



EFFECT OF DEFICIT IRRIGATION LEVELS ON YIELD AND WATER
USE EFFICIENCY OF GARLIC (*Allium sativum L.*) UNDER DIFFERENT
FURROW IRRIGATION TECHNIQUES AT HIGHLANDS OF DEBRE
BIRHAN, AMHARA REGION, ETHIOPIA

MSc. THESIS

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EXAMINER’S APPROVAL SHEET-1

As members of the Examining Board of the Final MSc Open Defense, we certify that we have read and evaluated the thesis prepared by BIRUK GETANEH AYELE; ID. No: GPIrDrR/0004/13 entitled “Effect of deficit irrigation levels on yield and water use efficiency of Garlic (*Allium Sativum L.*) under different furrow irrigation techniques at highland of Debre Birhan, Amhara Region, Ethiopia.” and examined the candidate. This is therefore to certify that the thesis report has been accepted in fulfilling the thesis requirement for the Degree of Master’s with specialization in Irrigation and Drainage Engineering of the graduate program of the Faculty of Bio-systems and Water Resource Engineering, Department of Water Resource and Irrigation Engineering, Institute of Technology.

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DEDICATION

I dedicate this thesis manuscript to the Enormous GOD for His never-ending love and encourage throughout the life span of this work and to my father Getaneh Ayele and my mother Abebech Wondimhun, to my wife Yeshe Shiferaw and my son Samuel Biruk for their love and dedicated partnership from the first line to this level of education.

STATEMENT OF AUTHOR

I hereby declare that this thesis entitled as “Effect of deficit irrigation levels on yield and water use efficiency of Garlic (*Allium sativum L.*) Under different furrow irrigation techniques at Debre Birhan, North Shewa, Amhara Region, Ethiopia” has been conducted with me under supervision of major advisor Dr. Shemelies Asseffa and co-advisor Dr. Abraham Woldemichael, department of water resource and irrigation engineering, graduate studies program, Hawassa University. I further declare that this thesis is my own original work and all sources of materials used for this thesis have been duly acknowledged and is not submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABGB	Above ground biomass
AFI	Alternative furrow irrigation
ANOVA	Analysis of variance
BMC	Billion metric cubes
CFI	Conventional furrow irrigation
CSA	Central Statistical Agency
CV	Coefficient of variation
DBARC	Debre Birhan Agricultural Research Center
DI	Deficit irrigation
EC	Electrical Conductivity (dS/m)
ET _c	Crop evapotranspiration
ET _o	Reference evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
FFI	Fixed furrow irrigation
GIR	Gross irrigation requirement
K ⁺	potassium
K _c	Cop coefficient
K _y	Yield response factor
LSD	Least significant difference
MAD	Manageable allowable deficit
NIR	Net irrigation water requirement
PH	Hydrogen ion concentration
PWP	Permanent wilting point
RAW	Readily available water
RCBD	Randomized complete block design
SAS	Statistical analysis system
TAW	Total available water
t/ha	Ton per hectare
USDA	United States Department of Agriculture
IWUE	Irrigation water use efficiency

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Abstract

*In the current time of overpopulation pressure and climate change, the competition for water resource is increasing over time and space. The improvement of irrigated agriculture is an important national issue. The experiment was conducted at Debre Birhan Agricultural Research Center to investigate the effect of deficit irrigation levels on yield and water use efficiency of garlic (*Allium sativum* L.) local cultivar under different furrow irrigation techniques. It was laid out in Randomized Complete Block Design with three replications with four irrigation levels (100, 85, 70, and 55% ETc) and three-furrow irrigation techniques (AFI, FFI and CFI). The amount of water applied was based on the soil water depletion. All collected data was subjected to ANOVA in SAS statistical software. The result obtained revealed that different irrigation levels had a highly significant ($P < 0.01$) effect on yield and WUE of garlic. A smaller reduction of irrigation levels would not have brought significant yield reduction. Similarly, yield and WUE were highly significantly ($p < 0.01$) affected by furrow irrigation techniques. AFI techniques gave a higher WUE with 10% yield reduction in comparison to CFI and 29% yield advantages over FFI. Moreover, the interaction effect of deficit levels and furrow techniques had highly significantly ($P < 0.01$) affected yield and WUE of garlic. The maximum yield of 9.1 t/ha was obtained with the application of 100 % ETc under CFI, while the maximum WUE of 4.1 kg/m³ with the application of 55 % ETc under AFI. The application of 85 % ETc under AFI resulted in statistically no significance difference in yield and WUE of 100 % ETc under AFI. In areas where there is abundant water, garlic could be irrigated with seasonal irrigation water of 592 mm (100% ETC) under CFI techniques in F.C state. The application of 85 % ETc under AFI techniques save irrigation water without having yield penalty, and this saved water could possibly produce an extra yield of 9.9 t/ha, save water usage and attain optimum garlic production. Therefore, the application of 85% ETc levels under AFI is the best choice under the conditions of the study area.*

Key words: Alternative furrow irrigation, Deficit irrigation, Garlic, water use efficiency.

