Fruit Width (cm)

The width of twenty randomly selected mature and ripe fruits from ten plants at each harvest of experimental unit was measured in centimeters (cm) at the biggest part of the fruit using a digital vernier caliper. Values were averaged to represent fruit width per plot.

3.5.3.2 Fruit Length (cm)

The length of twenty randomly selected mature and ripe fruits from ten plants at each harvest of experimental unit was measured in centimeters (cm) from the base of the fruit to the tip using a digital vernier caliper and recorded in centimeters (cm). Values were averaged to represent fruit length per plot.

3.5.3.3 Fruit Count per Plant

The number of fruits from ten randomly tagged plants within the middle row in experimental units were counted at the reproductive stage of the crops development and averaged to represent fruit count per plant. Again, at each harvest, ripped fruits per plot was counted and recorded.

3.5.3.4 Fruit Weight at Harvest

The total weight of twenty randomly selected ripped fruits from ten plants at each harvest was measured using an electronic weighing scale. The measured weight was averaged and recorded in grams (g) to represent weight of single fruit.

3.5.3.5 Total Fruit Yield

The ripe fruits harvested per plot from each round of harvest was weighed using a digital weighing scale and recorded in kilograms (kg). The recorded weights were converted to tonnes per hectare.

3.5.3.6 Harvest Index (HI)

The harvest index was determined as a ratio of fruit dry biomass weight to the aboveground biomass weight.

3.5.4 Fruit Quality Parameters and Data Collection Procedure

3.5.4.1 Fruit pH Measurement

Three randomly selected fully ripped fruits were hand-picked from treatment plots at harvest and tested for pH in the laboratory (Rangana, 1979). Fruit samples were washed, dried, and weighed into high density polypropylene sealed bags and crushed using an electric blender. The fruit juice was filtered through a sieve of l mm pore size facilitating the removal of fruit coats and seeds. The pH was then determined using the pH meter after it has been calibrated and readings recorded. The measurement was done in triplicates (Rangana, 1979).

3.5.4.2 Brix Content of Tomato Fruits

The brix content of randomly selected fully ripped fruits of tomato was determined from harvest of treatment plots. Measurement was taken using a Sucrose refractometer, Hanna Instruments (Model-HI-96801). The fruits were crushed using an electric blender and the juice transferred into 50 ml beakers. With the help of a teat pipette, 1 ml of the juice was extracted and placed on the hand refractometer after it had been calibrated and readings recorded. The measurement was done in triplicates.

3.5.4.3 Fruit Electrical Conductivity (EC)

Three randomly selected fully ripped fruits were hand-picked from treatment plots at harvest and tested for EC in the laboratory. Fruit samples were washed, dried, and weighed into high density polypropylene sealed bags and crushed using an electric blender. The juice of fruits was passed through a sieve of l mm pore size to facilitate the removal of fruit coats and seeds. The EC was then determined using the EC meter after it has been calibrated and readings recorded (Rangana, 1979). The measurement was done in triplicates and mixing plate together with meter was rinsed thoroughly with distilled water after every round of testing to avoid cross contamination.

3.6 Estimation of Irrigation Water-Use Efficiency and Crop Water Stress Index

3.6.1 Estimation of Irrigation Water-Use Efficiency (IWUE)

IWUE is the yield (Fruit and seed) obtained per seasonal water applied (Howell *et al.*, 2002). Water applied can be from irrigation or precipitation or both. However, emphasis is on irrigation water–use efficiency.

$$\text{IWUE (kg m}^{-3}\text{)} = \frac{\text{FY (kg)}}{SIW\ (mm)} \quad \text{……………………...……………....……………....……Eqn. 3.12}$$

Where:

FY - Total fruit yield of tomatoes

SIW - Seasonal irrigation water applied according to the individual irrigation regimes.

3.6.2 Estimation of Crop-Water Stress Index (CWSI)

The Crop Water Stress Index (CWSI) is a measure of the relative transpiration rate occurring from a plant at the time of measurement, using data from plant canopy temperature and vapor pressure deficit of the air (Jackson *et al*., 1981). The CWSI relationship proposed by Idso (1981), and Jackson *et al*. (1981) was followed as:

$$CWSI = \frac{[(T_c - T_a)_m - (T_c - T_a)_{li}]}{[(T_c - T_a)_{ls} - (T_c - T_a)_{li}]} \quad \text{......Eqn. 3.13}$$

Where:

Tc - Canopy temperature

Ta - Air temperature

The "*m*" subscript denotes the difference between the two measured temperatures, *li* (inferior limit) denotes the non-water stress baseline expressed as the difference between the two temperatures when evapotranspiration is not restricted by water availability, and *ls* (superior limit) denotes the hypothetical non-transpiring upper baseline expressed as the difference between the two temperatures when evapotranspiration is zero. The CWSI is estimated by determining the relative distance between the lower baseline representing non-stress conditions (well-irrigated condition) and the upper baseline representing no-transpiration (totally stressed condition). The CWSI varies between 0 (no water stress condition) and 1 (severe water stress condition).

The CWSI equation 3.13 can be reduced and rewritten as equation 3.14.

$$CWSI = \frac{(dT - dT_i)}{(dT_s - dT_i)} \quad \text{...... Eqn. 3.14}$$

Where:

dT - Difference of measured air and crop temperatures

dTs - Upper limit of air temperature minus canopy temperature of crops without transpiration

dTi - Lower limit of air temperature minus canopy temperature for fully-irrigated crop

To determine the upper and lower limits in the CWSI equation, the method developed by Idso *et al.* (1981) was used, which considers changes in both limits due to variations in the air vapor pressure deficit (VPD). The VPD is the difference between the saturation pressure (e_s) and the actual vapor pressure (e_a) (Eqn. 3.15), and it is a good indicator of the actual evaporating capacity of the air.

$$VPD = e_s - e_a \quad \text{.......... Eqn. 3.15}$$

The water vapor pressure at saturation (e_s), in kPa, is the maximum amount of water vapor that air can hold at a given temperature (T) (°C) and it is calculated using equation 3.16.

$$e_s(T) = 0.611\, exp\left[\frac{17.27\, T}{T + 237.3}\right] \quad \text{.......... Eqn. 3.16}$$

The actual water vapor pressure e_a can be obtained from equation (3.17) if the relative humidity (*RH*) and the temperature are measured.

$$RH = \frac{e_a}{e_s}\, 100 \quad \text{.......... Eqn. 3.17}$$

A VPD equal to zero indicates that the air holds the maximum water vapor possible (this corresponds to a relative humidity of 100 %). The lower limit of the CWSI changes as a function of the water vapor pressure due to the VPD. Idso (1982) demonstrated that the lower limit of the CWSI is a linear function of the VPD for several crops. The parameters are estimated by a linear regression plot to generate an equation for the relationship of temperature difference (canopy and air) verses VPD for the non-water stressed crop and the maximum stressed crop as shown in the following two equations:

$dT_i = a + b(VPD)$……………………………………………………........………....Eqn. 3.18

$dT_s = a + b[e_s(T_a) - e_s(T_a + a)]$……………………………………………...........Eqn. 3.19

Where:

VPD – Vapor Pressure Deficit, expressed in kPa.

es (*Ta*) - Saturation vapor pressure at air temperature, *Ta* (kPa)

es (*Ta*+ a) - Saturation vapor pressure at air temperature plus the value of the intercept for the crop.

3.7 The Crop-Water Productivity Modeling Phase: DSSAT Model

The Decision Support System for Agrotechnology Transfer (DSSAT) Model was calibrated and used to simulate the behavior of soil and Tomato varieties under irrigation and mulch management systems. The model operates on varied data sources that include crop, soil, weather, management, and field data. The data is required to calibrate the model prior to simulation.

3.7.1 Input Data Required By DSSAT Model

3.7.1.1 Weather Data Input

The DSSAT Model requires daily weather data to run prescribed simulations on crops. However, minimum data set are required by the model before simulations can be conducted by DSSAT. The weather parameters include daily temperature (minimum and maximum), rainfall and solar radiation of the experimental site. The weather of experimental site was monitored daily from a meteorological station situated on the field to provide the needed climatic data for the model calibration. The weather variables monitored, and outputs are presented in Figures 4.1A and B as well as 4.2A and B of the next chapter. The derived weather data were inputted into DSSAT using the WeatherMan software.

3.7.1.2 Soil Characteristics Data

The soil component data was obtained by the morphological characterization within 0 – 60 cm soil depths of the experimental site. Soil data included chemical, physical and hydraulic properties within the soil layers used as input file to the DSSAT Model. Pproperties of the soil are presented in Table 3.2. Other relevant soil data set were adjusted as proposed by Gijsman *et al*. (2007) and included Soil albedo (0.13), evaporation limit (6), fertility factor (1), drainage rate (0.6) and runoff curve number (61).

Table 3.2: Soil Properties of the Experimental Field used in the Calibration of DSSAT Model

Soil depth (cm)	**PWP (cm^3/cm^3)**	**FC (cm^3/cm^3)**	**SAT (cm^3/cm^3)**	**TAW (cm^3/cm^3)**	**Initial (cm^3/cm^3)**	**Bulk Density (g/cm3)**	**pH**	**Org. C (%)**	**Total N (%)**
0-5	0.091	0.183	0.458	0.092	0.183	1.48	5.40	0.98	0.09
5-15	0.091	0.183	0.458	0.092	0.183	1.48	5.40	0.98	0.09
15-20	0.091	0.183	0.458	0.092	0.183	1.48	5.40	0.98	0.09
20-30	0.069	0.180	0.419	0.111	0.180	1.68	5.40	0.74	0.07
30-40	0.069	0.180	0.419	0.111	0.180	1.68	5.40	0.74	0.07
40-50	0.096	0.204	0.381	0.108	0.204	1.69	5.40	0.53	0.05
50-60	0.096	0.204	0.381	0.108	0.204	1.69	5.40	0.53	0.05

Where, PWP=Permanent wilting point, FC=Field capacity, SAT=Saturation water content of soil, TAW=Soil available water content, pH=Soil alkalinity or acidity, Org. C=Organic Carbon content of soil, N=Nitrogen content of soils

3.7.1.3 Crop Management Data

Crop file was created for two local tomato cultivars (Mongal F1 and Pectomech) defining the inputs used during production. The management inputs considered were fertilizer (type, rate and time of application), daily irrigation amounts, organic residue type and quantity, planting date and method. Other input parameters under the crop file included planting density and related field conditions. Aside the above parameters, the treatment structure was defined and created for each factor; thus, variety/cultivar, irrigation regimes and quantity of rice straw mulch. The factors were then interacted and linked together keeping the other input variables constant. Model simulation was set to begin on the transplanting date; thus, 25th December 2020 until final harvest for the combined treatment. The test statistics was evaluated to ascertain the level of correlation to inform acceptance of model calibration.

3.7.2 Calibration of CROPGRO-DSSAT Model

Model calibration was meant to optimize the ability of the model in simulating outcomes comparable to field measured data under known environmental conditions. The optimal conditions for ideal plant growth were considered as non-stressed related treatment factors and input variables needed and used for the model calibration. The full irrigation regime (100 % ET_c) was considered as the optimum treatment and its associated measured variables pertaining to growth and yield was used during the calibration process of the model.

3.7.2.1 Calibration of the Cultivar file for Genetic Coefficient of Tomato

The genetic coefficient of the cultivars was generated from the default Florida 47 tomato cultivar already imbedded in the CROPGRO Model of DSSAT. The GLUE feature of the model assisted in generating close match coefficient for adoption (Anothai *et al*., 2008). The genetic coefficient of Florida 47 was then modified using crop phenology data for Mongal F1 and Pectomech from the non-stressed treatment of 100 % ET_c irrigation regime for the first season. Table 3.3 presents default and calibrated results on genetic coefficient of tomatoes from the cultivar file. The default represents genetic coefficient of Florida 47 tomato variety embedded in the cultivar file of the model. The EM-FI was adjusted for the cultivars from 24.40 default value to 24.61 photothermal days. The Also, FL-SH was revised from 2.2 to 3.29 and 3.20 photothermal days for Mongal F1 and Pectomech respectively (Table 3.3). The FL-SD also changed from 19 to 19.55 photothermal days for each cultivar. However, SD-PM reduced for the cultivars from default of 45.2 photothermal days to 39.36 and 38.20 for Mongal F1 and Pectomech respectively (Table 3.3). For proper response on leaf area index of plants, FL-LF, LFMAX, SLAVR, SIZLF and XFRT was recalibrated. FL-LF changed from 52 photothermal days to 48.61 for the two cultivars. Meanwhile, LFMAX was calibrated to 1.48 and 1.10 for Mongal F1 and Pectomech respectively. On the other hand, SLAVR increased slightly to 310 cm^2/g while SIZLF was reduced to 280 cm^2 for Pectomech only. The XFRT changed from 0.78 to 0.81 and 0.72 for Mongal F1 and Pectomech respectively (Table 3.3). The calibration was done with inputted soil and weather data of the experimental field as well as specified field cultural practices. Thereafter, the model was used to run simulations on the deficit irrigation treatments combined with the mulches against individual cultivars to ascertain the predictive performance of the model in comparison to measured data on selected parameters that included rootzone soil temperature, canopy height and fresh fruit weight of tomatoes. Predicted model outcomes on growth phenology and desired traits of soil temperature, canopy height and fresh fruit weight were checked for accuracy using the evaluation statistics of relative root mean square error (RRMSE), root mean square error (RMSE), Willmott's d-index of agreement (D) and coefficient of determination (R^2).

Table 3.3: Genetic Coefficients generated for Tomato varieties in CROPGRO-DSSAT Model

DEFINITION	CODE	FL. 47	MON.	PEC.
		DEF.	CAL.	CAL.
Ecotype	ECO#	TM0001	TM0001	TM0001
Critical Short Day Length	CSDL	12.33	12.33	12.33
Slope of relative response of development to photoperiod with time	PPSEN	0.00	0.00	0.00
Time from plant emergence to flower appearance (R1)	EM-FL	24.40	24.61	24.61
Time from first flower to first pod (R3) (photothermal days).	FL-SH	2.20	3.29	3.20
Time from first flower to first seed (R5)	FL-SD	19.00	19.55	19.55
Time from first seed (R5) to physiological maturity (R7	SD-PM	45.20	39.36	38.20
Time from first flower (R1) to end of leaf expansion	FL-LF	52.00	48.61	48.61
Maximum leaf photosynthesis rate at 30 ˚C, 350 vpm CO_2, and high light (mg CO_2/m^2-s).	LFMAX	1.36	1.48	1.10
Specific leaf area of cultivar under optimum growth conditions (cm^2/g).	SLAVR	300.00	310.00	310.00
Maximum size of full leaf (cm^2).	SIZLF	300.00	300.00	280.00
Maximum fraction of daily growth partitioned to seed plus shell	XFRT	0.78	0.81	0.72
Maximum weight per seed (g)	WTPSD	0.004	0.004	0.004
Duration of seed filling for pods at optimum growth conditions	SFDUR	26.00	26.80	26.80
Average seed per pod	SDPDV	300.00	300.00	300.00
Time to final pod load under optimal conditions	PODUR	55.00	54.70	44.20
Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity.	THRSH	8.50	8.50	8.50
Fraction protein in seeds (g(protein)/g(seed))	SDPRO	0.30	0.30	0.30
Fraction oil in seeds (g(oil)/g(seed))	SDLIP	0.05	0.05	0.05

Where, FL. 47=Florida 47 Variety, MON. =Mongal F1 variety, PEC. =Pectomech variety, DEF. =Default, CAL. =Calibrated, Time=Photothermal days

3.8 Data Management and Analysis Phase

3.8.1 Statistical Analysis of Agronomic and Soil Data

Data was tested for conformity to the analysis of variance (ANOVA) assumptions. The data was then subjected to analysis of variance (ANOVA) for spilt-splitplot design. Treatments means were separated using Duncan Multiple Range Test (DMRT) at 5 % confidence level where statistical differences was found by Genstat 12 edition statistical package. Pearson correlation and simple regression analysis was performed on the measured parameters to ascertain their level of associations and relationships where necessary. Microsoft excel was further used to graphically represent the relationship and model equations.

3.8.2 Model Performance

The performance of the CROPGRO Tomato model of DSSAT was evaluated using multiple statistical indicators of goodness-of-fit statistics such as the root mean square error (RMSE), Pearson's coefficient of determination (R^2), Relative root mean square error (RRMSE) and index of agreement (d) (Willmoty 1981; Willmott *et al.*, 2005, Willmott *et al.*, 2012).

3.8.2.1 Pearson's Coefficient of Determination (R^2)

The R^2 describes the "degree of colinearity between predicted and observed data. It describes the proportion of the variance in observed data explained by the model. Its value ranges from 0 to 1, with higher values indicating less error variance; typically, values greater than 0.5 are considered acceptable" (Santhi *et al.*, 2001; van Liew *et al.*, 2003). It can also be expressed as the "squared ratio between the covariance and the multiplied standard deviations of the observed and predicted values". Therefore, it estimates the combined dispersion against the single dispersion of the observed and predicted series. Its value is calculated using Equation 3.21.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \acute{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\ \sqrt{(P_i - \acute{P})^2}}\right]^2 \text{……………………………......……………………...Eqn. 3.21}$$

Where:

O_i - The ith observation for the parameter being evaluated

P_i - The ith predicted value for the parameter being evaluated

$\acute{P}$ - The mean of the predicted value

$\bar{O}$ - The mean of the observed value

n - The total number of observations

3.8.2.2 Index of Agreement (d)

The d index was developed by Willmot (1981) to overcome the poor sensitivity of NSE and R^2 in determining differences between observed and predicted means and variances (Legates and McCabe, 1999). It represents the "ratio of the mean square error and the potential error" (Willmot, 1984) and is defined as;

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}|) + |O_i - \bar{O}|^2} \quad \text{……………………………..………….........……Eqn. 3.22}$$

The potential error in the denominator represents the largest value that the squared difference of each pair can attain. The range of d is like that of R^2 where d lies between 0 (no correlation) and 1 (perfect fit). Willmot (1981) defined potential error as "the sum of the squared absolute values of the distances from the predicted values to the mean observed value and distances from the observed values to the mean observed value". The *d-index* can detect "additive and proportional differences in the observed and simulated means and variances"; however, it is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999).

3.8.2.3 Root Mean Square Error (RMSE)

RMSE is commonly used error index in statistics (Chu and Shirmohammadi, 2004; Singh *et al.*, 2004; Vasquez-Amábile and Engel, 2005). Lower values of RMSE is mostly used as an indicator for perfect model performance, however, few publications have quantified considerations of a low RMSE based on observed standard deviation (Singh *et al.*, 2004). RMSE is calculated as presented in Eq. 3.23:

$RMSE = \left[\frac{1}{n}\sum(Pi - Oi)^2\right]^{0.5}$ ....Eqn. 3.23

Where:

n - The number of observations,

Pi - The predicted value for the *i*th measurement,

Oi - The observed value for the *i*th measurement.

It varies from the optimal value of 0, depicting perfect model simulation to a large positive value.

3.8.2.4 Relative Root Mean Squared Error (RRMSE)

The RRMSE is the ratio of mean root squared error (RMSE) of the residuals squared to the mean of measured values. RRMSE of value 0 represents a perfect fit; RRMSE less than 10 % represents excellent model performance, whereas RRMSE value between 10-20 % represents good model performance. Also, RRMSE value between 20-30 % signifies a fair model performance, whereas RRMSE value greater than 30 % signifies poor model performance. It is defined by the empirical equation (3.24).

$RRMSE = \frac{RMSE}{\bar{O}}\ x\ 100$..Eqn. 3.24

Where:

Ō - Mean of observed values for the parameter

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Seasonal Weather Conditions of the Field during Crop Growing Seasons

4.1.1 Relative Humidity and Ambient Temperature of Experimental Site

The weather condition of the experimental site varied in time, days, and months during the two irrigated seasons. The daily mean relative humidity ranged from 9.7 – 87.3 % across the irrigated seasons of the experimental site. The month of March recorded the highest daily mean relative humidity of 86.9 % (Figure 4.1a) and 87.3 % (Figure 4.1b) during the first and second irrigated seasons respectively. Meanwhile, lowest daily mean relative humidity of 10 % was recorded in the month of February during the 2020/21 irrigated season, and 11 % in the month of January during the 2021/22 irrigated season. Despite the wide range in daily variations of mean relative humidity, the monthly mean relative humidity narrowed and gave a ranged from 20.9 - 54.2 % across irrigated seasons. Drier weather condition with mean relative humidity of 25.6 % and 25.9 % for December and February respectively was recorded in 2020/21 season (Figure 4.1a). This was different in the second irrigated season (2021/22) with December and January recording the driest months with monthly mean relative humidity 20.9 % and 21.8 % respectively (Figure 4.1b). The first irrigation season was drier than second season.

Also, daily ambient temperature of the site across the crop growing seasons ranged from 19.0 – 40.8 ºC (Figures 4.1a & 4.1b). The highest daily temperatures were recorded during the hours of 12-2:30pm within the season. However, monthly mean ambient temperature reduced and ranged from 28.3 – 32.1 ºC across the irrigated seasons. The results indicate that, March was the hottest month during the irrigated seasons recording highest daily and monthly mean ambient temperatures. During the first irrigated season (2020/21), the months of December and January were the coolest and recorded mean ambient temperatures below 30 ºC (Figure 4.1a) whereas in the 2021/22 irrigated season only January recorded temperature below 30 ºC (Figure 4.1b). The range of monthly mean temperature recorded during the experimental period of the two irrigated seasons were similar to the optimum range of 29 – 33 ºC for proper growth of tomato reported by Kumar (2012). Though tomato is tolerant to warm seasons, ambient temperatures above 43 °C produce intense heat that scorches leaves, cause flowers to abort and early fruit-sets to drop, whereas temperatures below 13 °C and greater than 35 °C reduces fruit setting and red coloration ratio (Sawant, 2018). The crop had majority of its growth cycle under conducive ambient temperature conditions just that during higher temperature days, the water demand of the crop increased more than the predicted, since higher ambient temperature eventually increased transpiration rate of plants. Shankara *et al*. (2005) stated that, tomato requires a relatively cool, dry climate for high yield and premium quality but can adapt to various climatic conditions. In addition, tomatoes are day-length neutral plants (Nuruddin, 2001). However, light intensity of 400 - 500 μmol.m^{-2}s^{-1} is optimal for growth and development. High light intensity may cause fruit cracking, sunscald, and green shoulders (Ha, 2015). Tomato plants reacted to temperature variation during the growth cycle at seedling growth, flower and fruit set and fruit quality. Fruit formation was influenced when cool or hot weather events persisted during the flowering stage.

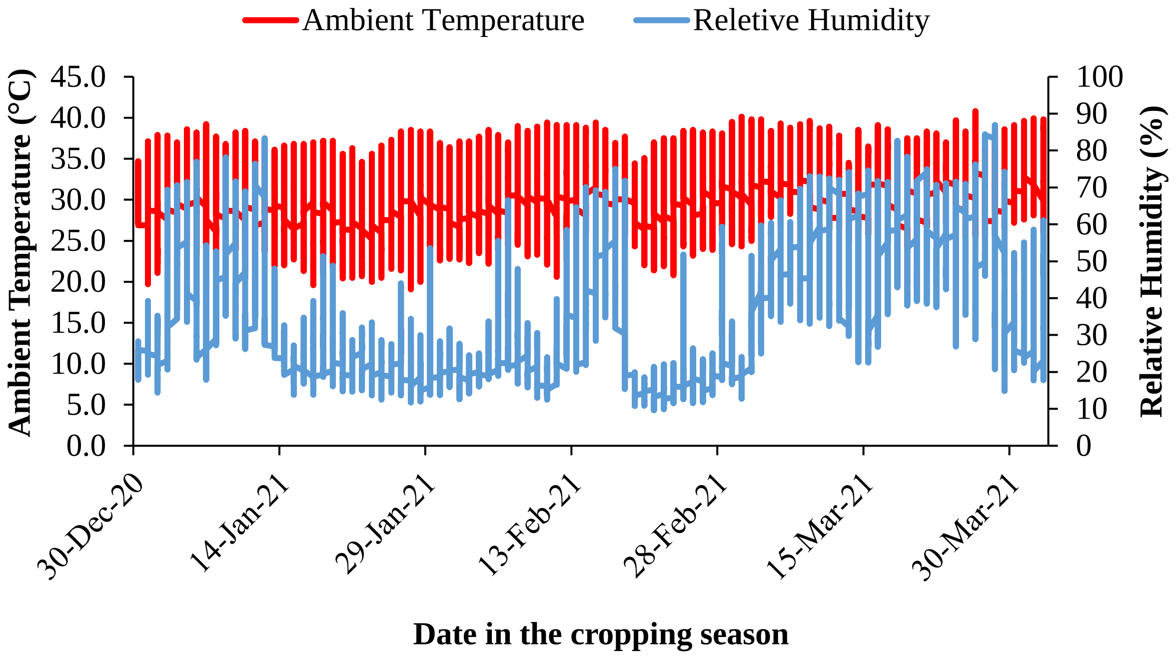

Figure 4.1a: Weather Condition of Ambient Temperature and Relative Humidity of the experiment field during the 2020/21 irrigated cropping season

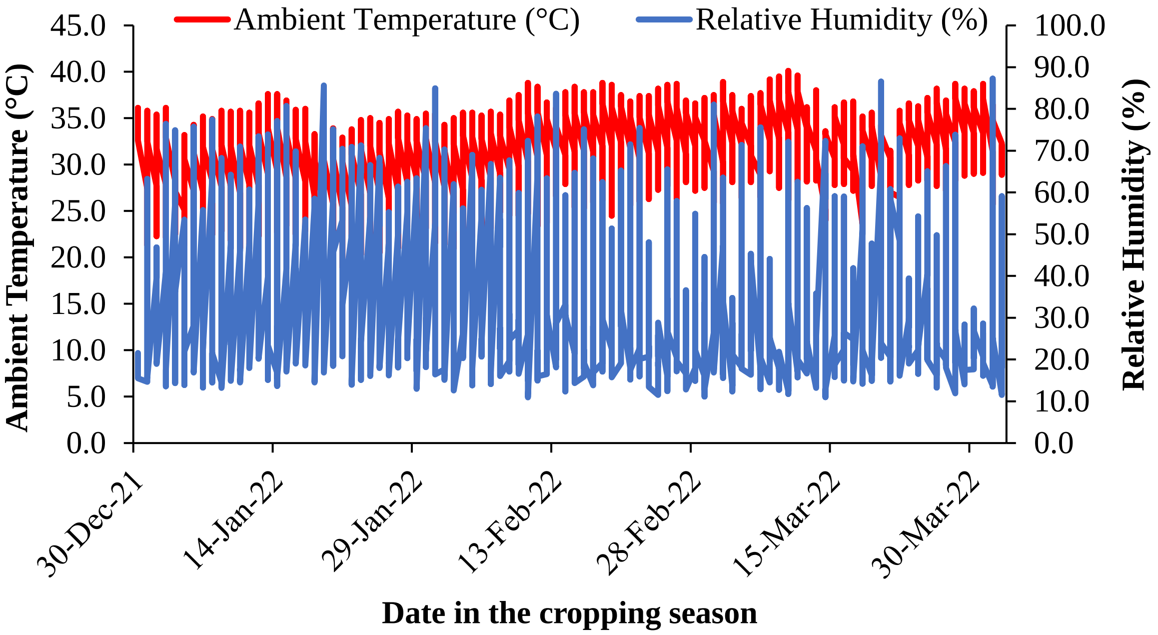

Figure 4.1b: Weather Condition of Ambient Temperature and Relative Humidity of the experiment field during the 2021/22 irrigated cropping season

4.1.2 Rainfall and Wind Speed of the Experimental Field

The experimental field did not receive rainfall during the first irrigated season (2020/21) and tomato plants depended solely on water applied through irrigation. However, rainfall amounted to 28.7 mm (Figure 4.2b) fell in the second irrigated season (2021/22) but did not have any influence on the growth and development of the crop, since the occurrence was during the maturity stage (mid to late march) of the crop; thus, fruit ripening.

The mean monthly wind speed was lowest in the first irrigated season (2020/21) with a mean of 1.67 km/h (Figure 4.2a) compared to the mean of 1.99 km/h (Figure 4.2b) recorded during the second irrigated season (2021/22). The maximum wind speed was recorded in the month of March with 5.24 km/h and 4.79 km/h during the 2020/21 and 2021/22 irrigated seasons respectively. The weather and climatic conditions of a location can largely influence growth and productivity of tomato (Ozores-hampton *et al.*, 2012; Puozaa, 2015; Arthanari and Dhanapalan, 2019; Vijayakumar *et al.*, 2021).

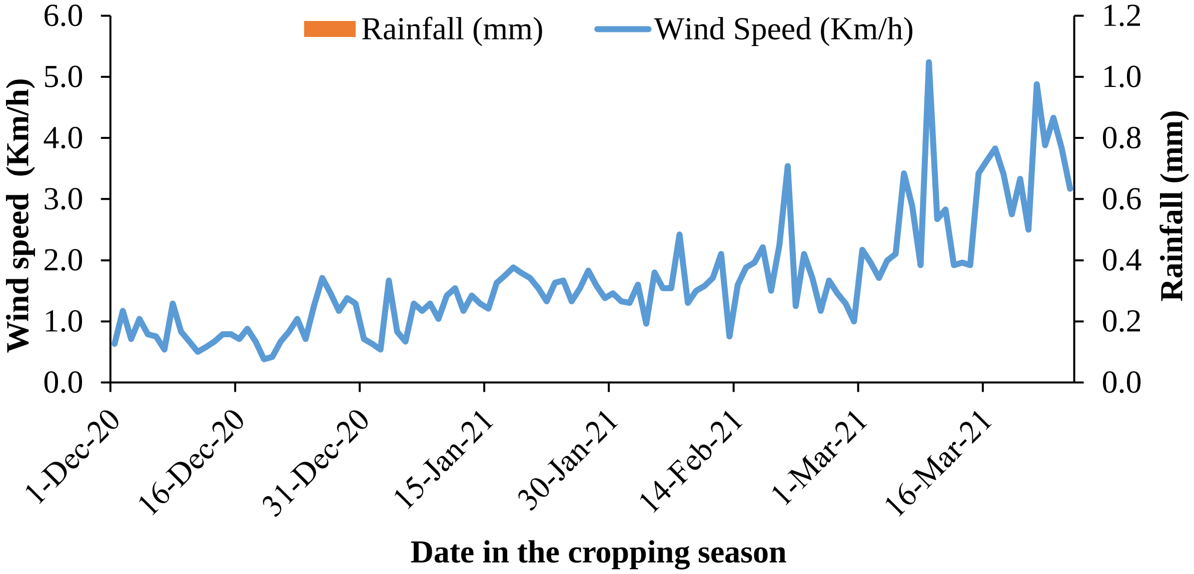

Figure 4.2a: **Weather Condition of Wind Speed and Rainfall of the experiment field during the 2020/21 irrigated cropping seasons**

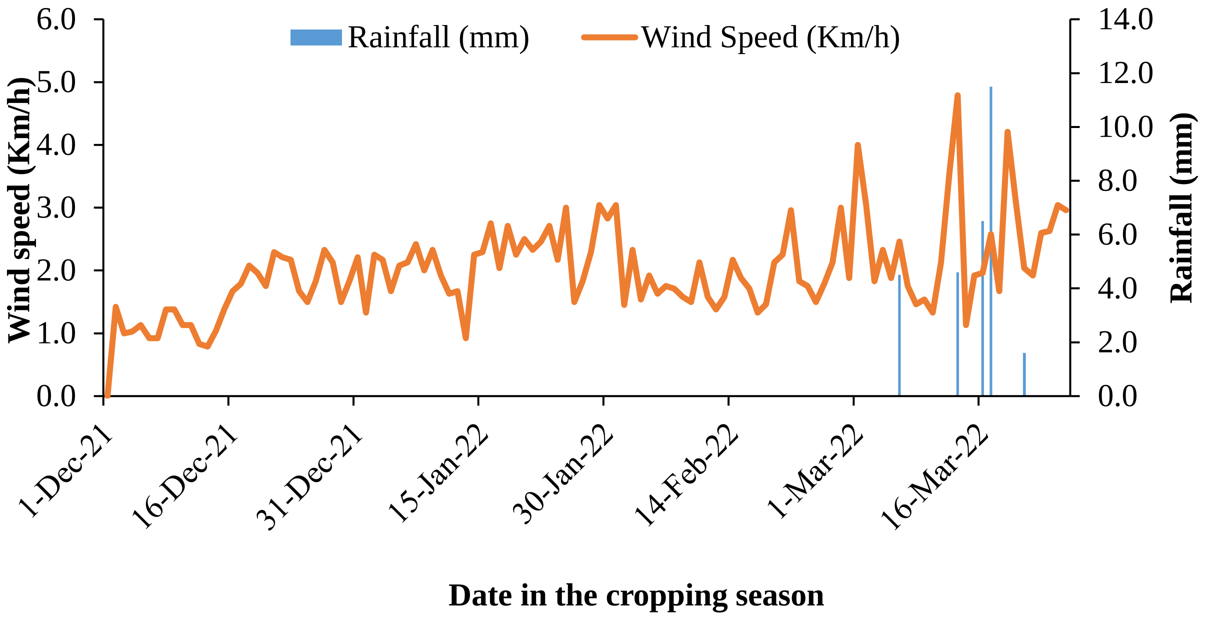

Figure 4.2b: Weather Condition of Wind Speed and Rainfall of the experiment field during the 2021/22 irrigated cropping seasons.

4.2 Soil Properties of the Experimental Field prior to Land Preparation

4.2.1 Hydraulic and Physical Soil Properties of the Field

Table 4.1 present results on soil properties at different soil depths prior to land preparation. The soil texture of the field is basically sandy loam (Table 4.1) which clearly characterises the Guinea Savanna Agroecology with low clay content. The soil within 0 - 60 cm depth recorded gravimetric bulk density that ranged from 1.48 to 1.69 g/cm^3: an indication of medium textured nature of the soil. The soil's bulk density (less than 1.80 g/cm^3) is good and ideal for the development and growth of tomato plant roots especially under irrigated conditions (USDA, 1987). This is evident in the permeable nature of the top layer with low bulk density attributed largely to the presence of high organic matter of 2.88 % (Table 4.1).

The volumetric water content at field capacity and permanent wilting point averaged 18.9 % and 8.5 % respectively given rise to total available water of 62.4 mm across the soil depths (Table 4.1). The values clearly fall within the desired range of 15 – 25 % for sandy soils as reported by Hillel (2004). In simple words, field capacity moisture content depicts the upper limit of total available water and the most desirable threshold when irrigating the soil. The application of irrigation water above the soil water holding capacity would result in high internal drainage and depletion of essential nutrients such as nitrate – nitrogen beyond the root zone of crops. On the other hand, permanent wilting point depicts the lower limit of total available water and most critical stage during irrigation; since plants would have to exert more energy to extract soil water which often leads to wilting of plants. It is therefore relevant to define a comfortable threshold of soil water depletion to trigger irrigations and avoiding soil water stress conditions by plants.

Table 4.1: The Pre-Cropping Season Physical and Hydraulic Soil Properties of the Field

Soil Properties	**Soil Layers (cm)**		
	0 – 20	**21 - 40**	**41 - 60**
Sand content (%)	70.12	60.24	59.35
Silt content (%)	21.2	29.24	30.02
Clay content (%)	8.68	10.52	10. 63
Soil texture	Sandy loam	Sandy loam	Sandy loam
Gravel percent by mass > 2mm (%)	30.10	39.30	41.20
Total Organic Matter (%)	2.90	1.44	1.21
Field Capacity (% v/v)	18.20	18.00	20.40
Permanent Wilting Point (% v/v)	9.10	6.90	9.60
Saturation (% v/v)	45.80	41.90	38.10
Available water (% v/v)	9.10	11.10	11.00
Bulk Density (g cm^{-3})	1.48	1.68	1.69
Porosity of Soil (%)	44.12	36.51	29.97
Saturated Hydraulic conductivity (cm/min)	0.081	0.044	0.041

Experiment, 2020/21, SARI Experimental Fields

4.2.2 Soil Chemical Properties of the Experimental Field

Table 4.2 summarises the chemical properties of soil essential for plant growth within the rootzone of the tomato crop. The fertility status of the experimental field's soil is generally poor and may not be able to support plant growth adequately without the application of fertilizer in either inorganic or organic form. This is evident in the low total nitrogen status of the soil (0.05 – 0.09 %) recorded across the soil depths prior to planting. The sandy loam soils of the agroecology are characterised by low levels of nitrogen due to the high runoff rates and deep percolation. Nitrogen is highly volatile and easily leached out of the rootzone in most light to medium textured soils such as the sandy loam soils of the experimental field (Kebede, 2019). The poor fertility status of the experimental soil is further confirmed by the low levels of organic carbon content of the soil (0.53 – 0.98 %) (Table 4.2). A decreasing trend in soil organic carbon was realized across the soil layers as in the case of total nitrogen content confirming slightly higher organic residue deposit in the topsoil than the lower soil depths. To overcome soil degradation, restoring soil organic carbon to levels within 1.1 - 1.5 % is recommended (Lal, 2015), since it is key in the determination of soil quality (Bunemann *et al*., 2018).

The soil's electrical conductivity ranged from 0.0070 - 0.013 dS/m (Table 4.2) and indicates non-saline soil condition (USDA, 1954; Motsara and Roy, 2008). However, the soils of the field was slightly acidic (Motsara and Roy, 2008) and pH ranged from 5.42 to 5.45 (Table 4.2). The pH values were close to the optimum range of 5.5 – 6.5 which is ideal to support plant growth (Motsara and Roy, 2008) but could affect the availability of essential nutrients such as Nitrogen, Potassium and Phosphorus in the soil. Acid soils usually contain low levels of Calcium as recorded in Table 4.2 (2.2 - 3.4 Cmol+/kg) and Magnesium (0.4 – 1.8 Cmol+/kg). The application of lime to the soil could improve the pH status. However, proper agronomic and irrigation practices was adopted in the study to improve the pH status of the soil since it was on the borderline recommended by Motsara and Roy (2008). The cation exchange capacity (CEC) of the soil was low and ranged from 4.93 – 5.80 Cmol+/kg (Table 4.2). The low soil CEC and activities on the field preceding the experiment probably resulted in the leaching of nitrogen and phosphorus out of the rootzone as reflected in the low values recorded. Phosphorus and Potassium content in the soil reduced drastically with soil depth (Table 4.2). There was the need for application of recommended rate of fertilizer to provide the essential soil nutrients needed for plant growth. However, long term benefits could be derived from the application of organic (both plant and animal base) manure to the soil.

Table 4.2: The Pre-Cropping Season Soil Chemical Properties of the Experimental Field

Soil Properties	**Units**	**Soil Layers (cm)**		
		0 - 20	21 - 40	41 - 60
Electrical conductivity (EC)	µS/cm	13.06	8.32	6.98
Acidity or alkalinity (pH)		5.45	5.42	5.42
Organic Carbon content (O.C)	%	0.98	0.74	0.53
Total Nitrogen content (N)	%	0.09	0.07	0.05
Exchangeable Phosphorus (P)	mg/kg	3.68	2.35	2.31
Exchangeable Potassium (K)	mg/kg	78.00	56.00	44.00
Calcium (Ca)	Cmol+/kg	3.40	2.40	2.20
Magnesium (Mg)	Cmol+/kg	0.40	1.80	1.60
Cation Exchange Capacity (CEC)	Cmol+/kg	5.80	5.64	4.93

Field Experiment, 2021, SARI Experimental Fields

4.3 Quality of Irrigation Water

The water for irrigation under this study was from the Wambong River located about 20 km from the research field. However, water was pumped into a 40 m^3 reservoir tank as night storage on the field to supply water periodically to plants via the drip irrigation system. The chemical quality of the water was required to ascertain its wholesomeness for irrigation purposes and presented in

Table 4.3. The pH of the water was normal with mean of 6.7 (Table 4.3). The total dissolved solid was low with an average value of 60.9 mg/kg. Electrical conductivity of the water was averaged 0.1 dS/m which is considered to be in the salinity class C1 reported by Zaman *et al*. (2018) and suitable for irrigation due to its low salinity hazard.

Table 4.3: Chemical Properties of the Irrigation Water

Chemical properties of irrigation water	2020/21 irrigated season	2021/22 irrigated season
Acidity or alkalinity (pH)	6.70	6.60
Electrical conductivity (EC) (µS/cm)	104.40	103.60
Salinity (µS/cm)	105.20	101.20
Total Dissolved Solids (TDS) (mg/kg)	63.30	58.40

Field Experiment, 2020/21 and 2021/22, SARI Experimental Field

4.4 Estimated Crop Water Requirements (ET$_c$) of Tomato for the Experimental Field

The daily water requirement of Tomato crop (Pectomech and Mongal F1) was predicted for the local climate and presented in Table 4.4. The crop was cultivated within the 3rd decade of November (21st) and 2nd decade of March (20th) for the two growing seasons (2020/21 and 2021/22) solely under drip irrigation. The daily water requirement of tomato peaked on the 3rd decade of February within the mid-season stage of the crop's development with a water demand of 56.90 mm/decade, thus 5.69 mm/d (Table 4.4). The predicted high water demand by the crop in the month of February is largely attributed to the historical high ambient temperatures and wind speed recorded over that period. This trend is largely seen in the weather conditions within the growing season and resulted in an increase in leaf temperature of tomato plants which drastically affected physiological processes in the plant system at certain growth stages (Parkash and Singh, 2020). The increase in transpiration rate as a requirement in regulating the temperature of plants (Cornic and Ghashghaie, 1991), certainly contributed to an increased water demand by plants. Also, the high canopy cover of tomato plants especially in the mid-season stage of growth significantly increased the water demand of plants due to the increase transpiration rate. However, the low canopy cover during the initial (transplanting) stage (2^{nd} decade in December) resulted in lowest water demand of 35.40 mm/decade thus 3.54 mm/d (Table 4.4) by plants due to the low transpiration rate. Physiological maturity and leaf senescence during late season stage of the crop development led to reduction of green canopy cover of plants. This resulted in a low transpiration rate due to reduced stomates, thus decline in water demand by plants (Table 4.4).

Table 4.4: Daily Water Requirement of Tomato Growing under the Local Climatic Conditions of the Guinea Savanna Agroecological Zone of Ghana

Month	Dec.	Date	Stage	K_c	ET_o (mm/d)	ETc (mm/d)	100 % ET_c (mm/dec)	75 % ET_c (mm/dec.)	50 % ET_c (mm/dec.)
Nov.	3	21st - 30th	Initial	0.90	4.43	3.86	37.60	28.20	18.80
Dec.	1	1st - 10th	Initial	0.90	4.03	3.74	36.50	27.30	18.20
Dec.	2	11th - 20th	Initial	0.90	4.03	3.63	35.40	26.50	17.70
Dec.	3	21st - 30th	Dev’t	0.94	4.03	3.91	38.10	28.60	19.10
Jan.	1	1st - 10th	Dev’t	1.00	4.46	4.33	42.20	31.70	21.10
Jan.	2	11th - 20th	Dev’t	1.06	4.46	4.75	46.30	34.70	23.10
Jan.	3	21st - 30th	Mid-	1.11	4.46	5.23	51.00	38.20	25.50
Feb.	1	1st - 10th	Mid-	1.12	5.16	5.50	53.60	40.20	26.80
Feb.	2	11th - 20th	Mid-	1.12	5.16	5.76	56.10	42.10	28.10
Feb.	3	21st - 28th	Mid-	1.12	5.16	5.84	56.90	42.70	28.50
Mar.	1	1st - 10th	Late	1.01	5.36	5.37	52.30	39.30	26.20
Mar.	2	11th - 20th	Late	0.83	5.36	4.43	43.20	32.40	21.60
TOTAL							549.20	411.90	274.70

Where, ETc - crop water requirement, dec. - decade (period of 10 days), Dev’t. - Crop development stage, Mid- - mid-season stage, Jan. - month of January, Feb. - February, Mar. - March, Dec. - December, Kc - crop coefficient derived from FAO tables for vegetables and adjusted to meet location field and climatic conditions

4.5 Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interactions on Soil Properties of the Experimental Field

4.5.1 Volumetric Soil Water Content (VWC) during the first (2020/21) irrigated season

4.5.1.1 Effect of Variety and Irrigation Regimes on Volumetric Water Content of the soils

Figures 4.3 - 4.5 present results on the daily soil water content before irrigations as affected by the irrigation regime treatments (100 %, 75 % and 50 % ET_c) and variety of tomatoes (Mongal F1 and Pectomech) during the first (2020/21) irrigated season. This was monitored starting from 3 weeks after transplanting and presented in volumetric basis. As shown in figures 4.3 – 4.5, Mongal F1 and Pectomech varieties had similar effect on daily volumetric soil water content considering the similarity in the trend shown on the graph over the season. The canopy cover of varieties as reflected in the leaf area index (LAI) resulted in uniform ground cover and reduction of evaporation losses of water.

Generally, soil water status was optimum on daily basis for the 100 % ET_c irrigated regime influenced by tomato variety (Pectomech and Mongal F1) as shown in Figure 4.3 than the soil moisture content profiled for the 75 % and 50 % ET_c deficit irrigation regimes (Figures 4.4 & 4.5). However, daily volumetric soil water variation was evident within the growing season considering the non-linearity of the line graphs in Figures 4.3 - 4.5. This was influenced by the varied consumptive pattern of water by plants over the season, which peaked in February and lowest in December. The lower water demand by plants in the late development and early mid-season stages resulted in adequate soil water condition within 30 % manageable allowed depletion of the field capacity value of 18.9 % (Figure 4.3). Also, the high ambient temperature and wind speed recorded over the season influenced the water demand of plants and led to the varied soil water condition.

Generally, tomato plants under 75 % and 50 % ET_c deficit irrigation experienced varying soil water stress levels ranging from mild (13 % v/v) (Figure 4.4) to severe of 2.61 % v/v (Figure 4.5). The severe soil water stress condition could pose detrimental effect on the growth and yield of most crops (Gulen *et al*., 2004). It causes the closure of leaf stomata of plants and limit transpiration and eventually reduces photosynthesis in plants (Parkash and Singh, 2020). However, moderate soil water stress condition has the tendency of increasing water-use efficiency of plants (Liu *et al*., 2005; Pazzagli *et al*., 2016).

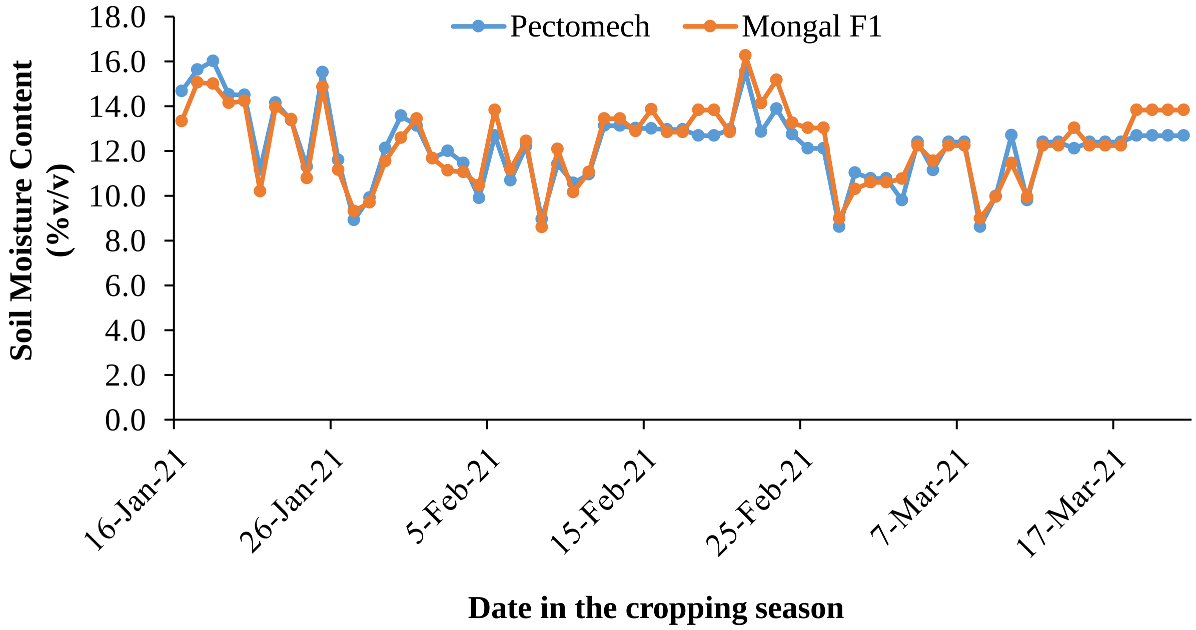

Figure 4.3: Soil Water Content before irrigations as affected by 100 % ET_c Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

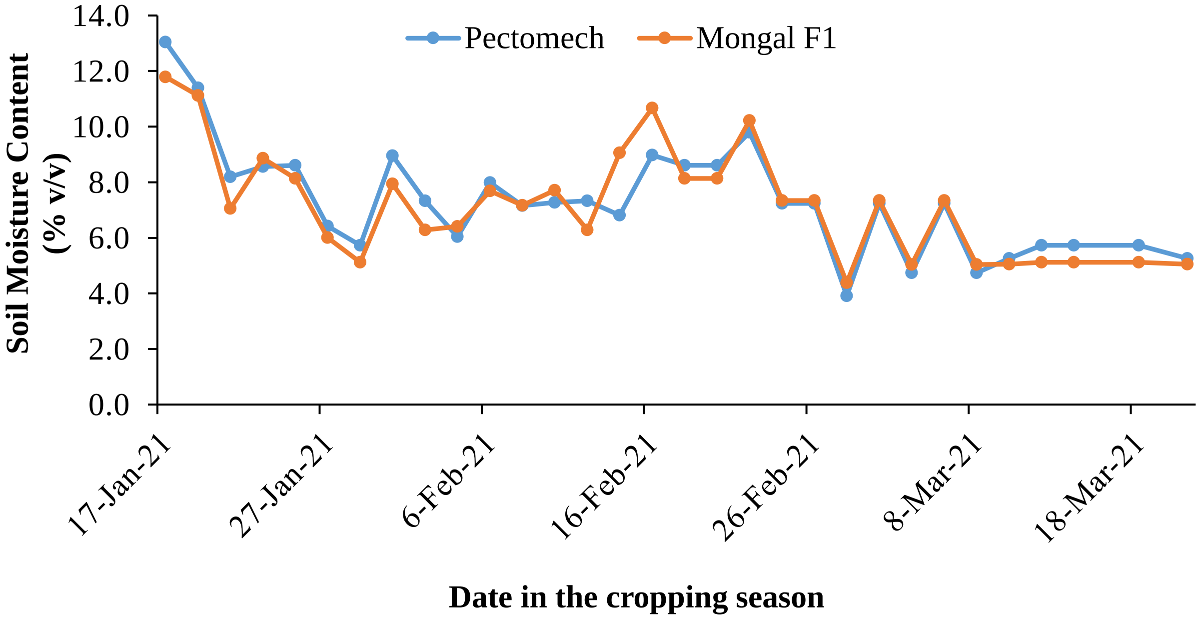

Figure 4.4: Soil Water Content before irrigations as affected by 75 % ET$_c$ Deficit Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

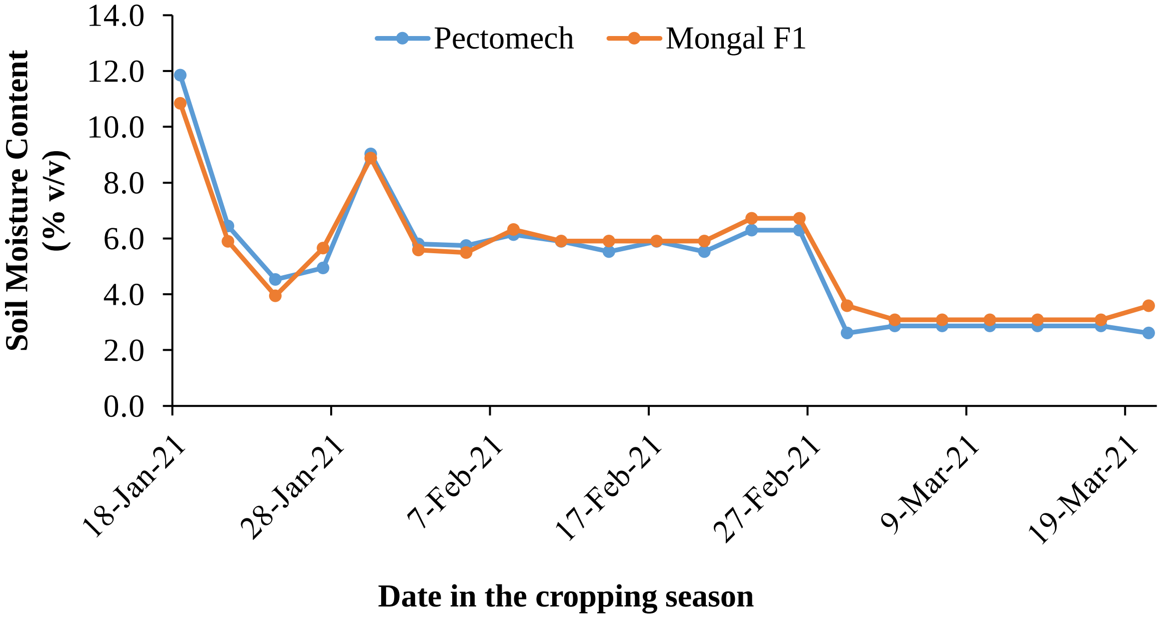

Figure 4.5: Soil Water Content before irrigations as affected by 50 % ET$_c$ Deficit Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

4.5.1.2 Effect of Irrigation Regimes and Quantity of Rice Straw Mulch on Volumetric Water Content of Soils

Figures 4.6 – 4.8 shows result on the daily volumetric soil water content before irrigations as influenced by the interaction effect of irrigation regimes (100 %, 75 % and 50 % ET_c) and the quantity of rice straw mulch (6 t/ha, 3t/ha and 0 t/ha) in the 2020/21 irrigated cropping season. For each of the deficit irrigation regime applied, soil water depletion patterns corresponding to the quantity of rice straw mulch were similar (Figures 4.6 – 4.8) and non-linear in nature. However, the volumes of water retained in the soil on daily basis varied significantly throughout the growing season for each treatment combination. The interaction effect of full irrigation (100 % ET_c) irrigation regime and rice straw mulch applied at 6 t/ha (Figure 4.6) accumulated highest daily soil water content, followed by the 3 t/ha in comparison with no mulch (0 t/ha) control. Also, similar gain in daily soil water content was observed for the mild deficit irrigation of 75 % ET_c (Figures 4.7) and severe deficit irrigation of 50 % ET_c (Figures 4.7) when rice straw mulch was applied. The proper use of crop residue as mulch helps to conserve soil water and maximise irrigation water and nutrient use (Hochmuth *et al.*, 2001; Kirnak *et al.*, 2001). Also, the addition of rice straw mulch improves soil infiltration rate; thereby increasing the volumetric water content of soils (Agyenim-Boateng and Dennis, 2001), as well as increase tomato fruit yield (Pandey *et al.*, 2015). It is worthy of mentioning that, covering the soil surface using organic mulch such as rice straw, green leaves, and coconut fronds at 10 to 20 t/ha significantly decreased soil temperature to 27.5 ^{o} C two weeks after transplanting (Ertek *et al.*, 2004).

Mulch materials especially organic, impact microclimate near the plant, and affects crop performance (Kader *et al.*, 2017). The choice of organic mulch material is relevant to maintain the adequate soil water conditions needed for effective plant growth. The comparison of soil water status under the irrigation regimes reveals the accumulation of more soil water in the rootzone soil of the 100 % ET_c ranging from 7.79 - 16.5 % v/v (Figure 4.6); followed by the 75 % ET_c ranging from 4.18 - 13.39 % v/v (Figure 4.7) and lastly by the severely stressed deficit irrigation regime of 50 % ET_c that ranged from 2.48 - 12.68 % v/v (Figure 4.8). Also, the application of no mulch treatment accumulated lowest soil water in the rootzone within the season when compared to the applied rice straw mulch. This is due to the high temperature and evaporation rates of the exposed soil surface under the no-mulch plots (Pandey *et al*., 2015).

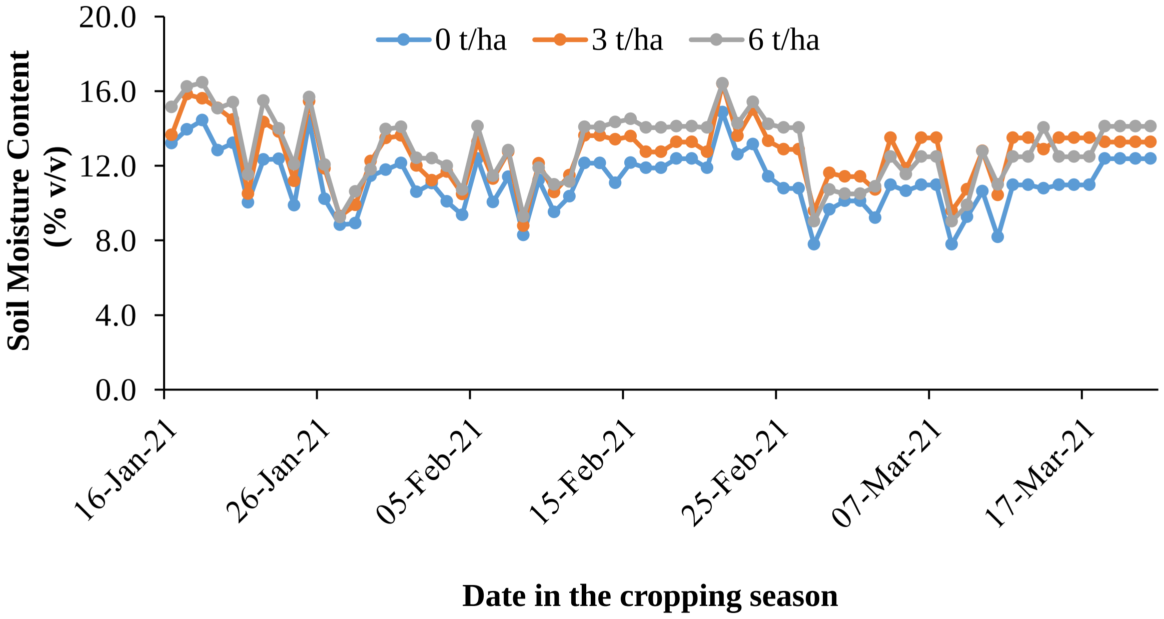

Figure 4.6: Soil Water Content before irrigations as affected by 100 % ET_c Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

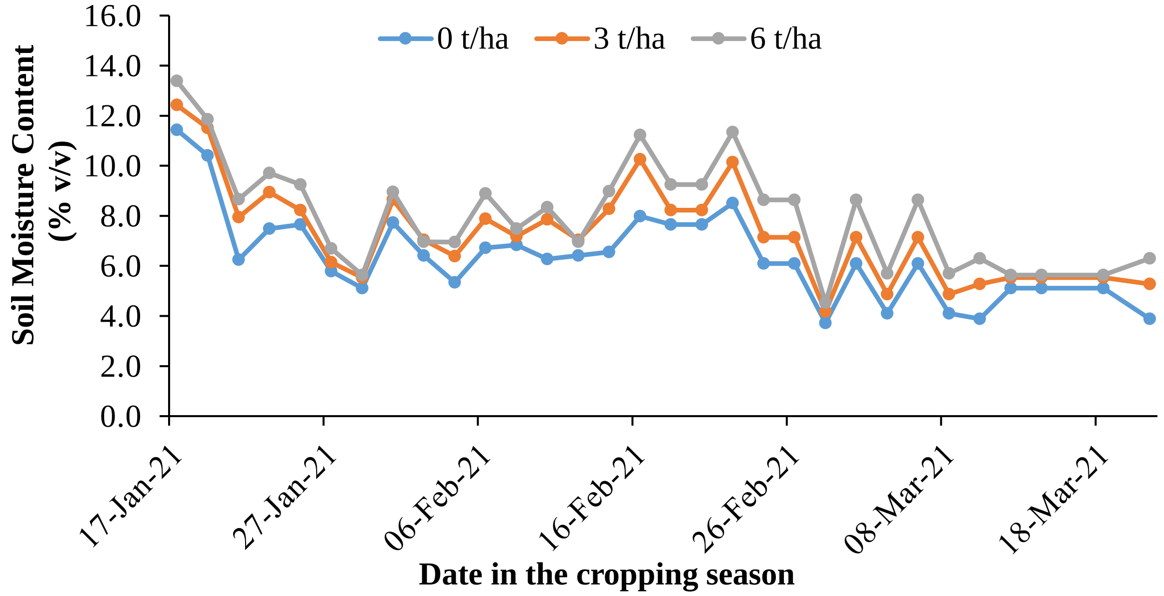

Figure 4.7: Soil Water Content before irrigations as affected by 75 % ET$_c$ Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

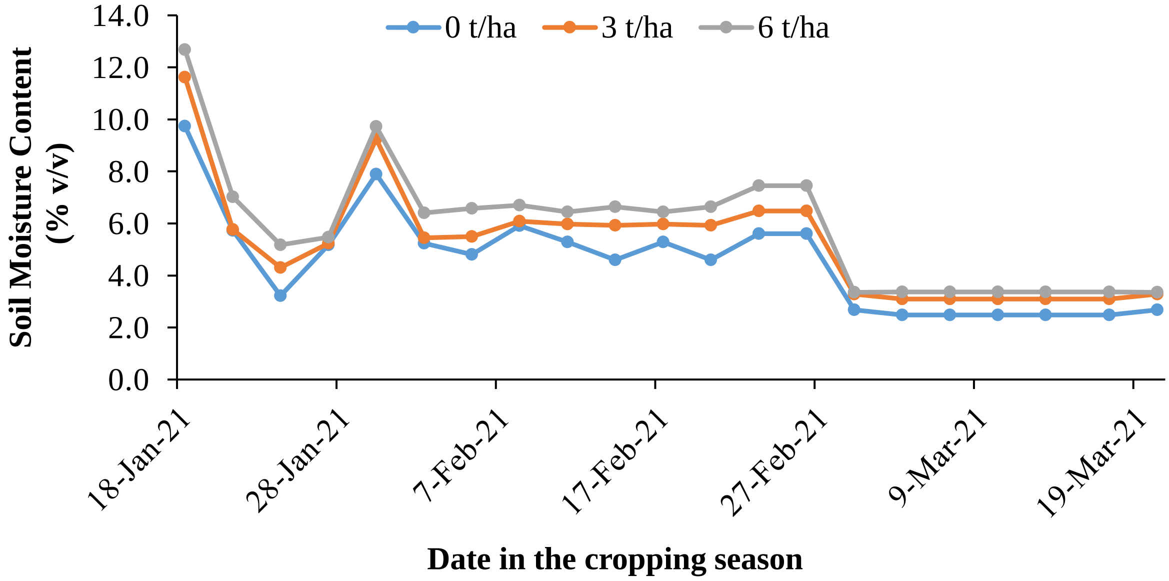

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Figure 4.8: Soil Water Content before irrigations as affected by 50 % ET$_c$ Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

4.5.2 Volumetric Soil Water Content (VWC) during the second (2021/22) irrigated season

4.5.2.1 Effect of Variety and Irrigation Regimes on Volumetric Water Content of Soils

Figures 4.9 - 4.11 present results on the daily volumetric rootzone soil water content before irrigations as influenced by the interaction effect of irrigation regimes (100 %, 75 % and 50 % ET_c) and variety (Mongal F1 and Pectomech) in the second irrigated season (2021/22). The Mongal F1 and Pectomech tomato varieties under the various irrigation regimes influenced soil water retention similarly as that reported for the first irrigated season in Figures 4.3 – 4.5. Similarly, the 100 % ET_c provided optimum soil water conditions (11 – 18 % v/v) needed to support growth of tomatoes (Figure 4.9). However, irrigating above field capacity will saturate the soil and increase the leaching of essential soil nutrients from the rootzone soil (Popova *et al.*, 2005). Also, soil saturation leads to poor crop performance (Tsige *et al.*, 2016). There is always the need to maintain soil water conditions within the region of field capacity of the soil for efficient use of water (Zheng *et al.*, 2015), thereby reducing the risk of nitrate leaching beyond the crop's root zone (Popova *et al.*, 2005). The application of irrigation water using the drip irrigation system improved irrigation uniformity and the efficiency of water use and performance of crops (Locascio, 2005; Michael, 2008). Despite the high water distribution uniformity and water-use efficiency of the drip irrigation system, the attainment of soil water at field capacity during irrigation is complex due to the different soil behavior and the constantly changing evaporative demand of the atmosphere as experienced during the seasons. The high daily ambient temperature, high wind speed and low humidity conditions of the study area certainly resulted in variations in evaporative demand of the atmosphere. This increased the crop's daily consumptive water-use as well as variations in soil water content.

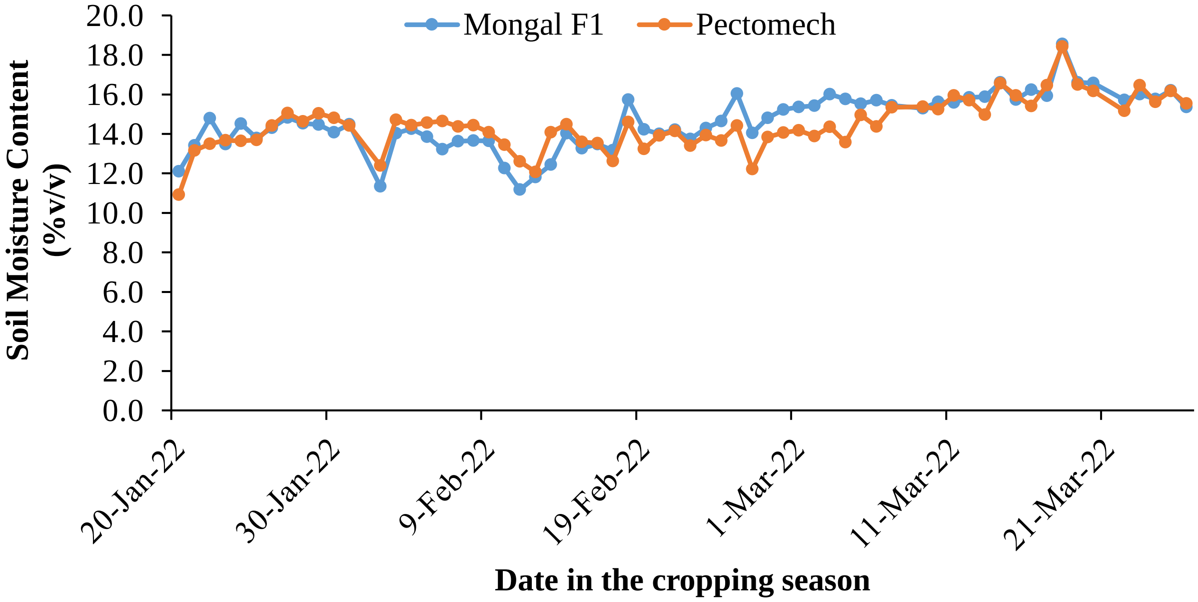

Figure 4.9: Soil Water Content before irrigations as affected by 100 % ET_c Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

The soil water stress conditions shown in figures 4.10 and 4.11 for the interaction effect of deficit irrigation regimes and varieties in the 2021/22 irrigated cropping season, had an influence on the volumetric soil water content accumulated due to the less irrigation water applied. Under mild deficit irrigation regime (75 % ET_c), the recorded volumetric soil water content during the entire growth stages of the Mongal F1 and Pectomech tomato varieties ranged from 9.4 – 13.22 % v/v (Figure 4.10); slightly lower than the soil water content profiled under the full irrigation regime (100 % ET_c). Also, soil water content ranged from 6.34 – 10.12 % v/v (Figure 4.11) under the severely stressed deficit irrigation regime (50 % ET_c) depicting inadequate soil water content that could have detrimental effect on the crop compared to soil water conditions of 100 % and 75 % ET_c irrigation regimes. The volumetric soil water content within threshold of permanent wilting point (8.5 % v/v) would pose severe soil water stress conditions which would certainly affect the growth and yield of tomato crop (Gulen *et al*., 2004).

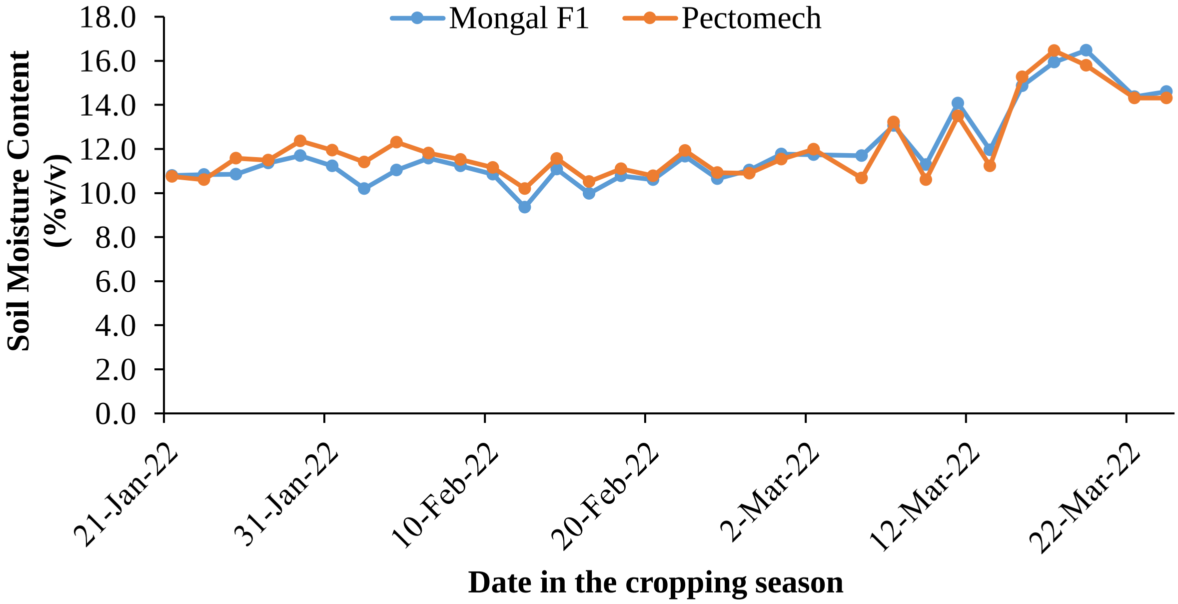

Figure 4.10: Soil Water Content before irrigations as affected by 75 % ET$_c$ Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

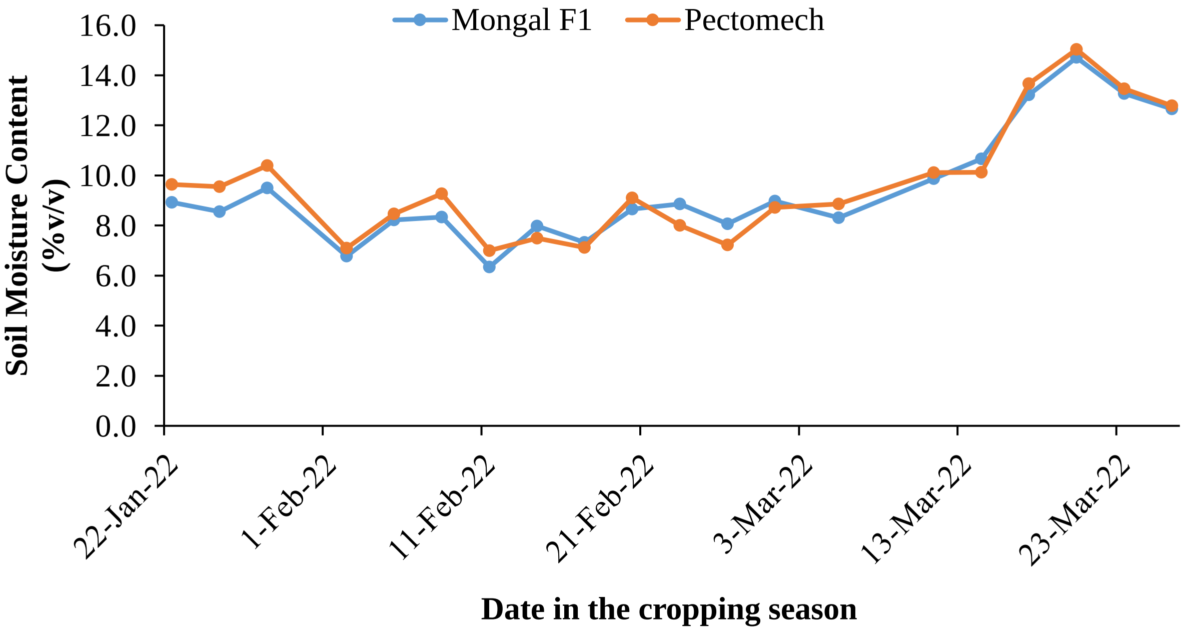

Figure 4.11: Soil Water Content before irrigations as affected by 50 % ET$_c$ Irrigation Regime and Tomato Varieties in the 2020/21 irrigated cropping season. †Data is pooled for mulching treatments

4.5.2.2 Effect of Deficit Irrigation Regimes and Quantity of Rice Straw Mulch on Volumetric Water Content of Soil

The figures 4.12 – 4.14 also show results on volumetric soil water content before irrigations in plots as influenced by irrigation regimes and quantity of rice straw mulch applied during the second (2021/22) irrigated cropping season. The seasonal soil water retention pattern is like that of the previous season and non-linear in nature. However, the daily volumes of soil water retained in treatment plots varied and ranged from 10.7 – 18.8 % v/v for rice straw mulch combined with 100 % ET_c (Figure 4.12). Interestingly, the 100 % ET_c in combination with 3 t/ha rice straw mulch gave highest pattern of soil water content before irrigations until 1st March 2022, given in to the 6 t/ha rice straw mulch (Figure 4.12). The plant canopy cover probably contributed to protecting the ground surface and reducing evaporative losses. Adequate ground cover protection enhanced using rice straw mulch has the tendency to conserve soil water and making it readily available in the rootzone for plant-use (Hochmuth *et al.*, 2001; Kirnak *et al.*, 2001). However, no application of rice straw mulch (0 t/ha) consistently gave lowest pattern of soil water content prior to irrigations due to high exposure of the soil to harsh weather conditions such as high temperatures and wind speed of the area. The climate of an area influences the choice of materials used as mulch as well as the cost-benefit ratio and common crops grown (Wang *et al.*, 2016). This emphasizes on the need to adopt rice straw in the vegetable industry of the Guinea savanna Agroecologies due to its high availability to help improve the soil environment for better crop performance.

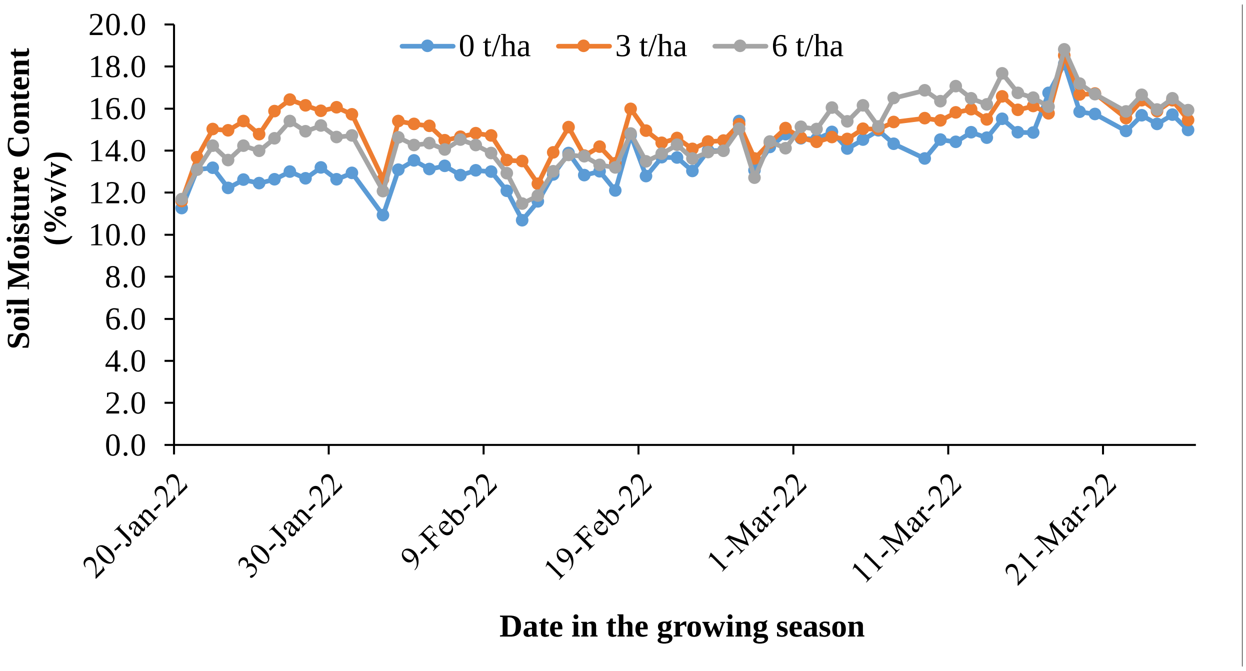

Figure 4.12: Soil water content before irrigations as affected by 100 % ET$_c$ irrigation regime and quantity of rice straw mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

Figure 4.13 also shows results of soil water condition under the various quantity of rice straw mulch receiving 75 % ET$_c$ deficit irrigation regime in the 2021/22 irrigated cropping season. Each level of applied quantity of rice straw produced a similar seasonal soil water retention pattern, however, the volumes of soil water depleted prior to irrigations varied significantly. Soil water content contributed by the combination of 75 % ET$_c$ and levels of rice straw mulch ranged from 8.6 – 16.6 % v/v (Figure 4.13). The combination of 75 % ET$_c$ and rice straw applied at 6 t/ha obtained the highest pattern of soil water content over the entire growing season. Meanwhile, a clear trend for soil water content obtained by the 3 t/ha and 0 t/ha rice straw mulch was not observed (Figure 4.13) though the no-mulch treatment produced averagely lower soil water content. This corroborates the findings of Kirnak *et al.* (2001) that, organic mulching can improve the performance of strawberry under deficit irrigation in arid field conditions.

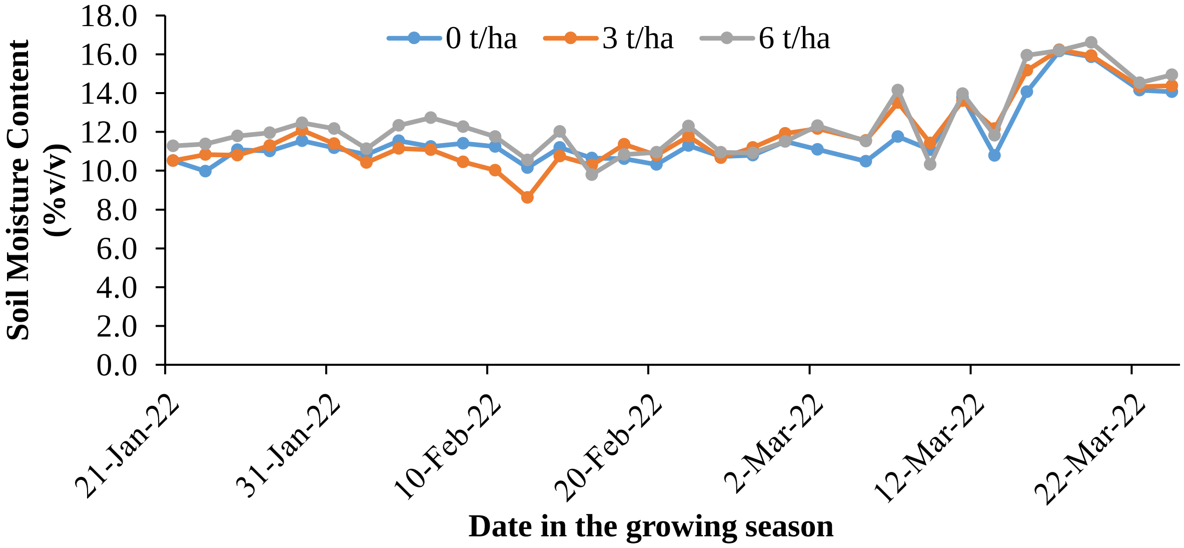

Figure 4.13: Soil Water Content before irrigations as affected by 75 % ET$_c$ Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

Also, figure 4.14 shows result on volumetric soil water content for the severely stressed deficit irrigation regime of 50 % ET$_c$ in combination with the levels of rice straw mulch in the 2021/22 irrigated cropping season. This irrigation regime recorded the lowest pattern of soil water content before irrigations over the growing season compared to the 100 % and 75 % ET$_c$ due to the prolonged water stress resulting from the three days irrigation interval. Soil water content of plots attributed to the combination of 50 % ET$_c$ and levels rice straw mulch ranged from 5.7 – 15.0 % v/v within the irrigated cropping season (Figure 4.14). The application of 6 t/ha rice straw is promising even under the severely stressed deficit irrigation: given the highest profile of soil water. Averagely, the application of 3 t/ha rice straw contributed more to soil water availability compared to the no-mulch (Figure 4.14). The soil water stress condition created by the lowest irrigation regime of 50 % ET$_c$ can be detrimental to plants that are sensitive to water stresses.

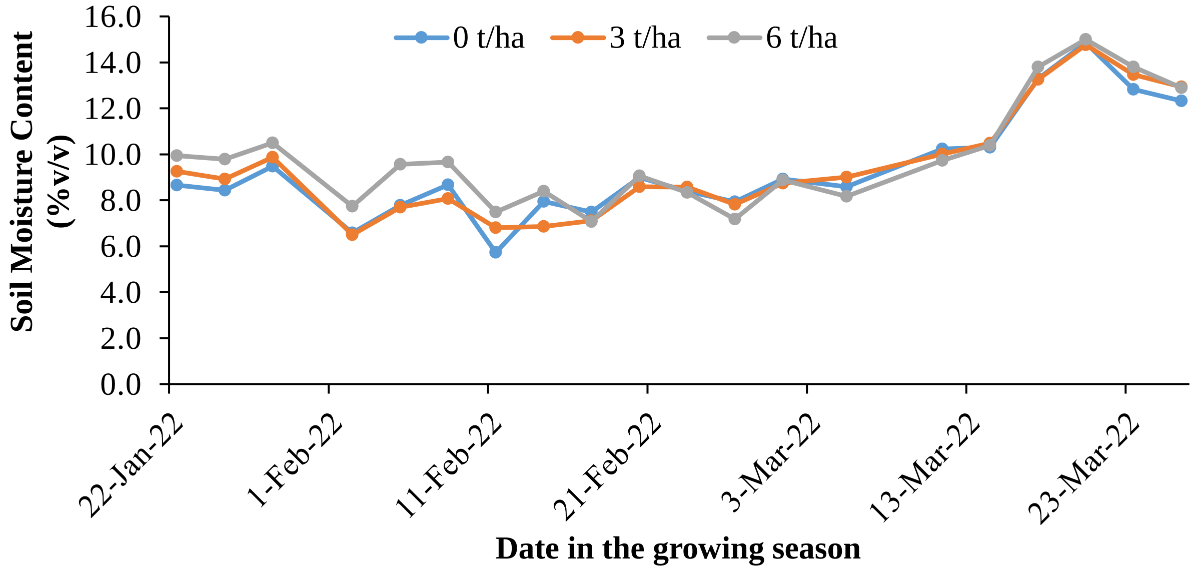

Figure 4.14: Soil Water Content before irrigations as affected by 50 % ET$_c$ Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

4.5.3 Treatment and their Interaction Effect on Soil Surface Temperature of the experimental field during the two irrigated cropping seasons

4.5.3.1 Effect of Irrigation Regimes and Quantity of Rice Straw Mulch on Soil Surface Temperature during the first (2020/21) irrigated cropping season

Figures 4.15 – 4.17 show results of soil surface temperature as influenced by the interaction effect of irrigation regimes and rice straw mulch thus, 6 t/ha, 3 t/ha and no-mulch (control) in the 2020/21 irrigated cropping season. Generally, the soil surface temperature was improved by the application of rice straw mulch under the various irrigation regimes. The application of 6 t/ha rice straw mulch to deficit irrigation regimes resulted in drastic reduction of soil surface temperature, followed by the 3 t/ha (Figures 4.15 - 4.17). Specifically, the no-mulch in combination with full irrigation (100 % ET$_c$) recorded highest soil surface temperature that ranged from 48.3 – 60.5 °C. The lowest soil surface temperature was recorded by the incorporation of 6 t/ha rice straw mulch and ranged from

34.6 – 48.8 °C (Figure 4.15). Ertek *et al.* (2004) reported on the significant reduction in soil temperature to 27.5 ⁰ C under organic mulch materials such as rice straw applied at 10 to 20 t/ha.

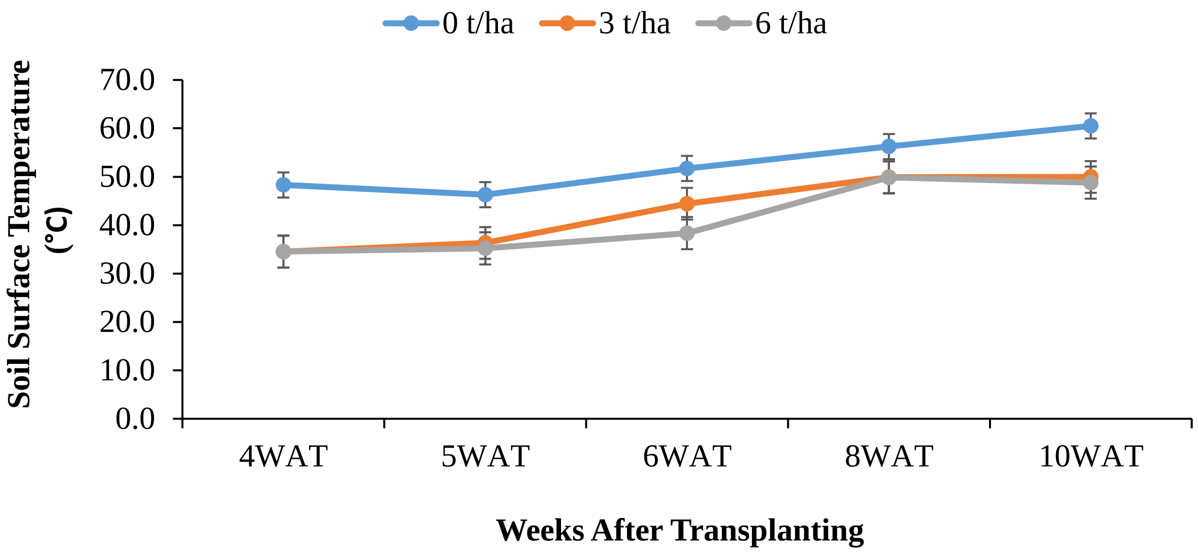

Figure 4.15: Soil Surface Temperature before irrigations as affected by 100 % ET_c Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

Also, the no-mulch treatment under the 75 % ET_c deficit irrigation regime recorded soil surface temperature range of 46.14 – 62.74 ⁰ C representing the highest. However, the lowest range of 34.08 – 50.14 ⁰ C was obtained by the 6 t/ha rice straw mulch (Figure 4.16). Further, under the severely stressed irrigation regime (50 % ET_c), the no-mulch treatment gave highest soil surface temperature that ranged from 46.19 – 62.90 ⁰ C. The 6 t/ha rice straw mulch improved soil surface temperature under the 50 % ET_c irrigation regime and kept it in a range of 32.20 – 56.04 ⁰ C (Figure 4.17). Organic mulch regulates soil temperature and increases tomato fruit yield (Pandey *et al.*, 2015). The potential of crop residue in reducing soil temperature is confirmed by findings of Ertek *et al.* (2004), that mulching of tomato plants using organic mulch at 10 to 20 t/ha significantly decreased soil temperature to 27.5 ⁰ C two weeks after transplanting. The lower rate used in this study varied significantly with the rate evaluated by Ertek *et al.* (2004). Also, irrigation water applied in high volumes improved and reduced soil surface temperature. The application of full irrigation (100 % ET$_c$) reduced soil surface temperature than the application of 50 % ET$_c$ deficit irrigation (Figures 4.15 & 4.17). The 75 % ET$_c$ deficit irrigation also gave lower soil surface temperature compared to the heavily stressed irrigation regime of 50 % ET$_c$ (Figures 4.16 & 4.17). The activities of microorganisms in the soil rootzone of un-mulched and severely stressed plots was affected and resulted in poor infiltration of water into soils (Agyenim-Boateng and Dennis, 2001).