1. INTRODUCTION

1.1. Background of the study

The ever-increasing population rate and climatic change profoundly affect the agriculture, induce drought problem making the limited water resource to be scarcer (Chai *et al.*, 2016 and Hussain *et al.*, 2009). As per the projection of FAO (2006), the water usage for developing countries for agriculture by 2030's will increase by 15 %. Water is the first and foremost limiting factor for crop production (Steduto *et al.*, 2012). Now, the production and productivity of crops in rain fed agriculture is restricted due to the erratic and uneven rainfall distribution. According to the report of IFAD (2005) and FAO, (2005), more than 95% of the crop production depends on rainfall. To attain food self-sufficiency of communities, crop production more than two times per year through irrigation is of a mandatory issue (Awulachew *et al.*, 2007 and Makombe *et al.*, 2007). Because it contributes to recover half of the crop production attained in rain fed agriculture by improving the agricultural production (Singh *et al.*, 2010 and Awulachew *et al.*, 2005).

In most of the irrigation schemes, farmers are irrigating their fields excessively without considering the crop water needs and with the scarce water resources by flooding irrigation method (Beyene *et al.*, 2018). However, the field application efficiency is lower, which ranges between 30 % and 50 % (Garg *et al.*, 2006). This will lead to poor agronomic practices and higher pumping energy cost, water logging, nutrient leaching from root zone, and wastage of energy and resource. Therefore, there is a need to improve the water use efficiency to obtain more crop production per drop of water with the uncertainty in the temporal and spatial variability of rainfall. It is mandatory to use an integration of optimized soil-water-plant management in the effective root zone system for better growth and yield of crops (Fanish, 2013).

Deficit irrigation is a planned water use fashion with applying fewer amounts than the full evapotranspiration of crop. The concept to use it was initiated by researcher at time of droughty because of climate change to produce optimum productivity (Wang *et al.*, 2012). In many highland part of the Ethiopia, garlic crop yields are low due to a number of constraints, among which lack of balanced nutrient supply, poor soil fertility, weed infestation, diseases, and moisture stress are the major ones (Marita *et al.*, 2000). Its production depends on the applied irrigation water amount and interval based on the soil type and the climate condition.

Garlic needs optimum moisture for better growth, bulb yield and quality (Karaye and Yakubu, 2007).

Both the application of excess water and more deficit stress could decrease bulb yield up to 60 % in reference to full ETc (Doro, 2012 and Miko *et al.*, 2000). Hanson *et al.* (2003) reported that the highest garlic yield was obtained by irrigating once a week. According to (Brewster and Rabinowitch, 1990):- garlic has a rather sparse and shallow root system with roots limited to the top 60 cm of the soil; best yields occur when the soil moisture content is maintained near field capacity; and irrigation should cease 21days before harvest to prevent rotting, discoloration of the bulb skins and exposure of outer cloves.

According to Michael *et al.*, (1997), furrow irrigation is well adapted to irrigating crops like garlic, which are susceptible to fungal root rot. In the study area, garlic is widely cultivated crop and it has high economic and medicinal value. Yet, there were no previously conducted research about garlic yield and water use efficiency response to deficit irrigation and furrow irrigation techniques. For this reason, the study aimed to examine the effect of deficit irrigation with furrow irrigation techniques on growth, yield and yield components of garlic at highlands of Debre Birhan.

1.2. Statement of the problem

The agrarian community's economy mainly depends on the erratic and unevenly distribution of rainfalls, which makes the crop production to be lower and farmers to faces in food insecurity problems. To sustain the rapidly increasing population under the vast climate change, supporting the crop production via irrigation with sound management is crucially important (Dessalegn, 2015). However, the irrigation development is challenged by different reasons like limited financial resources, technical challenges, lack of good governance, inaccessible water availability and lack of research in efficient water utilizations.

In highlands of Debre Birhan, on farm water management practices of the farmers is applying excess water without considering the crop water needs and the scarce water resources; flooding irrigation in most cases and furrow irrigation is rarely practiced. In addition to this, most of the surface water is being accessible to irrigation by pumping, so that they need additional expense for fuel energy. This means that they do not have the required level of knowledge as to how to, how much and when to irrigate the limited irrigation water resource

they have to tackle the shortage of rainfall and dry spell throughout the length of the growing period. This shows lack of water management strategies' information for users.

Among these strategies, the right amounts of water application at the right times and following the right mode of water application are of profoundly important. Since irrigation is costly, the farmers ought to have high values crops and good water management practices. In Debre Birhan, several studies were conducted on the effect of irrigation management practices on yield and WUE of most horticultural crops. However, there were no previous researches that determine the appropriate irrigation water management strategies for garlic crops. Garlic is the one of the widely cultivated and high value economic crops. In this research, the hypothesis of "irrigating by alternative furrows irrigation and deficit irrigation would save the limited water source thereby improving water use efficiency without yield reduction. Therefore, the study was conducted to achieve the following specific objectives.

1.3. Objectives of the study

1.3.1. General objectives of the study

The general objective of the study was to determine the optimum irrigation water management strategies that gave higher WUE and the optimum bulb yield of garlic with deficit irrigation under different furrow irrigation techniques.

1.3.2. Specific objectives of the study

The specific objectives of the study were -

- ❖ To determine the seasonal irrigation water demand of garlic crops.
- ❖ To determine the response yield and water use efficiency of garlic to deficit irrigations.
- ❖ To evaluate the effect of furrow irrigation techniques on yield and WUE of garlic.
- ❖ To ascertain the interaction effect of deficit irrigation levels and furrow irrigation techniques yield and WUE of garlic.

1.4. Research questions

This study was proposed to answer the following research questions: -

- What is the optimum levels of irrigation that produce optimum yield and water use efficiency of garlic?
- Which furrow techniques type is best suited for irrigating garlic?