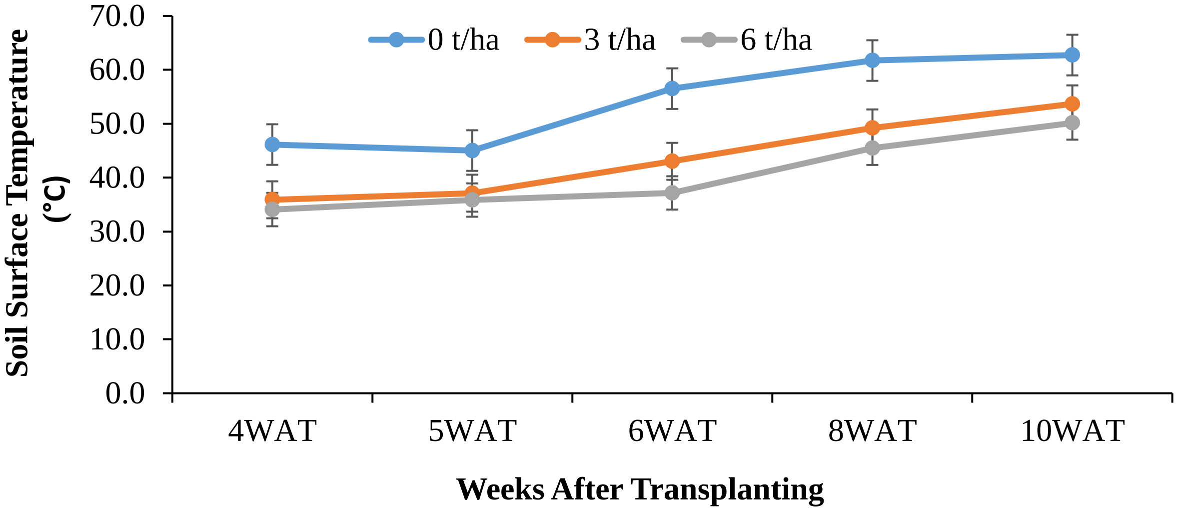

Figure 4.16: Soil Surface Temperature before irrigations as affected by 75 % ET$_c$ Deficit Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

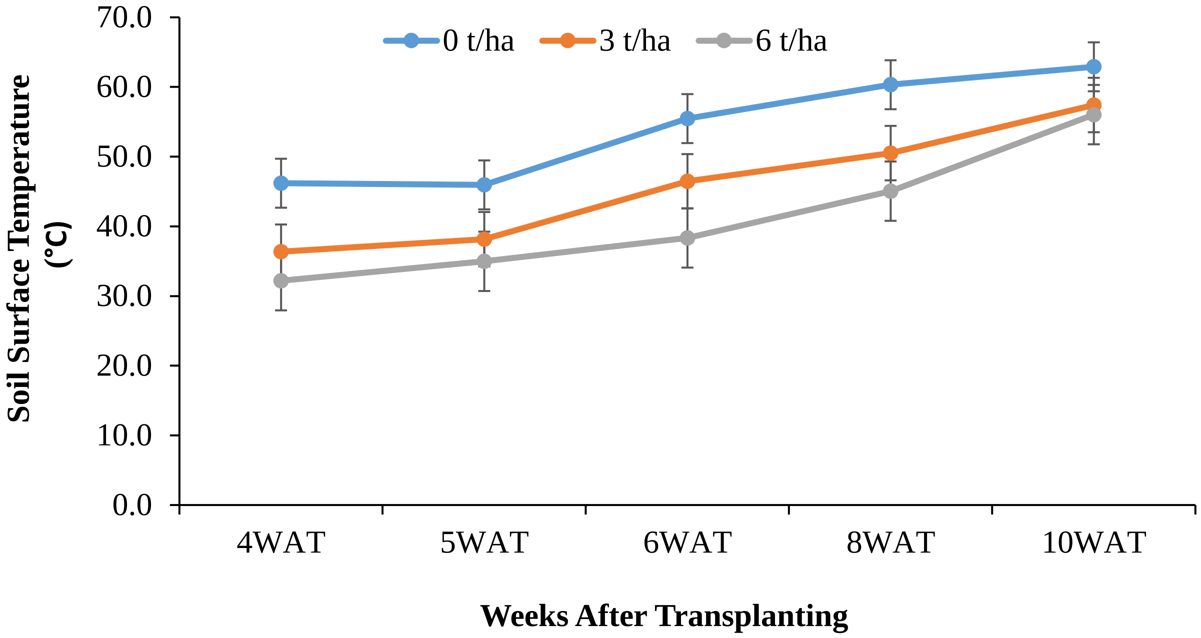

Figure 4.17: Soil Surface Temperature before irrigations as affected by 50 % ET$_c$ Deficit Irrigation Regime and Quantity of Rice Straw Mulch in the 2020/21 irrigated cropping season. †Data is pooled for variety treatments

4.5.3.2 Effect of Irrigation Regimes and Quantity of Rice Straw Mulch on Soil Surface Temperature during the second (2021/22) irrigated cropping season

The figures 4.18 – 4.20 present results on soil surface temperature for the combination treatments of levels of irrigation regimes and levels of quantity of rice straw mulch during the second irrigated cropping season. The combination of full irrigation (100% ET$_c$) and 6 t/ha rice straw recorded lowest soil surface temperature and ranged from 33.95 – 42.27 °C (Figure 4.18). The trend aligns with that observed during the first irrigated season.

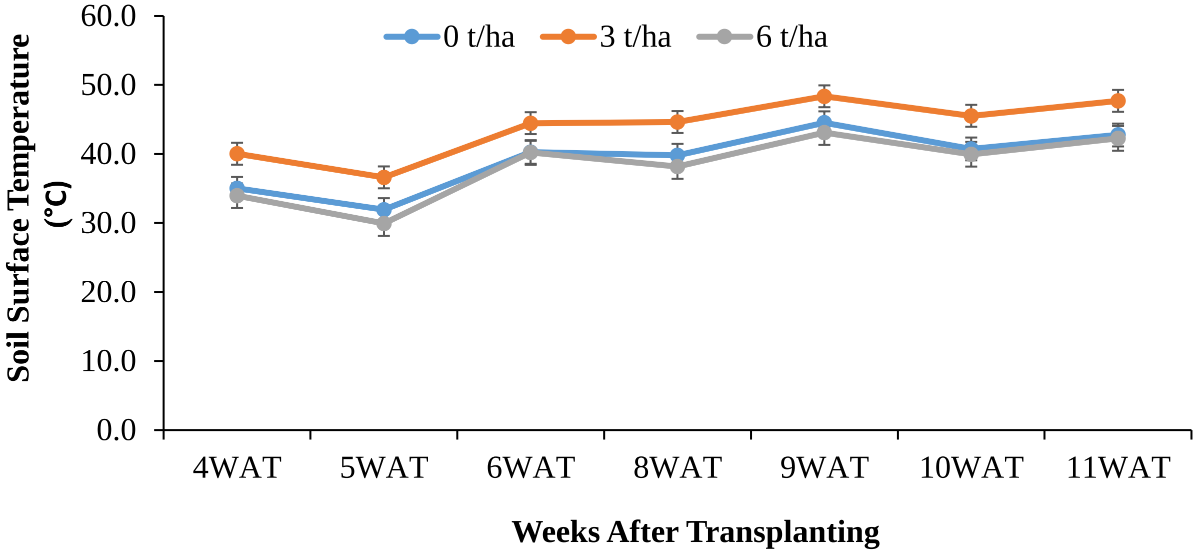

Figure 4.18: Soil Surface Temperature before irrigations as affected by 100 % ET_c Irrigation Regime and Quantity of Rice Straw Mulch in the 2021/22 irrigated cropping season. †Data is pooled for variety treatments

Also, the no-mulch treatment consistently gave highest soil surface temperature under the deficit irrigation regimes (75 % and 50 % ET_c) while the 6 t/ha gave the lowest (Figures 4.19 and 4.20). The no-mulch soil surface temperature fell in the range of 45.22 – 50.42 º C when combined with 75 % ET_c and 74.78 – 53.05 º C for the 50 % ET_c (Figures 4.19 and 4.20). Meanwhile, the soil surface temperature for the combination of 6 /ha rice straw mulch and 75 % ET_c ranged from 36.02 - 42.27 º C (Figure 4.19) and that of 6 /ha rice straw mulch and 50 % ET_c ranged from 36.37 - 43.33 º C (Figure 4.20). Again, the trend aligns with the soil surface temperature measurements of the first irrigated season.

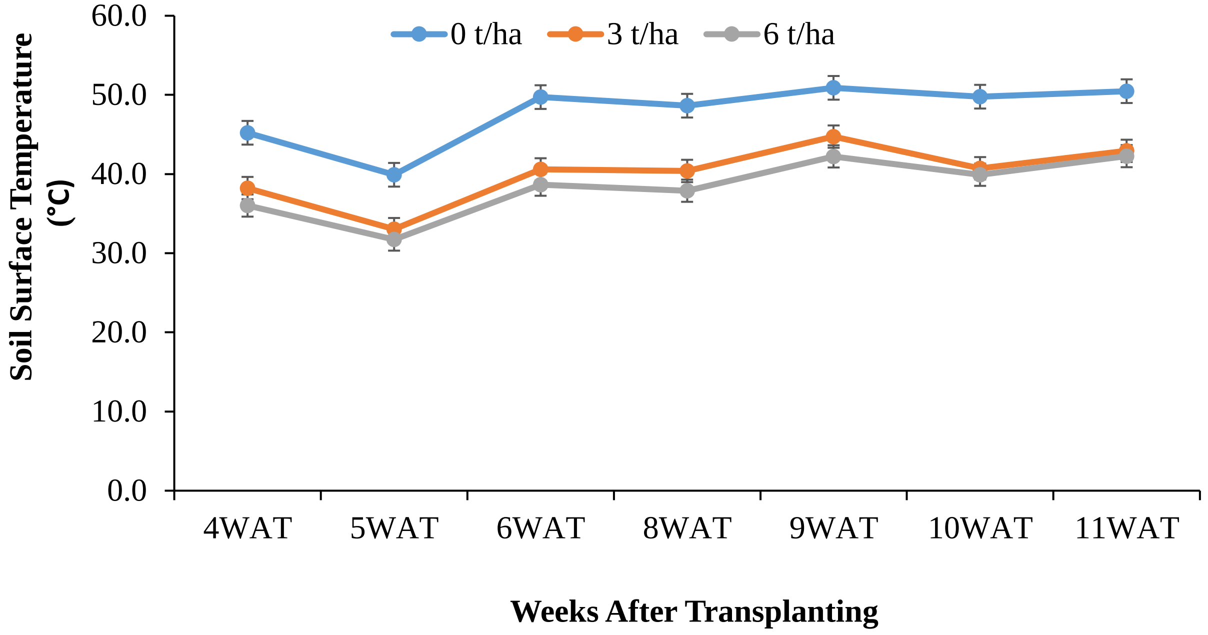

Figure 4.19: Soil Surface Temperature before irrigations as affected by 75 % ET_c Mild Deficit Irrigation Regime and Quantity of Rice Straw Mulch in the 2021/22 irrigated cropping season. †Data is pooled for variety treatments

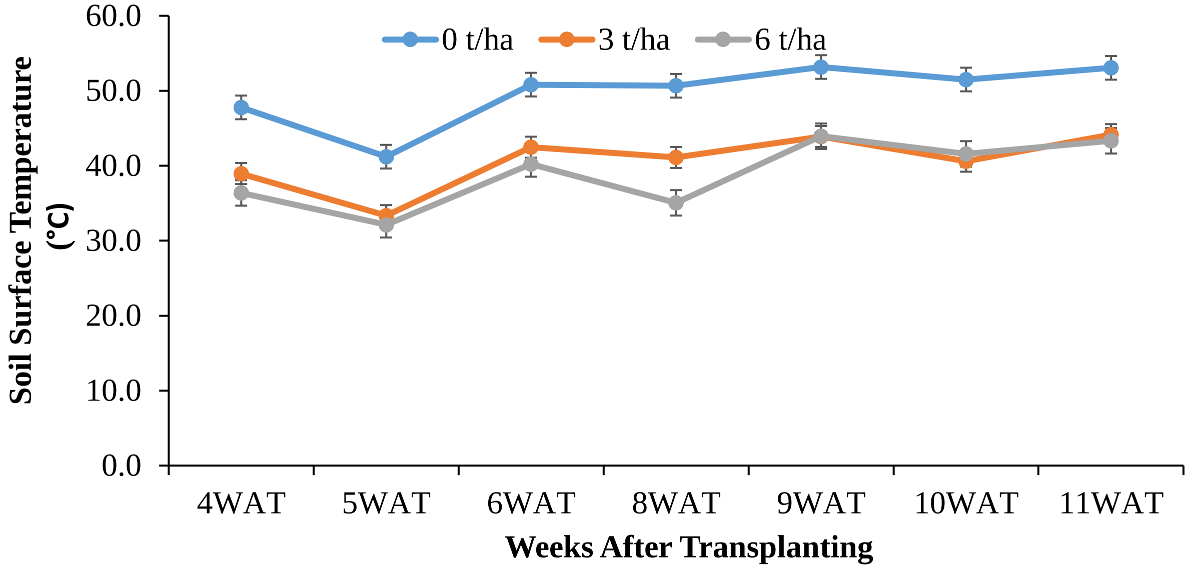

Figure 4.20: Soil Surface Temperature before irrigations as affected by 50 % ET_c Deficit Irrigation Regime and Quantity of Rice Straw Mulch in the 2021/22 irrigated cropping season. †Data is pooled for variety treatments

4.5.4 Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and their interactions on Soil Nitrogen, pH, and Electrical Conductivity (EC)

Table 4.5 presents result on the Total Nitrogen, pH, and EC of the rootzone soils at crop maturity stage as influenced by variety (V), irrigation regimes (I), quantity of rice straw mulch (M) and their interactions in the first and second irrigated cropping season. The results revealed significant interaction effect of treatments on soil pH (Table 4.5). The interaction (3-way) effect of variety, deficit irrigation regime and quantity of rice straw mulch (V x I x M) on soil pH was significant ($p<0.001$) (Table 4.5). The application of high irrigation water and mulch improved soil pH. The Mongal F1 in combination with 100 % ET_c and 6 t/ha rice straw gave highest soil pH of 6.41, followed by Pectomech in combination with 100 % ET_c and 6 t/ha rice straw with pH of 6.03 (Figure 4.21). The lowest soil pH of 5.39 was obtained by Mongal F1 in combination with 50 % ET_c and 0 t/ha rice straw (Figure 4.21). As reported, soil pH between 6 and 7 is excellent and highly recommended for crop growth including tomatoes (Sawant, 2018). However, soil pH below 5.5 would cause plant disorders such as blossom-end-rot in most open pollinated varieties (OPV's); and nutrient such as soil magnesium and molybdenum unavailability to the plants. Moreover, soil pH greater than 6.5 would result in zinc, manganese, and iron deficiency in plants (Ha, 2015). The study results concluded that, the application of full irrigation (100 % ET_c) in combination with rice straw mulch improved soil acidity for better crop performance. Soil pH improved in the second irrigated season compared to first due to the fallow period observed in between seasons.

The effect of variety, deficit irrigation regimes and quantity of rice straw mulch treatment levels on electrical conductivity (EC) of the soil was non-significant ($p>0.05$) (Table 4.5). However, the interaction effect of variety and quantity of rice straw mulch (V x M) on soil electrical conductivity was significant ($p<0.05$) (Table 4.5). The Pectomech in combination with no-mulch (0 t/ha) reduced the electrical conductivity (0.12 dS/m) of the soil drastically compared to the other combinations (Figure 4.22). The Pectomech in combination with 3 t/ha rice straw mulch produced the highest electrical conductivity of 0.18 dS/m (Figure 4.22). The electrical conductivity of soils was generally below the threshold reported by USDA (1954). Motsara and Roy (2008) depicted non-saline soil status. The rice straw mulch applied influenced the plant environment and improved soil conditions (Kader *et al.*, 2017).

Table 4.5: Effect of Variety, Irrigation Regime and Quantity of Rice Straw Mulch on Total Nitrogen, pH, and Electrical Conductivity of Rootzone Soils of the Experimental Field

	2020/21			**2021/22**	
Treatments	**Total Soil N. (%)**	**Soil pH**	**Soil EC (dS/m)**	**Soil pH**	**Soil EC (dS/m)**
Irrigation regimes (%ET_c) (I)					
100	0.05	5.98	1.17	8.30	0.15
75	0.06	5.75	1.03	8.22	0.13
50	0.06	5.63	1.12	8.12	0.17
LSD $_{(0.05)}$	0.01^{ns}	0.08***	0.38^{ns}	0.20^{ns}	0.04^{ns}
P. value	0.69	<.001	0.69	0.21	0.12
Quantity of rice straw (t/ha) (M)					
6	0.06	5.85	1.14	8.25	0.14
3	0.06	5.73	1.01	8.28	0.17
0	0.06	5.79	1.17	8.12	0.14
LSD $_{(0.05)}$	0.01^{ns}	0.03***	0.32^{ns}	0.10^{**}	0.03^{ns}
P. value	0.46	<.001	0.55	0.003	0.10
Interaction effects (LSD at 0.05)					
V x M	0.03^{ns}	0.04***	0.53^{ns}	0.18^{ns}	0.04*
V x I	0.03^{ns}	0.09**	0.56^{ns}	0.26^{ns}	0.05^{ns}
I x M	0.02^{ns}	0.08***	0.56^{ns}	0.23^{ns}	0.05^{ns}
V x I x M	0.03^{ns}	0.10***	0.80^{ns}	0.32^{ns}	0.07^{ns}
CV (%)	20.00	0.80	25.90	2.10	31.10

Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. LSD = Least significant difference at 5 %, N=Nitrogen, CV= Coefficient of variation, ETc= Crop water requirement, EC = Electrical Conductivity, pH = Soil acidity or alkalinity scale, P. value=Probability at 0.05.

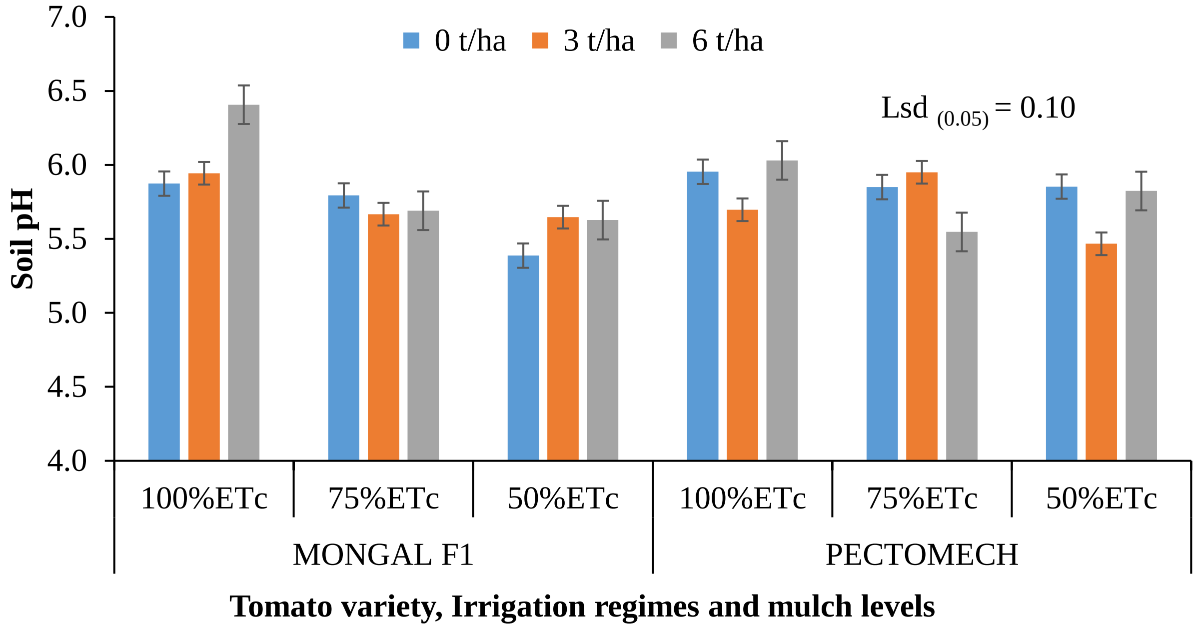

Figure 4.21: Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Rootzone Soil pH in the 2020/21 irrigated cropping season

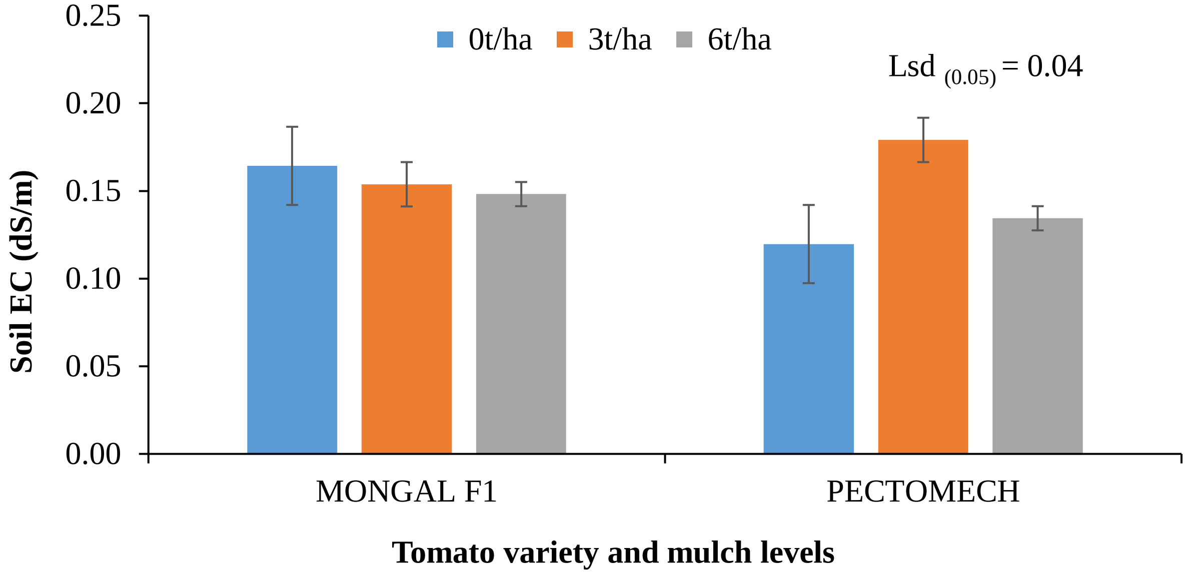

Figure 4.22: Effect of Variety and Quantity of Rice Straw Mulch on Rootzone Soil Electrical Conductivity (EC) at the maturity stage of Tomato

Also, soil nitrate concentration in the rootzone was not significantly influenced by the treatments in the first season (Table 4.5). However, the results in the second season revealed that, application of increased irrigation amounts contributed to decline in nitrate concentration in the rootzone soil. The full irrigation of 100 % ET_c resulted in lowest soil nitrate concentration of 18.33 mg/l. However, the severely stressed irrigation regime of 50 % ET_c recorded the highest nitrate concentration of 20.42 mg/l in the rootzone soil (Figure 4.23). The high nitrate concentration in the rootzone soil was probably due to the less irrigation water applied, since over irrigation increases the risk of nitrate leaching (Popova *et al.*, 2005). The right estimates of irrigation scheduling parameters ensured the proper operation of irrigation system and provided the appropriate daily crop water needs with little nutrient leaching (Zayzay, 2015). Also, the application of higher quantity of rice straw resulted in an increase in nitrate concentration in the rootzone soil. The applied 6 t/ha rice straw mulch gave mean nitrate concentration of 20 mg/l compared to the 19.6 mg/l and 19.2 mg/l obtained by the applied 3 t/ha and 0 t/ha rice straw mulch respectively (Figure 4.24). The application of crop residue such as rice straw as mulch has the tendency to reduce soil temperature (Ertek *et al.*, 2004) which resulted in reduction in soil nitrate losses influenced by evaporation from high ambient temperatures.

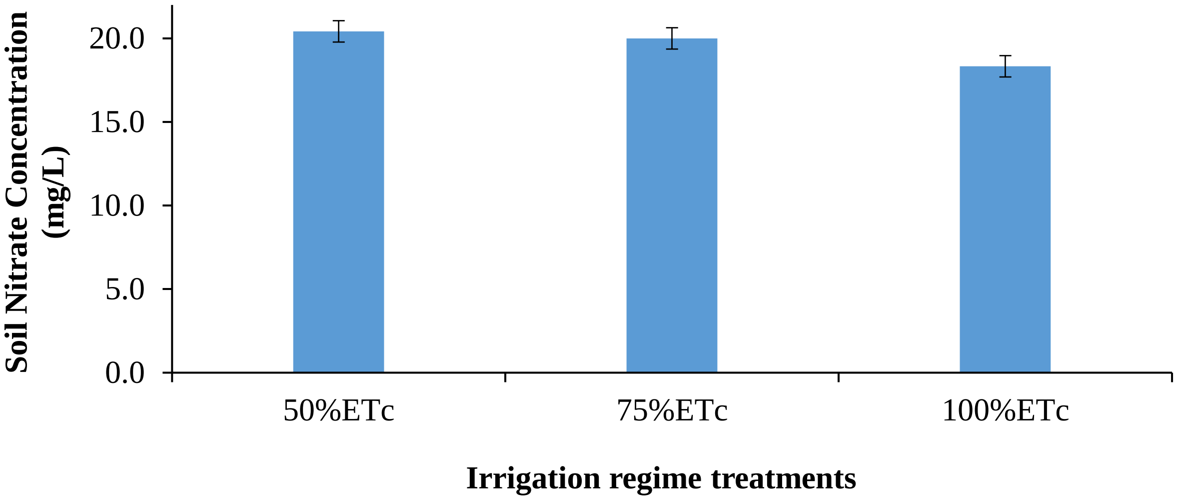

Figure 4.23: Effect of Irrigation Regimes on Rootzone Soil Nitrate Concentration at the maturity stage of crop growth

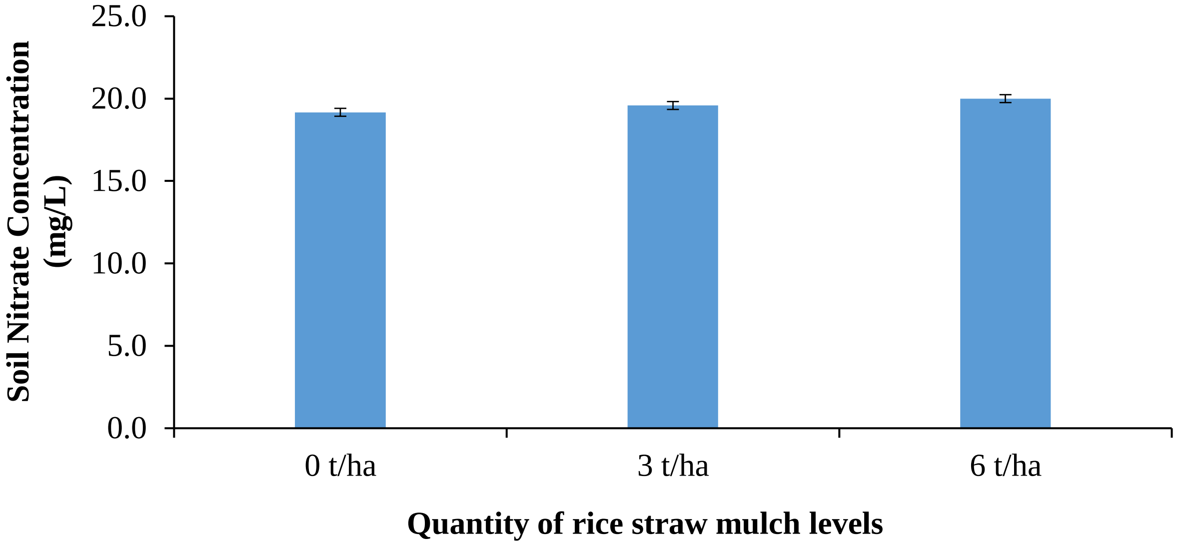

Figure 4.24: Mean Rootzone Soil Nitrate Concentration at the maturity stage of growth as affected by the Quantity of Rice Straw Mulch

4.6 Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and their interactions on the Growth and Yield Components of Tomato during the two irrigated cropping seasons

4.6.1 Treatments and Their Interaction Effect on Plant Height (cm)

Table 4.6 highlights experimental results on height of tomato plants as influenced by the variety irrigation regimes, quantity of rice straw mulch and their interactions. The results revealed significant ($p<0.05$) interaction effect of treatments (*3-way*; V x I x M) on plant height at the critical growth stage (4WAT) during the first irrigated cropping season (Table 4.6). The Mongal F1 in combination with 75 % ET_c and 3 t/ha mulch gave highest mean plant height of 26.40 cm, followed by Mongal F1 in combination with 50 % ET_c and 0 t/ha with 25.85 cm (Table 4.7). However, Pectomech in combination with 50 % ET_c and 6 t/ha produced the lowest mean plant height of 17.93 cm (Table 4.7). The differences in plant height may be attributed to differences in the growth rate of plants because of the different soil water conditions (Nkansah *et al.*, 2011). The

Mongal F1 in combination with the irrigation regimes and mulching treatments produced better plant growth probably due to its considerable tolerant level to soil water stress conditions (Liu *et al.,* 2006; Mohawesh, 2018; Singh *et al*., 2019). Arshad *et al*. (2017) reiterates the role of adequate soil water within the rootzone of crops in increasing plant height due to the availability of macronutrients such as nitrogen for plant use. The swift and prompt irrigations for the 75 % ET_c regime prior to onset of water stress condition that would have caused a detrimental effect on Mongal F1 in combination with 3 t/ha rice straw mulch resulted in the tallest plants (Parkash and Singh, 2020).

Due to high water demand of the crop (Patanè *et al*., 2011), any deficit supply will result in low evapotranspiration rate by severely stressed plants leading to retarded growth (Parkash and Singh, 2020). Similar trend was observed in green pepper under stress irrigation regimes that reduced transpiration and photosynthesis rate of the plants (Paku, 2016; de Souza *et al*., 2019). Arshad *et al*. (2017) and Parkash *et al.* (2021) contended that, the increase in plant height of vegetables depends on the environmental and agronomic factors of the field. These factors include harsh weather conditions such as high temperatures and wind speed that would cause stomatal closure in plants and lead to low evapotranspiration rate and poor growth as experienced by severely stressed plants (Parkash and Singh, 2020).

Also, during the second irrigated cropping season, the interaction (*2-way*) effect of variety (V) and quantity of rice straw mulch (M) thus; V x M on mean plant height was significant at 4WAT ($p<0.05$) and 10WAT ($p<0.01$) respectively (Table 4.8). During the early and critical growth stage (4WAT), Mongal F1 in combination with the quantity of rice straw mulch levels produced good plant growth. Mongal F1 in combination with 3 t/ha mulch produced tallest plants with mean of

29.29 cm, followed by Mongal F1 x 6 t/ha. Meanwhile, Pectomech in combination with 0 t/ha produced the lowest mean plant height of 24.44 cm (Table 4.8). This corroborates with findings of Nkansah *et al*. (2003); Awodoyin *et al*. (2007) that the application of organic mulches would increase height of tomato plants under field conditions. Studies by Liasu and Abdul (2007) observed that the use of sunflower leaves as mulch material produced taller tomato plants than the no-mulch control treatment under pot experiment. The choice of rice straw as mulch material depends largely on the climate of the study area, local availability, and the free access of the material (Wang *et al.*, 2016). Studies by Iftikhar *et al*. (2011) confirmed the positive effect of organic mulch material (rice straw, sugarcane bagasse and wheat straw) in increasing plant height of Chilli pepper significantly under field conditions. Their findings revealed that, rice straw mulch produced tallest plants of Chilli pepper, followed by the sugarcane bagasse and finally wheat straw. The no-mulch plots produced lowest mean plant height.

Towards the maturity growth stage (10WAT) in the second irrigated season, the Pectomech variety in combination with the quantity of rice straw mulch levels surprisingly produced taller plants than the Mongal F1. The Pectomech in combination with 6 t/ha produced tallest plants with a mean of 49.40 cm, followed by Pectomech in combination with no-mulch with 46.85 cm. The Mongal F1 in combination with no-mulch produced the lowest mean plant height of 41.37 cm (Table 4.8). The direct influence of rice straw mulch on the microclimate near the plant, resulted in the reduction of soil temperature thereby improving the plant's physiological processes and increasing plant height (Kader *et al.*, 2017). The tremendous benefits associated with the use of organic mulches have been reported for several crops such as tomato (Kosterna, 2014), potato (Zhao *et al.*, 2014), blueberry (Munner *et al.*, 2019), strawberry (Deschamps *et al.*, 2019), and maize (Wang *et al.*, 2019).

Table 4.6: Effect of Variety, Irrigation Regime and Quantity of Rice Straw Mulch and their interactions on Plant Height (cm)

Treatment	Plant Height (cm)							
	2020/21				2021/22			
Variety (V)	**4WAT**	**6WAT**	**8WAT**	**10WAT**	**4WAT**	**6WAT**	**8WAT**	**10WAT**
Mongal F1	24.29	47.42	49.04	48.71	27.82	41.31	43.39	43.74
Pectomech	19.50	47.08	49.69	50.90	25.28	41.87	46.28	47.37
LSD $_{(0.05)}$	3.85^{*}	4.35^{ns}	3.42^{ns}	2.73^{ns}	6.08^{ns}	8.27^{ns}	7.33^{ns}	6.37^{ns}
P. value	0.03	0.82	0.59	0.08	0.28	0.84	0.31	0.17
Irrigation regimes (%ETc) (I)								
100	22.28	48.99	50.90	51.66	26.29	41.10	44.35	44.62
75	21.85	46.97	49.05	49.76	27.54	41.69	44.37	45.69
50	21.56	45.79	48.00	48.00	25.82	41.97	45.79	46.34
LSD $_{(0.05)}$	1.65^{ns}	1.44^{**}	2.24^{*}	1.76^{**}	2.62^{ns}	2.86^{ns}	3.31^{ns}	3.09^{ns}
P. value	0.64	0.001	0.05	0.003	0.37	0.81	0.57	0.51
Quantity of rice straw (t/ha) (M)								
6	21.28	48.25	49.75	50.64	27.36	43.12	45.40	46.93
3	22.03	47.87	50.33	49.92	27.58	41.82	45.28	45.62
0	22.38	45.63	48.00	48.85	24.71	39.82	43.83	44.11
LSD $_{(0.05)}$	1.03^{ns}	0.98^{***}	1.11^{***}	1.38^{*}	1.37^{***}	1.75^{**}	1.52^{ns}	1.44^{**}
P. value	0.10	<.001	<.001	0.04	<.001	0.002	0.08	0.001
Interaction effect (LSD at 0.05)								
V x M)	3.56^{ns}	4.07^{ns}	3.14^{ns}	2.61^{ns}	5.69^{*}	7.77^{ns}	6.90^{ns}	5.96^{**}
V x I	3.59^{ns}	4.01^{ns}	3.53^{ns}	2.81^{ns}	5.67^{ns}	7.63^{ns}	6.87^{ns}	6.03^{ns}
I x M	2.13^{ns}	1.93^{ns}	2.65^{ns}	2.54^{ns}	3.14^{ns}	3.64^{ns}	3.82^{ns}	3.59^{ns}
V x I x M	3.85^{*}	4.13^{ns}	4.03^{ns}	3.77^{ns}	5.97^{ns}	7.83^{ns}	7.18^{ns}	6.41^{ns}
CV (%)	8.10	3.50	3.80	4.70	8.80	7.20	5.80	5.40

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. P. value; Probability value, LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * = significantly different at P≤0.05, ** = significantly different at P≤ 0.01., *** = significantly different at P≤0.001.*

Table 4.7: Interaction Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch (V x I x M) on Plant Height (cm)

Variety	**Deficit irrigation regime (I) (%ET$_c$)**	**Quantity of rice straw mulch (t/ha)**		
		0	**3**	**6**
Mongal F1	100	24.48	23.65	24.73
	75	23.65	26.40	22.78
	50	25.85	22.95	24.18
Pectomech	100	21.05	20.08	19.73
	75	20.68	19.23	18.38
	50	18.58	19.88	17.93
LSD at 0.05		**3.85**		
P. value		**0.03**		

Where, LSD; Least significance difference of means at 95% confidence level. P. value; Probability value, ETc; Crop water requirement of tomato

Table 4.8: Interaction Effect of Variety and Quantity of Rice Straw Mulch (V x M) on Plant Height (cm)

Treatments	**Quantity of rice straw mulch (M) (t/ha)**					
	4 WAT			**10 WAT**		
Variety (V)	**0**	**3**	**6**	**0**	**3**	**6**
Mongal F1	24.98	29.29	29.19	41.37	45.11	44.72
Pectomech	24.44	25.87	25.52	46.85	46.12	49.14
LSD at 5%	**5.69**			**5.96**		
P. value	**0.04**			**0.01**		

Where, LSD; Least significance difference of means at 95% confidence level, P. value; Probability value, ETc; Crop water requirement of tomato

4.6.2 Treatments and their Interaction Effect on Stem Diameter (mm) of Tomato Plants

Table 4.9 highlights the results on stem diameter of tomato plants as influenced by variety, irrigation regimes, quantity of rice straw mulch and their interactions over the two irrigated growing seasons. The results revealed significant ($p<0.05$) interaction effect of treatments on stem diameter only in the first irrigated cropping season (Table 4.9). The interaction of variety and irrigation regimes on stem diameter was significant at 10WAT ($p<0.05$) (Table 4.9). The Pectomech in combination with 100 % ET_c gave highest stem diameter of 10.21 mm, followed by Mongal F1 in combination with 100 % ET_c with 10.12 mm (Table 4.10). However, the lowest stem diameter of 9.27 mm was recorded by Mongal F1 in combination with 75 % ET_c, followed by Pectomech in combination with 50 % ET_c with 9.29 mm (Table 4.10). The trend clearly suggested that soil water stress conditions imposed by the deficit irrigation regimes caused a reduction in stem diameter of tomato plants compared to the full irrigation regime. This corroborates with findings of Taromi *et al.* (2019), in their study to determine effect of watering regimes of 50 %, 70 % and 100 % of the crop water requirement (CWR) and mulching using mood chip, composed wood chip, plastic mulch and no-mulch on growth of tomato. The researchers found that, 100 % CWR produced maximum stem diameter and 50 % CWR the minimum stem diameter. However, they observed statistical similarities for the effect of 70 % and 100 % CWR on the measured trait. This was because the tomato crop has high water demand and deficit supply of water will affect its growth traits especially when grown in the arid and semi-arid areas (Nangare *et al.*, 2016). Further, the results of this study agree with the findings of de Oliveira *et al*. (2019) who observed that the stem diameter of yellow finger pepper increased with increasing irrigation levels.

It is worth nothing that stem diameter increased along the plant growth stages towards maturity. The stem diameter variation is another method of determining plant water stress conditions in vegetables such as tomato (Parkash and Singh, 2020). The movement of water back and forth between the xylem and phloem causes variation in stem diameter due to shrinking and expanding of the xylem resulting from changing water potential (Parkash and Singh, 2020). Therefore, soil water availability is responsive to the expansion rate of the stem diameter (Parkash and Singh, 2020). According to findings by Gallardo *et al*. (2004) on melon and tomato, the maximum daily stem shrinkage (MDS) is observed to be sensitive to soil water stress conditions. Again, Gallardo *et al.* (2006) conducted a study on tomato and observed that water stress effect on the crop was more pronounced during the early growth stages. Also, during low vapor pressure deficit (VPD), stem diameter variation was less sensitive to water stress than during high VPD (Gallardo *et al.*, 2006).

Also, the interaction effect of variety (V) and quantity of rice straw mulch (M) thus; V x M on stem diameter was significant at 8WAT ($p<0.01$) in the first season. Pectomech in combination with 6 t/ha rice straw produced highest stem diameter of 9.88 mm, followed by Mongal F1 in combination with 6 t/ha with 9.67 mm. Meanwhile, the lowest stem diameter was recorded by Pectomech in combination with no-mulch (8.48 mm), followed by Mongal F1 in combination with no-mulch with 8.84 mm (Table 4.10). The trend indicated that, application of higher quantity of rice straw mulch interacted well with the varieties and produced plants with bigger mean stem diameter than the no-mulch treatment (Table 4.10). Mulches create conducive soil environment of cooler soil temperature that helps conserve soil water for plant use to improve physiological processes such as stem diameter (Kader *et al.*, 2017).

Table 4.9: Effect of Variety, Irrigation Regime and Quantity of Rice Straw Mulch and their interactions on Stem Diameter (mm)

Treatment	**Stem Diameter (mm)**					
	2020/21			**2021/22**		
Irrigation regimes (%ETc) (I)	**6WAT**	**8WAT**	**10WAT**	**6WAT**	**8WAT**	**10WAT**
100	8.85	9.81	10.16	7.35	8.09	8.37
75	8.20	9.21	9.59	7.41	8.05	8.33
50	8.07	8.85	9.43	7.28	8.13	8.41
LSD $_{(0.05)}$	0.31***	0.27***	0.35**	0.66^{ns}	0.54^{ns}	0.60^{ns}
P. value	<.001	<.001	0.002	0.92	0.95	0.96
Quantity of rice straw (t/ha) (M)						
6	8.66	9.77	10.11	7.81	8.53	8.79
3	8.56	9.43	10.12	7.60	8.46	8.75
0	7.90	8.66	8.94	6.63	7.28	7.57
LSD $_{(0.05)}$	0.25***	0.19***	0.43***	0.30***	0.34***	0.34***
P. value	<.001	<.001	<.001	<.001	<.001	<.001
Interaction effect (LSD at 0.05)						
V x M	1.19^{ns}	1.03**	0.96^{ns}	1.46^{ns}	1.47^{ns}	1.55^{ns}
V x I	1.18^{ns}	1.01^{ns}	0.96*	1.43^{ns}	1.44^{ns}	1.52^{ns}
I x M	0.45^{ns}	0.36^{ns}	0.68^{ns}	0.76^{ns}	0.70^{ns}	0.74^{ns}
V x I x M	1.17^{ns}	0.99^{ns}	1.18^{ns}	1.49^{ns}	1.49^{ns}	1.56^{ns}
CV (%)	5.10	3.40	7.50	7.00	7.20	6.90

*Where, V x M = Interaction effect of variety and mulching, V x I = Interaction effect of variety and irrigation regimes, I x M = Interaction effect of irrigation regimes and mulching, V x I x M = Interaction effect of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD: Least significance difference of means at 95% confidence level, P. value; Probability value, WAT; Weeks after Transplanting. * = significantly different at $P \leq 0.05$, ** = significantly different at $P \leq 0.01$., *** = significantly different at $P \leq 0.001$.*

Table 4.10: Interaction Effect of Variety and Quantity of Rice Straw Mulch (V x M), Variety and Irrigation Regime (V x I) on Stem Diameter (mm) of Tomato Plants

Treatment	**Quantity of rice straw mulch (M) (t/ha)**			**Deficit irrigation regimes (I) (%ET$_c$)**		
Variety (V)	**0**	**3**	**6**	**50**	**75**	**100**
Mongal F1	8.84	9.58	9.67	9.56	9.27	10.12
Pectomech	8.48	9.28	9.88	9.29	9.90	10.21
LSD at 0.05	1.03**			0.96*		
P. value	0.006			0.04		

*Where, LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value; Probability value*

4.6.3 Treatments and their Interaction Effect on Leaf Temperature (˚C) of Tomato Plants

The monitoring of leaf temperature started 4 – 9 WAT during the two irrigated cropping season. However, the study results revealed that significant interaction effect of treatments on leaf temperature (LT) of plants was only present during the first irrigated cropping season. The interaction (2-*way*) effect of variety and irrigation regimes (V x I) on LT was significant (P<0.01) (Table 4.11). The mean LT values for the interaction ranged from 39.01 - 44.56 ˚C with the highest obtained by Mongal F1 in combination with 75 % ETc (44.56 ˚C), followed by Pectomech in combination with 50 % ETc. (45.51 ˚C) (Figure 4.25). The lowest leaf temperature was recorded by Pectomech in combination with 100 % ETc (39.01 ˚C), followed by Mongal F1 in combination with 50 % ETc (42.82 ˚C) (Figure 4.25). Pectomech in combination with 100 % ETc recorded lowest LT due to the large leaf area of the variety that resulted in increased stomata opening and transpiration rate. The full irrigation regime of 100 % ETc also contributed to lowering LT by providing adequate soil moisture condition that increased transpiration rate of plants. The full irrigation plots received daily irrigations to bring soil water back to the upper threshold of field capacity which is the ideal point for adequate crop physiological performance. However, the deficit irrigation regimes when combined with varieties contributed to increasing the leaf temperature of tomato plants. The results agree with findings of Testi *et al.* (2008), when they reported that the reduction in transpiration rate of plants under water stress conditions (40 % ET_c and 60 % ET_c) resulted in relatively higher leaf temperature compared to full irrigation – 100 % ET_c.

The results clearly showed an increasing trend of leaf temperature for plants under soil water stress conditions largely due to the low stomatal conductance resulting in low transpiration rate (Pask *et al*., 2012). The major role of transpiration is to help in regulating the temperature of plants growing under optimum soil water conditions (Cornic and Ghashghaie, 1991). Therefore, a reduction in transpiration rate of plants will increase leaf temperature as observed in the field measurements. High leaf temperature of tomato plants affects certain physiological processes in the plant system (Parkash and Singh, 2020). The increase in leaf temperature disrupts activities of enzymes in the plant system (Labate *et al*., 1990). In addition, high temperature leads to the Rubisco inactivation, inhibition of photosystem II activity, and plasmalemma destruction which are important for the performance of plants: Destruction of plasmalemma kills plant cells, photosystem II activity provides the needed plant energy and reducing the CO_2 assimilation power while the activity of rubisco is also vital for the assimilation of CO_2 assimilation (Camejo *et al.*, 2005). Restriction of these plant processes by high temperature from soil water stress conditions can be detrimental to crop yields.

Table 4.11: Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Leaf Temperature (LT)

Treatments	**Leaf Temperature (˚C)**					
	2020/21			**2021/22**		
Tomato variety (V)	**4WAT**	**5WAT**	**9WAT**	**4WAT**	**5WAT**	**9WAT**
Irrigation regimes (%ETc) (I)						
100	29.79	32.61	41.62	29.98	31.26	36.17
75	31.01	33.65	43.22	30.33	28.69	34.01
50	30.87	36.68	43.66	50.88	28.82	34.57
LSD $_{(0.05)}$	0.97*	1.51***	1.88*	0.53*	4.55^{ns}	3.52^{ns}
P. value	0.04	<.001	0.08	0.01	0.41	0.41
Quantity of rice straw (t/ha) (M)						
6	30.36	33.91	41.90	30.22	28.96	36.29
3	29.89	34.13	42.60	30.39	31.01	34.03
0	31.42	34.91	44.01	30.58	28.80	34.43
LSD $_{(0.05)}$	1.11*	1.65^{ns}	1.81*	0.40^{ns}	4.21^{ns}	3.58^{ns}
P. value	0.03	0.44	0.06	0.21	0.51	0.40
Interaction effects (LSD at 0.05)						
V x M	1.45^{ns}	2.80^{ns}	3.61^{ns}	1.03^{ns}	6.20^{ns}	4.83^{ns}
V x I	1.31^{ns}	2.72^{ns}	3.63**	1.06^{ns}	6.42^{ns}	4.72^{ns}
I x M	1.81^{ns}	2.70^{ns}	3.06^{ns}	0.75^{ns}	7.25^{ns}	5.98^{ns}
V x I x M	2.52^{ns}	4.08^{ns}	4.82^{ns}	1.25^{ns}	10.27^{ns}	8.36^{ns}

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value; Probability value*

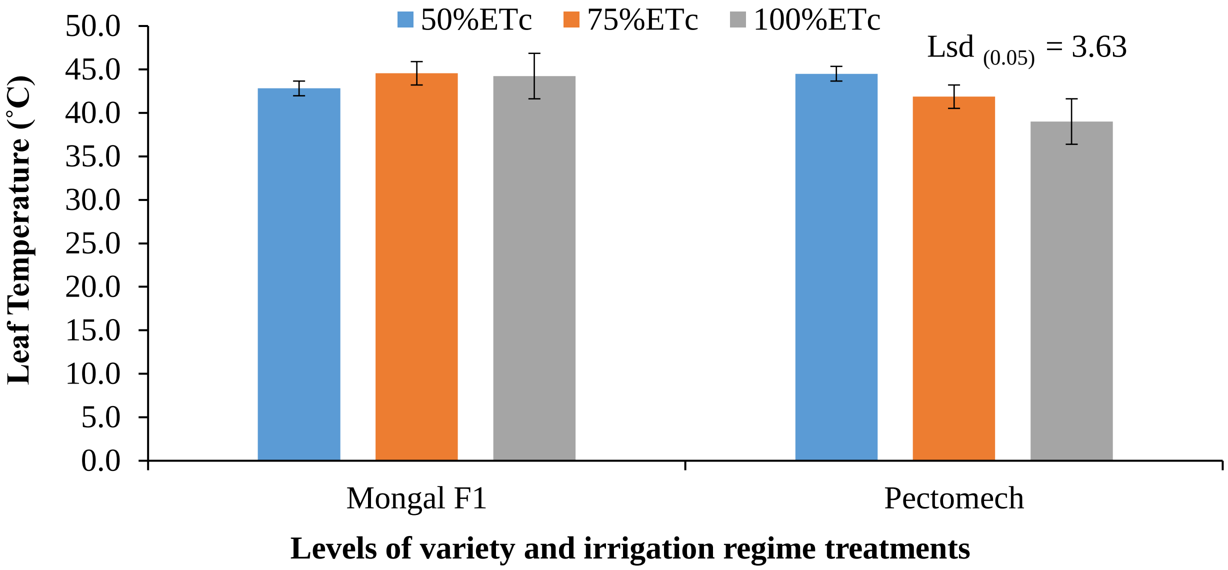

Figure 4.25: Effect of Variety and Irrigation Regimes (V x I) on Leaf Temperature (LT) of Tomato Plants

4.6.4 Treatments and their Interaction Effect on Leaf Chlorophyll Concentration (LCC) (µmol/m²) of Tomato Plants

Table 4.12 shows result of leaf chlorophyll concentration (LCC) of tomato plants as influenced by variety (V), deficit irrigation regimes (I), quantity of rice straw mulch (M) treatments and their interaction effect during the first (2020/21) and second (2021/22) irrigated cropping seasons. Fertilization provided the needed quantity of plant nutrients including nitrogen that builds up chlorophyll in the tissues of plants such as leaves to ensure adequate plant health. The study results showed that, interaction effect of treatment on LCC was present in the first season (Table 4.12).

The analysis of variance depicted a significant ($p<0.05$) interaction (*3-way*) effect of variety, irrigation regimes and quantity of rice straw mulch (V x I x M) on LCC at 5WAT during the first irrigated cropping season (Table 4.12). The Mongal F1 in combination with 75 % ET_c and 3 t/ha mulch gave the highest mean LCC of 69.35 µmol/m², followed by Mongal F1 in combination with 100 % ET_c and 6 t/ha mulch with 66.50 µmol/m². Mongal F1 combined with 75 % ET_c and no-mulch came third with LCC of 66.41 µmol/m² followed by Pectomech in combination with 75 % ET_c and 3 t/ha mulch with 64.17 µmol/m² (Figure 4.26). However, the lowest LCC of 49.92 µmol/m² was recorded by Pectomech in combination with 100 % ET_c and 6 t/ha mulch (Figure 4.26). The results suggested an increase in mean LCC of plants under deficit irrigation regimes compared to the full irrigation regime. This agrees with the findings of Medyoun *et al.* (2021) on tomato where 60 % soil water stress condition gave higher chlorophyll florescence than the well watered control. Higher soil water conditions certainly increased the risk of nitrate leaching out of the rootzone (Popova *et al.*, 2005) and reduced uptake thereby resulting in lower chlorophyll concentration of plant leaves as shown in the study results. The Mongal F1 during the study period appeared to be more efficient in water use than its counterpart variety that resulted in the higher LCC of plants due to the resultant increase in nitrogen uptake.

Also, the study results clearly suggested that the application of rice straw mulch significantly contributed to improving the LCC of plants when combined with tomato varieties and deficit irrigation regimes than the control of no-mulch (Figure 4.26). This corroborated the findings of Lahmod *et al.* (2019), where the application of wheat straw on *Trigonella foeunm graecum* L. increased the chlorophyll content of leaves (58.17 SPAD) at the maturity stage when compared to the control of no mulch (38.85 SPAD).

Table 4.12: Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Leaf Chlorophyll Concentration (LCC)

Treatment	**Leaf Chlorophyll Concentration (µmol/m²)**							
	2020/21				**2021/22**			
Variety (V)	5WAT	6WAT	7WAT	9WAT	6WAT	7WAT	9WAT	10WAT
Mongal F1	63.96	65.22	52.10	32.68	46.06	39.79	33.08	29.60
Pectomech	58.54	63.06	50.72	41.88	45.58	45.90	39.79	42.70
LSD $_{(0.05)}$	6.84^{ns}	5.87^{ns}	16.22^{ns}	11.10^{ns}	6.36^{ns}	3.66^{**}	13.10^{ns}	12.38^{*}
P.value	0.09	0.33	0.80	0.08	0.83	0.01	0.20	0.04
Irrigation regimes (%ET_c) (I)								
100	57.81	58.34	46.91	29.64	42.17	39.16	32.04	32.10
75	63.91	66.43	50.41	38.40	46.44	42.31	35.55	33.60
50	62.04	67.65	56.90	43.80	48.85	47.06	41.72	42.80
LSD $_{(0.05)}$	4.17*	3.49***	5.39**	5.93***	2.46^{***}	5.40^{*}	3.38^{***}	5.57^{**}
P.value	0.02	<.001	0.005	<.001	<.001	0.02	<.001	0.002
Quantity of rice straw (t/ha) (M)								
6	60.70	63.55	51.25	40.18	45.87	42.54	37.41	40.40
3	63.29	64.67	51.09	39.42	46.36	44.79	38.25	37.70
0	59.76	64.20	51.89	32.24	45.23	41.20	33.65	30.30
LSD $_{(0.05)}$	2.95*	4.04ns	4.17ns	4.52**	3.09^{ns}	3.82^{ns}	4.79^{ns}	5.16^{***}
P.value	0.05	0.85	0.94	0.002	0.76	0.17	0.13	<.001
Interaction effects (LSD at 0.05)								
V x M	6.35^{ns}	6.24^{ns}	14.93^{ns}	10.25^{ns}	6.02^{ns}	5.02^{ns}	12.03^{ns}	11.46^{ns}
V x I	6.87^{ns}	5.85^{ns}	14.97^{ns}	10.73*	5.88^{ns}	6.59^{ns}	12.23^{ns}	11.59^{ns}
I x M	5.68^{ns}	6.51^{ns}	8.28^{ns}	8.41^{ns}	4.89^{ns}	7.36^{ns}	7.41^{ns}	8.89^{ns}
V x I x M	8.66*	9.61^{ns}	16.15^{ns}	11.89^{ns}	7.93^{ns}	9.79^{ns}	13.79^{ns}	14.55^{ns}

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at $P \leq 0.05$, ** - significantly different at $P \leq 0.01$., *** - significantly different at $P \leq 0.001$, P. value; Probability value*

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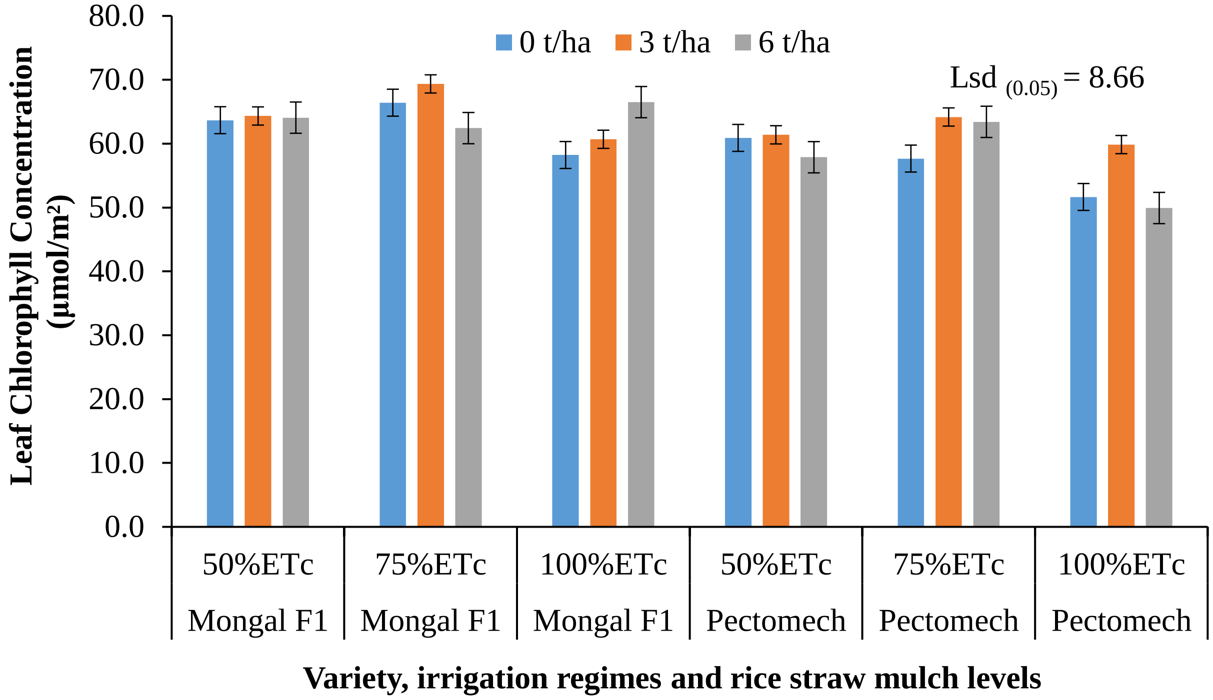

Figure 4.26: Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch (V x I x M) on Leaf Chlorophyll Concentration (LCC)

4.6.5 Treatments and Their Interaction Effect on Leaf Stomatal Conductance (mmol/m^{2}s)

Table 4.13 presents result on the effect of variety, irrigation regimes, quantity of rice straw mulch and their interactions on leaf stomatal conductance (LSC) of tomato plants during the first (2020/21) and second (2021/22) irrigated cropping seasons. The effect of irrigation and quantity of rice straw interaction (I x M) on LSC was significant ($p<0.05$) and recorded at 7 WAT during the first irrigated season (Table 4.13). LSC ranged from 51.70 – 74.10 mmol/m^{2}s (Figure 4.27). The 100 % ET$_c$ in combination with 6 t/ha rice straw produced the highest LSC of 74.10 mmol/m^{2}s, followed by 50 % ET$_c$ in combination with 6 t/ha rice straw with 64.30 mmol/m^{2}s. However, the 75 % ET$_c$ in combination with 3 t/ha rice straw produced the lowest LSC of 51.70 mmol/m^{2}s, followed by 50 % ET$_c$ in combination with no-mulch with LSC of 52.40 mmol/m^{2}s (Figure 4.27). The lowest mean LSC of 56.11 mmol/m^{2}s was produced by the 75 % ET$_c$ in combination with levels of rice straw mulch, followed by 57.10 mmol/m^{2}s produced by the 50 % $_{ETc}$ in combination with levels of rice straw mulch. The full irrigation (100 % ET$_c$) in combination with levels of rice straw mulch produced mean LSC of 64.70 mmol/m^{2}s (Figure 4.27). The result of the study agreed with findings of Pazzagli *et al.* (2016) for an evaluation on the effect of irrigation regimes (full irrigation regime of crop water requirement (CWR), deficit irrigation of 70 % CWR and partial rootzone drying (PRZD) of 70 % on tomato. They found significantly lower stomatal conductance of leaves under the deficit irrigation of 70 % and the 70 % PRZD when compared to the full irrigation regime. The authors; Sezen *et al.* (2019) also confirmed the assertion and reported similar trend with significant difference on LSC amongst irrigation regimes (full irrigation, deficit irrigation of 50 % and 75 %, PRZD of 50 %) on pepper.

Also in the second irrigated cropping season, interaction (3-way) effect of variety (V), deficit irrigation regimes (I) and quantity of rice straw mulch (M) thus; V x I x M was significant ($p<0.05$) at 2 WAT (Table 4.13). The Pectomech in combination with 100 % ET$_c$ and 3 t/ha rice straw produced the highest mean LSC of 143.70 mmol/m^{2}s, followed by Pectomech in combination with 50 % ET$_c$ and 3 t/ha rice straw with LSC of 136.60 mmol/m^{2}s (Table 14). However, Mongal F1 in combination with 100 % ET$_c$ and 0 t/ha rice straw produced lowest mean LSC of 92.40 mmol/m^{2}s, followed by Pectomech in combination with 50 % ET$_c$ and 0 t/ha rice straw with LSC of 100.80 mmol/m^{2}s (Table 14). The measurement of stomatal conductance of plant targets the resistances of gas movement between the atmospheric air and the interior of plant leaves (Pietragalla and Pask, 2012). This gas exchange results in the uptake of carbon dioxide and loss of water from the plants (Parkash and Singh, 2020). Soil water stress conditions imposed by the deficit irrigation regimes resulted in lower stomatal conductance and photosynthesis of tomato plants (Yuan *et al.*, 2010; Seng, 2014), especially for the Pectomech variety. The results suggested that Mongal F1 variety was more efficient in water-use even under soil water stress conditions and eventually recorded higher LSC values under deficit irrigation regimes. The variety might have been well adapted to the environment; hence minimising the influence of harsh weather conditions which is a contributory factor influencing the plant's stomata closure (Medyoun *et al.*, 2021; Parkash *et al.*, 2021).

Generally, the severely stressed irrigation regime in combination with no-mulch treatment resulted in lower leaf stomatal conductance of plants. This could be attributed to the closure of stomata by plants in response to soil water stress condition (Liu *et al.*, 2003; Parkash and Singh, 2020). Research by Liu *et al.* (2005) corroborates the findings of this study when they reported significant decrease in LSC of potato grown under soil water stress conditions imposed by irrigation schedule of 14 days irrigation interval compared to 9 days interval and the well watered plants. The stomatal closure caused by the soil water stress conditions eventually reduced the rate of transpiration and led to poor physiological performance of plants (Pask *et al.*, 2012). The applied rice straw mulch contributed to soil water conservation and increased stomatal conductance and transpiration (Hochmuth *et al.*, 2001; Kirnak *et al.*, 2001). The results agree with findings of Kirnak *et al.* (2001) on the huge potential of mulching in mitigating the negative effects of water stress on the growth of strawberry under semi-arid conditions. Therefore, the interactive use of rice straw mulch, slightly deficit irrigation regime and improved tomato variety such as Mongal F1 would increase stomatal conductance and transpiration rate thereby enhancing photosynthesis of plants.

Table 4.13: Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interactions on Leaf Stomatal Conductance (LSC)

Treatment	LSC (mmol/m^{2}s)					
	2020/21			2021/22		
	6WAT	7WAT	9WAT	2WAT	5WAT	8WAT
Irrigation regimes (%ETc) (I)						
100	101.10	64.70	58.10	120.70	76.60	46.07
75	95.20	55.90	55.30	121.90	78.40	49.37
50	80.00	57.10	66.80	125.30	83.50	45.26
LSD (0.05)	16.03*	8.61^{ns}	10.07^{ns}	12.89^{ns}	21.89^{ns}	3.37*
P. value	0.04	0.09	0.07	0.73	0.78	0.05
Quantity of rice straw (t/ha) (M)						
6	90.20	64.50	60.90	121.40	85.90	48.00
3	98.30	55.10	64.50	130.50	81.20	48.05
0	88.70	58.10	54.70	116.00	71.30	44.65
LSD (0.05)	8.44*	5.21**	7.64*	10.36*	9.82*	4.87^{ns}
P. value	0.05	0.003	0.04	0.02	0.02	0.28
Interaction effects (LSD at 0.05)						
V x M	23.24^{ns}	15.02^{ns}	11.97^{ns}	14.36^{ns}	41.19***	6.69^{ns}
V x I	25.82^{ns}	15.76^{ns}	13.79^{ns}	16.57^{ns}	41.85^{ns}	5.47**
I x M	19.29^{ns}	10.92*	14.25^{ns}	18.83^{ns}	25.10^{ns}	7.51^{ns}
V x I x M	29.68^{ns}	17.98^{ns}	19.94^{ns}	25.78*	44.38^{ns}	10.87^{ns}

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value; Probability value*

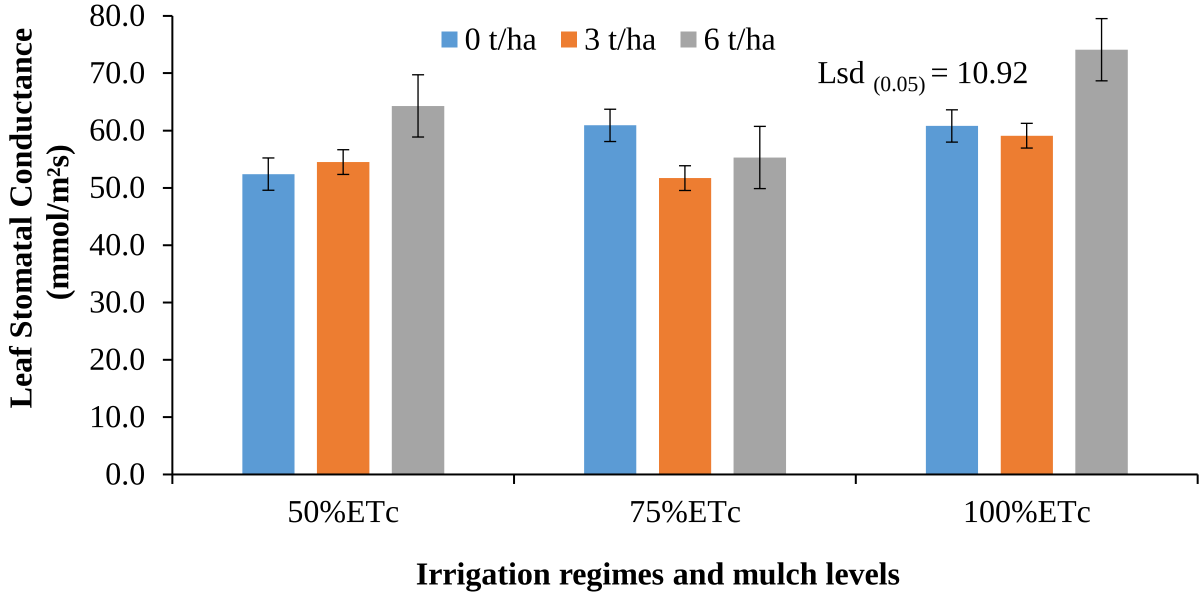

Figure 4.27: Effect of Irrigation Regimes and Quantity of Rice Straw Mulch (I x M) on Leaf Stomatal Conductance (LSC)

Table 4.14: Effect of Variety (V), Irrigation Regimes (I) and Quantity of Rice Straw Mulch (M) (V x I x M) on Leaf Stomatal Conductance (LSC) of Tomato Plants

Variety (V)	**Irrigation regimes (I) (%ET$_c$)**	**Quantity of rice straw (t ha^{-1}) (M)**		
		0	**3**	**6**
Mongal F1	100	92.40	127.00	123.90
	75	116.40	125.30	101.80
	50	134.00	125.20	134.90
Pectomech	100	118.80	143.70	118.30
	75	133.20	125.10	129.50
	50	100.80	136.60	120.10
LSD at 0.05		25.78		
P. value		0.03		

LSD; Least significance difference of means at 95% confidence level, ETc=Crop water requirement, P. value=Probability value

4.6.6 Treatments and their Interaction Effect on Leaf Area Index (LAI) of Tomato Plants

Table 4.15 highlights the result of leaf area index (LAI) as influenced by variety, irrigation regimes, quantity of rice straw and their interactions in the two irrigated cropping seasons. The study results revealed that in both irrigated seasons, interaction (*3-way*) effect of variety, irrigation regimes and quantity of rice straw mulch (V x I x M) on LAI was significant ($P<0.05$) at 9 WAT (Table 4.15). In the first irrigated cropping season, Pectomech in combination with 100 % ET_c and 3 t/ha rice straw mulch produced plants with highest LAI of 0.86 m^2/m^2, followed by Pectomech in combination with 75 % ET_c and 6 t/ha (0.83 m^2/m^2). Thirdly, Pectomech in combination with 50 % ET_c and 6 t/ha rice straw mulch produced 0.80 m^2/m^2 representing 56.98 %, 55.42 % and 53.75 % increase respectively over the lowest LAI of 0.37 m^2/m^2 obtained by Mongal F1 in combination with 50 % ET_c and 0 t/ha rice straw mulch (Figure 4.28).

Also, the 3-way interaction (V x I x M) registered during the second irrigated cropping season produced similar results and trend compared with the first irrigated season (Table 4.15 and 4.16). The results corroborate the findings of Ragab *et al.* (2018), where the full irrigation regime (100 % evapotranspiration) reportedly gave highest leaf area than deficit irrigation regimes of 85 %, 70 % and 55 % respectively. Further, a study conducted by Mukherjee *et al.* (2017), reported higher LAI values for frequently watered (Cumulative pan evaporation of 50 mm - CPE_{50}) tomato plants than less watered plants (CPE_{25}). Also, Mohawesh (2018), reiterated on the significant reduction in leaf area of eggplant under deficit irrigation regime of 80 % of the crop evapotranspiration (ET_c) requirement when compared to the control of 100 % ET_c. According to Parkash *et al.* (2021), soil water has a strong influence on the leaf expansion rate of crops. However, the leaf expansion rate starts to decline earlier than net photosynthesis of most crops (Sharma *et al*., 2019). The assertion agrees with that stated by Seng (2014) and Biswas *et al*. (2015). According to Majnoun *et al.*

(2009); Sánchez-Rodríguez *et al*. (2010); Mishra *et al*. (2012) and Taiz *et al*. (2015), soil water stress conditions resulted in the decline in LAI. Parkash *et al*. (2021), reported that, the leaf area of cucumber was reduced by 42 %, 33 % and 7 % in 40 % ET_c, 60 % ET_c and 80 % ET_c respectively when compared to 100 % ET_c. The lower LAI measured on plants under soil water stress conditions imposed by deficit irrigation regimes resulted in the decrease in photosynthetic rate per leaf area and overall photosynthesis (Basu *et al*., 2016). The limited uptake of water by plants under soil water stress condition led to decline of water movement into the cytoplasm and vacuole of plant cells. This reduced the cell expansion rate which eventually inhibited leaf elongation and resulted in decline in leaf area (Jones, 1990).

Also, plants adapt to the impact of soil water stress conditions by reducing their leaf area to conserve the water stored in their tissues (Jones, 2004). This could be attributed to the poor LAI recorded by the Mongal F1 in combination to the other treatments. Mukherjee *et al*. (2017), reported decline in LAI starting 60 days after transplanting (DAT) of tomato. According to the study results, the inclusion of rice straw mulch to the deficit irrigation regimes improved LAI of tomato plants of both varieties than when combined with no-mulch. The findings of Mukherjee *et al*. (2017) agree perfectly with the study results on LAI. The authors reported an increase in LAI for plants under mulched treatments than un-mulched treatments and further developed a linear regression equation for the relationship between LAI and mulch materials over time. They obtained an R^2 value of 0.81 indicating strong relationship between LAI and rice straw mulch.

Table 4.15: Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interaction Effect on Leaf Area Index (LAI)

Treatment	**LAI (m^2/m^2)**					
	2020/22			**2021/22**		
Irrigation regimes (%ETc) (I)	**6WAT**	**8WAT**	**9WAT**	**6WAT**	**8WAT**	**9WAT**
100	0.91	0.75	0.68	0.70	0.71	0.67
75	0.75	0.70	0.62	0.54	0.69	0.61
50	0.74	0.72	0.59	0.53	0.75	0.58
LSD $_{(0.05)}$	0.11**	0.19^{ns}	0.09^{ns}	0.11**	0.21^{ns}	0.09^{ns}
P. value	0.009	0.82	0.14	0.002	0.79	0.14
Quantity of rice straw (t/ha) (M)						
6	0.86	0.77	0.71	0.65	0.75	0.69
3	0.82	0.77	0.66	0.61	0.76	0.64
0	0.72	0.63	0.53	0.51	0.63	0.52
LSD $_{(0.05)}$	0.11*	0.12*	0.07***	0.11*	0.12^{ns}	0.07***
P. value	0.04	0.02	<.001	0.03	0.06	<.001
Interaction effects (LSD at 0.05)						
V x M	0.20^{ns}	0.21^{ns}	0.12^{ns}	0.20^{ns}	0.27^{ns}	0.35^{ns}
V x I	0.21^{ns}	0.25^{ns}	0.13^{ns}	0.20^{ns}	0.31^{ns}	0.35^{ns}
I x M	0.19^{ns}	0.24^{ns}	0.13^{ns}	0.19^{ns}	0.26^{ns}	0.13^{ns}
V x I x M	0.88^{ns}	0.33^{ns}	0.19*	0.29^{ns}	0.38^{ns}	0.35*

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at $P \leq 0.05$, ** - significantly different at $P \leq 0.01$., *** - significantly different at $P \leq 0.001$, P. value; Probability value*

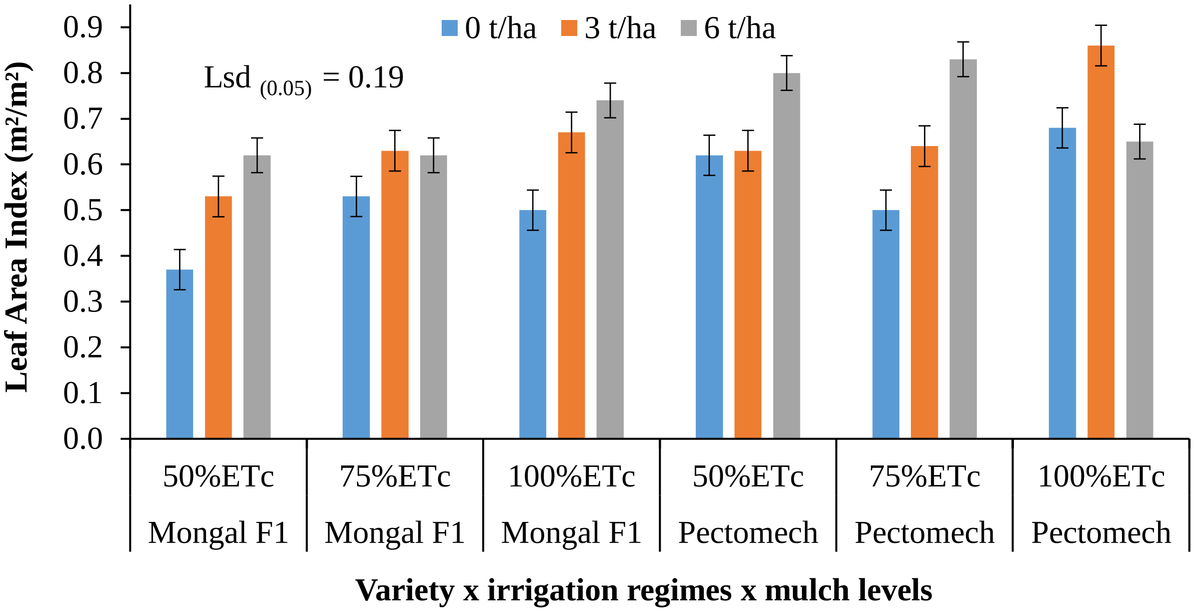

Figure 4.28: Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch (V x I x M) Levels on Leaf Area Index (LAI)

Table 4.16: Interaction Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on LAI (m^2/m^2) of Tomato Plants

Treatment	**Irrigation regimes (I) (%ET$_c$)**	**LAI (m^2/m^2)**		
		Quantity of rice straw mulch (M) (t/ha)		
		0	**3**	**6**
Mongal F1	100	0.43	0.60	0.67
	75	0.46	0.56	0.55
	50	0.30	0.46	0.55
Pectomech	100	0.71	0.89	0.69
	75	0.54	0.67	0.86
	50	0.65	0.66	0.83
LSD at 0.05		**0.35**		
P. value		**<.001**		

Where, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level, P. value=Probability value

4.6.7 Treatments and their Interaction Effect on Fruit Width (mm) of Tomato Plants

Table 4.17 highlight results on fruit width of tomatoes as influenced by variety (V), irrigation regimes (I), quantity of rice straw mulch (M) and their interactions during the two irrigated seasons. The results revealed significant interaction (2-way) effect of treatments on fruit width in both irrigated seasons (Table 4.17). The first irrigated season recorded significant interaction effect of V x I at 11 WAT ($p<0.01$) and 12 WAT ($p<0.05$) (Table 4.17). The Mongal F1 in combination with 100 % ET_c produced highest mean fruit width of 42.40 mm at 11 WAT and 38.91 mm at 12 WAT due to tolerance level of the variety to the local climate as well as the optimum soil water conditions created by the full irrigation regime. However, the lowest mean fruit width was produced by Pectomech in combination with 50 % ET_c with 29.09 mm at 11 WAT and 30.22 mm at 12 WAT respectively (Table 4.18).

The overall mean fruit width as influenced by Pectomech in combination with deficit irrigation regimes was poor compared with Mongal F1 in combination with deficit irrigation regimes (Table 4.18). The Pectomech variety is highly intolerant to heat stress (Melomey *et al.*, 2019) that could have influenced the fruit size. On the other hand, Mongal F1 variety was well adapted to the climatic conditions of the study area despite the harsh weather conditions of the dry season (Ochar *et al.*, 2019). Several studies have also shown rich diversity across the morphological characteristics of tomato and descriptors displayed large variations in fruit shape, size, productivity, yield components, and fruit quality (Mavromatis *et al.*, 2013; Omar *et al.*, 2019; Salim *et al.*, 2020). The varied soil water conditions especially during critical growth stages of tomato such as the flowering and fruit development stages can cause blossom end rot and fruit cracking affecting fruit quality (Steduto *et al.*, 2012). Though the Pectomech variety was susceptible to blossom end rot especially on the first batch of fruits (Melomey *et al.,* 2019), the effect was rather more on the fruit length.

The varieties in combination with full irrigation regime resulted in optimum soil water conditions in the rootzone of plants which enhanced cell enlargement and other plant metabolic activities that led to bigger fruit size (Tadesse, 1997). The tomato fruit consist of above 90 % water, therefore limiting the amount of irrigation water applied to the plant during its critical growth stages like flowering and fruit development could result in a drastic reduction on yield and quality (Tsige *et al*., 2016). Meanwhile, soil water stress conditions in the rootzone imposed by the deficit irrigation regimes lowered transpiration rate by plants; increased plant canopy temperature and resulted in the detrimental effect on fruit size of tomato (Pask *et al*., 2012). Abdel-Razzak *et al*. (2016) found that, the application of full irrigation regime of 100 % ET_c produced bigger size fruits of tomatoes.

Also in the first irrigated cropping season, the interaction effect of I x M levels; thus, 100 % ET_c in combination with 3 t/ha rice straw mulch resulted in highest fruit width of 37.18 mm, followed by 100 % ET_c in combination with 6 t/ha with fruit width of 36.39 mm at 11 WAT (Table 4.19). However, the 50 % ET_c in combination with 0 t/ha (no-mulch) resulted in lowest fruit width of 31.52 mm (Table 4.19). The trend of results suggested that deficit irrigation regimes in combination with no-mulch treatment produced small size fruits. According to findings by Wang *et al*. (2012), irrigation depths and scheduling of irrigation application significantly affected tomato fruit width. On the other hand, fruit size of tomato was improved under deficit irrigation regimes in combination with rice straw mulch. The fruit width obtained by the higher levels of the two factors reiterates the need for adequate soil water conditions throughout the growth stages of tomatoes. Rice straw mulch has a strong potential of improving the soil environment as well as the physiological performance of tomato plants.

Finally, the interaction effect of V x M was significant in both seasons (Table 4.17). The Mongal F1 in combination with 6 t/ha rice straw mulch produced fruits with highest mean width of 39.41 mm, followed by Mongal F1 in combination with 3 t/ha rice straw mulch with 38.34 mm at 11 WAT (Table 4.20). The same trend was observed at 12 WAT in the first irrigated season, where Mongal F1 in combination with 6 t/ha rice straw mulch produced highest fruit width of 37.04 mm (Table 4.20). Furthermore, in the second irrigated season, Mongal F1 in combination with 6 t/ha rice straw mulch produced highest fruit width of 43.08 mm, followed by Mongal F1 in combination with 3 t/ha rice straw mulch with 41.38 mm. However, Pectomech in combination with no-mulch produced lowest mean fruit width of 29.68 mm (Table 4.20). The rice straw mulch helps to conserve soil water within the plant's rootzone for prolong use in the physiological processes of plants. The adequate conserved soil water help improves the transpiration rates of plants leading to high crop performance such as improved fruit size (Taromi *et al*., 2019; Parkash and Singh, 2020). Kirnak *et al.* (2001) reported on the huge potential of mulches in overcoming the negative influence of deficit irrigation on the growth of plants. The no-mulch treatment encourages evaporation of water, thereby increasing the stress conditions in the soil. This limits transpiration by plants as well as uptake of essential soil nutrients such as nitrogen leading to poor physiological performance of the crop. Soil water stress condition reduces the water content of tomato plants (Seng, 2014).

Table 4.17: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Fruit Width (mm)

Treatment	**Fruit Width (mm)**			
	2020/21		**2021/22**	
Tomato variety (V)	11WAT	12WAT	11WAT	12WAT
Mongal F1	38.01	35.96	41.12	39.15
Pectomech	30.15	31.81	36.01	36.97
LSD $_{(0.05)}$	4.53^{**}	3.15^{*}	3.75^{*}	3.13^{ns}
P. value	0.01	0.03	0.02	0.11
Irrigation regimes (%ET$_C$) (I)				
100	36.48	35.31	39.75	38.73
75	33.78	34.26	37.90	38.20
50	31.99	32.09	38.05	37.25
LSD $_{(0.05)}$	1.57^{***}	1.81^{**}	2.48^{ns}	2.03^{ns}
P. value	<0.001	0.01	0.24	0.31
Quantity of rice straw (t ha^{-1}) (M)				
6	34.73	34.26	39.35	39.17
3	34.53	34.30	38.96	37.98
0	32.99	33.10	37.40	37.03
LSD $_{(0.05)}$	0.95^{**}	1.21^{ns}	1.55^{*}	1.36^{*}
P. value	0.001	0.09	0.04	0.01
Interaction effects (LSD at 0.05)				
V x M	4.26^{*}	2.90^{**}	3.47^{*}	2.91^{ns}
V x I	4.18^{**}	3.11^{*}	3.89^{ns}	3.22^{ns}
I x M	1.99^{*}	2.40^{ns}	3.19^{ns}	2.69^{ns}
V x I x M	4.28^{ns}	3.75^{ns}	4.78^{ns}	4.04^{ns}
CV (%)	4.80	6.10	6.90	6.10

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value; Probability value*

Table 4.18: Interaction Effect of Variety (V) and Irrigation Regimes (I) (V x I) on Fruit Width (mm)

Treatment	Fruit Width (mm)					
	Irrigation regimes (I) (%ETc)					
	50	75	100	50	75	100
Variety (V)	11 WAT			12 WAT		
Mongal F1	34.90	36.74	42.40	33.95	35.01	38.91
Pectomech	29.09	30.81	30.55	30.22	33.52	31.70
LSD at 0.05	4.18			3.11		
P. value	0.002			0.02		

*Where, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value=Probability value*

Table 4.19: Interaction Effect of Irrigation Regimes (I) and Quantity of Rice Straw Mulch (M) on Fruit Width (mm)

Treatments	Fruit Width (mm) at 11 WAT		
	Mulch (I) (t/ha)		
Irrigation regimes (I) (%ETc)	0	3	6
100	35.86	37.18	36.39
75	31.58	34.65	35.11
50	31.52	31.76	32.70
LSD at 0.05	1.99		
P. value	0.045		

Where; LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. P. value=Probability value

Table 4.20: Interaction Effect of Variety (V) and Quantity of Rice Straw Mulch (M) on Fruit Width (mm)

Treatment	**Fruit Width (mm)**								
	Mulching (M) (t ha^{-1})								
	0	**3**	**6**	**0**	**3**	**6**	**0**	**3**	**6**
Variety (V)	**2020/21 @ 11WAT**			**2020/21@12WAT**			**2021/22@11WAT**		
Mongal F1	36.29	38.34	39.41	33.95	36.89	37.04	38.97	41.38	43.03
Pectomech	29.68	30.72	30.06	32.24	31.72	31.48	35.83	36.54	35.67
LSD at 0.05	4.26			2.90			3.47		
P. value	0.02			0.004			0.03		

Where, LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. P. value=Probability value

4.6.8 Treatments and their Interaction Effect on the Fruit Length (mm) of Tomatoes

Table 4.21 highlight results on fruit length of tomato as influenced by variety, irrigation regimes and quantity of rice straw mulch levels and their interactions during the two irrigated cropping seasons. However, the interaction effect on fruit length was significantly present only in the first irrigated season (Table 4.21). The interaction effect of variety and deficit irrigation regime (V x I) was significant ($p<0.01$) at 11 WAT (Table 4.21). The Mongal F1 in combination with 100 % ET_c produced highest fruit length of 35.22 mm, followed by Pectomech in combination with 75 % ET_c with fruit length of 33.75 mm. Meanwhile, Mongal F1 in combination with 50 % ET_c produced fruits with lowest length of 30.95 mm probably due to soil water stress condition posed by the severely stressed irrigation regime (Table 4.22). The trend of results clearly depicts the role of adequate soil water in improving fruit size of tomato plants. This agrees with findings of Shammout *et al*. (2018) on sweet pepper when they found that, the application of 100 % ET_c gave the longest mean fruit length compared to the deficit regimes of 80 % ET_c and 60 % ET_c. This could be driven mainly by proper cell enlargement and other plant metabolic activities that resulted from the adequate availability of soil water supplied by the full irrigation (Tadesse, 1997). The deficit irrigation regimes posed soil water stress conditions that decreased the transpiration rate of plants especially during critical growth stages and led to the reduction in fruit length (Medyoun *et al.*, 2021; Parkash *et al.*, 2021). The poor transpiration rate by plants contributed to increased plant canopy temperature that affected growth and fruit quality of tomato (Pask *et al*., 2012). Abdel-Razzak *et al*. (2016) found that, the application of full irrigation regime of 100 % ETc produced bigger size fruits of tomatoes.

Furthermore, the Pectomech variety in combination with irrigation regimes produced fruit length with greater grand mean compared to Mongal F1 in combination with irrigation regimes (Table 4.22). The conical-oval fruit shape of Pectomech variety contributed significantly to the wider fruit length observed in the results. The variation in fruit length could also be attributed to the different tolerant levels of varieties at different growth stages to soil water stress conditions (Liu *et al.*, 2006; Mohawesh, 2018; Singh *et al*., 2019), as well as the environmental factors pertaining to the field (Parkash *et al.*, 2021).

Also, the interaction effect of variety and quantity of rice straw mulch (V x M) was significant (($p<0.05$) at 12 WAT (Table 4.22). Surprisingly, Pectomech in combination with no-mulch (0 t/ha) produced highest fruit length of 38.18 mm, followed by Pectomech in combination with 3 t/ha rice straw with 36.78 mm and thirdly by Pectomech in combination with 6 t/ha rice straw with 36.43 mm (Table 4.22). The trend suggested a decline in fruit length of Pectomech with increasing quantity of rice straw mulch. However, an inverse trend in results was observed when Mongal F1 in combination with 6 t/ha rice straw mulch produced highest fruit length of 32.11 mm, followed by Mongal F1 in combination with 3 t/ha rice straw mulch with 31.31 mm. The lowest fruit length was produced by Mongal F1 in combination with no-mulch with 30.46 mm (Table 4.22). The trend could be attributed to the dense canopy architecture of Pectomech especially at the vegetative stage that played a significant role in protecting the soil surface from evaporation of water. This phenomenon minimised the relevance of rice straw mulch as a protective cover and resulted in greater fruit length for no-mulch treatment combination. However, the application of rice straw mulch in combination with Mongal F1 significantly affected fruit length due to the role of mulch material in protecting the soil surface layer from evaporation of water.

The less dense canopy architecture of Mongal F1 variety allowed for the transmission of heat to un-mulched soil surface that led to evaporation of water and resulted in poor fruit size. The results emphasized the importance of rice straw mulch in soil water conservation for improved vegetable crop variety grown under irrigation systems.

Table 4.21: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Fruit Length (mm)

Treatment	Fruit Length (mm)			
	2020/21		2021/22	
Tomato variety (V)	**11WAT**	**12WAT**	**11WAT**	**12WAT**
Mongal F1	32.58	31.29	34.92	33.06
Pectomech	33.41	37.13	40.37	40.72
LSD $_{(0.05)}$	3.97^{ns}	2.24^{**}	2.18^{**}	1.96^{**}
P. value	0.55	0.004	0.004	0.001
Irrigation regimes (%ETc) (I)				
100	34.28	34.48	38.07	36.85
75	32.67	34.49	37.34	37.23
50	32.04	33.66	37.54	36.60
LSD $_{(0.05)}$	1.04^{**}	2.28^{ns}	2.53^{ns}	1.96^{ns}
P. value	0.001	0.67	0.82	0.78
Quantity of rice straw (t/ha) (M)				
6	33.53	34.27	38.21	37.43
3	32.62	34.04	37.73	36.64
0	32.85	34.32	37.00	36.61
LSD $_{(0.05)}$	0.80^{ns}	1.20^{ns}	1.97^{ns}	1.51^{ns}
P. value	0.07	0.88	0.47	0.46
Interaction effects (LSD at 0.05)				
V x M	3.75^{ns}	2.17^{*}	2.71^{ns}	2.21^{ns}
V x I	3.70^{**}	2.98^{ns}	3.21^{ns}	2.57^{ns}
I x M	1.48^{ns}	2.74^{ns}	3.64^{ns}	2.80^{ns}
V x I x M	3.68^{ns}	3.71^{ns}	4.94^{ns}	3.86^{ns}
CV (%)	4.10	6.00	9.00	7.00

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value; Probability value*

Table 4.22: Interaction Effect of Variety (V) and Irrigation Regimes (I) (V x I), Variety (V) and Quantity of Rice Straw Mulch (M) (V x M) on Fruit Length of Tomatoes

Treatment	**Fruit Length (mm)**					
	Irrigation regimes (I)(%ETc)			**Quantity of rice straw mulch (M) (t ha^{-1})**		
Variety (V)	**50**	**75**	**100**	**0**	**3**	**6**
	11 WAT			**12 WAT**		
Mongal F1	30.95	31.59	35.22	30.46	31.31	32.11
Pectomech	33.14	33.75	33.35	38.18	36.78	36.43
LSD at 0.05	3.70			2.17		
P. value	0.001			0.02		

Where, LSD; Least significance difference of means at 95 % confidence level. WAT; Weeks after Transplanting. P. value=Probability value

4.6.9 Treatments and Their Interaction Effect on Total Fruit Yield (TFY) (t ha^{-1})

Table 4.23 highlight results on total fruit yield (TFY) of tomato as influenced by the treatments during the two irrigated cropping seasons. The interaction effect of treatments on TFY of tomatoes was non-significant ($p>0.05$) in the first irrigated season. Therefore, discussions would focus on main effects on treatment on TFY. The effect of variety on total fruit yield was significant ($p<0.05$) (Table 4.23). The Mongal F1 variety produced significantly ($p<0.05$) higher TFY than popular Pectomech. The Mongal F1 produced 12.08 t ha^{-1} TFY representing 184 % higher than that obtained by Pectomech (4.26 t ha^{-1}). The mean TFY produced by Pectomech was below the grand mean of 8.17 t ha^{-1} (Table 4.23) and far below the national achievable average of 7.5 t ha^{-1} (MoFA, 2013). The Mongal F1 was well adapted to the climate of the dry season of the study area and efficiently utilized soil water that translated in the high mean TFY (Ochar *et al.*, 2019). The environmental factors of the field during crop growth could influence varietal response to soil water stress leading to the variations in fruit yield (Lekshmi and Celine, 2015; Parkash *et al.*, 2021)

Steduto *et al*. (2012) reported that, ambient temperatures above 27 °C together with high relative humidity had detrimental effect on the growth and yield of crops. The condition was observed in the months of January and February in each growing season when the crop was at its critical growth stages. Research findings by Melomey *et al.* (2019) reported that, the Pectomech tomato variety is highly intolerant to heat stress and could have contributed to the low fruit yield.