- What is the maximum deficit irrigation level that allowed with insignificant reduction on garlic yield?
- What is the interaction effect of deficit irrigation levels and furrow irrigation techniques on yield and WUE?

1.5. Scope of the study

The study was carried out at one location of highlands of Debre Birhan on garlic to determine the effect of deficit irrigation amount under Conventional, Fixed, and Alternative furrow irrigation techniques. The major data collected and analyzed were the climatic data, crop data, the soil hydro physical properties data, economic data and irrigation management strategies like soil infiltration rate, bulk density, and soil moisture content before irrigation, crop water requirement, irrigation water requirement, and timing of irrigation, crop water use efficiency, irrigation water productivity, and yield response to deficit irrigation.

1.6. Significance of the study

At this vast era of population growth rate and climate change, the competition for land and water resource became increasing exponentially. Sustainable and effective utilization of these scarce resources could promote and contribute to increasing crop production and productivity. Therefore, the study aimed to provide the right water management strategy that assures higher water productivity with minimum yield penalty of garlic in Debre Birhan. The seasonal water demand of garlic and appropriate methods to apply the irrigation water was determined. Moreover, the operational cost, pumping cost and fixed cost of production for garlic was also diminished significantly by the water management strategies.

The results would have been applicable for the highlands part of North Shewa and other similar agro ecological zones of Ethiopia. Besides, the paper would provide further information for researcher, policy maker and to create awareness for the irrigators about the effects of deficit irrigation and furrow irrigation techniques on yield and water productivity of garlic.

2. LITERATURE REVIEW

2.1. Yield of garlic under irrigation

Garlic (*Allium sativum* L.) is the most known high value vegetable crops in the world as well as in Ethiopia. It is one of the oldest cultivated vegetables and the second most widely produced *Allium* next to onion (Voigt, 2004). It belongs to the family Alliaceae, genus *Allium* and originated in central Asia (Brewster, 1994). Ethiopia is the seventh producer in the World by producing 222,548 tons annually. It has many social and economic purposes like, medicinal value, religious, daily diet, and economic value. Garlic has miraculous pharmaceutical effects and is used to cure a number of diseases like blood pressure, cholesterol, cancer, chronic fever, anthelmintic, antioxidant, and antifungal and wound healing, arthritis, malaria, diabetes, kidney stone and night blindness (Kilgori *et al.*, 2007).

Moreover, it has an advantages such as violates fungal, viral and bacterial diseases, adjust blood pressures and heartbeat, reduce excess cholesterol and insulin amount in the body. However, its production is constrained from time to time due to different factors. According to (Mohamed *et al.*, 2014), these biotic and abiotic including lack of high yielding varieties, non-availability of quality seeds, imbalanced fertilizer use, lack of irrigation facilities, lack of proper disease, insect, and pest management and other agronomic practices, low storability, and lack of proper marketing facilities.

Nevertheless, the main limiting factors for garlic production are soil moistures and fertility status of the soil. Garlic can be practiced on mid and high lands areas to give satisfactorily yields above 2000m. Its development is much slower during colder weather than hotter. The alliums are distributed widely throughout the temperate, warm temperate and boreal zones of the northern hemisphere (Brewster, 1994). The average yield of garlic in Ethiopia was 9.34 t/ha, which is far from the world average of 23.5 t/ha (Mulu and Negasi, 2021). Based on the (CSA, 2014 and 2017), the yield potential of garlic in Ethiopia is about 6.96 t/ha and 9.05 t/ha respectively. The maximum bulb yield (20.3t/ha) was recorded under treatment of 100% ETC which was found significantly higher over all other treatments (Kavita, 2015).

However, the yields vary depending on the varieties and the management systems; reached up to 25 t/ha. The maximum bulb yield of 7.11 t/ha was obtained from plots fertilized with nitrogen and phosphorus at the rate of 92 N, and 46 P₂O₅ kg/ha under irrigation at Waga-Lasta District (Workat *et al.*, 2018). As per Fabeiro *et al.*, (2003), studied a controlled deficit

irrigation management for garlic crop production in a semiarid climatic zone of Spain. Garlic bulb yield is highly sensitive to water stress, and hence the yield of garlic bulb depends on proper irrigation management (Ghadami *et al.*, 2010). The deficit amount imposed at time of blubbing and ripening stages negatively affects both quantity and quality of bulb.

2.2. Crop evapotranspiration and irrigation regimes

2.2.1. Reference evapotranspiration and crop evapotranspiration

Reference evapotranspiration (ET_o) is climatic parameters that express the evaporation and transpiration demand of the atmosphere. Accurately estimating evapotranspiration is very important for water resources and watershed management, as well as in agricultural and hydrological studies (Antonio *et al.*, 2015). According to Alkaeed *et al.*, (2006), reliable and consistent estimate of evapotranspiration is of great importance for the management of water resources. For the process of ET_o , three basic physical requirements in the soil-plant-atmosphere system must be met; continuously available supply of water, energy to change liquid into vapor and vapor gradient to maintain a flux from the evaporating surface to the atmosphere.

There are several reference ET equations that have been developed and used depends on the availability of weather data. According to Allen *et al.*, (1998), the FAO Penman-Montiteh is the combined methods to compute ET_o from meteorological data, which is effective way of estimating ET_o . It has been accepted worldwide as an excellent ET_o estimator than other methods (Cai *et al.*, 2007). Because it takes into account parameters like temperature, humidity, sunshine hour, and wind speed. This method has been reported as consistent ET_o value finders in many regions and climates (Allen *et al.*, 2006). Many researchers have used it and they suggest that it is better than other methods for determining ET_o (Gowda *et al.*, 2016). Even though this method has performed excellently, the requirements of many meteorological variables restricts its use especially in area of lacking meteorological stations.