Also, the effect of deficit irrigation regimes on TFY was significant ($p<0.05$) (Table 4.23). The full irrigation regime produced higher TFY than the deficit irrigation regimes. The full (100 % ETc) irrigation regime produced highest TFY of 9.56 t ha^{-1}, followed by the slightly stressed regime (75 % ETc) with 8.04 t ha^{-1} and finally the severely stressed regime (50 % ETc) with 6.91 t ha^{-1} (Table 4.23). The full irrigation obtained 19% higher TFY over the slightly stressed regime (75 % ETc) and 38 % over the severely stressed regime of 50 % ETc. The results corroborate with findings by Pulvento *et al.* (2008); Abdel-Razzak *et al*. (2016); Nangare *et al*. (2016); Giuliani *et al*. (2018); Ganeva *et al*. (2019) who reported decrease in fruit weight as influenced by deficit irrigation regimes. Also, findings by Taromi *et al*. (2019) reported that, total fruit yield of tomato was highest under full irrigation treatment of 100 % ETc, followed by the deficit regime of 70 % ET_c and finally by the severely stressed regime of 50 % ETc. In Nigeria, Igbadun *et al*. (2012) investigated the response of onion yield and water productivity as influenced by managed deficit irrigation and mulching. They found that onion bulb yield was reduced by 50 % for 25% ET_c, and 16 – 23 % for 50 % ET_c. However, 75 % ET_c was not significant ($p>0.05$) in yield reduction compared to 100% ET_c (Igbadun *et al.*, 2012). The application of full irrigation requirement provided optimum soil water condition needed by the tomato plants to increase TFY (Biswas *et al.,* 2015; Hott *et al.*, 2018). In the findings of a study by Kebede (2019), application of full irrigation (100 % ETc) resulted in greater bulb yield of onion compared with yield of the deficit irrigation regime of 60 % ET_c. The severely stressed irrigation regime resulted in stomata closure; hence reduction in leaf stomatal conductance and transpiration rate by plants that negatively influenced fruit yield of tomato (Liu *et al.*, 2003; Parkash and Singh, 2020).

In addition, the quantity of rice straw mulch significantly ($p<0.001$) influenced TFY of tomatoes (Table 4.23). The 6 t ha^{-1} rice straw mulch resulted in highest TFY of 9.42 t ha^{-1}, followed by the 3 t ha^{-1} rice straw mulch with 8.84 t ha^{-1} and finally by the no-mulch (0 t ha^{-1}) with 6.24 t ha^{-1} (Table 4.23). The 6 t ha^{-1} rice straw mulch produced 7 % more TFY over the 3 t ha^{-1} and 51 % over the no-mulch treatment. The results corroborates the findings of Igbadun *et al*. (2012) who found that, the mulch treatment recorded 12 – 15 % yield increase compared to non-mulched conditions. The evidence on the benefits of mulching was more pronounced by Malik *et al*. (2018), in their studies on sugar beet in areas of limited water supply. The authors reported an increase from 11.96 to 19.45 % root yield for mulched treatments compared to no-mulch treatment. Also, mulching improved plant growth and yield of strawberry (Fan *et al.*, 2012). Also, Kebede (2019) reported significant gain in bulb yield of onion under mulching compared to the no-mulch control. As observed, adequate soil water played a key role in the growth and yield response of tomato: therefore, high levels of rice straw mulch; thus, 6 t ha^{-1} helped to conserve soil water for prolong use by plants to take up soil nutrients as well as maintaining high transpiration rate and photosynthesis especially during the critical growth stages that eventually translated in the increase in TFY. The no-mulch on the other hand, contributed to soil water stress conditions in the rootzone of plants due to high evaporation rates of the area. Soil water stress conditions trigger the closure of stomata by plants that leads to a reduction in transpiration rates and a resultant decrease in TFY (Liu *et al.*, 2003; Parkash and Singh, 2020).

In a comparative study by Ahmad *et al.* (2011) on mulching using rice straw, sugarcane straw and wheat straw and no-mulch as control on chilli pepper, the authors reported significant gains in fruit weight for mulched plots than the un-mulched plots. Kamal and Shashi (2012), also reported an increase in fruit yield of tomato from 20.7 to 29.8 % for the temperate region of Uttarakhand. The use of black plastic mulch increased Okro yields significantly by 30 % over no-mulch treatment (Patel *et al*., 2009). Further, the benefit associated with the use of black plastic mulch was reported by Berihun (2011) with fruit yield of 55.32 t ha^{-1} and 70.85 t ha^{-1} for two seasons. The authors; Biswas *et al*. (2015) reiterated that, the combination of mulching with drip irrigation is relevant for water savings and improving tomato fruit yield. The authors reported tomato fruit yield of 79.49 t ha^{-1} and 81.12 t ha^{-1} for rice straw and polyethylene mulch, respectively. Also, the effect of high soil surface and leaf canopy temperatures on the physiological processes of the tomato plant was reduced drastically under the rice straw mulch compared to the no-mulch control.

Most importantly, interaction effect of variety (V) and quantity of rice straw (M) thus; V x M was significant ($p<0.05$) during the second irrigated cropping season (Table 4.23). The Mongal F1 in combination with levels of rice straw mulch produced higher TFY than that produced by Pectomech and levels of rice straw mulch (Figure 4.29). The Mongal F1 in combination with 6 t ha^{-1} rice straw mulch produced highest TFY of 11.93 t ha^{-1}, followed by Mongal F1 in combination with 3 t ha^{-1} with 10.83 t ha^{-1} (Figure 4.29). The Mongal F1 in combination with 6 t ha^{-1} mulch produced 120 % more TFY over Mongal F1 in combination with no-mulch treatment (Figure 4.29). However, the overall lowest TFY was produced by Pectomech in combination with no-mulch with 2.18 t ha^{-1} (Figure 4.29). Several authors including; Osei-Bonsu and Asibuo (2013) and Kassahun, (2017) have reported on significant yield increase amounting to 100 % for management strategies compared to the lowest yield by the un-mulched treatment. Therefore, the role of rice straw mulch in soil water conservation under dry and water limited environments cannot be overemphasized. It is evident from the results that, soil water conserved by each level of rice straw mulch positively contributed to the increase in TFY of tomato plants.

Table 4.23: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Total Fruit Yield (TFY)

Treatment	**Total Fruit Yield (TFY) (t ha^{-1})**	
Tomato variety (V)	**2020/21**	**2021/22**
Mongal F1	12.08	9.39
Pectomech	4.26	4.08
LSD $_{(0.05)}$	4.72*	7.70^{ns}
P. value	0.01	0.12
Irrigation regimes (%ET$_c$) (I)		
100	9.56	7.24
75	8.04	6.87
50	6.91	6.10
LSD $_{(0.05)}$	1.89*	2.66^{ns}
P. value	0.03	0.65
Quantity of rice straw (t ha^{-1}) (M)		
6	9.42	8.54
3	8.84	7.88
0	6.24	3.80
LSD $_{(0.05)}$	0.97***	1.20***
P. value	<.001	<.001
Interaction effects (LSD at 0.05)		
V x M	4.45^{ns}	7.39*
V x I	4.37^{ns}	7.10^{ns}
I x M	2.25^{ns}	3.05^{ns}
V x I x M	4.53^{ns}	7.14^{ns}
CV (%)	20.20	30.40

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value -Probability value at 0.05*

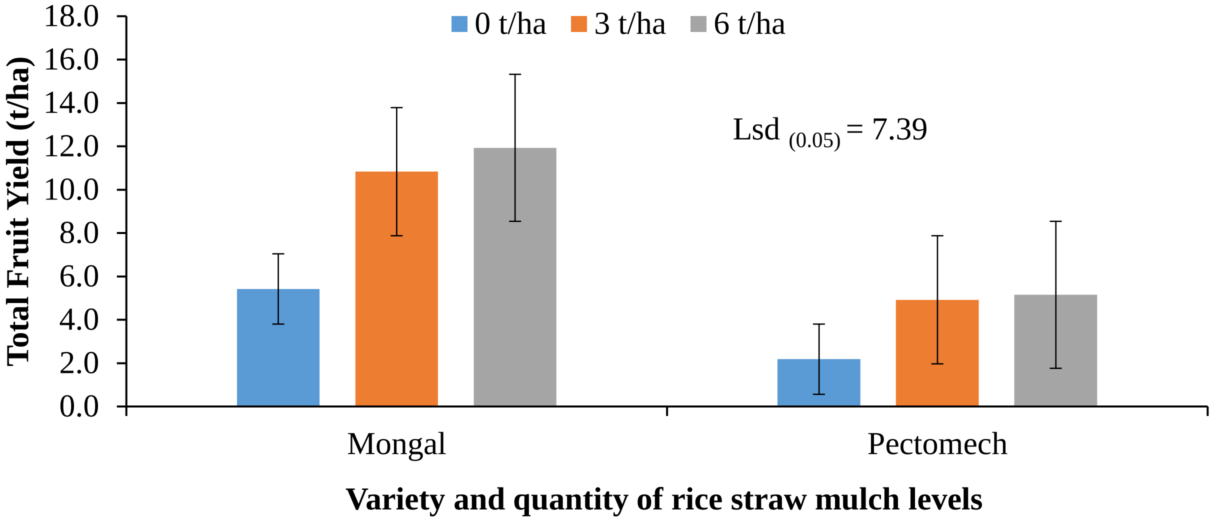

Figure 4.29: Interaction Effect of Variety and Quantity of Rice Straw Mulch on Total Fruit Yield (TFY) of Tomato

4.6.10 Treatments and Their Interaction Effect on Fruit pH and Brix Content of Tomato

4.6.10.1 Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interaction on Fruit pH

Table 4.24 presents result on the effect of variety, irrigation regimes, quantity of rice straw mulch and their interaction on fruit pH of tomatoes during the two irrigated cropping seasons. The results revealed significant ($p<0.01$) interaction (3-way) effect of treatments; thus, V x I x M in both irrigated seasons (Table 4.24). In the first irrigated cropping season, Pectomech in combination with 100 % ET_c and 3 t/ha rice straw as well as Pectomech in combination with 75 % ET_c and 6 t/ha rice straw mulch produced fruits with highest pH of 4.48, followed by Pectomech in combination with 100 % ET_c and no-mulch with a pH of 4.47 (Table 4.25). However, Pectomech in combination with 75 % ET_c and 3 t/ha rice straw mulch produced fruits with lowest pH of 4.24, followed by Mongal F1 in combination with 50 % ET_c and 6 t/ha rice straw mulch with pH of 4.29 (Table 4.25). The results agree with studies by Karaer *et al.* (2020) on table tomatoes, when they reported higher fruit pH of 4.60 for treatment combination of full irrigation and mulching (I100×M) and pH of 4.57 for full irrigation and no-mulch control (I100×NM) during the first season. The authors again measured fruit pH of 4.62 for the treatment combination of full irrigation and mulching (I100×M) during the second season. Also, research by the following authors: Ünlü *et al*. (2006); Lahoz *et al*. (2016); Tarı and Sapmaz, (2017) found similar trend where decrease in irrigation water applied resulted in decrease in fruit pH. The results further suggested that Mongal F1 variety produced more acidic fruits compared to the Pectomech. The pH and acidity indicators are relevant in describing the fruit quality of tomatoes. According to Taromi *et al*. (2019), lower fruit pH measurement, increases the risk of fruit spoilage during storage (Taromi *et al*., 2019). This implies that, Mongal F1 when subjected to shelf-life studies has the tendency of high spoilage than the landrace tomato variety; Pectomech due to its high acidic content. However, the authors; Atherton and Rudich (2012) brought to light that, tomato fruits with lower pH are most preferred by consumers and easily sells in the market. This assertion is binding on the Mongal F1 due to its appealing nature; thus, low pH, attractive and uniform color as well as presentable fruit shape. Studies by Ochar *et al*. (2019), reported on the high physiological performance of hybrid tomato genotypes such as Mongal F1 over the landraces

In contrast, the second irrigated cropping season had Pectomech in combination with 75 % ET_c and no-mulch treatment emerging with highest fruit pH of 6.69, followed by Mongal F1 in combination with 50 % ET_c and 3 t/ha rice straw mulch with 6.23 (Table 4.25). The lowest fruit pH of 5.68 was obtained by Mongal F1 in combination with 100 % ET_c and 0 t/ha (no-mulch) (Table 4.25). The results corroborate findings by Patanè *et al.* (2011); Abdel-Razzak *et al*. (2013); Abdel-Razzak *et al.* (2016); Taromi *et al.* (2019); Alordzinu *et al.* (2022). For example, studies by Abdel-Razzak *et al*. (2016) found that severely stressed irrigation regime of 50 % ET_c resulted in the increasing in fruit pH. Also, Alordzinu *et al.* (2022) found that, soil water stress between 40 – 50 % (ET_o) produced tomato fruits with higher pH and titratable acidity compared to fruits under 50 – 60 % (ET_o), 60 – 70 % (ET_o) and 70 - 100 % (ET_o) treatments in a pot experiment under greenhouse conditions. The disparities in observed trend could be because of environmental variations such as soil and weather conditions across the seasons. The field was left fallow, and plots maintained in the second irrigated cropping season that might have influenced the results.

Table 4.24: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Fruit pH of Tomatoes

Treatment	Fruit pH	
	2020/21	2021/22
Variety (V)		
Mongal F1	4.36	5.87
Pectomech	4.38	6.16
LSD (0.05)	0.05^{ns}	0.08^{**}
P. value	0.13	0.001
Irrigation regimes (%ET_c) (I)		
100	4.41	5.93
75	4.37	6.02
50	4.34	6.09
LSD (0.05)	0.03^{**}	0.08^{**}
P. value	0.003	0.002
Quantity of rice straw mulch (tha^{-1}) (M)		
6	4.38	6.01
3	4.35	5.98
0	4.38	6.04
LSD (0.05)	0.03^{*}	0.07^{ns}
P. value	0.04	0.22
Interaction effect (LSD at 0.05)		
V x M	0.04^{**}	0.10^{***}
V x I	0.04^{*}	0.10^{***}
I x M	0.05^{***}	0.12^{***}
V x I x M	0.07^{**}	0.17^{**}
CV (%)	0.90	2.00

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value -Probability value at 0.05*

Table 4.25: Interaction Effect of Variety (V), Irrigation Regimes (I) and Quantity of Rice Straw Mulch (M) (V x I x M) on Fruit pH of Tomatoes

Treatment		Fruit pH					
		Quantity of rice straw mulch (M) (t/ha)					
		0	3	6	0	3	6
Variety (V)	Irrigation regimes (I) (%ET$_c$)	2020/21			2021/22		
Mongal F1	100	4.42	4.38	4.30	5.68	5.71	5.75
	75	4.31	4.36	4.43	5.76	5.83	5.86
	50	4.38	4.33	4.29	5.97	6.32	5.94
Pectomech	100	4.47	4.48	4.39	6.16	6.06	6.23
	75	4.38	4.24	4.48	6.61	5.85	6.21
	50	4.32	4.30	4.41	6.09	6.13	6.09
LSD at 0.05	0.07				0.17		
P. value	0.01				0.002		

Where, LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. P. value=Probability value

4.6.10.2 Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interaction on Fruit Brix Content of Tomatoes

Table 4.26 highlight results on brix content of tomato fruits as influenced by treatments and their interactions during the two irrigated cropping seasons. The interaction effect of treatments on fruit brix content was significant ($p<0.05$) in the first irrigated cropping season. The interaction (3-way) effect of variety, irrigation regimes and quantity of rice straw mulch; thus, V x I x M on fruit brix content was significant ($p<0.001$) (Table 4.26). The Pectomech in combination with irrigation regimes and rice straw gave higher brix content (Table 4.27). The highest brix content was produced by Pectomech in combination with 50 % ET$_c$ and 3 t/ha rice straw mulch with 9.10 %, followed by Pectomech in combination with 50 % ETc and 6 t/ha rice straw mulch with 8.57 %. The lowest brix content was obtained by Mongal F1 in combination with 100 % ET$_c$ and 0 t/ha (no-mulch) with 5.77 %, followed by Mongal F1 in combination with 100 % ET$_c$ and 6 t/ha rice straw mulch with 6.13 % (Table 4.27). The results suggested that deficit irrigation regimes in combination with rice straw mulch levels improved the brix content of tomatoes. The result agrees with findings of several authors including Yin *et al.* (2010); Patanè *et al.* (2011); Helyes *et al.* (2013); Abdel-Razzak *et al*. (2013); Abdel-Razzak *et al*. (2016) and Alordzinu *et al.* (2022). For example, research by Abdel-Razzak *et al*. (2016) found that, severely stressed irrigation regime of 50 % ET_c resulted in an increased fruit brix content. Also, findings by Taromi *et al*. (2019), reported highest brix content for the severely stressed irrigation regime of 50 % ET_c when compared to the other treatments and control. The authors further reported that, the full irrigation (100 % ET_c) produced lowest fruit brix content. Another research by Alordzinu *et al.* (2022) found that, soil water stress between 40 – 50 % (ET_o) produced tomato fruits with higher brix content compared to fruits under 50 – 60 % (ET_o), 60 – 70 % (ET_o) and 70 – 100 % (ET_o) treatments in a pot experiment under greenhouse conditions. The increase in fruit brix content under water stress condition could be attributed to the increase in osmotic potential that led to decline in water stored in tomato plants (Mitchell *et al.*, 1991). The high brix content denotes high sugar levels that increases the sweet taste of fresh tomato fruits; hence higher market value for such fruits (Klunklin and Savage, 2017).

The application of rice straw mulch produced fruits with higher brix content than the no-mulch control. This corrorate findings of Taromi *et al*. (2019), who reported higher fruit brix content for mulched treatment compared to un-mulched. Also, Karaer *et al.* (2020) found significant differences in fruit brix content of table tomatoes that was affected by mulching and irrigation. The authors observed that, highest fruit brix content of 23.12 % was obtained by full irrigation (100 %) in combination with mulch, followed by slight irrigation (75 %) in combination with mulch with 22.62 %, and lastly by slight irrigation (75 %) in combination with no-mulch treatment with 22.61 %.

Table 4.26: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Fruit Brix Content of Tomatoes

Treatment	**Fruit brix content (%)**	
	2020/21	**2021/22**
Variety (V)		
Mongal F1	6.42	5.39
Pectomech	7.94	5.84
LSD $_{(0.05)}$	0.22^{**}	0.36^{*}
P. value	0.001	0.03
Irrigation regimes (%ET$_c$) (I)		
100	6.73	5.42
75	7.18	5.50
50	7.63	5.91
LSD $_{(0.05)}$	0.05^{***}	0.54^{ns}
P. value	<.001	0.15
Quantity of rice straw mulch (tha^{-1}) (M)		
6	7.16	5.59
3	7.28	5.60
0	6.73	5.65
LSD $_{(0.05)}$	0.12^{*}	0.50^{ns}
P. value	0.02	0.97
Interaction effect (LSD at 0.05)		
V x M	0.18^{**}	0.62^{ns}
V x I	0.18^{***}	0.65^{ns}
I x M	0.17^{ns}	0.85^{ns}
V x I x M	0.26^{***}	1.16^{ns}
CV (%)	2.40	15.10

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value -Probability value at 0.05*

Table 4.27: Interaction Effect of Variety (V), Irrigation Regimes (I) and Quantity of Rice Straw Mulch (M) (V x I x M) on Fruit Brix Content of Tomatoes

Variety (V)	Irrigation regimes (I) (%ET$_c$)	Quantity of rice straw mulch (M) (t ha^{-1})		
		0	3	6
Mongal F1	100	5.77	6.27	6.13
	75	7.03	6.37	6.40
	50	6.57	6.57	6.67
Pectomech	100	7.53	7.33	7.33
	75	7.43	8.03	7.83
	50	8.33	9.10	8.57
LSD at 0.05		0.26		
P. value		<.001		

Where, LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. P. value=Probability value

4.7 Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interactions on Irrigation Water –Use Efficiency (IWUE) of Tomato

Table 4.28 highlights experimental results on irrigation water-use efficiency (IWUE) as influenced by varieties, irrigation regimes, quantity of rice straw mulch and their interactions during the two irrigated seasons. The increasing water scarcity of the Guinea Savannah Zone of Ghana; thus, unavailable water in good quantity and quality due to competing uses calls for measures to improve water-use efficiency in maintaining adequate water levels in rivers and lakes to sustain ecosystems diversity while meeting demands of industry (Sharma *et al.*, 2015). In line with this, interaction (*2-way*) effect of variety and irrigation regimes (V x I) on IWUE of plants was significant at $P<0.05$ during the first irrigated season (Table 4.28). The mean values of IWUE for the interaction ranged from 0.81- 3.88 kg m^{-3} (Figure 4.30). The highest IWUE was obtained by Mongal F1 in combination with 50 % ET$_c$ (3.88 kg m^{-3}) and the lowest IWUE of 0.81 kg m^{-3} obtained by Pectomech in combination with 100 % ET$_c$ (Figure 4.30). The result corroborates the research findings of several authors, Molden and Oweis, (2007); Tadesse *et al.* (2017); Mubarak and Hamdan, (2018); Ragab *et al.* (2019), who reported that IWUE reduced significantly as irrigation water increased. For example, Shammout *et al*. (2018) assessed irrigation regimes effect on bell pepper yield and water- use efficiency and found that; full (100 %) irrigation gave lowest IWUE whilst the severely stressed irrigation of 60 % gave highest water-use efficiency. On the other hand, under moderate soil water stress conditions, water use efficiency will increase over the full irrigation (Liu *et al.*, 2005; Pazzagli *et al*., 2016). The deficit irrigation levels resulted in an increase in the plant root system (Taromi *et al*., 2019); which enhanced the uptake of essential plant nutrients as well as ensured increase in IWUE (Ngouajio *et al*., 2007). It is worth noting that, the practice of deficit irrigation must be done with caution since the soil water stress conditions posed (Parkash and Singh, 2020), could result in poor physiological and biochemical performance of the crop (Yuan *et al.*, 2016; Sharma *et al.*, 2019). Asenso (2011) further added that, the choice of irrigation method, crop and soil type, irrigation time and amount are very relevant in achieving high water-use efficiency of crops. Walters and Jha, (2016) reported on the significance of drip irrigation method in increasing water-use efficiency of vegetables growing under water scarce environments.

Generally, the Pectomech in combination with irrigation regimes gave much lower grand mean of IWUE (1.07 kg m^{-3}) compared to the grand mean IWUE of 3.06 kg m^{-3} obtained by Mongal F1 in combination with irrigation regimes (Figure 4.30). Mongal F1 hybrid exhibited superiority over its counterpart variety in been efficient in water-use. The authors: Rashidi and Gholami (2008), in their literature review reported the range of Crop Water Productivity (CWP) for tomato to be between 2.58 – 11.88 kg m^{-3}. Based on the CWP reported by the authors, IWUE of Pectomech in combination with deficit irrigation regimes fell below the range of CWP (Figure 4.30). However, the Mongal F1 hybrid in combination with deficit irrigation regimes produced IWUE which is well placed within the CWP range. The variation in environmental conditions over the seasons influenced on how the varieties responded to soil water conditions (Lekshmi and Celine, 2015; Parkash *et al.*, 2021). The Mongal F1 was well acclimatised in the dry season of the study area and efficiently utilised soil water especially under the severe water stress conditions that translated in the high mean IWUE (Ochar *et al.*, 2019). Evans *et al*. (2008) reiterated on the need to maximise crop yield per unit water consumed rather than maximising yield per unit of land area.

Also, the interaction (*2-way*) effect of variety and quantity of rice straw mulch (V x M) on IWUE of plants was significant ($p<0.05$) during the second irrigated cropping season (Table 4.28). The V x M interaction means for IWUE ranged from 0.53 - 3.10 kg m^{-3} (Figure 4.31). The Mongal F1 in combination with 6 t/ha rice straw mulch produced highest IWUE of 3.10 kg m^{-3}, whereas Pectomech in combination with no-mulch treatment recorded the lowest IWUE of 0.53 kg m^{-3} (Figure 4.31). The results of the study suggested that, only Mongal F1 in combination with 3 t/ha and Mongal F1 in combination with 6 t/ha produced IWUE values (Figure 4.31) that fell within the acceptable CWP range of 2.58 - 11.88 kg m^{-3} reported by Rashidi and Gholami (2008). The application of rice straw mulch influenced the varieties to produce higher IWUE. Research by Jain *et al*. (2000) found that, IWUE was significantly affected by plastic mulch and drip irrigation. The rice straw mulch applied significantly reduced soil water loss through evaporation and conserved the water for plant-use. Also, the proper use of crop residue as mulch contributes to conserve soil water and maximise irrigation water and nutrient use (Hochmuth *et al.*, 2001). Shen *et al*. (2012) reported improved IWUE of Maize under straw mulch in arid regions. Liang *et al*. (2011) conducted a study on the influence of plastic film mulch, wheat straw mulch and combined mulch, on the performance of greenhouse hot pepper (*Capsicum annuum* L.). The authors found that

IWUE was significantly affected by mulches; thus, wheat straw mulch obtained 97.9 %, plastic film mulch with 60.1 % and combined mulch obtained 104 % respectively over the control of no-mulch. According to findings by Kassahun (2017), mulching is needed under deficit irrigation strategies to help maximise water-use efficiency of field crops especially vegetables.

Table 4.28: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw Mulch and Their Interaction on Irrigation Water-Use Efficiency (IWUE) of Tomatoes

Treatment	**IWUE (Kg m^{-3})**	
Tomato variety (V)	**2020/21**	**2021/22**
Mongal F1	3.07	2.43
Pectomech	1.07	1.05
LSD $_{(0.05)}$	1.30*	1.91^{ns}
P. value	0.02	0.11
Irrigation regimes (%ET$_c$) (I)		
100	1.74	1.32
75	1.95	1.67
50	2.51	2.22
LSD $_{(0.05)}$	0.53*	0.74^{ns}
P. value	0.02	0.06
Quantity of rice straw (t/ha) (M)		
6	2.43	2.22
3	2.22	2.04
0	1.56	0.95
LSD $_{(0.05)}$	0.27***	0.32***
P. value	<.001	<.001
Interaction effect (LSD at 0.05)		
V x M	1.22^{ns}	1.82*
V x I	1.20*	1.76^{ns}
I x M	0.63^{ns}	0.84^{ns}
V x I x M	1.25^{ns}	1.79^{ns}
CV (%)	22.60	31.50^{ns}

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at $P \leq 0.05$, ** - significantly different at $P \leq 0.01$., *** - significantly different at $P \leq 0.001$, P. value -Probability value at 0.05*

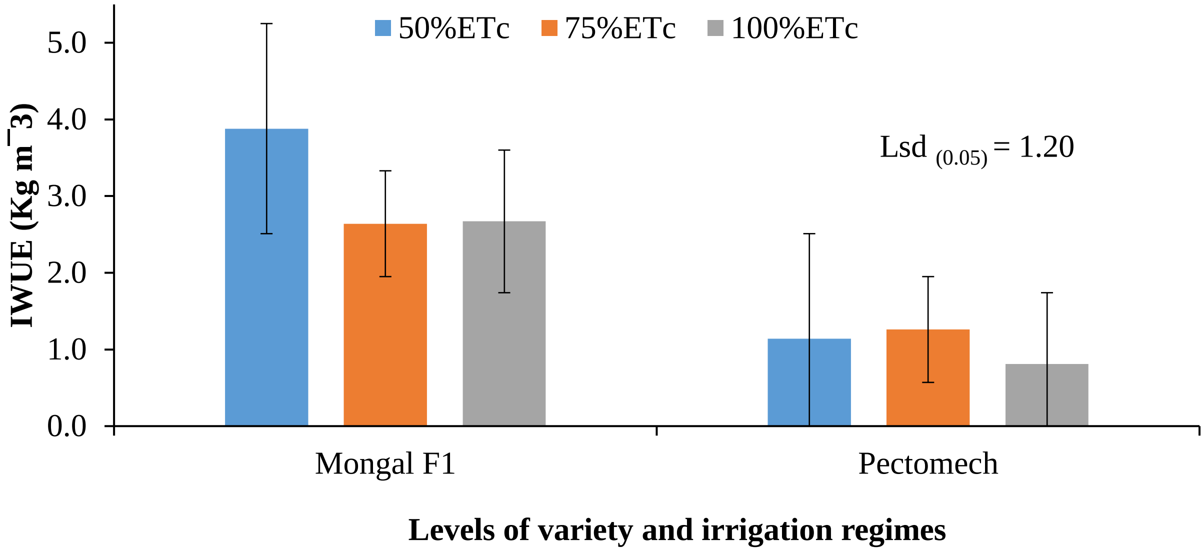

Figure 4.30: Interaction Effect of Variety and Irrigation Regimes on Irrigation Water – Use Efficiency (IWUE)

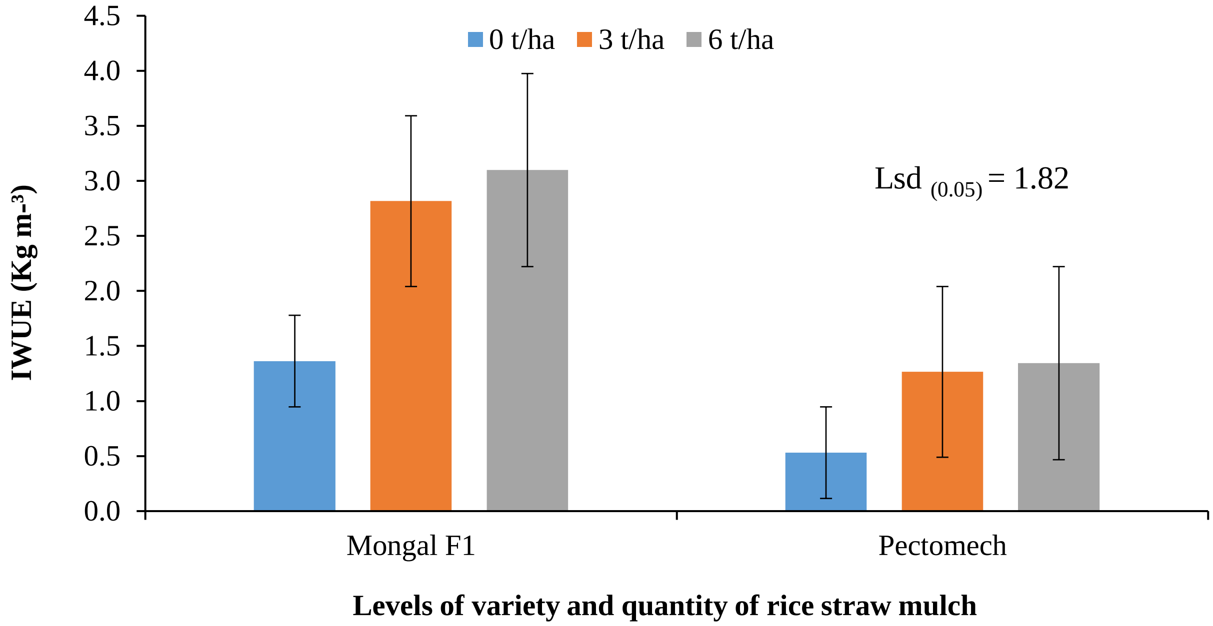

Figure 4.31: Interaction Effect of Variety and Quantity of Rice Straw Mulch on Irrigation Water – Use Efficiency (IWUE)

4.8 Effect of Variety (V), Irrigation Regimes (I), Quantity of Rice Straw Mulch (M) and Their Interactions on CWSI of Tomatoes

Table 4.29 highlight study results on treatment effect on crop water stress index (CWSI) of tomato plants estimated from canopy temperature of plant during the irrigated cropping seasons. Several authors such as Idso *et al.* (1982), have developed baseline equations for tomatoes, however, the study developed a regression baseline equation:$\mathrm{Tc} - \mathrm{Ta} = 5.59 - 2.58\ (\mathrm{VPD})\ (\mathrm{Eqn.}\ 4.1)$, with coefficient of determination (r^2) value of 0.75 to guide in the estimation of CWSI as influenced by the treatments. The results showed significant interaction (3-way) effect of variety, irrigation regimes and quantity of rice straw mulch (V x I x M) on CWSI at 6WAT ($p<0.05$) and 9 WAT ($p<0.05$) (Table 4.29). Mongal F1 in combination with 100 % ETc and 3 t/ha rice straw mulch gave lowest CWSI of 0.03, followed by Mongal F1 in combination with 100 % ET_c and 6 t/ha with 0.12, and thirdly by Mongal F1 in combination with 100 % ET_c and 0 t/ha (no-mulch) with CWSI of 0.18 (Table 4.30). However, the most stressed plants with highest CWSI were produced by Pectomech in combination with 75 % ET_c and 0 t/ha (0.39), followed by Pectomech in combination with 75 % ET_c and 3 t/ha with 0.38 (Table 4.30). The tomato varieties responded differently to CWSI at the different growth stages probably due to their different tolerant levels to soil water stress (Liu *et al.*, 2006; Mohawesh, 2018; Singh *et al.*, 2019). The Mongal F1 appeared to be more tolerant to soil water stress and highly efficient in water-use compared to its counterpart variety, especially during the critical growth (flowering) stage. The CWSI ranged from 0 to 1 scale with 1 depicting higher water stress condition of plants. The environmental conditions at the time could also greatly influence on how the varieties responded to soil water stress conditions (Parkash *et al.*, 2021).

The trend in results showed highest CWSI recorded at the reproductive stage of the crop's development due to the harsh environmental conditions of high temperature and vapor pressure deficit (Ramírez *et al*., 2015). The application of full and mild deficit irrigation regimes in combination with rice straw mulch resulted in lower CWSI compared to the severely stressed irrigation regime of 50 % ET_c in combination with mulch. This agrees with findings reported by López *et al*. (2009) on husk tomato, Ramírez *et al.* (2015) on cherry tomato and Ghaemi *et al.* (2015) on eggplant.

Also, Erdem *et al.* (2005) and Çolak *et al.* (2015) reported higher CWSI under water stress treatments on watermelon and eggplant respectively. The higher CWSI for plants under deficit irrigation regimes could be attributed to the low soil water status within the rootzone of plants that caused decline in transpiration rate due to stomatal closure and resulted in increased leaf temperature and CWSI (Testi *et al.*, 2008; Pask *et al*., 2012; Parkash and Singh, 2020; Medyoun *et al.*, 2021; Parkash *et al.*, 2021).

Table 4.29: Effect of Variety, Irrigation Regimes, Quantity of Rice Straw, and their Interactions on Crop Water Stress Index (CWSI) of Tomato

Treatment	**Crop Water Stress Index (CWSI)**					
	2020/21			**2021/22**		
Variety (V)	**4WAT**	**6WAT**	**9WAT**	**6WAT**	**9WAT**	**11WAT**
Mongal F1	0.35	0.20	0.56	0.43	0.31	0.60
Pectomech	0.32	0.31	0.51	0.42	0.30	0.58
LSD (0.05)	0.23^{ns}	0.02**	0.24^{ns}	0.13^{ns}	0.11^{ns}	0.05^{ns}
P.value	0.60	0.002	0.46	0.91	0.85	0.42
Irrigation regimes (%ET$_c$) (I)						
100	0.35	0.19	0.52	0.38	0.30	0.56
75	0.27	0.26	0.54	0.42	0.27	0.53
50	0.38	0.32	0.53	0.47	0.34	0.67
LSD (0.05)	0.06*	0.096*	0.09^{ns}	0.04***	0.07^{ns}	0.07**
P.value	0.01	0.04	0.93	<.001	0.13	0.003
Quantity of rice straw (t/ha) (M)						
6	0.35	0.23	0.50	0.44	0.29	0.58
3	0.31	0.25	0.55	0.40	0.29	0.58
0	0.34	0.28	0.54	0.44	0.32	0.61
LSD (0.05)	0.07^{ns}	0.05^{ns}	0.06^{ns}	0.05^{ns}	0.08^{ns}	0.06^{ns}
P.value	0.58	0.25	0.17	0.12	0.65	0.54
Interaction effects (LSD at 0.05)						
V x M	0.18^{ns}	0.06^{ns}	0.19^{ns}	0.12^{ns}	0.12^{ns}	0.08^{ns}
V x I	0.18^{ns}	0.11^{ns}	0.18^{ns}	0.12*	0.11^{ns}	0.09*
I x M	0.12^{ns}	0.12^{ns}	0.12^{ns}	0.07^{ns}	0.13^{ns}	0.12^{ns}
V x I x M	0.20^{ns}	0.15*	0.195*	0.13^{ns}	0.18^{ns}	0.15^{ns}
CV (%)	32.30	30.50	15.00	18.00	43.80	18.00

*Where, V x M = Combination of variety and mulching, V x I = Combination of variety and irrigation regimes, I x M = Combination of irrigation regimes and mulching, V x I x M = Combination of variety, irrigation regimes and mulching. CV= Coefficient of variation, ETc= Crop water requirement. LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. * - significantly different at P≤0.05, ** - significantly different at P≤ 0.01., *** - significantly different at P≤0.001, P. value -Probability value at 0.05*

Table 4.30: Interaction (3-Way) Effect of Variety (V), Irrigation Regimes (I) and Quantity Of Rice Straw Mulch (M) (V x I x M) on Crop Water Stress Index (CWSI) of Tomato

Treatment	**Irrigation regimes**	**Quantity of rice straw mulch (M) (t ha^{-1})**		
Variety (V)	**(%ETc) (I)**	**0**	**3**	**6**
Mongal F1	100	0.18	0.03	0.12
	75	0.24	0.14	0.15
	50	0.31	0.36	0.25
Pectomech	100	0.21	0.34	0.24
	75	0.39	0.38	0.26
	50	0.33	0.29	0.36
LSD at 0.05	**0.15**			
P. value	**0.03**			

Where; LSD; Least significance difference of means at 95% confidence level. WAT; Weeks after Transplanting. P. value=Probability value

4.9 Relationship between Irrigation Regimes and Crop Water Stress Index (CWSI)

The relationship between irrigation regimes and CWSI of tomatoes was linear (Figure 4.32 and Figure 4.33). The relationship between measured variables was strong and produced a simple regression model equation of $Y = -0.0012\ (\%\ ET_c) + 0.46$ (Eqn. 4.1) and coefficient of determination (R^2) value of 0.99 (Figure 4.32) during the first season. Meanwhile a simple regression model equation of $Y = -0.0019\ (\%\ ET_c) + 0.57$ (Eqn. 4.2) and an R^2 value of 0.83 was produced for the relationship between deficit irrigation regimes and CWSI during the second season (Figure 4.33). The strong relationship between the variables showed a decline in CWSI with increase in irrigation water depth applied to the crop. The trend implies that, full irrigation regime of 100 % ET_c produced less stressed plants with lower CWSI than the slightly and severely stressed irrigation regimes. However, the severely stressed irrigation regime of 50 % ET_c produced higher plant stress condition and resulted in higher CWSI (Figures 4.32 and 4.33). According to studies by Giuliani *et al.* (2017), irrigation regime treatments of 70 % ET_c and 100 % ET_c produced significant effect on CWSI. The beneficial effect of moderate soil water stress conditions was emphasized at the ripening stage of tomato fruits (Giuliani *et al.*, 2019).

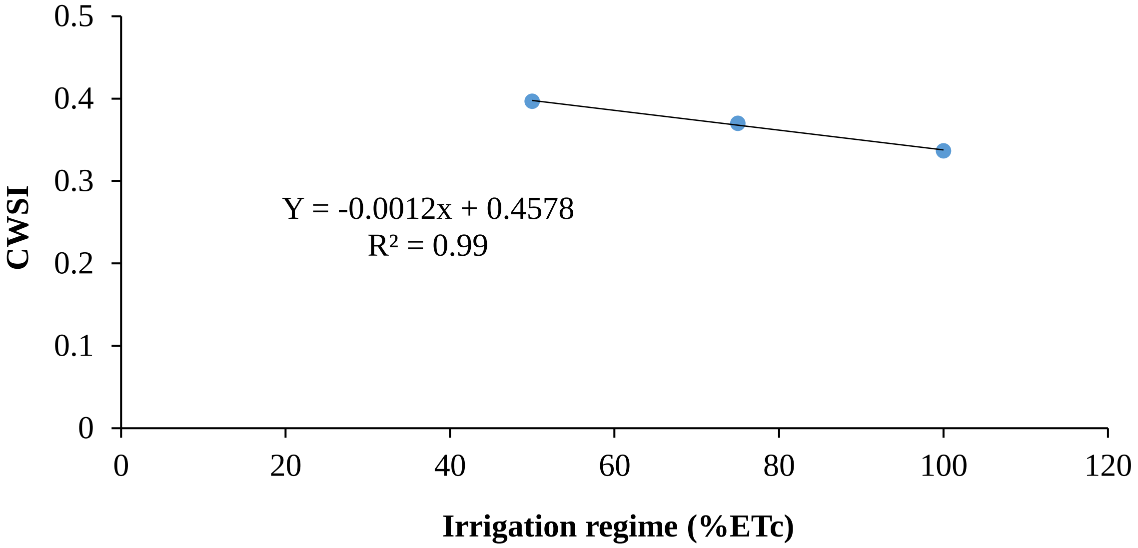

Figure 4.32: Crop Water Stress Index (CWSI) as a Function of Irrigation Regimes during the first irrigated cropping season

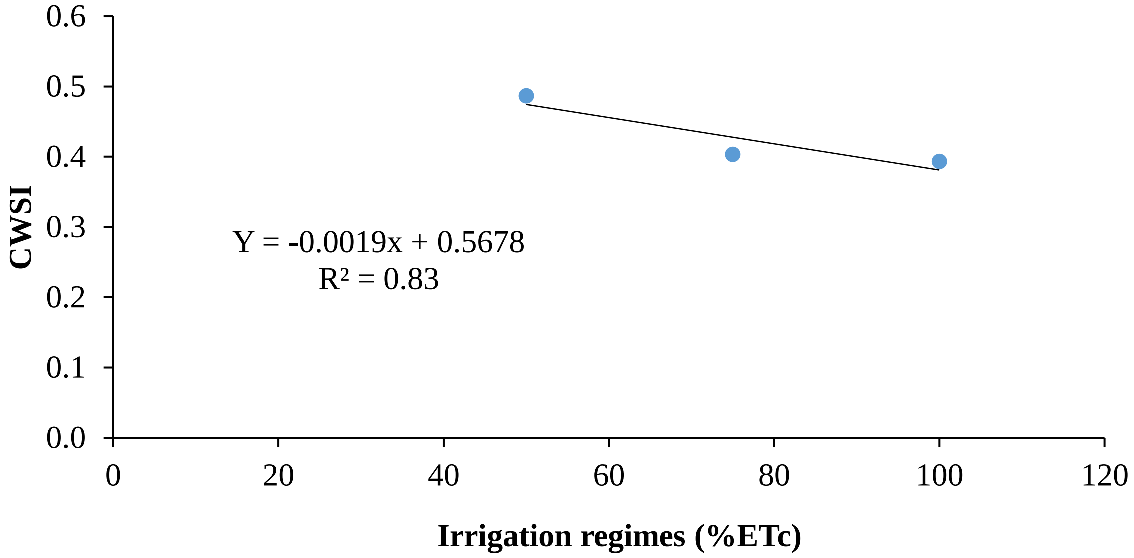

Figure 4.33: Crop Water Stress Index (CWSI) as a Function of Irrigation Regimes during the second irrigated cropping season

4.10 Relationship between Quantity of Rice Straw Mulch and Crop Water Stress Index

The relationship between quantity of rice straw mulch and CWSI was strong and linear (Figure 4.34 and Figure 4.35). The simple regression model equation of Y = -0.0083 (x) + 0.28 (Eqn. 4.3) and R^2 value of 0.89 was produced for the relationship during the first year (Figure 4.34). Also, the second season's relationship between quantity of rice straw mulch and CWSI produced a simple regression model equation of Y = -0.0067 (x) + 0.39 (Eqn. 4.4) and an R^2 of 0.84 (Figure 4.35). The application of rice straw mulch in incremental quantity resulted in decline of CWSI due to the minimal water evaporation and conserved soil water. Meanwhile, the no-mulch treatment with no soil surface produced plants with higher CSWI due to the increased canopy temperature of plants that resulted from the higher soil water losses through evaporation.