Calculation of crop water requirements and crop irrigation requirements can be carried out from basic information from the crops selected and should include, average planting date and average harvesting data (FAO, 1996). Crop coefficient (K_c) integrates the effects of characteristics that distinguish field crops from grass; consequently, different crops have different K_c coefficients. Crop growth period can be divided into four different growth stages (Allen *et al.*, 1998): initial stage, crop development stage, mid-season stage and the late

season stage. The Kc value of garlic is established as 0.7, 1.05, and 0.95 for initial, mid and late season stages respectively (Allen *et al.*, 1998).

2.2.2. Irrigation water requirement

During the later stages of maturity, water use decreases as the crops ripen (Schwab *et al.*, 1995). In drier climates, some people like to heavily irrigate at the pre-planting phase to help build a deep soil moisture reserve (FAO, 2007). Garlic requires between 25 mm and 50 mm of water per week (Tadesse, 2015). Adequate moisture is still needed after bulging, but irrigation should be stopped at least two weeks prior to the expected harvest date. According to Brewster and Rabinowitch, (1990), irrigation event must be ceased 3 weeks before harvest. Late-season irrigation tends to stain the skins and reduce quality bulb yield due to white rotting, and bulb discoloration (Goldy, 2000). As per Hickey, (2012) in Australia, for optimum yields, water stress should be avoided in garlic crops prior to maturity.

2.2.3. Irrigation scheduling by soil moisture monitoring

The purpose of irrigation scheduling is to determine the exact amount of water to apply and the exact timing for application (Cahn and Johnson, 2017). Field capacity (FC) is upper limit that the amount of water left in the soil after the excess water has drained off and down ward movement of water cease. It can be attained after 1-day irrigation for sandy soils and from 2 to 3 days for heavier-textured soils. Permanent wilting point (PWP) is the lower limit of water holding capacity that the plants hardly extract moisture.

The amount of water that should be applied during irrigation depends on the current moisture content in the root zone and the amount of water it takes to “fill” the root zone. The Volumetric soil water content can be determined directly by gravimetric methods, with drying to constant weight in an oven at 105 °C (Thompson and Voogt, 2016), and the latest generation of soil moisture measuring instruments is based on measuring the dielectric constant of the soil, which depends fundamentally on its water content (Gallardo and Thompson, 2018). Direct soil sampling method is time consuming and involves destructive method of soil sampling. Therefore, it is necessary to have other simple and less time-consuming methods of soil moisture determination.

The indirect methods to determine soil water content are widely used in research and in practical applications as an alternative to gravimetric determination. They are non-destructive, measured data are immediately available, the measurement can be repeated

several times in the same spot or the measurement can be taken continuously and operated by a computer. The tensiometer consists essentially of a porous cup filled with water and connected by a continuous water column to a vacuum measuring device, either a gage or manometer. Some authors consider tensiometer as a water determining instruments. However, it indicates the water movements from the soil or from the instruments.

The TDR system determines the speed of propagation of an electromagnetic wave through the closed circuit by two or three parallel steel rods. The TDR allows to measure a considerable volume of soil does not need calibration and allows continuous measurements of humidity. The higher the dielectric constant of the soil in contact with the transmission line, the slower the speed of the voltage pulse (Evelt and Heng, 2008).

The comparison between the various commercially available gypsum block meters showed that all of them had nearly the same interdependence between block resistance and meter readings. In sandy soil with the moisture content at field capacity prior to the rapid growth stage, yield was strongly dependent on applied water, and weekly irrigation was needed for maximum yield. Whereas; in clay loam, yield did not much influence by applied water because the garlic plants were able to extract sufficient soil moisture to offset deficit irrigation (Blaine *et al.*, 2002)

2.2.4. Deficit irrigation management strategies

Deficit irrigation (DI) has been widely practiced as a valuable and sustainable crop production strategy in dry areas and in areas where water is present but not available for irrigation purpose. It provides a means of reducing water consumption while minimizing adverse effects on yield (Mermoud *et al.*, 2005 and Smith *et al.*, 2002). The potential benefits of deficit irrigation are derived from increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water (English *et al.*, 1990).

In case of using DI strategies to save water, monitoring the soil or plant water status as an irrigation scheduling approach is even more critical for minimizing the risk of yield reduction, particularly under the uncertainties in determining the exact water requirement (Feres and Soriano, 2007). DI is the application of smaller irrigation amount than the full crop water requirements (Galindo *et al.*, 2018). Thus, it is a technique of optimizing yields with restricting on the irrigation amount with different adjustments in the soil. As per Yang *et*

al., (2017), the irrigation regimes with deficit irrigation management assure efficient water saving and increasing yields per unit area.

Additionally, it creates an ideal porous medium for crop root than full irrigation; reduce effect of fungal disease (Cicogna *et al.*, 2005). The value for depletion factor “p” is also a function of the soil type, for fine textured soils (clay) the recommended p values should be reduced by 5-10%, while for coarser textured soils (sand), it can be increased by 5-10%. However, management and economic factors in addition to the physical factors influencing p influence values for MAD. The factor p differs from one crop to another. It varies from 0.30 for shallow rooted plants at high rates of ET_c (> 8 mm/day) to 0.70 for deep-rooted plants at low rates of ET_c (< 3 mm/day).

2.3. Types of furrow irrigation systems

All irrigation systems should be designed and managed to ensure adequate and uniform water application over the field, while minimizing the potential losses. The adoption of efficient irrigation application methods is a fundamental issue to improve the water management problems in terms of quantity and availability. The mode of applying the irrigation water is crucially important to improve the on farm water managements. The most common application methods are surface irrigation, sprinkler irrigation and drip irrigation. However, surface irrigation is widely used methods in farmers’ levels. Based on the actual crop requirements, irrigation techniques improved to get maximum yield and water use efficiency.

In Ethiopia, about 98 % of irrigation application is practiced with surface irrigation methods (FAO, (2001); which includes furrow irrigation, basin irrigation, and boarder irrigation systems. Furrow irrigation is the most widely practiced form of surface irrigation especially for irrigating row planted crop (James, 1988 and FAO, 2002). Furrow irrigation had an advantage over other surface irrigation methods including; lower wetted area, less evaporation and deep percolation, bitterly used in case of small stream size, for uneven topographical, early cultivation after irrigating, flexible for wide range of slope and soils, need small labor, little wastage of land for furrows, suitable for row crops (Michael, 2008).

Furrows are small channels, which carry water down the land slope between the crop rows and allow on-farm water management flexibility than other surface irrigation techniques. Water infiltrates into the soil as it moves along the slope both laterally and vertically. The crop is usually grown on the ridges between the furrows. According to Michael *et al.*, (1997),

furrow irrigation is well adapted to irrigating crops like garlic, which are susceptible to fungal root rot. Moderate to high can be obtained if good water management practices are followed and the land is properly prepared. According to [Kassa and Fekadu, \(2003\)](#), with furrow irrigation methods the application efficiency of 64% was achieved. Furrows provide more opportunity to manage irrigations towards higher efficiencies and lower wetted area.

2.3.1. Alternate furrow irrigation

Alternate furrow irrigation (AFI) is a technique of furrow irrigation where one of the two neighboring furrows alternately irrigated during consecutive watering. As [Hsiao *et al*, \(2007\)](#), using furrow irrigation wetted out only part of the surface, thus reducing evaporation losses and deep percolation losses, and allow to cultivate the soil after irrigation. Since there is lateral movement of water and restricted deep percolation losses, the amount of water and time will be saved.

Alternative furrow irrigation improves irrigation water use efficiency without yields penalty ([Shayannejad and Moharreri, 2009](#)). This system saves quite a good amount of water and is very useful and crucial in areas of water scarcity and salt problems ([Majumdar, 2002](#)). The reduced evapotranspiration due to a reduction for wet soil surface could improve WUE. According to [Karajeh *et al*, \(2000\)](#), 56.7 to 72% of the water supply has been used to replenish soil moisture, 12 - 21.1% for infiltration and 11.3-17.8% for surface runoff.

Even though AFI uses smaller irrigation water, it produces similar yield as CFI ([Zhang *et al*., 2000](#) and [Luis *et al*., 2012](#)).The amount of water required for ([Nelson and Alkaisi, 2011](#)) reported different crops reduced due to AFI. As per [Kang *et al*, \(2000\)](#), WUE were found to be higher in AFI than CFI and FFI with the same amount of water application. AFI with 100 % ETc full irrigation was the recommended irrigation water management strategies to save the scarce water with insignificant yield reduction ([Geerts and Raes, 2009](#)). However, AFI with 70 ETc irrigation WUE was maximized, 65% of water amount could be saved ([Mulugeta and Kannan, 2015](#)).

According to [Yemane *et al*, \(2018\)](#), AFI saves amount of water to be applied and the time to irrigate and labor and energy requirements to irrigate. This indicates that crop WUE and Irrigation WUE are influenced by measurement of ETc, irrigation method, crop and climatic characteristics of the region. AFI is appropriate to increase WP and WUE of crop because they allow applying less irrigation water for garlic production. Alternate furrow irrigation

(AFI) is considered to be one of the most effective tools to minimize water application and irrigation costs and produce a higher crop yield (Awad, 2013). According to Graterol *et al.*, (1993), who found that AFI methods could supply water in a way that greatly reduces the amount of wetted surface, which lead to less evapotranspiration and less deep percolation. However, it is attributed to more frequent irrigation (Abdelmaksoud *et al.*, 2002).

2.3.2. Fixed furrow irrigation

Fixed furrow irrigation (FFI) a technique of furrow irrigation where irrigation is fixed to one of the two neighboring furrows throughout the growing season. It is a way to save water with small improvement over the alternate furrow irrigation (Slatni, 2011). This technique applies water to more area in a given amount of time than conventional furrow irrigation thereby save water. According to Yonts *et al.*, (2003), irrigation water application may be reduced 20 to 30 % by implementing every other furrow irrigation. Because of increased lateral infiltration, infiltration is not reduced by one half compared to watering every furrow (Yonts *et al.*, 2003). This technique will save the amount of water by half but there could be moisture deficiency for crops in furrow not water flow it. Due to this, the yield reduction may face. FFI technique is a trade-off between lower yield and higher WUE (Kang *et al.*, 2000).