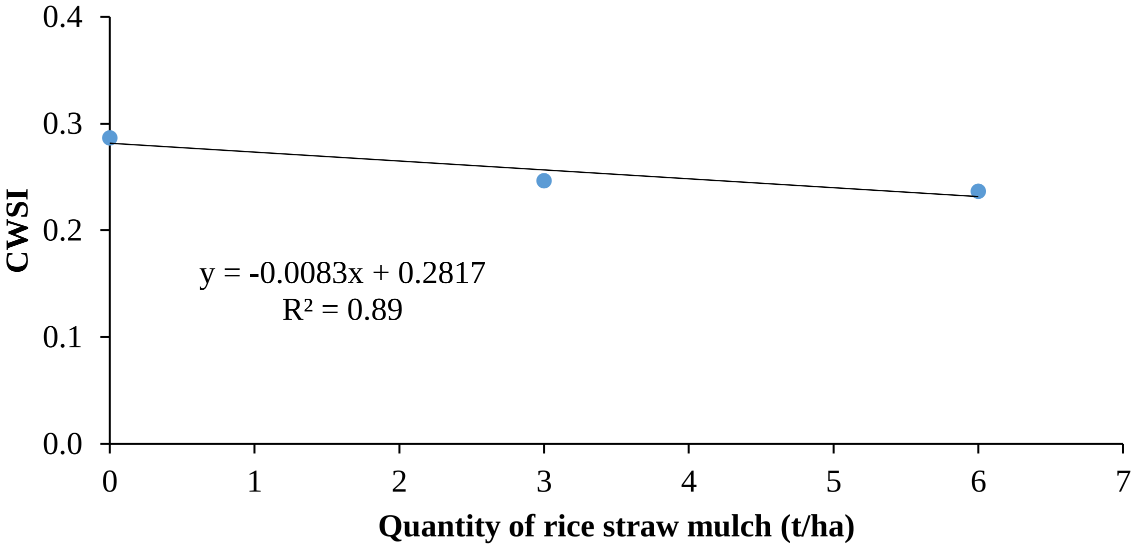

Figure 4.34: Crop Water Stress Index (CWSI) as a Function of Quantity of Rice Straw Mulch during the first irrigated cropping season

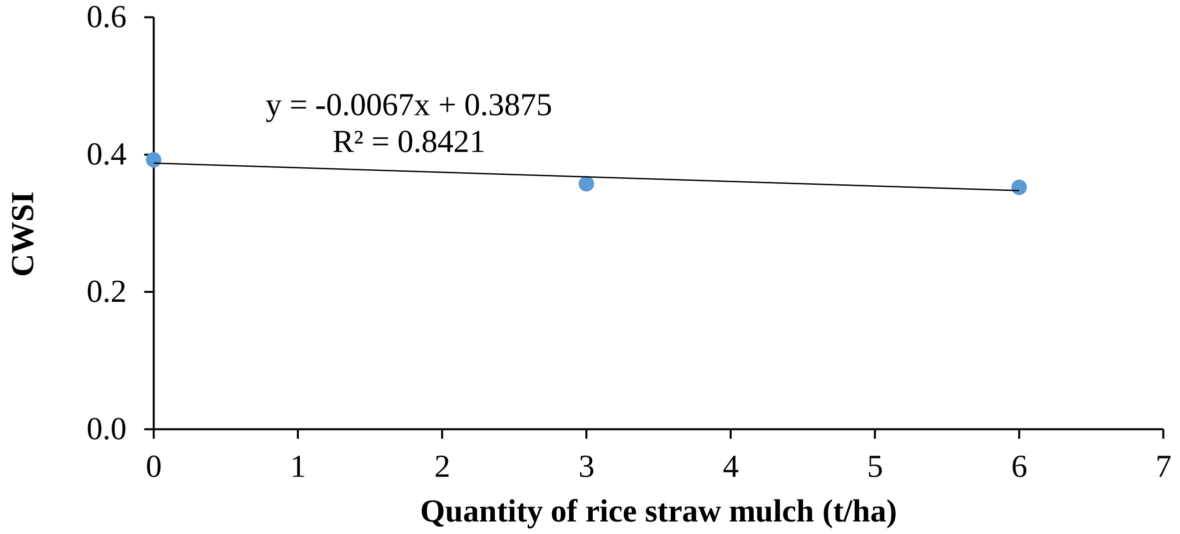

Figure 4.35: Crop Water Stress Index (CWSI) as a Function of Quantity of Rice Straw Mulch during the second irrigated cropping season

4.11 Relationship between Crop Water Stress Index (CWSI) and Tomatoes Fruit Yield (TFY) as affected by Irrigation Regimes

Simple linear relationship between CWSI and tomatoes fruit yield (TFY) under irrigation regimes was strong and linear (Figures 4.36 & 4.37). The relationship produced a simple regression model equation of Y = -44.23 (CWSI) + 24.44 (Eqn. 4.5) and a coefficient of determination (R^2) value of 0.99 during the first season (Figure 4.36). Also, a simple regression model equation of Y = -11.06 (CWSI) + 11.47 (Eqn. 4.6) and R^2 value of 0.95 was recorded during the second season (Figure 4.37). The R^2 values (>0.95) for the relationship is an indication of a stronger correlation between CSWI and TFY under the irrigation regimes applied to the tomato crop. The findings agree with results of a study on broccoli by Erdem *et al*. (2010) were significant correlation (R^2= 0.99) was found for the relationship between CWSI and yield. Similarly, studies on pumpkin plant by Kirnak *et al.* (2019) also found significant correlations for CWSI and attained yield. The strong association between CWSI and crop yield have further been reported by several other authors including (Sezen *et al*., 2014; Çolak *et al*., 2015; Han *et al*., 2018). In addition, studies by Sándor *et al*. (2020), found a best fit linear relationship between CWSI and total yield of tomatoes given an R^2 value of 0.86 at $p < 0.001$ significance level. The authors reiterated that, lower CWSI resulted in higher yield of tomatoes. However, they reported yield dropped below 4 t/ha when CWSI was above 0.51. Similar linear relationship between CWSI and tomato fruit yield was reported by Silva *et al*. (2018). The authors concluded that, lower water stress of plants gave higher fruit yield. The studies reiterate the usefulness of CWSI in predicting crop growth and yield components.

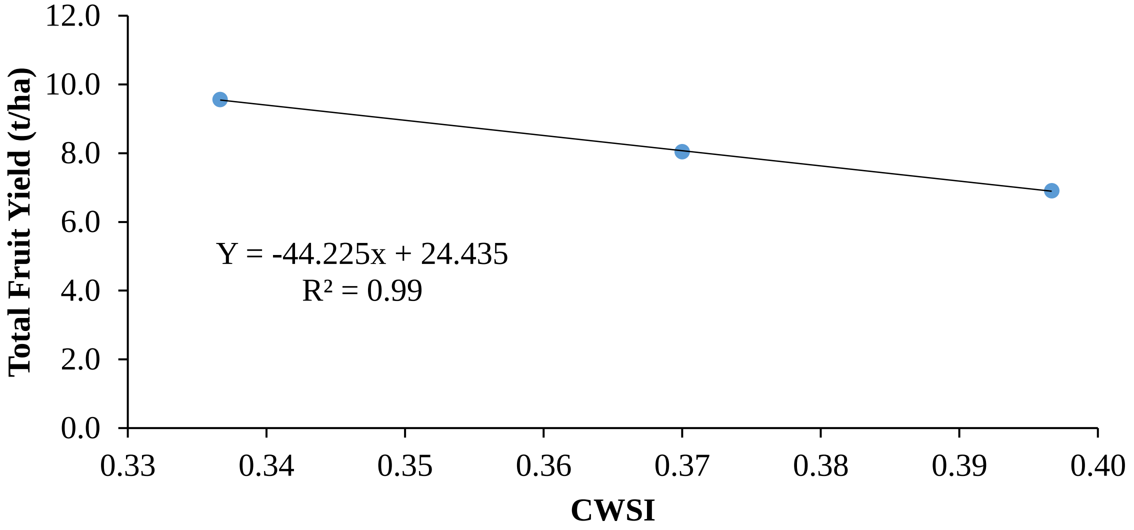

Figure 4.36: Total fruit yield (TFY) as a Function of Crop Water Stress Index (CWSI) Influenced by Irrigation Regimes during the first irrigated cropping season

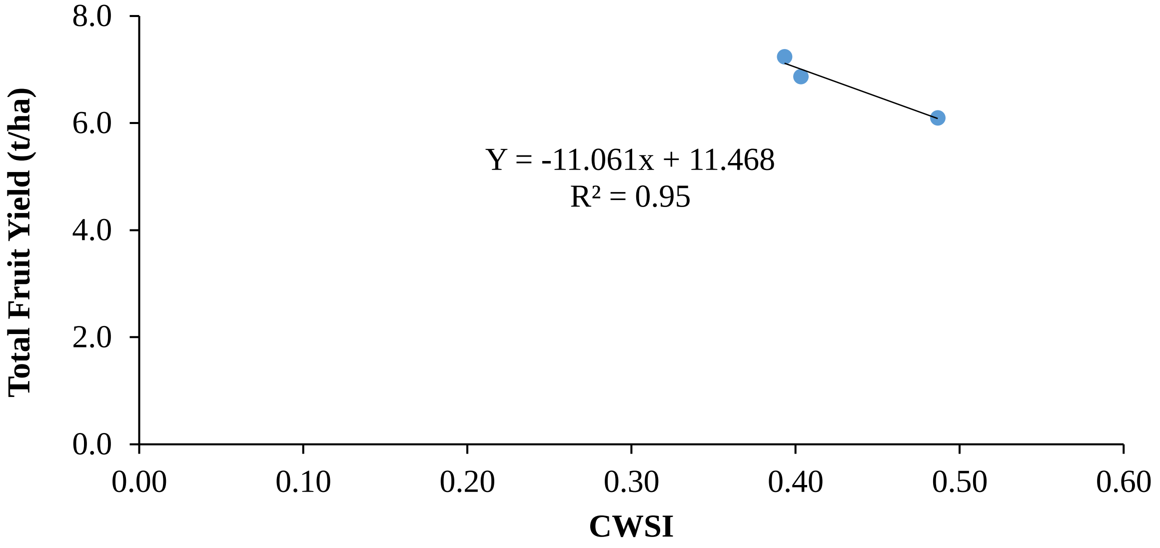

Figure 4.37: Total fruit yield (TFY) as a Function of Crop Water Stress Index (CWSI) Influenced by Irrigation Regimes during the second irrigated cropping season

4.12 Relationship between Crop Water Stress Index (CWSI) and Total Fruit Yield (TFY) of Tomatoes as Influenced by Quantity of Rice Straw Mulch

The simple relationship between CWSI and TFY of tomatoes as influenced by quantity of rice straw mulch was linear in nature (Figures 4.38 & 4.39). The relationship produced a simple regression model equation of $Y = -64\ (CWSI) + 24.59$ (Eqn. 4.7) and an R^2 value of 0.99 (Figure 4.38). Also, a simple regression model equation of $Y = -117.79\ (CWSI) + 50.03$ (Eqn. 4.8) and an R^2 value of 0.99 (Figure 4.39) was produced for the observed relationship during the second irrigated season. The trend relies heavily on the adequate soil water status produced by the moisture conservation potential of the applied rice straw mulch which tends to reduce CWSI and thus a resultant increase in TFY.

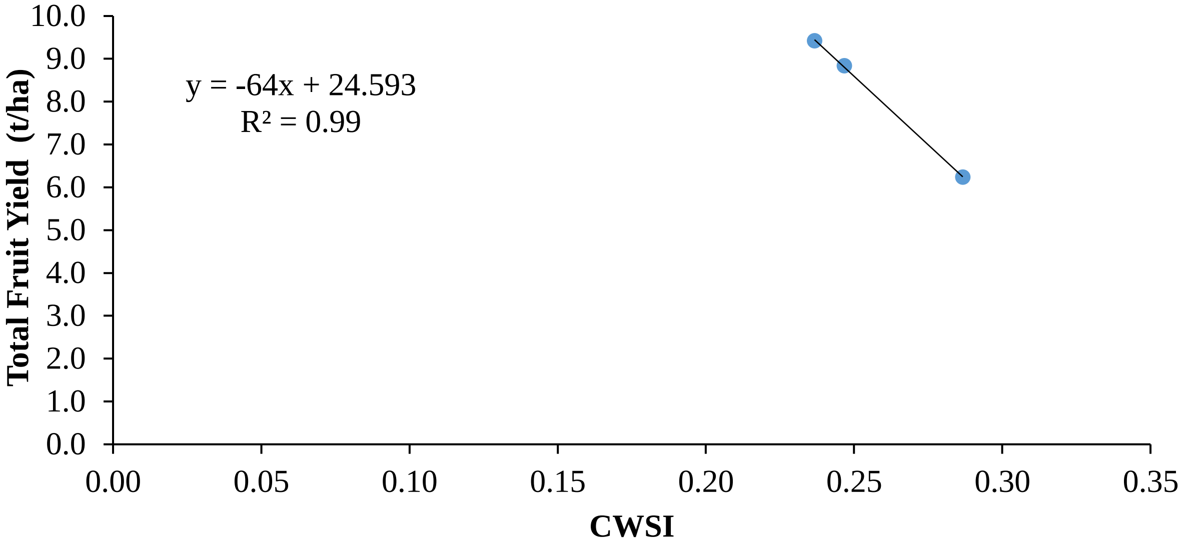

Figure 4.38: Total fruit yield (TFY) as a Function of Crop Water Stress Index (CWSI) Influenced by Rice Straw Mulch during the first irrigated cropping season

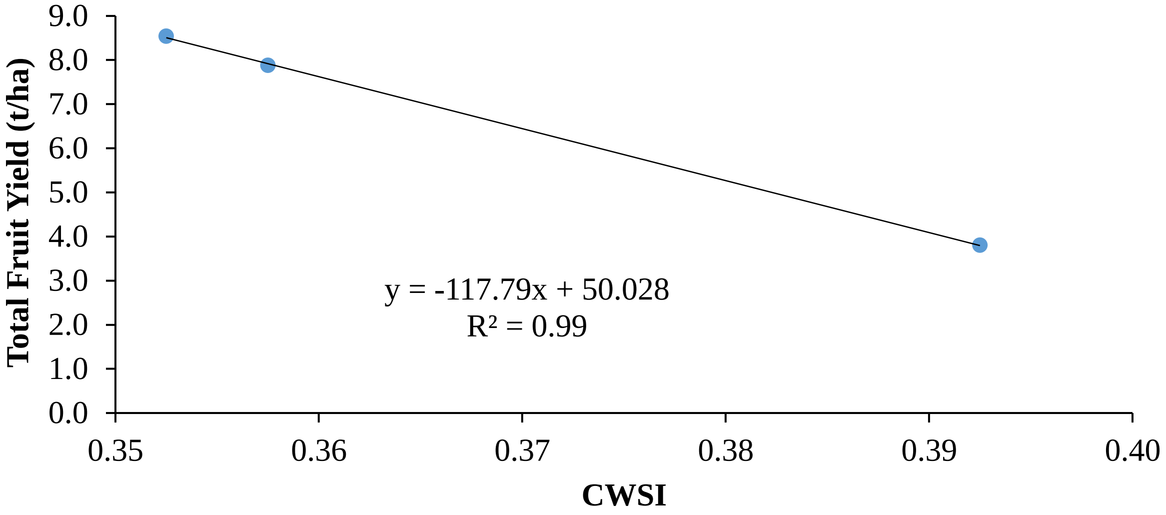

Figure 4.39: Total Fruit Yield (TFY) as a Function of Crop Water Stress Index (CWSI) Influenced by Rice Straw Mulch during the second irrigated cropping season

4.13 Relationship between Crop Water Stress Index (CWSI) and Irrigation Water-Use Efficiency (IWUE) of Tomatoes as Influenced by Irrigation Regimes

The simple relationship between CWSI and irrigation water-use efficiency (IWUE) as influenced by irrigation regimes was linear and strong (Figures 4.40 & 4.41). The relationship produced a simple regression model equation of Y = 12.57 (CWSI) - 2.56 (Eqn. 4.9) and a coefficient of determination (R^2) value of 0.90 (Figure 4.40) during the first irrigated season. Also, the relationship produced a regression model equation of Y = 8.46 (CWSI) - 1.88 (Eqn. 4.10) and an R^2 value of 0.91 (Figure 4.41) during the second irrigated cropping season. The relationship showed an increase in IWUE with an increase in CWSI. This implies that, the tomato varieties evaluated under irrigation regimes were more efficient in water use under soil water stress condition especially that posed by the 50 % ETc deficit irrigation regime. Arbex de Castro Vilas Boas *et al*. (2017) also recorded increase in dry yield under water deficit and attributed the trend to genotypic variations as well as other unknown external factors.

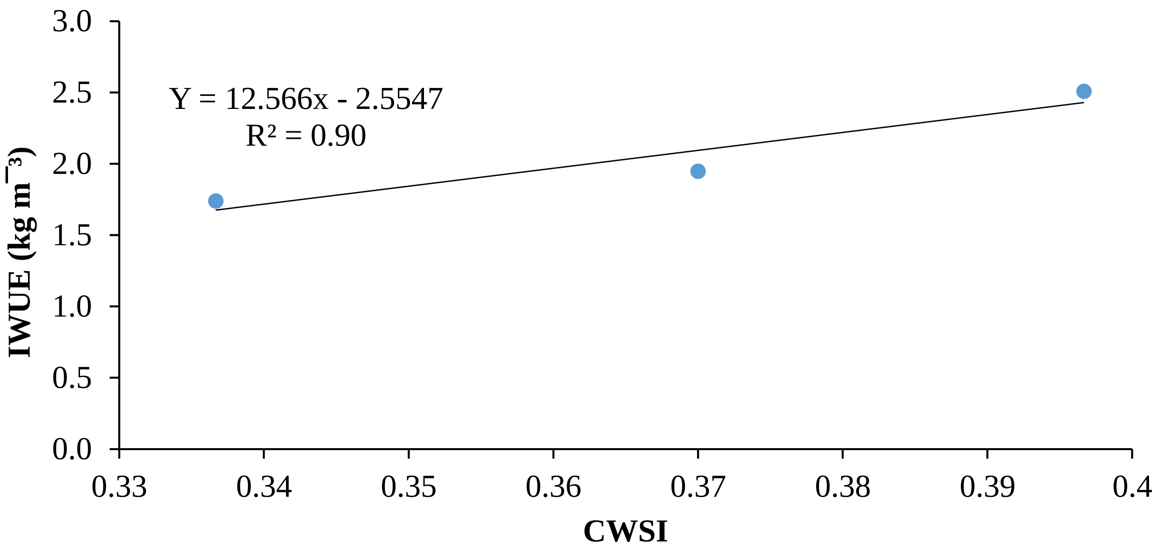

Figure 4.40: Irrigation Water-Use Efficiency (IWUE) as a Function of CWSI Influenced by Irrigation Regimes during the first irrigated cropping season

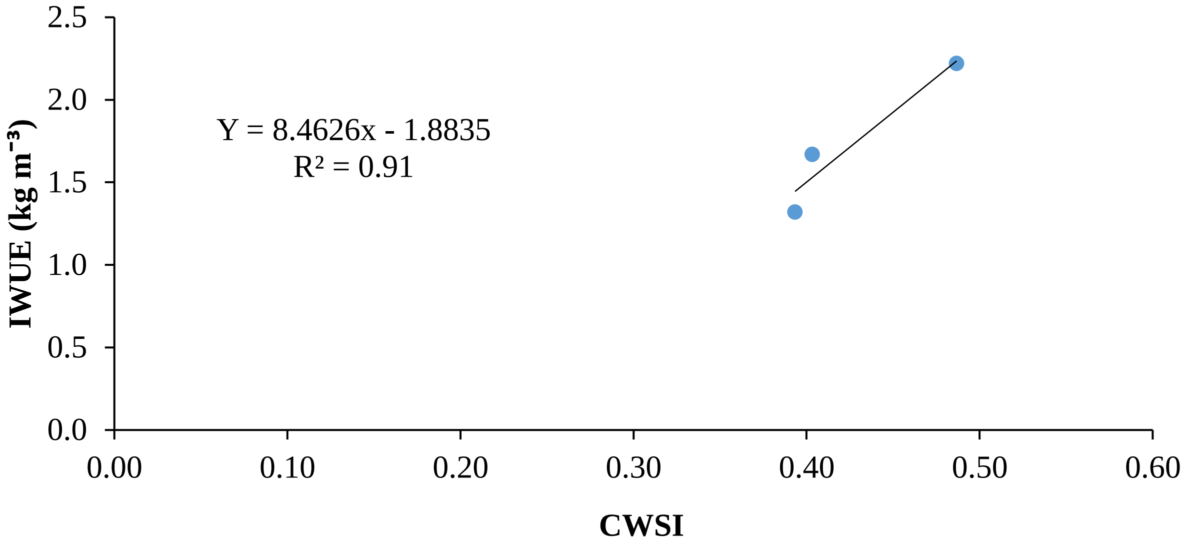

Figure 4.41: Irrigation Water-Use Efficiency (IWUE) as a Function of CWSI Influenced by Irrigation Regimes during the second irrigated cropping season

4.14 Relationship between Crop Water Stress Index (CWSI) and Irrigation Water-Use Efficiency (IWUE) of Tomatoes as Influenced by Quantity of Rice Straw Mulch

The simple relationship between CWSI and IWUE of tomatoes as influenced by rice straw mulch was strong and linear (Figures 4.42 & 4.43). The relationship produced a simple regression model equation of Y = -17.143 (CWSI) + 6.47 (Eqn. 4.11) with R^2 of 0.99 (Figure 4.42) during the first irrigated season. Also, the relationship produced a simple regression model equation of Y = -31.53 (CWSI) + 13.32 (Eqn. 4.12) and an R^2 of 0.99 (Figure 4.43) during the second irrigated cropping season. The relationship showed an increase in IWUE with a decline in CWSI. The role of mulches in cooling down soil temperature especially at the topsoil layer contributed to the lower CWSI and a resultant increase in IWUE.

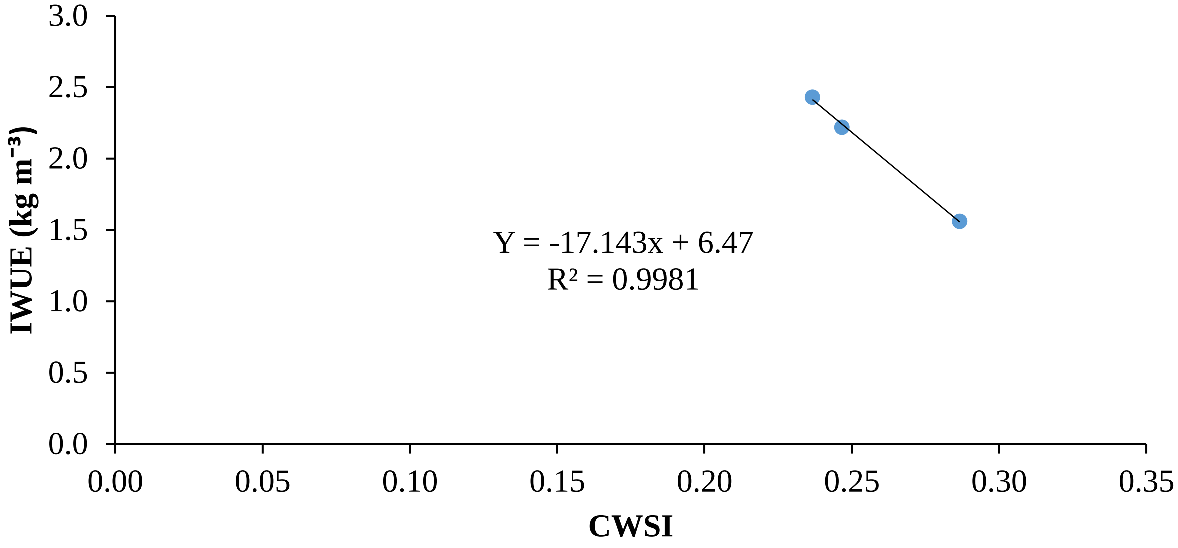

Figure 4.42: Irrigation Water-Use Efficiency (IWUE) as a Function of CWSI Influenced by Rice Straw Mulch during the first irrigated cropping season

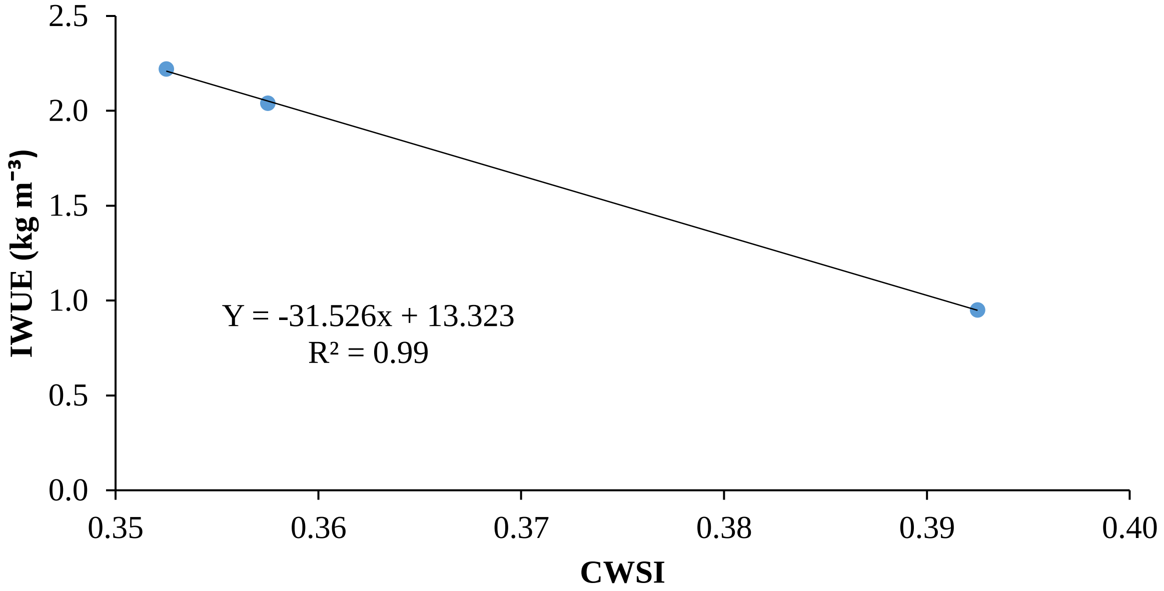

Figure 4.43: Irrigation Water-Use Efficiency (IWUE) as a Function of CWSI Influenced by Rice Straw Mulch during the second irrigated cropping season

4.15 Model Calibration Statistics

The CROPGRO-Tomato model of DSSAT was calibrated for simulations of soil temperature, canopy height of plants and fresh fruit weight of tomatoes associated to non-stressed treatment with optimum soil water condition. For testing the capability of model in simulating the response of tomato varieties to irrigation regimes and quantity of rice straw mulch, comparisons between predicted and measured were performed. The calibration for Mongal F1 produced RMSE, RRMSE, and D-index values of 2.32 °C, 7.39 % and 0.72 respectively for soil temperature, RMSE (0.10 m), Willmott's d-index of agreement of 0.86 and R^2 of 0.91 for canopy height of plants. The calibration of fresh fruit weight of tomatoes was very good with RRMSE of 7.89 % and Willmott's d index of 0.99. Also, the calibration for Pectomech variety under optimum soil water condition of 100 % ET_c irrigation regime resulted in RMSE of 3.01 °C, RRMSE of 9.79 % and Willmott's d index of 0.67 for soil temperature. Further, RMSE of 0.05 m, RRMSE of 11.04 % and D of 0.97 with R^2 value of 0.95 was observed between the predicted and measured canopy height of plants. For the fresh fruit weight of tomatoes, RRMSE of 13.7 %, RMSE of 495 kg/ha and Willmott's d-index of 0.98 with R^2 of 0.98 was produced.

4.16 Model Evaluation Statistics on the Effect of Varieties, Irrigation Regimes and Quantity of Rice Straw Mulch on Rootzone (0 - 20 cm) Soil Temperature

4.16.1 Interaction Effect of Varieties (Mongal F1 and Pectomech), 100 % ETc and Quantity of Rice Straw Mulch Levels (0 t/ha, 3 t/ha and 6 t/ha) on Rootzone Soil Temperature

The relevance of soil temperature is enormous since it affects the chemical, physical and biological processes in the soil medium. Therefore, a good model performance in predicting soil temperature is relevant in understanding nutrient losses and gas emission processes from the soil. The CROPGRO model accurately predicted rootzone soil temperature as influenced by Mongal F1 in combination with 100 % ET_c and 0 t/ha rice straw mulch (Figure 4.44a). The RRMSE of 9.42 % and RMSE of 3.30 °C depicted an excellent model performance in simulating soil temperature. The D-index of agreement of 0.61 further confirmed the good performance of the model. An agreement of goodness of fit between observed and measured soil temperature was 61 % (Figure 4.44a). Also, the model had similar excellent prediction outcome for the effect of Pectomech in combination with 100 % ET_c and 0 t/ha rice straw mulch. It produced RMSE of 3.05 °C, RRMSE of 8.68 % and D of 0.61 (Figure 4.44a). The model under predicted soil temperature at 23 DAT, 29 DAT, 59 DAT and 69 DAT. Hwoever, the variation between measured and predicted was wider at 59 DAT and 69 DAT (Figure 4.44a).

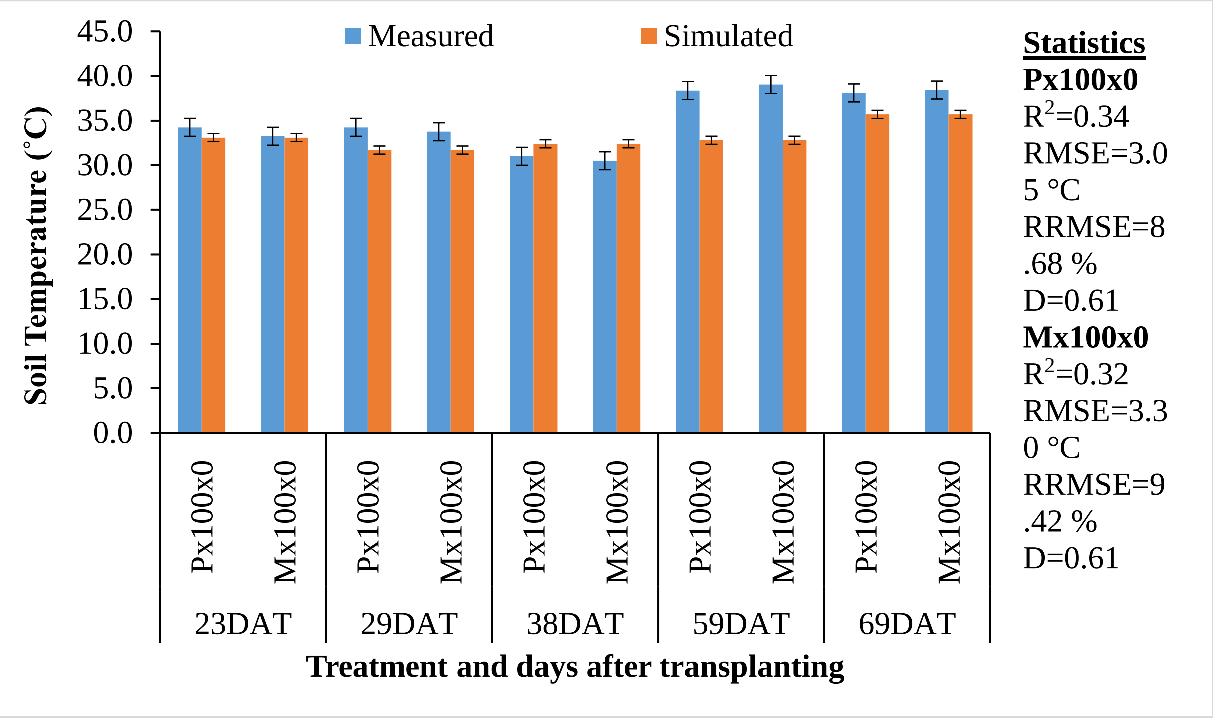

Figure 4.44 (a): Measured and Predicted Rootzone (0 - 20 cm) Soil Temperature (°C) as Influenced by Variety Levels (Pectomech and Mongal F1) in combination with 100 % ET_c and 0 t/ha Rice Straw Mulch

Furthermore, the effect of Mongal F1 in combination with 100 % ET_c and 3 t/ha rice straw mulch on soil temperature was equally well simulated with an overall good model performance. The

RMSE of 2.52 °C, RRMSE of 7.90 % and D-index of 0.60 signifies an excellent model performance in predicting soil temperature (Figure 4.44b). The 3 t/ha rice straw mulch applied resulted in moderate water evaporation from the soil compared to the no-mulch treatment combination. Similarly, the model's predictive outcome on effect of Pectomech in combination with 100 % ET$_c$ and 3 t/ha rice straw mulch on soil temperature was excellent following the evaluation statistics of RMSE of 1.99 °C, RRMSE of 6.10 % and D-index of 0.70 (Figure 4.44b). The coefficient of determination (R^2) of 0.5 was recorded for the relationship between predicted and measured soil temperature improved with the inclusion of 3 t/ha rice straw mulch (Figure 4.44b).

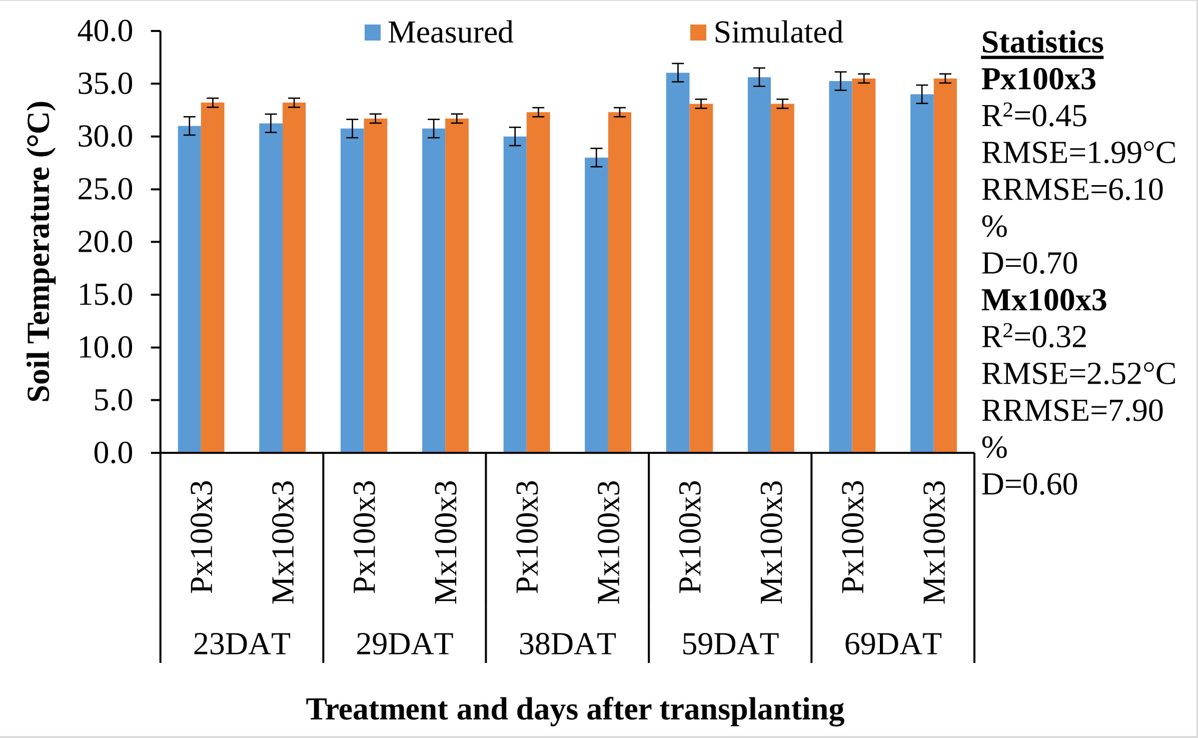

Figure 4.44 (b): Measured and Predicted Rootzone (0 - 20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 100 % ET$_c$ and 3 t/ha Rice Straw Mulch

Also, the soil temperature condition was improved when rice straw of 6 t/ha was applied in the treatment interaction of Mongal F1, 100 % ET$_c$ and 6/ha. The model's performance in predicting soil temperature increased compared to when rice straw of 0 t/ha and 3 t/ha was applied as mulch material to the soil. The goodness of fit was excellent with an RMSE, RRMSE, and D-index values of 2.32 °C, 7.39 % and 0.72 respectively (Figure 4.44c). The simulation produced slightly higher soil temperature than the measured and a sign of good model performance. The results and trend were similar for Pectomech in combination with 100 % ET_c and 6 t/ha. The relationship between measured and predicted soil temperature produced an R^2 value of 0.67, RMSE of 3.01 °C, RRMSE of 9.79 % and Willmott's D-index of 0.67 (Figure 4.44c). The application of higher level of rice straw (6 t/ha) significantly improved soil temperature. Ertek *et al.* (2004) reported on the significant reduction in soil temperature to 27.5 ⁰ C under organic mulch materials such as rice straw.

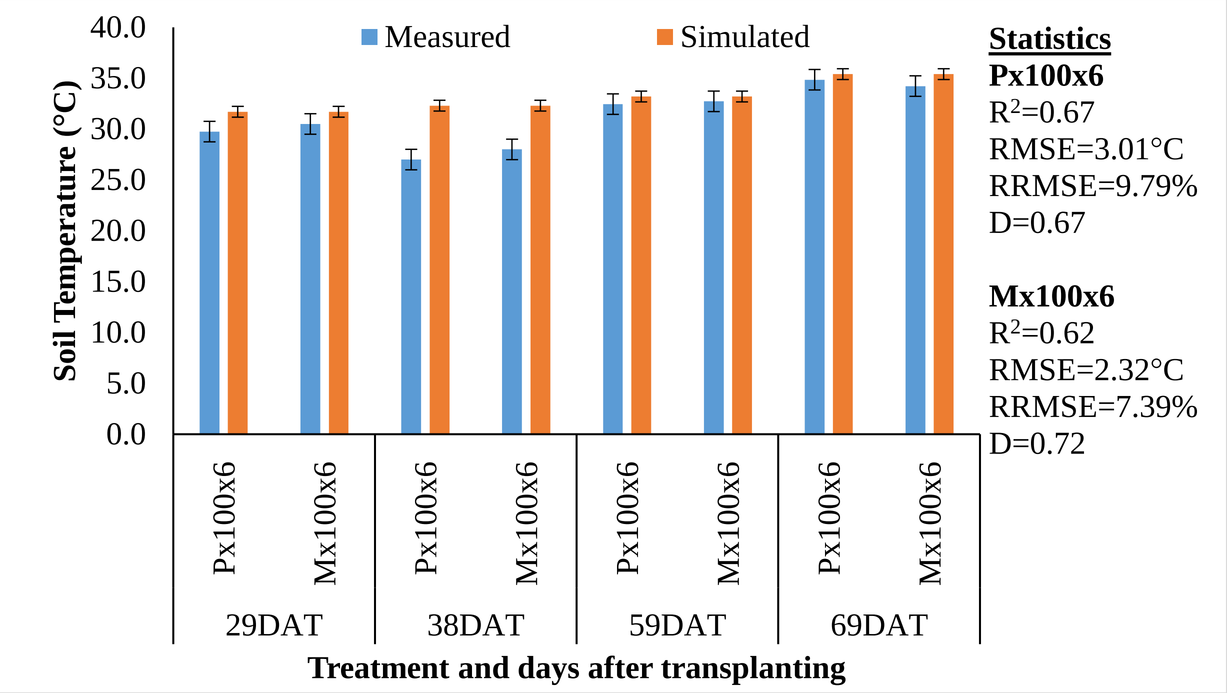

Figure 4.44 (c): Measured and Predicted Rootzone (0 - 20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech And Mongal F1) in combination with 100 % ET_c and 6 t/ha Rice Straw Mulch

4.16.2 Interaction Effect of Varieties (Mongal F1 and Pectomech), 75 % ETc and Quantity of Rice Straw Mulch Levels (0 t/ha, 3 t/ha and 6 t/ha) on Rootzone Soil Temperature

The effect of Mongal F1 in combination with 75 % ET_c and 0 t/ha rice straw mulch on soil temperature predicted by the model was good with an RMSE, RRMSE, and D-index values of 3.92 °C, 10.79 % and 0.58 respectively (Figure 4.44d). The relationship between predicted and measured soil temperature was good and acceptable considering the R^2 value of 0.58. Furthermore, the model's prediction ability was excellent for the effect of Pectomech in combination with 75 % ET_c and 0 t/ha rice straw mulch on soil temperature. The model's prediction produced RMSE of 3.32 °C, RRMSE of 9.34 %, D-index of 0.63 and R^2 value of 0.61 (Figure 4.44d). The model predicted slightly lower mean soil temperature compared to the measured (Figure 4.44d).

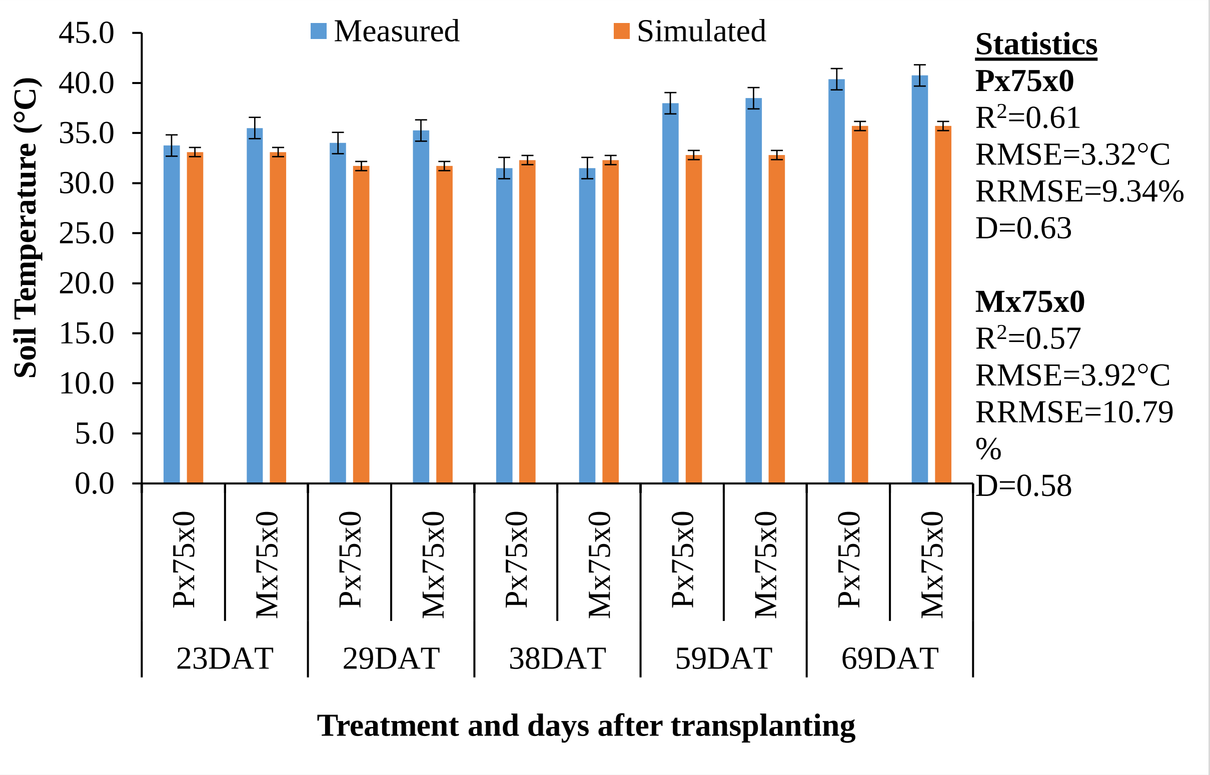

Figure 4.44 (d): Measured and Predicted Rootzone (0 - 20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 75 % ET_c and 0 t/ha Rice Straw Mulch

The coefficient of determination (R^2 of 0.72) between predicted and measured soil temperature was stronger for Mongal F1 in combination with 75 % ET_c and 3t/ha rice straw mulch (Figure 4.44e). Also, RMSE, RRMSE and D-index of 1.75 °C, 5.25 % and 0.80 respectively was recorded and signified an excellent model performance in simulating soil temperature (Figure 4.44e). For the effect of Pectomech in combination with 75 % ET_c and 3 t/ha rice straw mulch on soil temperature, the model was excellent in its prediction given rise to RMSE of 1.23 °C, RRMSE of 3.69 %, D-index of 0.87 and R^2 value of 0.76 (Figure 4.44e). Lower mean soil temperature was measured and predicted compared to the treatment combination with no-mulch applied due to the influence of rice straw mulch in decreasing soil temperature (Kader *et al.* 2017).

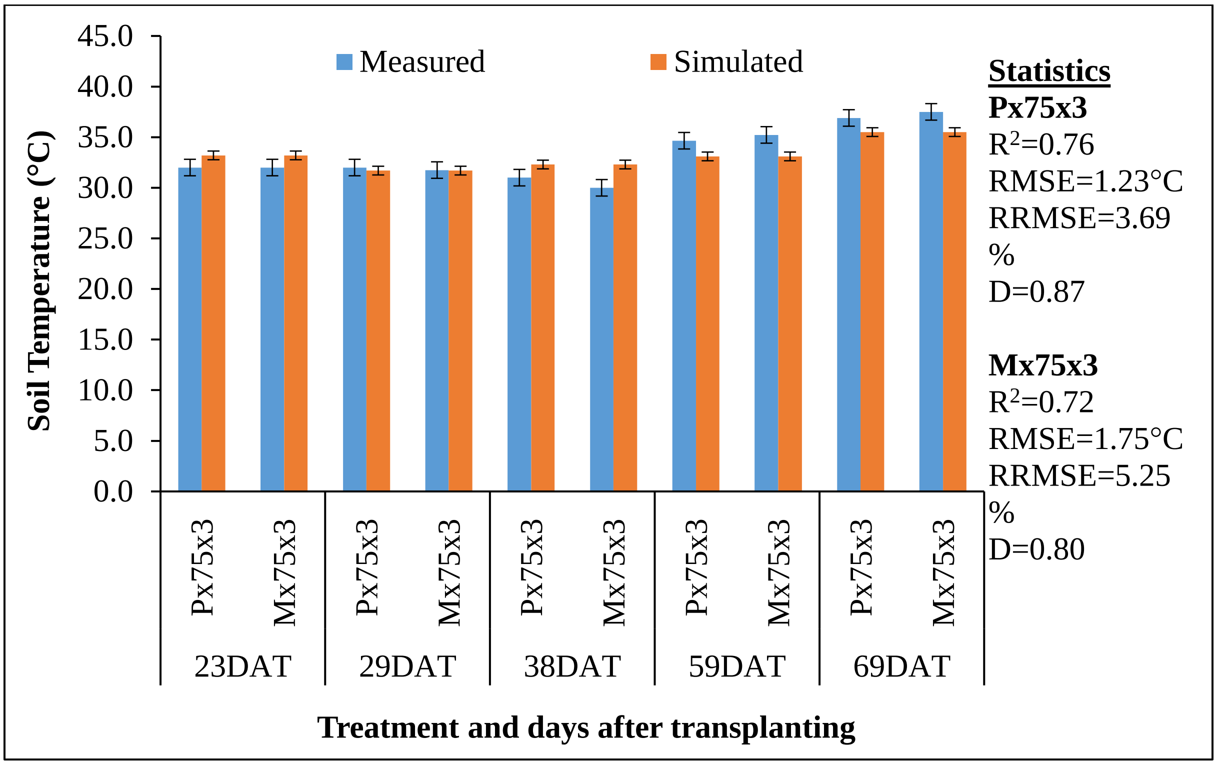

Figure 4.44 (e): Measured and Predicted Rootzone (0 - 20 cm) soil temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 75 % ET_c and 3 t/ha Rice Straw Mulch

Also, the higher quantity of rice straw in the treatment of Mongal F1 in combination with 75 % ET_c and 6 t/ha rice straw mulch improved soil temperature and was well predicted by the model (Figure 4.44f). There was similarity in the response of treatment to soil temperature compared to that recorded by Mongal F1 in combination with 75 % ET_c and 3 t/ha depicting the role of organic mulch in improving the soil environment. The relationship between predicted and measured soil temperature was excellent with an R^2, RMSE, RRMSE and D-index of 0.7, 1.9 °C, 6.0 % and 0.8 respectively (Figure 4.44f). The CROPGRO Model again had a very good prediction of soil temperature influenced by Pectomech in combination with 75 % ET_c and 6 t/ha rice straw mulch. This was evident in the outcome of evaluation statistics of R^2 value of 0.73, RMSE of 1.58 °C, RRMSE of 4.86 % and d-index of 0.82 (Figure 4.44f). The observed simulations showed more accurate prediction of rootzone soil temperature for mulched fields than un-mulched.