2.3.3. Conventional furrow irrigation

Conventional furrow irrigation (CFI) or traditional irrigation means irrigating every furrow. Under CFI option, irrigation water is used in the form that: 51-54% of the total water supply was used to moisturize soil (saturation), 20-25% for infiltration within the temporary irrigation network and in the fields, 5 to 6 % for the evaporation from water surface, and 18-21% for surface runoff (Karajeh *et al.*, 2000).

This irrigation system has speed up the processes of decomposition and removal of organic elements and mobile forms of nutrients in the root zone that eventually, brought to soil fertility losses in addition to the higher deep percolation and runoff losses (Karajeh *et al.*, 2000). The highest yield was observed under CFI with 100% ET_c water application, but the WUE was found to be minimum in CFI (Subhan *et al.*, 2021). Similarly, the highest grain yield was obtained from CFI at 100% ET_c (Mulugeta and Kannan, 2015). Therefore; proper furrow irrigation system should be practiced to save water, time and energy, and produce higher land and water productivity.

2.4. Yield response factor

The actual evaluation of water stress related to the yield due to soil water deficit during the growing season can be obtained by the estimation of the yield response factor (K_y) that represents the relationship between a relative yield decrease ($1 - Y_a/Y_m$) and a relative evaporation deficit ($1 - ET_a/ET_m$). For $K_y \leq 1$ the plant is tolerant, for $K_y \geq 1$, the plant is sensitive to water stress. The complexity of crop response to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water (Doorenbos and Kassam, 1979).

The crop yield response factor for a crop at a particular stage is estimated by considering the deficit irrigation at a particular stage while keeping the crop fully irrigated at other stage. It can be also determined at seasonal level by exposing the crops at DI during completely growing season and the relationship between relative yield reduction and seasonal relative ET reduction (Garg and Dadhich, 2014). Similarly, Hanson *et al.*, (2003) reported that garlic is a sensitive crop to water deficiencies.

2.5. Irrigation water use efficiency

In areas with limited water resources, where water is the greatest limitation to production, WP is the main criterion for evaluating the performance of production systems (FAO, 2002). Water productivity with respect to crop production is referred to as crop water productivity (CWP), and is defined as the amount of crop produced per volume of water used (Michael, 2008). Opportunities for improving crop water productivity mainly lie in choosing adapted, water efficient crops, reducing unproductive water losses and ensuring ideal agronomic conditions for crop production (Bouman, 2007).

In crop production system, WUE is used to define the relationship between crop production and the amount of water used in crop production, expressed as crop yield per unit volume of water (Raes *et al.*, 2009). As noted by Luis *et al.*, (2012); the amount of water saved by AFI and DI could irrigate extra land and produce more yields, further on assures the sustainability of the environments and the overall ecosystem. Therefore, the improvement of water use efficiency in irrigated agriculture is crucial (Haileslassie *et al.*, 2016).

3. MATERIALS AND METHODS

3.1. Description of the study area

3.1.1. Geographical locations

The field experiment was conducted at Debre Birhan Agricultural Research Center field site, Basona werena wereda, North Shewa Administrative zone. This area is located 110km from Addis Ababa, in North Shewa near to Debre Birhan town. The geographical location is at $10^{\circ}01'00''$ to $10^{\circ}17'10''$ Northing and $39^{\circ}45'00''$ to $39^{\circ}58'20''$ Easting and Altitude of 2806 m.