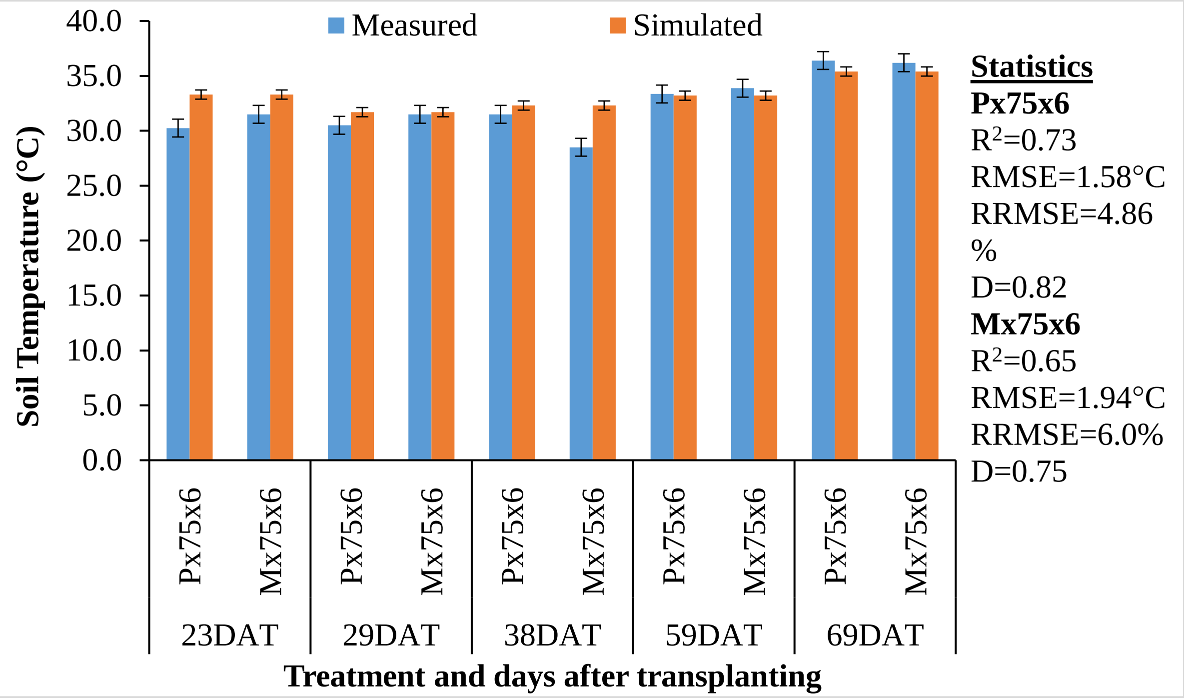

Figure 4.44 (f): Measured and Predicted Rootzone (0-20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 75 % ET_c and 6 t/ha Rice Straw Mulch

4.16.3 Interaction Effect of Varieties (Mongal F1 and Pectomech), 50 % ET$_c$ and Quantity of Rice Straw Mulch Levels (0 t/ha, 3 t/ha and 6 t/ha) on Rootzone Soil Temperature

In predicting soil temperature by CROPGRO Model for severely stressed irrigation regime of 50 % ET$_c$, the outcome was poor for no-mulch treatment compared to the mulched treatment combinations. The model simulation on the effect of Mongal F1 in combination with 50 % ET$_c$ deficit irrigation and 0 t/ha rice straw mulch on soil temperature within the rootzone resulted in an RMSE of 3.6 °C, RRMSE of 10.15 % and Willmott's D-index of 0.60 (Figure 4.44g). The R^2 for measured and predicted mean soil temperature of the rootzone soil was within the acceptable rage of model performance given the recorded R^2 of 0.50 (Figure 4.44g). Also, the influenced by Pectomech in combination with 50 % ET$_c$ and 0 t/ha rice straw mulch on soil temperature was similar and produced an RMSE of 3.88 °C, RRMSE of 10.75 % and D-index of 0.57 (Figure 4.44g). The coefficient of determination (R^2=0.45) denoted slightly weak relationship between the predicted and measured soil temperature. Generally, the model under predicted soil temperature compared to the measured except for 38 DAT (Figure 4.44g).

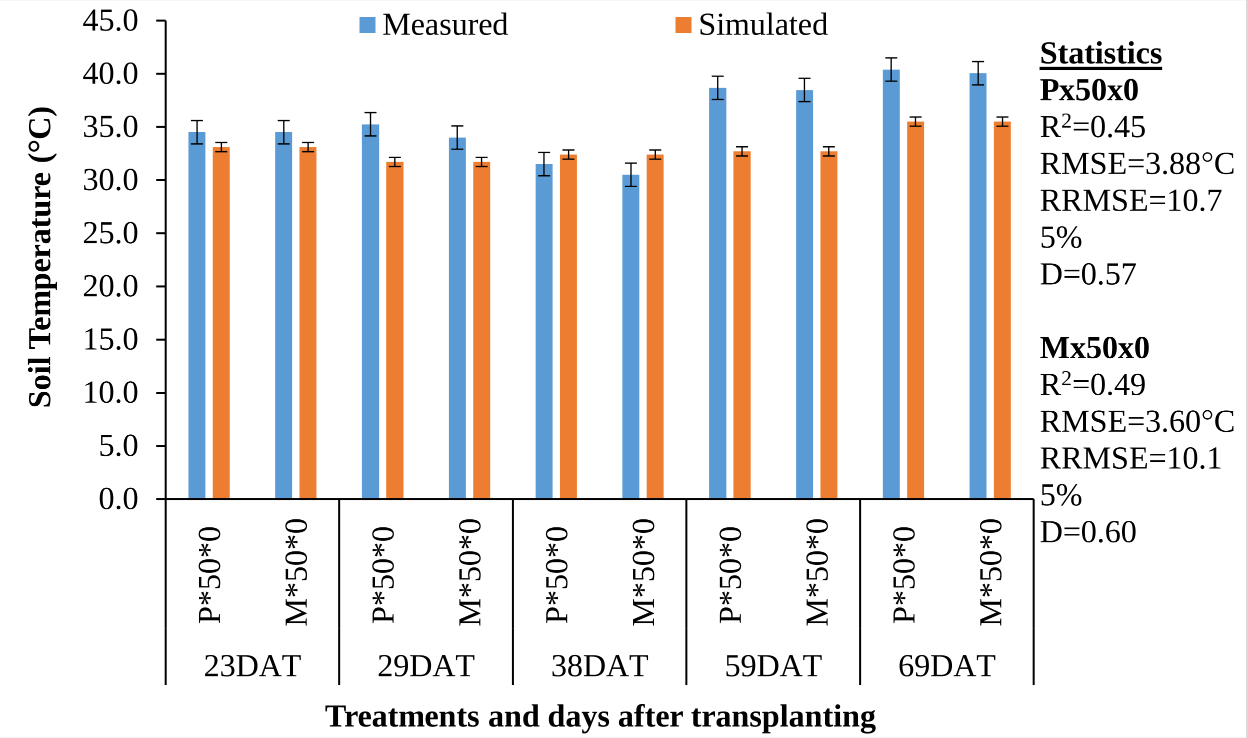

Figure 4.44 (g): Measured and Predicted Rootzone (0 - 20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 50 % ET$_c$ and 0 t/ha Rice Straw Mulch

The CROPGRO Model had an excellent prediction of soil temperature as influenced by Mongal F1 in combination with 50 % ET$_c$ and 3 t/ha rice straw mulch and resulted in an R^2 of 0.53, RMSE of 2.54 °C, RRMSE of 7.65 % and Willmott's D-index of 0.7 (Figure 4.44h). Again, the interaction effect of Pectomech in combination with 50 % ETc and 3 t/ha on soil temperature was excellently predicted by the model. The interaction produced a very good model evaluation statistics of RMSE of 2.19 °C, RRMSE of 6.65 %, Wilmott's index of agreement (d) of 0.74 and R^2 of 0.73 (Figure 4.44h). The model's performance in predicting soil temperature improved with the inclusion of rice straw mulch compared to the no-mulch. This confirms the positive influence of rice straw in reducing soil temperature (Pandey *et al.*, 2015).

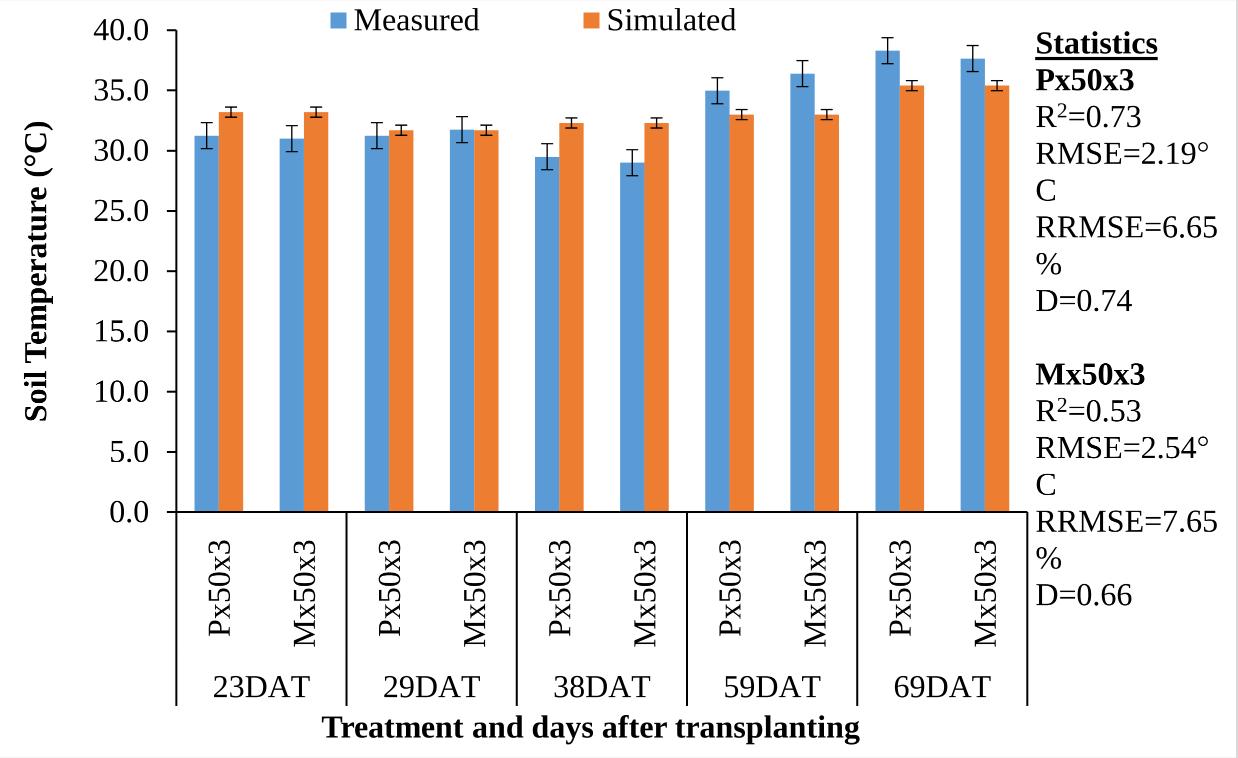

Figure 4.44 (h): Measured and Predicted Rootzone (0-20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 50 % ET_c and 3 t/ha Rice Straw Mulch

The inclusion of 6 t/ha rice straw further improved the model's performance in predicting soil temperature. Model prediction on the effect of Mongal F1 in combination with 50 % ET_c deficit irrigation and 6 t/ha rice straw on soil temperature was excellent and resulted in RMSE of 2.48 °C, RRMSE of 7.8 %, D-index of 0.71 and an R^2 of 0.78 (Figure 4.44i). The same similar excellent performance was recorded for the effect of Pectomech in combination with 50 % ET_c and 6 t/ha on soil temperature. It resulted in RMSE of 2.34 °C, RRMSE of 7.37 % and D- index of 0.74 (Figure 4.44i).

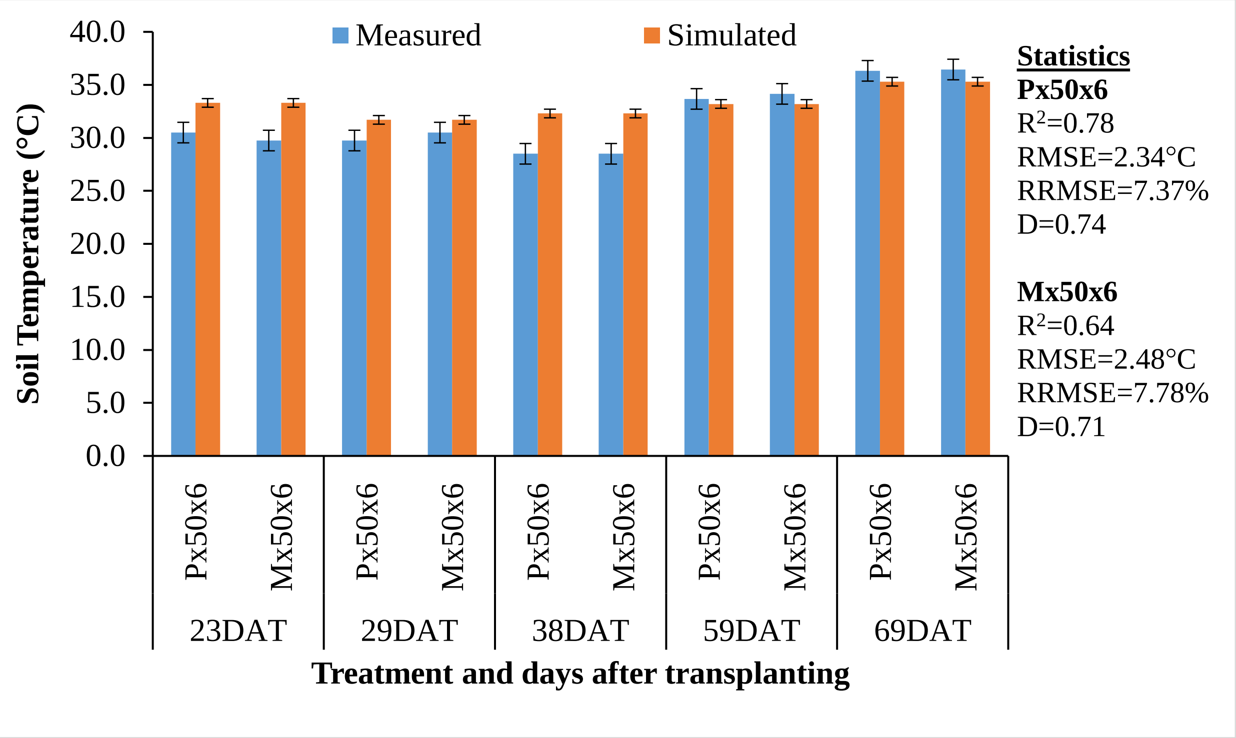

Figure 4.44 (i): Measured and Predicted Rootzone (0-20 cm) Soil Temperature (°C) as Influenced by Varieties (Pectomech and Mongal F1) in combination with 50 % ET_c and 6 t/ha Rice Straw Mulch

4.17 Model Evaluation on the Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch Levels on Plant Canopy Height (m)

The CROPGRO model's prediction on canopy height of tomato plants as influenced by variety, deficit irrigation regimes and quantity of rice straw mulch levels was generally excellent (Table 4.31). The evaluation statistics on RMSE, D-index and R^2 sugested that, the model performance was excellent and one that is acceptable for the prediction of plant canopy height as influenced by the treatment interactions. However, the evaluation statistics on RRMSE classified the model performance in predicting plant canopy height into excellent (<10 %), good (10 – 20 %) and fair (20 – 30 %) and poor (>30 %). In line with this, effect of the following treatment combinations;

Pectomech x 75 % ET$_c$ x 6 t/ha and Pectomech x 100 % ET$_c$ x 3 t/ha on plant canopy height was excellently predicted by the model with RRMSE of 5.87 % and 9.85 % respectively (Table 4.31). However, the model prediction on plant canopy height was good for the following treatment combinations; Pectomech x 100 % ET$_c$ x 6 t/ha (11.04 %), Pectomech x 50 % ET$_c$ x 0 t/ha (11.5 %), Pectomech x 75 % ET$_c$ x 3 t/ha (12.64 %), Pectomech x 100 % ET$_c$ x 0 t/ha (14.04 %), Pectomech x 50 % ET$_c$ x 6 t/ha (16.23 %), Mongal F1 x 100 % ET$_c$ x 3 t/ha (16.63 %), Mongal F1 x 75 % ET$_c$ x 3 t/ha (17.11 %), Mongal F1 x 50 % ET$_c$ x 0 t/ha (17.51 %), Mongal F1 x 100 % ET$_c$ x 0 t/ha (18.61 %) and Pectomech x 75 % ET$_c$ x 0 t/ha (19.39 %) (Table 4.31).

On the other hand, the model predicted fairly on plant canopy height as influenced by the following treatment combinations; Mongal F1 x 50 % ET$_c$ x 6 t/ha (22.06 %), Mongal F1 x 100 % ET$_c$ x 6 t/ha (22.72 %), Pectomech x 50 % ETc x 3 t/ha (22.78 %), Mongal F1 x 75 % ET$_c$ x 6 t/ha (26.19 %), Mongal F1 x 50 % ET$_c$ x 3 t/ha (27.01 %) and Mongal F1 x 75 % ET$_c$ x 0 t/ha (28.56 %) (Table 4.31). According to the range of RRMSE recorded; thus, 5.87 - 28.56 %, the model's performance in predicting plant canopy height as influenced by the treatments was very good and acceptable for use.

Table 4.31: Model Evaluation on the Interaction Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Mean Canopy Height of Tomatoes

Treatment	**Means of Canopy Height (m)**		**Statistical Evaluation on Model Performance**			
	Measured	Predicted	RRMSE (%)	RMSE (m)	D	R^2
Mongal F1x100 % ETc x 0 t/ha	0.42	0.43	18.61	0.08	0.92	0.98
Mongal F1x100 % ETc x 3 t/ha	0.45	0.47	16.63	0.08	0.93	0.95
Mongal F1x100 % ETc x 6 t/ha	0.43	0.47	22.72	0.10	0.86	0.91
Mongal F1x75 % ETc x 0 t/ha	0.41	0.49	28.56	0.12	0.83	0.96
Mongal F1x75 % ETc x 3 t/ha	0.46	0.47	17.11	0.08	0.92	0.94
Mongal F1x75 % ETc x 6 t/ha	0.40	0.47	26.19	0.11	0.86	0.93
Mongal F1x50 % ETc x 0 t/ha	0.43	0.45	17.51	0.01	0.89	0.98
Mongal F1x50 % ETc x 3 t/ha	0.39	0.46	27.01	0.11	0.84	0.94
Mongal F1x50 % ETc x 6 t/ha	0.43	0.43	22.06	0.09	0.87	0.93
Pectomech x100 % ETc x 0 t/ha	0.43	0.45	14.04	0.06	0.95	0.96
Pectomech x100 % ETc x 3 t/ha	0.44	0.48	9.85	0.04	0.98	0.98
Pectomech x100 % ETc x 6 t/ha	0.47	0.44	11.04	0.05	0.97	0.95
Pectomech x75 % ETc x 0 t/ha	0.41	0.45	19.39	0.08	0.90	0.97
Pectomech x75 % ETc x 3 t/ha	0.43	0.44	12.64	0.05	0.96	0.96
Pectomech x75 % ETc x 6 t/ha	0.45	0.44	5.87	0.03	0.99	0.98
Pectomech x50 % ETc x 0 t/ha	0.39	0.42	11.50	0.04	0.97	0.97
Pectomech x50 % ETc x 3 t/ha	0.38	0.44	22.78	0.09	0.89	0.94
Pectomech x50 % ETc x 6 t/ha	0.43	044	16.23	0.07	0.93	0.85

Where; RRMSE=Relative root mean square error, RMSE= Root mean square error, D=Willmott's d-index of agreement, R2=Coefficient of determination, ETc=Crop water requirement

4.18 Model Evaluation on the Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Fresh Fruit Weight of Tomatoes

Table 4.32 present results of evaluation statistics for model prediction performance on fresh fruit weight as influenced by the interactive effect of variety levels (Mongal F1, Pectomech), irrigation regimes (100 %, 75 % and 50 % ET_C) and quantity of rice straw mulch levels (6 t/ha, 3 t/ha, 0 t/ha). For variety effect on mean fresh fruit weight, the model predicted higher mean weight for Mongal F1 than the Pectomech variety. This could largely be attributed to the environmental conditions especially weather that posed severe effect on soil water condition and resulted in the variations in fruit weight (Lekshmi and Celine, 2015; Parkash *et al.*, 2021), as predicted by the model. The Mongal F1 proved to be well adapted to the harsh climate of the dry season and efficiently utilized soil water that translated in the high fruit weight (Ochar *et al.*, 2019).

Also, the model predicted higher mean fruit weight for the 100 % ET_c irrigation regime, followed by the 75 % ET_c and lastly by the severely stressed regime of 50 % ET_c (Table 4.32). Deficit soil water will decrease evapotranspiration rate by severely stressed plants (Parkash and Singh, 2020). This agrees with the trend observed from the measured mean fresh fruit yield of tomatoes as well as the findings by Pulvento *et al*. (2008); Abdel-Razzak *et al*. (2016); Nangare *et al*. (2016); Giuliani *et al*. (2018) and Ganeva *et al*. (2019) who reported decrease in fruit weight of tomatoes influenced by deficit irrigation regimes. Taromi *et al*. (2019), also reported on highest fruit weight of tomato under the full irrigation treatment of 100 % ET_c, followed by the deficit regime of 70 % ET_c and finally by the severely stressed regime of 50 % ET_c.

In general, the evaluation statistics on RMSE, D-index and R^2 sugested that, the model performance was excellent and one that is acceptable for the prediction of fresh fruit weight as influenced by the treatment interactions. The CROPGRO model's simulation on effect of Mongal F1 in combination with irrigation regimes (I) levels and quantity of rice straw mulch (M) levels, thus; Mongal F1 x I x M on fresh fruit weight was excellently predicted. The model excellently predicted fresh fruit weight as reflected in the evaluation statistics for the following treatment interactions; Mongal F1 x 100 % ET_c x 0 t/ha (RRMSE of 7.89 %), Mongal F1 x 75 % ET_c x 3 t/ha (RRMSE of 8.28 %) and Mongal F1 x 75 % ET_c x 6 t/ha (RRMSE of 5.99 %) (Table 4.32).

Also, the model's prediction on fresh fruit weight of tomatoes was good for the following treatment interactions; Mongal F1 x 100ET_c x 6 t/ha (RRMSE of 11.66 %), Mongal F1 x 75ET_c x 0 t/ha (RRMSE of 11.77 %) and Mongal F1 x 50 % ET_c x 0 t/ha (RRMSE of 13.92 %) (Table 4.32).

However, the model's prediction was fair for the interaction effect of Mongal F1 x 100 % ET_c x 3 t/ha (RRMSE of 30 %) and Mongal F1 x 50 % ET_c x 3 t/ha mulch (RRMSE of 21 %). In addition, the model prediction was poor for the effect of Mongal F1 x 50 % ET_c x 6 t/ha mulch (RRMSE of 31.5 %) on fresh fruit weight (Table 4.32). Despite the fair predictions made by the model informed by the greater than 30 % RRMSE, the relationship between observed and simulated fresh fruit weight was strong, positively correlated, and acceptable with an R^2 value ranging from 0.89 – 0.99 and D-index value raning from 0.79 – 0.99 (Table 4.32).

The CROPGRO model also made excellent simulations on the interactive effect of Pectomech, irrigation regimes (I) and quantity of rice straw mulch (M) levels, thus; Pectomech x I x M on fresh fruit weight of tomatoes. The following treatment interactions had excellent model prediction on fresh fruit yield; Pectomech x 75 % ET_c x 3 t/ha mulch (RRMSE of 8.9 %) and Pectomech x 50 % ET_c x 6 t/ha mulch (RRMSE of 4.7 %). Also, good prediction was made by the model on fresh fruit weight for the interaction of Pectomech x 100 % ET_c x 3 t/ha (RRMSE of 14.5 %), Pectomech x 100 % ET_c x 6 t/ha (RRMSE of 13.7 %), Pectomech x 75 % ET_c x 0 t/ha (RRMSE of 11.7 %), Pectomech x 75 % ET_c x 6 t/ha (RRMSE of 11.4 %), Pectomech x 50 % ET_c x 3 t/ha (RRMSE of 14.1 %) (Figure 4.33).

Nonetheless, the model performed fairly in predicting fresh fruit weight for the effect of Pectomech in combination with 100 % ET_c and 0 t/ha (RRMSE of 29.4 %). The model further performed poorly in predicting fresh fruit weight for the interaction effect of Pectomech x 50 % ET_c x 0 t/ha (RRMSE of 40.5 % (Table 4.32). Despite the poor model performance as suggested by RRMSE >30 % for some treatment interactions the measured and predicted fresh fruit weight was highly correlated given acceptable R^2 values ranging from 0.91- 0.99 and D-index ranging from 0.76 – 1.00 (Table 4.32).

Table 4.32: Model Evaluation on the Combine Effect of Variety, Irrigation Regimes and Quantity of Rice Straw Mulch on Mean Fresh Fruit Weight of Tomatoes

Treatment	Means of Fruit Weight (Kg/ha)		Statistical Evaluation on Model Performance			
	Measured	Predicted	RRMSE (%)	RMSE (Kg/ha)	D	R^2
Mongal F1x100 % ETc x 0 t/ha	23,460	18,135	7.89	1,283.0	0.99	0.94
Mongal F1x100 % ETc x 3 t/ha	20,895	23,203	30.40	4,317.0	0.87	0.94
Mongal F1x100 % ETc x 6 t/ha	20,895	21,770	11.66	1,658.0	0.97	0.96
Mongal F1x75 % ETc x 0 t/ha	10,803	12,491	11.77	911.35	0.98	0.99
Mongal F1x75 % ETc x 3 t/ha	16,904	18,267	8.28	987.80	0.99	0.99
Mongal F1x75 % ETc x 6 t/ha	17,393	18,550	5.99	737.84	0.99	0.99
Mongal F1x50 % ETc x 0 t/ha	11,495	11,289	13.92	1,152.91	0.98	0.98
Mongal F1x50 % ETc x 3 t/ha	14,667	10,789	21.00	2,028.40	0.90	0.91
Mongal F1x50 % ETc x 6 t/ha	18,565	11,734	31.50	3,808.40	0.79	0.89
Pectomechx100 % ETc x 0 t/ha	3,074	4,902	29.42	731.03	0.80	0.94
Pectomechx100 % ETc x 3 t/ha	6,056	5,290	14.54	522.01	0.98	0.98
Pectomechx100 % ETc x 6 t/ha	6,056	5,327	13.72	495.34	0.98	0.98
Pectomechx75 % ETc x 0 t/ha	4,536	5,382	11.65	365.50	0.98	0.98
Pectomechx75 % ETc x 3 t/ha	5,948	5,550	8.93	359.70	0.99	0.98
Pectomechx75 % ETc x 6 t/ha	6,173	5,601	11.38	477.90	0.98	0.98
Pectomechx50 % ETc x 0 t/ha	1,806	2,880	40.53	563.18	0.76	0.91
Pectomechx50 % ETc x 3 t/ha	3,864	3,596	14.07	355.42	0.97	0.96
Pectomechx50 % ETc x 6 t/ha	4,343	4,064	4.67	136.40	1.00	0.99

Where; RRMSE=Relative root mean square error, RMSE= Root mean square error, D=Willmott's d-index of agreement, R2=Coefficient of determination, ETc=Crop water requirement

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Irrigation scheduling under water scarce environments as that of the Guinea Savanna Agroecological Zone of Ghana is crucial in mitigating the impact of climate change on agriculture. The nexus between irrigation scheduling and crop-water productivity of high value vegetables such tomato is relevant in arriving at best technological packages to improve farmer livelihoods. Nonetheless, the conservation of scarce soil water resources using organic mulch materials such as rice straw is necessary to overcome the effects of high ambient temperatures on the soil environment. The combination of irrigation regimes and mulching using rice straw had significant positive impact on the soil and plant environment. The result of this study has the following conclusions.

5.1.1 Soil Environment: Physical and Chemical Status

The soil of the experimental field was sandy loam with good water holding capacity that adequately supported growth of tomato plants. However, inorganic fertilizer was added to improve the nutrient levels most importantly nitrogen due to the poor fertility status. The available soil water content in-season was greatly affected by the irrigation regimes and rice straw mulch applied as treatments under the tomato varieties. The full irrigation regime (100 % ET_c) accumulated more daily volumetric water content than the deficit irrigation regimes of 75 % ETc and 50 % ET_c. The application of rice straw (3 t/ha and 6 t/ha) also ensured that adequate soil water was conserved and resulted in increased volumetric water content than the no-mulch treatment plots. The treatment combination of 100 % ET_c and 6 t/ha rice straw produced adequate soil water content within the rootzone of tomato plants.

Furthermore, soil surface temperature of the experimental units decreased with the application of full irrigation regime and rice straw mulch especially the highest quantity of rice straw (6 t/ha). However, the severely stressed regime (50 % ET_c) together with no-mulch gave higher soil surface temperature. The soil pH was also largely influenced by the interaction of treatments especially during the first season's evaluation. The application of full irrigation regime (100 % ET_c) and highest quantity of rice straw (6 t/ha) improved soil pH by reducing the acidic content of soil for proper plant growth.

5.1.2 Plant Growth and Yield Components of Tomatoes

The plant parameter leaf/canopy temperature is relevant in the estimation of crop water stress index (CWSI) in predicting plant stresses. The leaf temperature of tomato plants was greatly affected by the irrigation regimes and rice straw mulch treatments. The application of full (100 % ET_c) irrigation regime in combination with 6 t/ha rice straw reduced the temperature of plant leaves and resulted in non-stressed and healthy plants. Also, the chlorophyll concentration of plant leaves was surprisingly higher under the severely stressed irrigation regime of 50 % ET_c over the seasons due to efficient utilization of soil nitrogen. The applied rice straw mulch also increased leaf chlorophyll concentration of plants. In addition, the application of full irrigation regime (100 % ET_c) in combination with 6 t/ha rice straw increased leaf stomatal conductance of plants compared to the treatment combination of deficit irrigation regimes (75 % and 50 % ET_c) and No-mulch.

The yield component of tomato crop was greatly influenced by the treatments and their interactions. Fruit size and yield of tomatoes was reduced drastically by the deficit irrigation regimes (75 % and 50 % ET_c) compared to the full (100 % ET_c) irrigation regime. Also, the Mongal F1 tomato variety produced highest total fruit yield over the seasons compared to that obtained by Pectomech. The application of 100 % ET_c irrigation regime produced more fruit yield than the deficit irrigation regimes. Also, the rice straw mulch applied created conducive soil environment and improved fruit yield of tomatoes especially for the 6 t/ha. The interaction of Mongal F1 and 6 t/ha rice straw produced highest fruit yield.

5.1.3 Irrigation Water-Use Efficiency (IWUE) and Crop Water Stress Index (CWSI)

The Mongal F1 tomato variety was 187 % and 131 % more efficient in irrigation water-use than the Pectomech variety in the two seasons respectively. The severely stressed irrigation regime of 50 % ET_c also produced higher irrigation water-use efficiency compared to the full and moderate irrigation regimes. Also, the application of rice straw mulch produced higher irrigation water-use efficiency compared with the No-mulch treatment. The interaction of Mongal F1 and 50 % ET_c gave higher IWUE and could be adopted under water scarce environment of the agroecology.

Furthermore, the relevance of crop water stress index is enormous in irrigation scheduling of dry season tomato farming. The application of irrigation regimes and quantity of rice straw mulch influenced crop water stress index of tomatoes. Full irrigation (100 % ET_c) lowered crop water stress index but similar compared to the mild deficit irrigation. Also, the application of rice straw especially at 6 t/ha lowered CWSI when interacted with the full irrigation regime due to the created adequate soil water condition. The lowered crop water stress index resulted in increased in plant health and agronomic performance.

5.1.4 Improved Irrigation Scheduling Strategies using CROPGRO Model

The CROPGRO Tomato Model of DSSAT was well calibrated and used to perform predictions on soil processes; thus, rootzone soil temperature and plant growth processes that consisted of plant canopy height and fresh fruit weight of Mongal F1 and Pectomech tomato cultivars influenced by irrigation regimes and quantity of rice straw mulch. The model calibration and evaluation produced very good to excellent statistics on root mean square error (RMSE), relative root mean square error

(RRMSE), Willmott d-index of agreement (d) and Pearson's coefficient of determination (R^2). The inclusion of rice straw as mulch material in the model improved its simulation performance for the soil and plant processes especially under the stressed irrigation. The model was less sensitive in simulating the predicted mean canopy height and mean fresh fruit weight for the No-mulch treatment combination.

The test variety had great influence on the simulation of fresh fruit weight of tomatoes under irrigation regimes and quantity of rice straw mulch. For Mongal F1 variety, the application of full irrigation regime (100 % ET_c) and 6 t/ha rice straw resulted in good model performance (RRMSE=11.66 %). Also, the imposition of slightly stressed irrigation regime (75 % ET_c) and 6 t/ha rice straw mulch resulted in most excellent performance of the model (RRMSE=5.91 %).

Also, for the conclusion on Pectomech variety, the model performance was good in predicting fresh fruit weight under full (100 % ET_c) irrigation regime with inclusion of rice straw mulch (3 t/ha; RRMSE of 14.5 % and 6 t/ha; RRMSE of 13.7 %). Similar trend was observed under the slightly stressed irrigation regime (75 % ET_c), however, the inclusion of 3 t/ha rice straw resulted in excellent model performance (8.93 %). The interaction of 50 % ET_c and 6 t/ha rice straw also resulted in excellent model performance (RRMSE=4.67 %). The CROPGRO Tomato model if well calibrated could be used to simulate the effect of deficit irrigation regimes and quantity of rice straw mulch on soil processes within the rootzone of plants and tomato fruit yield for Mongal F1 and Pectomech in the study location.

5.2 Recommendations

The following research and policy driven recommendations are made.

5.2.1 Research and Development

i. The improvement of tomato yield and fruit quality traits under drip irrigation can be achieved by the adoption 100 % ET_c irrigation regime and 6 t/ha rice straw mulch. However, under water scarce environments, the mild deficit irrigation (75% ET_c) in combination with rice straw at 6 t/ha could be adopted.

ii. To further maximise water-use under drip irrigation, the Mongal F1 variety is the best candidate for the location. The variety can combine with severely stressed regime of 50 % ET_c especially at insensitive growth stages and still produce high yield per unit irrigation water used.

iii. Further research is recommended on varied levels of irrigation regimes especially above the computed 100 % ET_c to ascertain growth and yield response of the Mongal F1 variety. This would help provide adequate information for stakeholder to adjust their irrigation scheduling needs to meet with the increasing evaporative demand of the atmosphere due to high ambient temperatures resulting from climate change.

iv. Also, investigations on the incorporation of rice straw mulch into the soil rather than placing on the soil surface as done in this study, is recommended to ascertain its contribution to improving the microbial properties, water holding capacity and fertility levels of the soil.

v. Also, it is recommended in the determination of the maximum water stress baseline for the estimation of crop water stress index (CWSI) to completely halt transpiration by plants to measure canopy temperature. This study computed the upper baseline from the severely stressed regime of 50 % ET_c which still had some level of transpiration by plants. The use of

Petroleum jelly or Shea butter oil on the leaves of selected plants will cover the stomates of plant leaves thereby halting transpiration. The variation between temperature differentials (canopy – air temperature) of well watered plants and stressed (non-transpiring) plants will widen and can be used in irrigation scheduling decisions even beyond 50 % ET_c soil water stress level.

vi. The Mongal F1 tomato variety based on its outstanding performance on yield, fruit quality and irrigation water-use efficiency in the agroecology, should further be demonstrated on-farm under drip irrigation especially in small scale and farmer-led irrigation schemes. This will improve the adoption of the variety by farmers to improve tomato production and farmer livelihoods. The Ministry of food and agriculture (MoFA) should partner research institutions like the CSIR-SARI with research mandate in the zone to demonstrate the best performing strategies. This would introduce the water saving and soil water conservation potential of the technologies to farmers and increase adoption.

vii. The experiment should be repeated and modeled for different soil texture conditions; since this study was limited to the most common soil textural class of the study area; thus, sandy loam soil. The modeling aspect should include the environmental effect on irrigation water resource and crop yield.

5.2.2 Policy

i. The use of irrigation scheduling tools such as chameleon sensors and other cheaper soil water sensors should be promoted by stakeholders in the irrigation value chain. However, this can be fully achieved when policy directions are channeled towards reducing the tax on the importation of related instruments into the country.

ii. Agricultural incentives provided by the government to farmers should include those tailored towards dry season crop production to improve the livelihood of farmers through all year round improved crop production.

iii. Legal instruments should be enacted by the government towards the irrigation subsector to maximise irrigation water-use. In line with this initiative, the drip irrigation system should be promoted for dry season cultivation of vegetables including tomatoes to maximise the use of water and fertilizer.

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APPENDICES

Appendix 1a. Analysis of variance (ANOVA) table for effect of treatments on plant height at 4WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	310.09	103.37	3.92	
Variety (V)	1	413.76	413.76	15.69	0.03
Residual	3	79.12	26.37	3.82	
Irrigation regimes	2	6.39	3.19	0.46	0.64
Variety x Irrigation regimes (V x I)	2	7.08	3.54	0.51	0.61
Residual	12	82.85	6.90	2.22	
Mulching (M)	2	15.04	7.52	2.42	0.10
Variety x Mulching (V x M)	2	1.61	0.81	0.26	0.77
Irrigation regimes x Mulching (I x M)	4	15.10	3.78	1.21	0.32
Variety x Irrigation regimes x Mulching	4	38.84	9.71	3.12	0.03
Residual	36	111.96	3.11		
Total	71	1081.84			

Appendix 1b. Analysis of variance (ANOVA) table for effect of treatments on plant height at 6WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	10.39	3.46	0.10	
Variety (V)	1	2.10	2.10	0.06	0.819
Residual	3	100.84	33.61	6.43	
Irrigation regimes	2	126.06	63.03	12.06	0.001
Variety x Irrigation regimes (V x I)	2	3.63	1.82	0.35	0.713
Residual	12	62.70	5.23	1.86	
Mulching (M)	2	95.65	47.83	17.03	<.001
Variety x Mulching (V x M)	2	3.80	1.90	0.68	0.515
Irrigation regimes x Mulching (I x M)	4	27.25	6.81	2.43	0.066
Variety x Irrigation regimes x Mulching	4	24.88	6.22	2.21	0.087
Residual	36	101.12	2.81		
Total	71	558.42			

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Appendix 1c. Analysis of variance (ANOVA) table for effect of treatments on plant height at 8WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	4.67	1.56	0.08	
Variety (V)	1	7.61	7.61	0.37	0.59
Residual	3	62.28	20.76	1.63	
Irrigation regimes	2	95.34	47.67	3.75	0.05
Variety x Irrigation regimes (V x I)	2	2.80	1.40	0.11	0.90
Residual	12	152.68	12.72	3.54	
Mulching (M)	2	70.78	35.39	9.83	<.001
Variety x Mulching (V x M)	2	13.61	6.81	1.89	0.17
Irrigation regimes x Mulching (I x M)	4	36.73	9.18	2.55	0.06
Variety x Irrigation regimes x Mulching	4	24.77	6.19	1.72	0.17
Residual	36	129.54	3.60		
Total	71	600.81			

Appendix 1d. Analysis of variance (ANOVA) table for effect of treatments on plant height at 10WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	60.14	20.05	1.51	
Variety (V)	1	86.79	86.79	6.55	0.083
Residual	3	39.75	13.25	1.68	
Irrigation regimes	2	160.99	80.49	10.23	0.003
Variety x Irrigation regimes (V x I)	2	6.67	3.33	0.42	0.664
Residual	12	94.41	7.87	1.42	
Mulching (M)	2	38.90	19.45	3.52	0.040
Variety x Mulching (V x M)	2	22.90	11.45	2.07	0.141
Irrigation regimes x Mulching (I x M)	4	6.67	1.67	0.30	0.875
Variety x Irrigation regimes x Mulching	4	33.54	8.38	1.52	0.218
Residual	36	199.16	5.53		
Total	71	749.91			

Appendix 1e. Analysis of variance (ANOVA) table for effect of treatments on plant height at 4WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	331.41	110.47	1.68	
Variety (V)	1	116.28	116.28	1.77	0.276
Residual	3	197.24	65.75	3.79	
Irrigation regimes	2	37.62	18.81	1.08	0.369
Variety x Irrigation regimes (V x I)	2	19.77	9.89	0.57	0.580
Residual	12	208.04	17.34	3.16	
Mulching (M)	2	122.34	61.17	11.17	<.001
Variety x Mulching (V x M)	2	36.19	18.09	3.30	0.048
Irrigation regimes x Mulching (I x M)	4	15.27	3.82	0.70	0.599
Variety x Irrigation regimes x Mulching	4	9.20	2.30	0.42	0.793
Residual	36	197.22	5.48		
Total	71	1290.58			

Appendix 1f. Analysis of variance (ANOVA) table for effect of treatments on plant height at 6WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	463.88	154.63	1.27	
Variety (V)	1	5.65	5.65	0.05	0.843
Residual	3	364.29	121.43	5.87	
Irrigation regimes	2	9.47	4.73	0.23	0.799
Variety x Irrigation regimes (V x I)	2	79.98	39.99	1.93	0.187
Residual	12	248.32	20.69	2.32	
Mulching (M)	2	132.54	66.27	7.45	0.002
Variety x Mulching (V x M)	2	29.41	14.71	1.65	0.206
Irrigation regimes x Mulching (I x M)	4	11.82	2.95	0.33	0.855
Variety x Irrigation regimes x Mulching	4	29.92	7.48	0.84	0.509
Residual	36	320.44	8.90		
Total	71	1695.72			

Appendix 1g. Analysis of variance (ANOVA) table for effect of treatments on plant height at 8WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	52.61	17.54	0.18	
Variety (V)	1	149.84	149.84	1.57	0.30
Residual	3	286.73	95.58	3.45	
Irrigation regimes	2	32.94	16.47	0.60	0.57
Variety x Irrigation regimes (V x I)	2	11.64	5.82	0.21	0.81
Residual	12	332.14	27.68	4.08	
Mulching (M)	2	36.40	18.20	2.68	0.08
Variety x Mulching (V x M)	2	7.68	3.84	0.57	0.57
Irrigation regimes x Mulching (I x M)	4	6.71	1.68	0.25	0.91
Variety x Irrigation regimes x Mulching	4	37.08	9.27	1.37	0.27
Residual	36	244.09	6.78		
Total	71	1197.86			

Appendix 1h. Analysis of variance (ANOVA) table for effect of treatments on plant height at 10WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	330.58	110.20	1.53	
Variety (V)	1	237.74	237.74	3.30	0.167
Residual	3	216.45	72.15	2.98	
Irrigation regimes	2	36.02	18.01	0.74	0.496
Variety x Irrigation regimes (V x I)	2	60.21	30.11	1.24	0.323
Residual	12	290.29	24.19	3.98	
Mulching (M)	2	95.54	47.77	7.86	0.001
Variety x Mulching (V x M)	2	65.14	32.57	5.36	0.009
Irrigation regimes x Mulching (I x M)	4	19.08	4.77	0.78	0.543
Variety x Irrigation regimes x Mulching	4	18.05	4.51	0.74	0.569
Residual	36	218.82	6.08		
Total	71	1587.94			

Appendix 2a. Analysis of variance (ANOVA) table for effect of treatments on stem girth at 6WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	1.14	0.38	0.13	
Variety (V)	1	2.37	2.37	0.84	0.427
Residual	3	8.49	2.83	11.77	
Irrigation regimes	2	8.40	4.20	17.45	<.001
Variety x Irrigation regimes (V x I)	2	1.00	0.50	2.07	0.168
Residual	12	2.89	0.24	1.31	
Mulching (M)	2	8.13	4.07	22.06	<.001
Variety x Mulching (V x M)	2	0.35	0.18	0.96	0.393
Irrigation regimes x Mulching (I x M)	4	0.47	0.12	0.64	0.635
Variety x Irrigation regimes x Mulching	4	0.31	0.08	0.43	0.788
Residual	36	6.63	0.18		
Total	71	40.19			