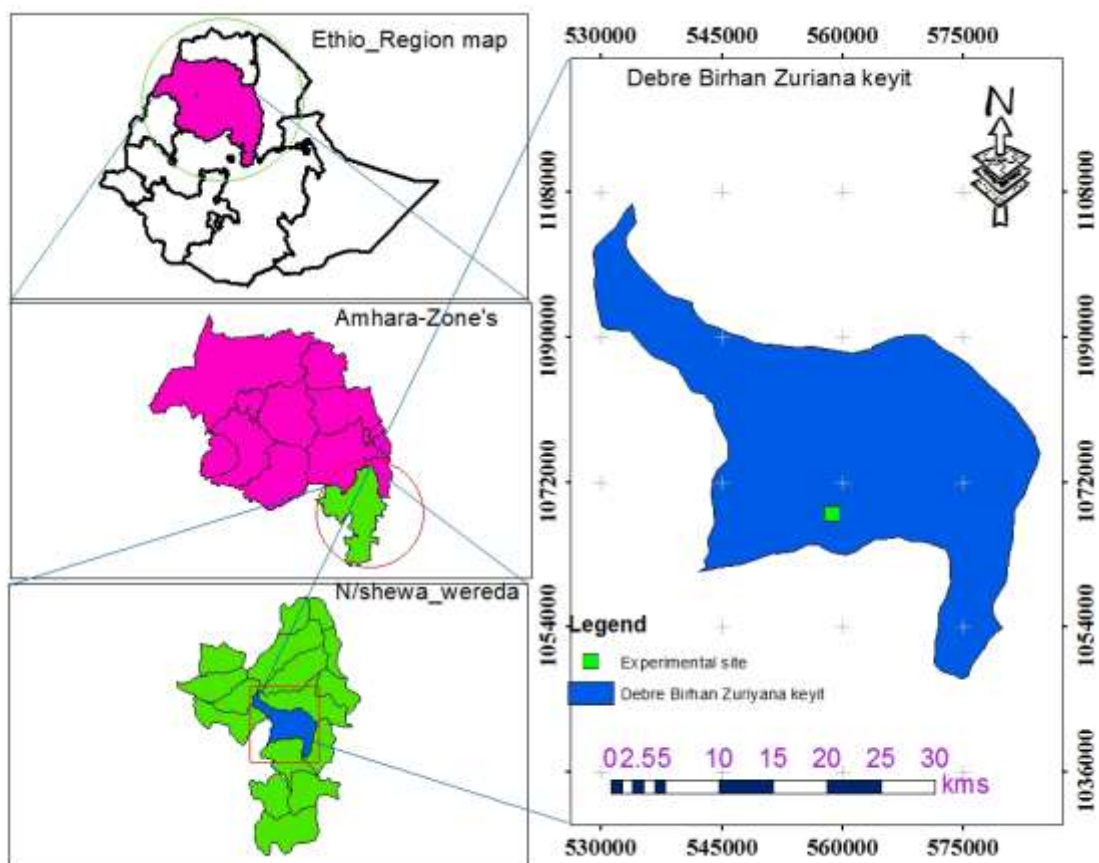


Figure 1. Geographical location of the study areas.

3.1.2. Climatic conditions

Based on the 30 years data, the long-term annual rainfall of the area is about 985mm. The long-term average minimum and maximum temperature of the area is 80C and 20.30C respectively. The maximum evaporative demand of the atmosphere was found on ay (4.07mm/day) and the minimum ETo is found on July and August (3.06mm/day). The microclimate of the study areas is cool and sub-humid to humid.

3.1.3. Soil types and topography

The land topography is near to flat (2%) and is categorized in the dega agro-ecological Zone. Crop production and productivity is constrained by excess water logging problems. The agricultural land most of the time was out of production. The farmers were applied animal production to escape from the crop failure problems. There were no enough drainage practices following the excess rain fed farming. The soil of the is clay to clay-loams. The infiltration rate is too low and the organic matter is low, which inhibits the crop production.

3.1.4. Socio economics of area

The farmers practiced barley, wheat, faba bean, and forage in main season. The farmers have one irrigation season from December to May. The major crops cultivated in the irrigation season are carrot, garlic, potato, beetroot, cabbage, barley and faba bean. The farmers were applied animal production to escape from the crop failure problems.

3.1.5. Water sources and irrigation practices

The water resources system in the area is from the constructed small dams, ponds, and by pumping from the perennial rivers system and ground water resource. The irrigation systems practiced is simple flooding; they invest too much for pumping water and suffer high shortage of water among users from dam's source. The existed irrigation practice was simple flooding irrigation by cultivating carrot, garlic, potato, beetroot, cabbage, and barley.

3.2. Data collection and analysis

Meteorological data (30 years) required for determining reference evapotranspiration, crop water requirement and computation of irrigation regimes was obtained from nearby meteorological station, DBARC (1990-2021). Data quality and arrangement like outlier detection and missing value filling was done. These include maximum temperature and minimum temperature, relative humidity, rainfall, and wind speed and sunshine hours on daily basis. Based on the analysis, the climatic water balance of the study area showed a water stress period from January to June and September to December (Figure 2). To attain crop production in these periods, the application of irrigation as a supplement or a complement significantly important.

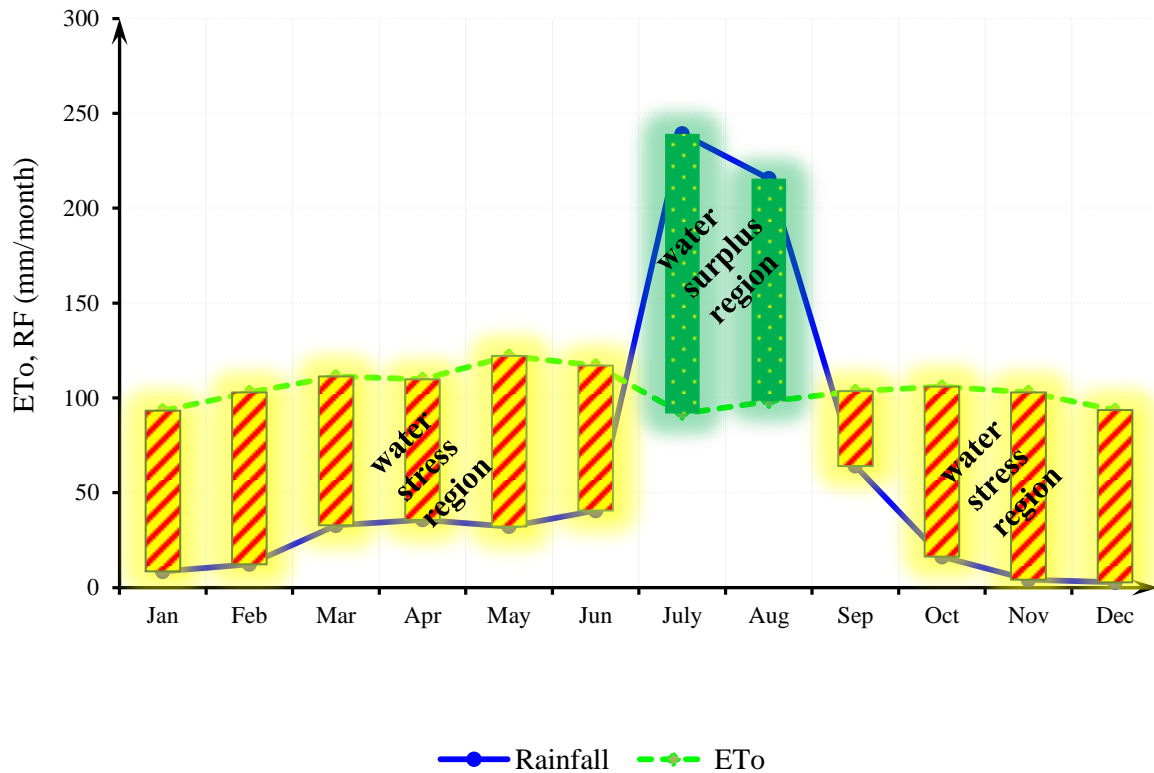


Figure 2. Climatic water balance of the study area (1990-2021)