Appendix 2b. Analysis of variance (ANOVA) table for effect of treatments on stem girth at 8WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	1.86	0.62	0.30	
Variety (V)	1	0.40	0.40	0.20	0.687
Residual	3	6.16	2.05	11.37	
Irrigation regimes	2	11.36	5.68	31.45	<.001
Variety x Irrigation regimes (V x I)	2	1.25	0.62	3.45	0.065
Residual	12	2.17	0.18	1.76	
Mulching (M)	2	15.54	7.77	75.91	<.001
Variety x Mulching (V x M)	2	1.21	0.61	5.93	0.006
Irrigation regimes x Mulching (I x M)	4	0.66	0.16	1.61	0.193
Variety x Irrigation regimes x Mulching	4	0.34	0.09	0.83	0.513
Residual	36	3.68	0.10		
Total	71	44.63			

Appendix 2c. Analysis of variance (ANOVA) table for effect of treatments on stem girth at 6WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	4.37	1.46	0.35	
Variety (V)	1	17.14	17.14	4.07	0.137
Residual	3	12.63	4.21	3.78	
Irrigation regimes	2	0.20	0.10	0.09	0.915
Variety x Irrigation regimes (V x I)	2	1.75	0.88	0.79	0.478
Residual	12	13.38	1.11	4.17	
Mulching (M)	2	19.07	9.53	35.69	<.001
Variety x Mulching (V x M)	2	1.09	0.55	2.04	0.144
Irrigation regimes x Mulching (I x M)	4	0.51	0.13	0.48	0.750
Variety x Irrigation regimes x Mulching	4	1.37	0.34	1.28	0.294
Residual	36	9.61	0.27		
Total	71	81.13			

Appendix 2d. Analysis of variance (ANOVA) table for effect of treatments on stem girth at 8WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	5.92	1.97	0.45	
Variety (V)	1	9.98	9.98	2.29	0.227
Residual	3	13.06	4.35	5.85	
Irrigation regimes	2	0.07	0.04	0.05	0.953
Variety x Irrigation regimes (V x I)	2	2.87	1.44	1.93	0.188
Residual	12	8.92	0.74	2.20	
Mulching (M)	2	23.79	11.89	35.23	<.001
Variety x Mulching (V x M)	2	1.58	0.79	2.34	0.111
Irrigation regimes x Mulching (I x M)	4	1.19	0.30	0.88	0.483
Variety x Irrigation regimes x Mulching	4	3.04	0.76	2.25	0.083
Residual	36	12.15	0.34		
Total	71	82.57			

Appendix 2e. Analysis of variance (ANOVA) table for effect of treatments on stem girth at 10WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	3.23	1.08	0.22	
Variety (V)	1	9.33	9.33	1.95	0.257
Residual	3	14.38	4.79	5.21	
Irrigation regimes	2	0.08	0.04	0.04	0.960
Variety x Irrigation regimes (V x I)	2	3.91	1.95	2.12	0.162
Residual	12	11.04	0.92	2.72	
Mulching (M)	2	22.86	11.43	33.78	<.001
Variety x Mulching (V x M)	2	1.73	0.86	2.55	0.092
Irrigation regimes x Mulching (I x M)	4	1.09	0.27	0.80	0.531
Variety x Irrigation regimes x Mulching	4	3.28	0.82	2.42	0.066
Residual	36	12.18	0.34		
Total	71	83.09			

Appendix 3a. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 3WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	126.26	42.09	2.75	
Variety (V)	1	4.60	4.60	0.30	0.62
Residual	3	45.88	15.29	1.81	
Irrigation regimes	2	17.83	8.91	1.06	0.38
Variety x Irrigation regimes (V x I)	2	6.09	3.05	0.36	0.70
Residual	12	101.25	8.44	3.44	
Mulching (M)	2	14.29	7.14	2.91	0.07
Variety x Mulching (V x M)	2	7.37	3.69	1.50	0.24
Irrigation regimes x Mulching (I x M)	4	4.49	1.12	0.46	0.77
Variety x Irrigation regimes x Mulching	4	24.05	6.01	2.45	0.06
Residual	36	88.35	2.45		
Total	71	440.46			

Appendix 3b. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 4WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	13.06	4.35	2.33	
Variety (V)	1	0.13	0.13	0.07	0.81
Residual	3	5.60	1.87	0.78	
Irrigation regimes	2	21.34	10.67	4.47	0.04
Variety x Irrigation regimes (V x I)	2	8.92	4.46	1.87	0.20
Residual	12	28.62	2.39	0.66	
Mulching (M)	2	29.48	14.74	4.09	0.03
Variety x Mulching (V x M)	2	2.93	1.46	0.41	0.67
Irrigation regimes x Mulching (I x M)	4	2.61	0.65	0.18	0.95
Variety x Irrigation regimes x Mulching	4	11.94	2.99	0.83	0.52
Residual	36	129.83	3.61		
Total	71	254.46			

Appendix 3c. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 5WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	6.17	2.06	0.15	
Variety (V)	1	4.81	4.81	0.34	0.599
Residual	3	42.06	14.02	2.43	
Irrigation regimes	2	214.66	107.33	18.63	<.001
Variety x Irrigation regimes (V x I)	2	14.69	7.35	1.28	0.315
Residual	12	69.12	5.76	0.72	
Mulching (M)	2	13.21	6.61	0.83	0.444
Variety x Mulching (V x M)	2	28.00	14.00	1.76	0.187
Irrigation regimes x Mulching (I x M)	4	25.28	6.32	0.79	0.537
Variety x Irrigation regimes x Mulching	4	13.33	3.33	0.42	0.794
Residual	36	286.45	7.96		
Total	71	717.78			

Appendix 3d. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 9WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	49.00	16.33	0.63	
Variety (V)	1	77.50	77.50	2.98	0.18
Residual	3	77.97	25.99	2.92	
Irrigation regimes	2	55.07	27.53	3.10	0.08
Variety x Irrigation regimes (V x I)	2	147.20	73.60	8.28	0.01
Residual	12	106.63	8.89	0.95	
Mulching (M)	2	55.82	27.91	2.97	0.06
Variety x Mulching (V x M)	2	16.03	8.02	0.85	0.44
Irrigation regimes x Mulching (I x M)	4	39.60	9.90	1.05	0.39
Variety x Irrigation regimes x Mulching	4	12.12	3.03	0.32	0.86
Residual	36	338.29	9.40		
Total	71	975.22			

Appendix 3e. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 4WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	1.74	0.58	0.26	
Variety (V)	1	0.53	0.53	0.24	0.66
Residual	3	6.73	2.24	3.10	
Irrigation regimes	2	9.82	4.91	6.79	0.01
Variety x Irrigation regimes (V x I)	2	0.63	0.32	0.44	0.66
Residual	12	8.67	0.72	1.55	
Mulching (M)	2	1.51	0.75	1.61	0.21
Variety x Mulching (V x M)	2	1.81	0.90	1.94	0.16
Irrigation regimes x Mulching (I x M)	4	2.22	0.55	1.19	0.33
Variety x Irrigation regimes x Mulching	4	0.95	0.24	0.51	0.73
Residual	36	16.78	0.47		
Total	71	51.38			

Appendix 3f. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 5WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	332.15	110.72	2.01	
Variety (V)	1	110.26	110.26	2.00	0.25
Residual	3	165.23	55.08	1.05	
Irrigation regimes	2	100.86	50.43	0.96	0.41
Variety x Irrigation regimes (V x I)	2	121.39	60.70	1.16	0.35
Residual	12	627.44	52.29	1.01	
Mulching (M)	2	73.21	36.60	0.71	0.50
Variety x Mulching (V x M)	2	89.64	44.82	0.87	0.43
Irrigation regimes x Mulching (I x M)	4	200.93	50.23	0.97	0.43
Variety x Irrigation regimes x Mulching	4	246.95	61.74	1.20	0.33
Residual	36	1858.47	51.62		
Total	71	3926.53			

Appendix 3g. Analysis of variance (ANOVA) table for effect of treatments on leaf temperature at 9WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	18.23	6.08	0.24	
Variety (V)	1	25.92	25.92	1.04	0.38
Residual	3	75.10	25.03	0.80	
Irrigation regimes	2	60.68	30.34	0.97	0.41
Variety x Irrigation regimes (V x I)	2	66.16	33.08	1.06	0.38
Residual	12	375.57	31.30	0.84	
Mulching (M)	2	69.79	34.89	0.93	0.40
Variety x Mulching (V x M)	2	77.45	38.72	1.04	0.37
Irrigation regimes x Mulching (I x M)	4	190.47	47.62	1.27	0.30
Variety x Irrigation regimes x Mulching	4	161.39	40.35	1.08	0.38
Residual	36	1346.72	37.41		
Total	71	2467.48			

Appendix 4a. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 5WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	180.58	60.19	0.72	
Variety (V)	1	529.59	529.59	6.37	0.09
Residual	3	249.31	83.10	1.89	
Irrigation regimes	2	468.49	234.24	5.34	0.02
Variety x Irrigation regimes (V x I)	2	59.03	29.52	0.67	0.53
Residual	12	526.86	43.91	1.73	
Mulching (M)	2	161.05	80.52	3.18	0.05
Variety x Mulching (V x M)	2	58.10	29.05	1.15	0.33
Irrigation regimes x Mulching (I x M)	4	69.77	17.44	0.69	0.61
Variety x Irrigation regimes x Mulching	4	308.35	77.09	3.04	0.03
Residual	36	912.54	25.35		
Total	71	3523.66			

Appendix 4b. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 6WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	309.25	103.08	1.68	
Variety (V)	1	83.42	83.42	1.36	0.327
Residual	3	183.65	61.22	1.99	
Irrigation regimes	2	1230.48	615.24	20.04	<.001
Variety x Irrigation regimes (V x I)	2	154.07	77.03	2.51	0.123
Residual	12	368.38	30.70	0.65	
Mulching (M)	2	15.16	7.58	0.16	0.853
Variety x Mulching (V x M)	2	20.83	10.42	0.22	0.804
Irrigation regimes x Mulching (I x M)	4	52.96	13.24	0.28	0.890
Variety x Irrigation regimes x Mulching	4	173.00	43.25	0.91	0.469
Residual	36	1711.77	47.55		
Total	71	4302.96			

Appendix 4c. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 7WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	492.32	164.11	0.35	
Variety (V)	1	34.20	34.20	0.07	0.80
Residual	3	1402.60	467.53	6.37	
Irrigation regimes	2	1233.81	616.91	8.41	0.01
Variety x Irrigation regimes (V x I)	2	80.50	40.25	0.55	0.59
Residual	12	880.44	73.37	1.13	
Mulching (M)	2	8.67	4.33	0.07	0.94
Variety x Mulching (V x M)	2	174.04	87.02	1.35	0.27
Irrigation regimes x Mulching (I x M)	4	94.27	23.57	0.36	0.83
Variety x Irrigation regimes x Mulching	4	162.23	40.56	0.63	0.65
Residual	36	2328.35	64.68		
Total	71	6891.43			

Appendix 4d. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 9WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	1093.95	364.65	1.67	
Variety (V)	1	1524.44	1524.44	6.96	0.078
Residual	3	656.89	218.96	2.46	
Irrigation regimes	2	2452.97	1226.48	13.79	<.001
Variety x Irrigation regimes (V x I)	2	757.77	378.88	4.26	0.040
Residual	12	1067.11	88.93	1.49	
Mulching (M)	2	922.43	461.21	7.74	0.002
Variety x Mulching (V x M)	2	115.81	57.90	0.97	0.388
Irrigation regimes x Mulching (I x M)	4	385.02	96.26	1.61	0.192
Variety x Irrigation regimes x Mulching	4	394.98	98.75	1.66	0.182
Residual	36	2146.15	59.62		
Total	71	11517.51			

Appendix 4e. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 6WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	159.00	53.00	0.74	
Variety (V)	1	4.01	4.01	0.06	0.828
Residual	3	215.43	71.81	4.70	
Irrigation regimes	2	550.42	275.21	18.02	<.001
Variety x Irrigation regimes (V x I)	2	58.36	29.18	1.91	0.190
Residual	12	183.27	15.27	0.55	
Mulching (M)	2	15.40	7.70	0.28	0.761
Variety x Mulching (V x M)	2	10.93	5.46	0.20	0.823
Irrigation regimes x Mulching (I x M)	4	23.44	5.86	0.21	0.931
Variety x Irrigation regimes x Mulching	4	109.21	27.30	0.98	0.432
Residual	36	1005.21	27.92		
Total	71	2334.67			

Appendix 4f. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 7WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	519.02	173.01	7.26	
Variety (V)	1	672.83	672.83	28.22	0.01
Residual	3	71.53	23.84	0.32	
Irrigation regimes	2	759.16	379.58	5.14	0.02
Variety x Irrigation regimes (V x I)	2	80.03	40.01	0.54	0.60
Residual	12	885.51	73.79	1.74	
Mulching (M)	2	157.77	78.89	1.86	0.17
Variety x Mulching (V x M)	2	82.98	41.49	0.98	0.39
Irrigation regimes x Mulching (I x M)	4	267.65	66.91	1.58	0.20
Variety x Irrigation regimes x Mulching	4	157.99	39.50	0.93	0.46
Residual	36	1529.27	42.48		
Total	71	5183.74			

Appendix 4g. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 9WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	291.42	97.14	0.32	
Variety (V)	1	808.69	808.69	2.65	0.202
Residual	3	915.25	305.08	10.57	
Irrigation regimes	2	1151.71	575.86	19.96	<.001
Variety x Irrigation regimes (V x I)	2	123.53	61.76	2.14	0.160
Residual	12	346.20	28.85	0.43	
Mulching (M)	2	287.59	143.79	2.15	0.132
Variety x Mulching (V x M)	2	244.57	122.29	1.83	0.176
Irrigation regimes x Mulching (I x M)	4	92.76	23.19	0.35	0.845
Variety x Irrigation regimes x Mulching	4	209.26	52.31	0.78	0.545
Residual	36	2411.13	66.98		
Total	71	6882.10			

Appendix 4h. Analysis of variance (ANOVA) table for effect of treatments on Leaf chlorophyll concentration at 10WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	179.34	59.78	0.22	
Variety (V)	1	3121.82	3121.82	11.47	0.043
Residual	3	816.72	272.24	3.47	
Irrigation regimes	2	1619.71	809.86	10.31	0.002
Variety x Irrigation regimes (V x I)	2	216.28	108.14	1.38	0.290
Residual	12	942.74	78.56	1.01	
Mulching (M)	2	1317.38	658.69	8.47	<.001
Variety x Mulching (V x M)	2	391.52	195.76	2.52	0.095
Irrigation regimes x Mulching (I x M)	4	254.06	63.51	0.82	0.523
Variety x Irrigation regimes x Mulching	4	221.05	55.26	0.71	0.590
Residual	36	2801.26	77.81		
Total	71	11881.87			

Appendix 5a. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 6WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	8829.2	2943.1	2.6	
Variety (V)	1	281.8	281.8	0.3	0.7
Residual	3	3423.2	1141.1	1.8	
Irrigation regimes	2	5176.3	2588.1	4.0	0.0
Variety x Irrigation regimes (V x I)	2	3301.4	1650.7	2.5	0.1
Residual	12	7790.6	649.2	3.1	
Mulching (M)	2	1281.3	640.6	3.1	0.1
Variety x Mulching (V x M)	2	798.6	399.3	1.9	0.2
Irrigation regimes x Mulching (I x M)	4	1130.9	282.7	1.4	0.3
Variety x Irrigation regimes x Mulching	4	837.5	209.4	1.0	0.4
Residual	36	7488.5	208.0		
Total	71	40339.4			

Appendix 5b. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 7WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	5093.08	1697.69	3.56	
Variety (V)	1	313.75	313.75	0.66	0.48
Residual	3	1428.71	476.24	2.54	
Irrigation regimes	2	1081.89	540.95	2.88	0.10
Variety x Irrigation regimes (V x I)	2	722.92	361.46	1.93	0.19
Residual	12	2251.09	187.59	2.37	
Mulching (M)	2	1120.15	560.08	7.08	0.00
Variety x Mulching (V x M)	2	76.58	38.29	0.48	0.62
Irrigation regimes x Mulching (I x M)	4	938.49	234.62	2.97	0.03
Variety x Irrigation regimes x Mulching	4	83.51	20.88	0.26	0.90
Residual	36	2845.98	79.06		
Total	71	15956.15			

Appendix 5c. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 9WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	2681.50	893.80	3.87	
Variety (V)	1	455.00	455.00	1.97	0.26
Residual	3	692.30	230.80	0.90	
Irrigation regimes	2	1726.30	863.20	3.37	0.07
Variety x Irrigation regimes (V x I)	2	836.90	418.40	1.63	0.24
Residual	12	3073.00	256.10	1.50	
Mulching (M)	2	1187.20	593.60	3.48	0.04
Variety x Mulching (V x M)	2	412.20	206.10	1.21	0.31
Irrigation regimes x Mulching (I x M)	4	485.30	121.30	0.71	0.59
Variety x Irrigation regimes x Mulching	4	560.00	140.00	0.82	0.52
Residual	36	6138.20	170.50		
Total	71	18248.00			

Appendix 5d. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 2WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	5302.30	1767.40	7.16	
Variety (V)	1	455.00	455.00	1.84	0.27
Residual	3	740.80	246.90	0.59	
Irrigation regimes	2	269.80	134.90	0.32	0.73
Variety x Irrigation regimes (V x I)	2	2686.40	1343.20	3.20	0.08
Residual	12	5041.10	420.10	1.34	
Mulching (M)	2	2583.10	1291.50	4.13	0.02
Variety x Mulching (V x M)	2	166.00	83.00	0.27	0.77
Irrigation regimes x Mulching (I x M)	4	2189.60	547.40	1.75	0.16
Variety x Irrigation regimes x Mulching	4	3702.40	925.60	2.96	0.03
Residual	36	11267.50	313.00		
Total	71	34404.00			

Appendix 5e. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 5WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	25581.50	8527.20	2.48	
Variety (V)	1	31.90	31.90	0.01	0.929
Residual	3	10321.40	3440.50	2.84	
Irrigation regimes	2	619.50	309.70	0.26	0.778
Variety x Irrigation regimes (V x I)	2	1643.80	821.90	0.68	0.526
Residual	12	14534.20	1211.20	4.30	
Mulching (M)	2	2646.80	1323.40	4.70	0.015
Variety x Mulching (V x M)	2	6469.70	3234.80	11.49	<.001
Irrigation regimes x Mulching (I x M)	4	1110.90	277.70	0.99	0.427
Variety x Irrigation regimes x Mulching	4	1261.10	315.30	1.12	0.362
Residual	36	10136.30	281.60		
Total	71	74356.90			

Appendix 5f. Analysis of variance (ANOVA) table for effect of treatments on Leaf stomatal conductance at 8WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	396.07	132.02	2.55	
Variety (V)	1	2.46	2.46	0.05	0.84
Residual	3	155.22	51.74	1.80	
Irrigation regimes	2	227.87	113.93	3.96	0.05
Variety x Irrigation regimes (V x I)	2	458.18	229.09	7.97	0.01
Residual	12	344.89	28.74	0.41	
Mulching (M)	2	181.38	90.69	1.31	0.28
Variety x Mulching (V x M)	2	243.98	121.99	1.76	0.19
Irrigation regimes x Mulching (I x M)	4	148.11	37.03	0.53	0.71
Variety x Irrigation regimes x Mulching	4	49.53	12.38	0.18	0.95
Residual	36	2494.21	69.28		
Total	71	4701.91			

Appendix 5a. Analysis of variance (ANOVA) table for effect of treatments on Leaf area index (LAI) at 6WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.14	0.05	0.65	
Variety (V)	1	0.27	0.27	3.69	0.15
Residual	3	0.22	0.07	2.42	
Irrigation regimes	2	0.45	0.22	7.26	0.01
Variety x Irrigation regimes (V x I)	2	0.04	0.02	0.59	0.57
Residual	12	0.37	0.03	0.82	
Mulching (M)	2	0.25	0.12	3.31	0.05
Variety x Mulching (V x M)	2	0.15	0.08	2.06	0.14
Irrigation regimes x Mulching (I x M)	4	0.07	0.02	0.46	0.77
Variety x Irrigation regimes x Mulching	4	0.04	0.01	0.29	0.88
Residual	36	1.34	0.04		
Total	71	3.34			

Appendix 5b. Analysis of variance (ANOVA) table for effect of treatments on Leaf area index (LAI) at 8WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.16	0.05	0.75	
Variety (V)	1	0.45	0.45	6.32	0.09
Residual	3	0.21	0.07	0.80	
Irrigation regimes	2	0.04	0.02	0.21	0.82
Variety x Irrigation regimes (V x I)	2	0.06	0.03	0.33	0.73
Residual	12	1.07	0.09	2.33	
Mulching (M)	2	0.34	0.17	4.42	0.02
Variety x Mulching (V x M)	2	0.11	0.06	1.46	0.25
Irrigation regimes x Mulching (I x M)	4	0.07	0.02	0.46	0.77
Variety x Irrigation regimes x Mulching	4	0.02	0.00	0.13	0.97
Residual	36	1.38	0.04		
Total	71	3.92			

Appendix 5c. Analysis of variance (ANOVA) table for effect of treatments on Leaf area index (LAI) at 9WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	1.06	0.35	16.00	
Variety (V)	1	0.21	0.21	9.63	0.053
Residual	3	0.07	0.02	1.04	
Irrigation regimes	2	0.10	0.05	2.30	0.142
Variety x Irrigation regimes (V x I)	2	0.04	0.02	0.88	0.442
Residual	12	0.25	0.02	1.37	
Mulching (M)	2	0.40	0.20	13.09	<.001
Variety x Mulching (V x M)	2	0.00	0.00	0.16	0.856
Irrigation regimes x Mulching (I x M)	4	0.09	0.02	1.51	0.220
Variety x Irrigation regimes x Mulching	4	0.17	0.04	2.77	0.042
Residual	36	0.55	0.02		
Total	71	2.95			

Appendix 5d. Analysis of variance (ANOVA) table for effect of treatments on Leaf area index (LAI) at 7WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	1.57	0.52	3.52	
Variety (V)	1	0.79	0.79	5.33	0.10
Residual	3	0.45	0.15	1.38	
Irrigation regimes	2	0.05	0.02	0.23	0.80
Variety x Irrigation regimes (V x I)	2	0.16	0.08	0.73	0.50
Residual	12	1.30	0.11	2.56	
Mulching (M)	2	0.25	0.13	2.98	0.06
Variety x Mulching (V x M)	2	0.11	0.06	1.33	0.28
Irrigation regimes x Mulching (I x M)	4	0.03	0.01	0.20	0.94
Variety x Irrigation regimes x Mulching	4	0.01	0.00	0.05	0.99
Residual	36	1.52	0.04		
Total	71	6.24			

Appendix 5e. Analysis of variance (ANOVA) table for effect of treatments on Leaf area index (LAI) at 9WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	1.71	0.57	2.29	
Variety (V)	1	0.82	0.82	3.30	0.167
Residual	3	0.75	0.25	11.79	
Irrigation regimes	2	0.10	0.05	2.30	0.142
Variety x Irrigation regimes (V x I)	2	0.04	0.02	0.88	0.442
Residual	12	0.25	0.02	1.37	
Mulching (M)	2	0.40	0.20	13.09	<.001
Variety x Mulching (V x M)	2	0.00	0.00	0.16	0.856
Irrigation regimes x Mulching (I x M)	4	0.09	0.02	1.51	0.220
Variety x Irrigation regimes x Mulching	4	0.17	0.04	2.77	0.042
Residual	36	0.55	0.02		
Total	71	4.89			

Appendix 6a. Analysis of variance (ANOVA) table for effect of treatments on Fruit width at 11WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	1.40	0.47	0.01	
Variety (V)	1	1112.30	1112.30	30.54	0.012
Residual	3	109.28	36.43	5.85	
Irrigation regimes	2	244.70	122.35	19.66	<.001
Variety x Irrigation regimes (V x I)	2	143.08	71.54	11.50	0.002
Residual	12	74.68	6.22	2.37	
Mulching (M)	2	43.76	21.88	8.34	0.001
Variety x Mulching (V x M)	2	22.93	11.46	4.37	0.020
Irrigation regimes x Mulching (I x M)	4	28.40	7.10	2.71	0.045
Variety x Irrigation regimes x Mulching	4	11.15	2.79	1.06	0.389
Residual	36	94.40	2.62		
Total	71	1886.06			

Appendix 6b. Analysis of variance (ANOVA) table for effect of treatments on Fruit width at 12WAT in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	98.77	32.92	1.87	
Variety (V)	1	309.26	309.26	17.53	0.03
Residual	3	52.92	17.64	2.13	
Irrigation regimes	2	129.35	64.68	7.82	0.01
Variety x Irrigation regimes (V x I)	2	99.34	49.67	6.00	0.02
Residual	12	99.26	8.27	1.95	
Mulching (M)	2	22.46	11.23	2.65	0.09
Variety x Mulching (V x M)	2	53.97	26.98	6.36	0.00
Irrigation regimes x Mulching (I x M)	4	11.87	2.97	0.70	0.60
Variety x Irrigation regimes x Mulching	4	20.07	5.02	1.18	0.34
Residual	36	152.83	4.25		
Total	71	1050.10			

Appendix 6c. Analysis of variance (ANOVA) table for effect of treatments on Fruit width at 11WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	52.61	17.54	0.70	
Variety (V)	1	470.32	470.32	18.81	0.02
Residual	3	75.01	25.00	1.60	
Irrigation regimes	2	50.95	25.47	1.63	0.24
Variety x Irrigation regimes (V x I)	2	4.89	2.44	0.16	0.86
Residual	12	187.05	15.59	2.23	
Mulching (M)	2	51.03	25.51	3.64	0.04
Variety x Mulching (V x M)	2	54.49	27.24	3.89	0.03
Irrigation regimes x Mulching (I x M)	4	21.74	5.43	0.78	0.55
Variety x Irrigation regimes x Mulching	4	26.33	6.58	0.94	0.45
Residual	36	252.09	7.00		
Total	71	1246.50			

Appendix 6d. Analysis of variance (ANOVA) table for effect of treatments on Fruit width at 12WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	116.92	38.97	2.24	
Variety (V)	1	86.07	86.07	4.95	0.11
Residual	3	52.12	17.37	1.67	
Irrigation regimes	2	26.79	13.40	1.29	0.31
Variety x Irrigation regimes (V x I)	2	0.11	0.06	0.01	1.00
Residual	12	125.07	10.42	1.94	
Mulching (M)	2	55.26	27.63	5.13	0.01
Variety x Mulching (V x M)	2	2.59	1.30	0.24	0.79
Irrigation regimes x Mulching (I x M)	4	14.12	3.53	0.66	0.63
Variety x Irrigation regimes x Mulching	4	14.65	3.66	0.68	0.61
Residual	36	193.83	5.38		
Total	71	687.52			

Appendix 7a. Analysis of variance (ANOVA) table for effect of treatments on Fruit length at 11WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	25.10	8.37	0.30	
Variety (V)	1	12.36	12.36	0.44	0.554
Residual	3	84.10	28.03	10.32	
Irrigation regimes	2	63.99	32.00	11.78	0.001
Variety x Irrigation regimes (V x I)	2	65.38	32.69	12.03	0.001
Residual	12	32.61	2.72	1.47	
Mulching (M)	2	10.71	5.35	2.90	0.068
Variety x Mulching (V x M)	2	6.98	3.49	1.89	0.166
Irrigation regimes x Mulching (I x M)	4	7.79	1.95	1.05	0.393
Variety x Irrigation regimes x Mulching	4	2.90	0.73	0.39	0.812
Residual	36	66.48	1.85		
Total	71	378.38			

Appendix 7b. Analysis of variance (ANOVA) table for effect of treatments on Fruit length at 12WAT in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	61.34	20.45	2.30	
Variety (V)	1	612.73	612.73	68.96	0.00
Residual	3	26.66	8.89	0.68	
Irrigation regimes	2	11.02	5.51	0.42	0.67
Variety x Irrigation regimes (V x I)	2	9.06	4.53	0.35	0.72
Residual	12	157.40	13.12	3.14	
Mulching (M)	2	1.05	0.52	0.13	0.88
Variety x Mulching (V x M)	2	35.83	17.92	4.29	0.02
Irrigation regimes x Mulching (I x M)	4	4.09	1.02	0.24	0.91
Variety x Irrigation regimes x Mulching	4	10.82	2.70	0.65	0.63
Residual	36	150.46	4.18		
Total	71	1080.45			

Appendix 7c. Analysis of variance (ANOVA) table for effect of treatments on Fruit length at 11WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	123.51	41.17	6.05	
Variety (V)	1	1056.05	1056.05	155.30	0.001
Residual	3	20.40	6.80	0.70	
Irrigation regimes	2	4.85	2.42	0.25	0.782
Variety x Irrigation regimes (V x I)	2	12.93	6.47	0.67	0.531
Residual	12	116.10	9.68	1.45	
Mulching (M)	2	10.53	5.26	0.79	0.463
Variety x Mulching (V x M)	2	3.58	1.79	0.27	0.766
Irrigation regimes x Mulching (I x M)	4	12.27	3.07	0.46	0.765
Variety x Irrigation regimes x Mulching	4	3.75	0.94	0.14	0.966
Residual	36	240.58	6.68		
Total	71	1604.54			

Appendix 7d. Analysis of variance (ANOVA) table for effect of treatments on Fruit length at 12WAT in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	68.03	22.68	2.69	
Variety (V)	1	534.92	534.92	63.57	0.004
Residual	3	25.24	8.41	0.52	
Irrigation regimes	2	6.75	3.37	0.21	0.815
Variety x Irrigation regimes (V x I)	2	14.58	7.29	0.45	0.648
Residual	12	194.27	16.19	1.42	
Mulching (M)	2	17.71	8.86	0.78	0.466
Variety x Mulching (V x M)	2	33.92	16.96	1.49	0.239
Irrigation regimes x Mulching (I x M)	4	72.37	18.09	1.59	0.198
Variety x Irrigation regimes x Mulching	4	31.11	7.78	0.68	0.608
Residual	36	409.28	11.37		
Total	71	1408.18			

Appendix 8a. Analysis of variance (ANOVA) table for effect of treatments on Total fruit yield in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	61.25	20.42	0.52	
Variety (V)	1	1099.82	1099.82	27.80	0.013
Residual	3	118.67	39.56	4.40	
Irrigation regimes	2	84.86	42.43	4.72	0.031
Variety x Irrigation regimes (V x I)	2	62.10	31.05	3.45	0.065
Residual	12	107.91	8.99	3.30	
Mulching (M)	2	137.20	68.60	25.20	<.001
Variety x Mulching (V x M)	2	15.93	7.96	2.93	0.067
Irrigation regimes x Mulching (I x M)	4	7.02	1.75	0.64	0.635
Variety x Irrigation regimes x Mulching	4	8.99	2.25	0.83	0.518
Residual	36	98.01	2.72		
Total	71	1801.75			

Appendix 8b. Analysis of variance (ANOVA) table for effect of treatments on Total fruit yield in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	116.43	38.81	0.37	
Variety (V)	1	507.07	507.07	4.82	0.116
Residual	3	315.88	105.29	5.89	
Irrigation regimes	2	16.20	8.10	0.45	0.646
Variety x Irrigation regimes (V x I)	2	20.80	10.40	0.58	0.574
Residual	12	214.61	17.88	4.27	
Mulching (M)	2	316.70	158.35	37.80	<.001
Variety x Mulching (V x M)	2	40.81	20.40	4.87	0.013
Irrigation regimes x Mulching (I x M)	4	2.51	0.63	0.15	0.962
Variety x Irrigation regimes x Mulching	4	11.49	2.87	0.69	0.607
Residual	36	150.81	4.19		
Total	71	1713.30			

Appendix 9a. Analysis of variance (ANOVA) table for effect of treatments on Fruit pH in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	2	0.0002	0.0001	0.0600	
Variety (V)	1	0.0104	0.0104	6.1700	0.1310
Residual	2	0.0034	0.0017	1.0600	
Irrigation regimes	2	0.0396	0.0198	12.4600	0.0030
Variety x Irrigation regimes (V x I)	2	0.0173	0.0087	5.4500	0.0320
Residual	8	0.0127	0.0016	0.9300	
Mulching (M)	2	0.0126	0.0063	3.6800	0.0400
Variety x Mulching (V x M)	2	0.0247	0.0124	7.2400	0.0030
Irrigation regimes x Mulching (I x M)	4	0.1019	0.0255	14.9400	<.001
Variety x Irrigation regimes x Mulching	4	0.0340	0.0085	4.9800	0.0050
Residual	24	0.0409	0.0017		
Total	53	0.2977			

Appendix 9b. Analysis of variance (ANOVA) table for effect of treatments on Fruit pH in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.05	0.02	1.52	
Variety (V)	1	1.51	1.51	130.48	0.001
Residual	3	0.03	0.01	0.79	
Irrigation regimes	2	0.31	0.15	10.55	0.002
Variety x Irrigation regimes (V x I)	2	0.62	0.31	21.31	<.001
Residual	12	0.18	0.01	0.98	
Mulching (M)	2	0.05	0.02	1.59	0.218
Variety x Mulching (V x M)	2	0.55	0.27	18.30	<.001
Irrigation regimes x Mulching (I x M)	4	0.71	0.18	11.84	<.001
Variety x Irrigation regimes x Mulching	4	0.30	0.08	5.04	0.002
Residual	36	0.54	0.01		
Total	71	4.85			

Appendix 10a. Analysis of variance (ANOVA) table for effect of treatments on Fruit Brix content in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	2	0.10	0.05	1.37	
Variety (V)	1	31.43	31.43	866.04	0.001
Residual	2	0.07	0.04	7.84	
Irrigation regimes	2	7.38	3.69	797.08	<.001
Variety x Irrigation regimes (V x I)	2	2.04	1.02	220.84	<.001
Residual	8	0.04	0.00	0.16	
Mulching (M)	2	0.27	0.13	4.61	0.020
Variety x Mulching (V x M)	2	0.45	0.22	7.67	0.003
Irrigation regimes x Mulching (I x M)	4	0.29	0.07	2.46	0.073
Variety x Irrigation regimes x Mulching	4	1.84	0.46	15.78	<.001
Residual	24	0.70	0.03		
Total	53	44.60			

Appendix 10b. Analysis of variance (ANOVA) table for effect of treatments on Fruit Brix content in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	0.31	0.10	0.44	
Variety (V)	1	3.65	3.65	15.91	0.03
Residual	3	0.69	0.23	0.31	
Irrigation regimes	2	3.26	1.63	2.24	0.15
Variety x Irrigation regimes (V x I)	2	1.08	0.54	0.74	0.50
Residual	12	8.73	0.73	1.02	
Mulching (M)	2	0.05	0.02	0.03	0.97
Variety x Mulching (V x M)	2	0.70	0.35	0.49	0.62
Irrigation regimes x Mulching (I x M)	4	4.22	1.06	1.47	0.23
Variety x Irrigation regimes x Mulching	4	1.46	0.37	0.51	0.73
Residual	36	25.78	0.72		
Total	71	49.91			

Appendix 11a. Analysis of variance (ANOVA) table for effect of treatments on Irrigation water-use efficiency (IWUE) in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	4.48	1.49	0.50	
Variety (V)	1	71.65	71.65	24.06	0.016
Residual	3	8.94	2.98	4.19	
Irrigation regimes	2	7.69	3.85	5.41	0.021
Variety x Irrigation regimes (V x I)	2	5.68	2.84	3.99	0.047
Residual	12	8.53	0.71	3.24	
Mulching (M)	2	9.87	4.93	22.49	<.001
Variety x Mulching (V x M)	2	1.22	0.61	2.78	0.075
Irrigation regimes x Mulching (I x M)	4	1.78	0.44	2.02	0.112
Variety x Irrigation regimes x Mulching	4	0.84	0.21	0.96	0.441
Residual	36	7.90	0.22		
Total	71	128.57			

Appendix 11b. Analysis of variance (ANOVA) table for effect of treatments on Irrigation water-use efficiency (IWUE) in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	10.48	3.49	0.54	
Variety (V)	1	34.23	34.23	5.29	0.105
Residual	3	19.41	6.47	4.66	
Irrigation regimes	2	9.95	4.97	3.58	0.06
Variety x Irrigation regimes (V x I)	2	3.67	1.83	1.32	0.303
Residual	12	16.67	1.39	4.64	
Mulching (M)	2	22.82	11.41	38.08	<.001
Variety x Mulching (V x M)	2	2.82	1.41	4.70	0.015
Irrigation regimes x Mulching (I x M)	4	2.96	0.74	2.47	0.062
Variety x Irrigation regimes x Mulching	4	1.03	0.26	0.86	0.497
Residual	36	10.79	0.30		
Total	71	134.80			

Appendix 12a. Analysis of variance (ANOVA) table for effect of treatments on Crop water stress index (CWSI) at 4WAT in the 2020/21 irrigated season.

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	2	0.10	0.05	1.24	
Variety (V)	1	0.01	0.01	0.38	0.60
Residual	2	0.08	0.04	6.27	
Irrigation regimes	2	0.11	0.05	8.77	0.01
Variety x Irrigation regimes (V x I)	2	0.01	0.00	0.44	0.66
Residual	8	0.05	0.01	0.53	
Mulching (M)	2	0.01	0.01	0.55	0.58
Variety x Mulching (V x M)	2	0.06	0.03	2.61	0.09
Irrigation regimes x Mulching (I x M)	4	0.02	0.01	0.51	0.73
Variety x Irrigation regimes x Mulching	4	0.03	0.01	0.60	0.67
Residual	24	0.28	0.01		
Total	53	0.75			

Appendix 12b. Analysis of variance (ANOVA) table for effect of treatments on Crop water stress index (CWSI) at 6WAT in the 2020/21 irrigated season.

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	2	0.123	0.061	156.360	
Variety (V)	1	0.173	0.173	441.510	0.002
Residual	2	0.001	0.000	0.030	
Irrigation regimes	2	0.152	0.076	4.870	0.041
Variety x Irrigation regimes (V x I)	2	0.062	0.031	1.980	0.200
Residual	8	0.125	0.016	2.610	
Mulching (M)	2	0.017	0.009	1.450	0.254
Variety x Mulching (V x M)	2	0.022	0.011	1.830	0.182
Irrigation regimes x Mulching (I x M)	4	0.017	0.004	0.700	0.598
Variety x Irrigation regimes x Mulching	4	0.081	0.020	3.370	0.025
Residual	24	0.144	0.006		
Total	53	0.917			

Appendix 12c. Analysis of variance (ANOVA) table for effect of treatments on Crop water stress index (CWSI) at 6WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.116	0.039	1.360	
Variety (V)	1	0.000	0.000	0.010	0.911
Residual	3	0.085	0.028	8.940	
Irrigation regimes	2	0.107	0.053	16.800	<.001
Variety x Irrigation regimes (V x I)	2	0.029	0.015	4.590	0.033
Residual	12	0.038	0.003	0.540	
Mulching (M)	2	0.027	0.013	2.290	0.116
Variety x Mulching (V x M)	2	0.000	0.000	0.010	0.987
Irrigation regimes x Mulching (I x M)	4	0.011	0.003	0.460	0.766
Variety x Irrigation regimes x Mulching	4	0.017	0.004	0.720	0.583
Residual	36	0.210	0.006		
Total	71	0.641			

Appendix 12d. Analysis of variance (ANOVA) table for effect of treatments on Crop water stress index (CWSI) at 9WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.964	0.321	15.230	
Variety (V)	1	0.001	0.001	0.040	0.854
Residual	3	0.063	0.021	1.890	
Irrigation regimes	2	0.055	0.027	2.450	0.128
Variety x Irrigation regimes (V x I)	2	0.024	0.012	1.080	0.369
Residual	12	0.134	0.011	0.640	
Mulching (M)	2	0.015	0.008	0.440	0.647
Variety x Mulching (V x M)	2	0.007	0.004	0.210	0.809
Irrigation regimes x Mulching (I x M)	4	0.053	0.013	0.760	0.560
Variety x Irrigation regimes x Mulching	4	0.067	0.017	0.950	0.444
Residual	36	0.630	0.018		
Total	71	2.013			

Appendix 12e. Analysis of variance (ANOVA) table for effect of treatments on Crop water stress index (CWSI) at 11WAT in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3	0.311	0.104	21.470	
Variety (V)	1	0.004	0.004	0.860	0.422
Residual	3	0.015	0.005	0.370	
Irrigation regimes	2	0.249	0.125	9.640	0.003
Variety x Irrigation regimes (V x I)	2	0.108	0.054	4.200	0.041
Residual	12	0.155	0.013	1.150	
Mulching (M)	2	0.014	0.007	0.620	0.544
Variety x Mulching (V x M)	2	0.004	0.002	0.180	0.838
Irrigation regimes x Mulching (I x M)	4	0.016	0.004	0.350	0.842
Variety x Irrigation regimes x Mulching	4	0.023	0.006	0.510	0.73
Residual	36	0.403	0.011		
Total	71	1.302			

Appendix 13a. Analysis of variance (ANOVA) table for effect of treatments on Fruit electrical conductivity (EC) in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	2	3.17	1.59	4.95	
Variety (V)	1	0.02	0.02	0.08	0.81
Residual	2	0.64	0.32	1.30	
Irrigation regimes	2	0.19	0.10	0.39	0.69
Variety x Irrigation regimes (V x I)	2	0.78	0.39	1.59	0.26
Residual	8	1.97	0.25	1.17	
Mulching (M)	2	0.25	0.13	0.61	0.55
Variety x Mulching (V x M)	2	0.08	0.04	0.18	0.84
Irrigation regimes x Mulching (I x M)	4	0.73	0.18	0.87	0.50
Variety x Irrigation regimes x Mulching	4	1.32	0.33	1.57	0.21
Residual	24	5.04	0.21		
Total	53	14.19			

Appendix 13b. Analysis of variance (ANOVA) table for effect of treatments on Fruit electrical conductivity (EC) in the 2021/22 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	3.00	133018.00	44339.00	16.32	
Variety (V)	1.00	1872.00	1872.00	0.69	0.47
Residual	3.00	8151.00	2717.00	0.91	
Irrigation regimes	2.00	15611.00	7805.00	2.60	0.12
Variety x Irrigation regimes (V x I)	2.00	7649.00	3824.00	1.28	0.32
Residual	12.00	35990.00	2999.00	1.35	
Mulching (M)	2.00	10903.00	5452.00	2.45	0.10
Variety x Mulching (V x M)	2.00	15877.00	7938.00	3.56	0.04
Irrigation regimes x Mulching (I x M)	4.00	14258.00	3564.00	1.60	0.20
Variety x Irrigation regimes x Mulching	4.00	8493.00	2123.00	0.95	0.45
Residual	36.00	78011.00	2229.00		
Total	71.00	322592.00			

Appendix 14. Analysis of variance (ANOVA) table for effect of treatments on rootzone soil nitrogen concentration in the 2020/21 irrigated season

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	F calculated	F probability
Rep stratum	2	0.002	0.001	0.890	
Variety (V)	1	0.001	0.001	1.510	0.344
Residual	2	0.002	0.001	2.220	
Irrigation regimes	2	0.000	0.000	0.380	0.694
Variety x Irrigation regimes (V x I)	2	0.000	0.000	0.010	0.990
Residual	8	0.003	0.000	2.830	
Mulching (M)	2	0.000	0.000	0.800	0.460
Variety x Mulching (V x M)	2	0.000	0.000	1.270	0.300
Irrigation regimes x Mulching (I x M)	4	0.000	0.000	0.790	0.543
Variety x Irrigation regimes x Mulching	4	0.001	0.000	1.030	0.411
Residual	24	0.003	0.000		
Total	53	0.013			

Appendix 15a. Analysis of variance (ANOVA) table for effect of treatments on rootzone soil pH in the 2020/21 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	2	0.537	0.268	182.150	
Variety (V)	1	0.003	0.003	2.110	0.283
Residual	2	0.003	0.001	0.150	
Irrigation regimes	2	1.145	0.572	60.110	<.001
Variety x Irrigation regimes (V x I)	2	0.281	0.140	14.730	0.002
Residual	8	0.076	0.010	4.740	
Mulching (M)	2	0.142	0.071	35.430	<.001
Variety x Mulching (V x M)	2	0.241	0.121	60.110	<.001
Irrigation regimes x Mulching (I x M)	4	0.620	0.155	77.240	<.001
Variety x Irrigation regimes x Mulching	4	0.378	0.094	47.030	<.001
Residual	24	0.048	0.002		
Total	53	3.475			

Appendix 15b. Analysis of variance (ANOVA) table for effect of treatments on rootzone soil pH in the 2021/22 irrigated season

Source of variation	**Degree of freedom**	**Sum of squares**	**Mean sum of squares**	**F calculated**	**F probability**
Rep stratum	3	37.549	12.516	193.340	
Variety (V)	1	0.134	0.134	2.080	0.245
Residual	3	0.194	0.065	0.660	
Irrigation regimes	2	0.355	0.177	1.810	0.206
Variety x Irrigation regimes (V x I)	2	0.158	0.079	0.800	0.471
Residual	12	1.178	0.098	3.310	
Mulching (M)	2	0.418	0.209	7.040	0.003
Variety x Mulching (V x M)	2	0.141	0.071	2.380	0.107
Irrigation regimes x Mulching (I x M)	4	0.052	0.013	0.440	0.780
Variety x Irrigation regimes x Mulching	4	0.033	0.008	0.280	0.890
Residual	36	1.068	0.030		
Total	71	41.279			

Appendix 16: Distribution Uniformity Test and Emitter Discharge Results for Drip Irrigation System at Experimental Field

Replication	**Distribution Uniformity (%)**	**Emitter Discharge (l/h)**
One	0.84	0.90
Two	0.87	0.74
Three	0.87	0.75
Four	0.85	0.79
Average	0.86	0.81