3.3. Experimental materials

Local garlic cultivar was used for planting as a test crop for the experiment that is widely cultivated in the study area. NPS and Urea fertilizers were used as per the recommended rate of the crop uniformly in all treatments. Global Positioning System, digital camera, paper bag for crop leaf plastic bag, auger for soil sample, storage tank, generator, hose, and fuels.

3.4. Experimental design and layout

The experimental treatments were laid out with RCBD design with three replications. The treatments were included four irrigation levels (55, 70, 85, and 100% ETC) and three furrow irrigation techniques (FFI, CFI, and AFI) with 12 treatments. The treatment combinations are assigned in (Table1). Land preparation was made using tractor and oxen plough to lose the soil and make the field to be leveled. Then, row and furrow was prepared by a man labor and pre irrigation was applied. The spacing between plots was fixed as 1m and the spacing between replication was fixed as 2m.

The area of the plot was 3.6 m by 2m. Furrow width and ridge height was fixed as 30cm and 15cm respectively. The seed was sown with row-to-row spacing of 30 cm, and plant-to-plant spacing of 10cm on the day of 06/01/2022. Common irrigation depth of 59 mm was applied

equally to each plot. Treatments application was started 30 days after planting. Then, the amount of water applied was determined based on the sampled moisture content with in the effective root zone for each treatment. The amount of rainfall, which was happened unexpectedly during experimentation, was recorded with a rain gauge.

Table 1. Treatments setup and coding for the experiment

FIT	DI levels			
	55 % ETC	70 % ETC	85 % ETC	100 % ETC
AFI	55% ETc @ AFI	70% ETc @ AFI	85% ETc @ AFI	100%ETc @ AFI
FFI	55% ETc @ FFI	70%ETc @ FFI	85%ETc @ FFI	100%ETc @ FFI
CFI	55%ETc @ CFI	70%ETc @ CFI	85%ETc @CFI	100%ETc @ CFI

AFI, FFI and CFI ---Alternative, Fixed, and Conventional furrow respectively.

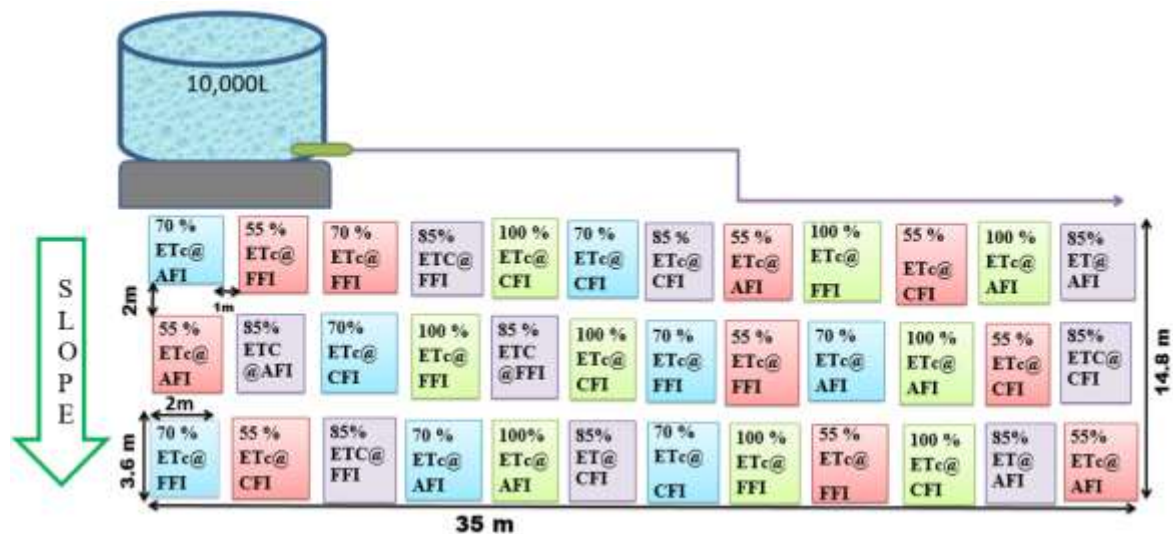


Figure 3. The field layout of the experiment

3.5. Agronomic and crop management practices

The variety of Garlic used was local garlic cultivar. At planting time, cloves were separated from the bulb and sorted (i.e. diseased, damaged and very small size clove were separated). Cloves with the same size were used for planting. After land prepared, fertilizers were applied according to the national recommendation at the rate of 92 kg/ha P₂O₅ and 105 kg/ ha N from NPS and urea fertilizers respectively. The NPS was applied at planting and the urea was splinted and applied half during planting, and the rest half were applied as side dressing after 55 DAS plant emergence. Crop management practices hoeing, weeding and ridging were held with 10 days' intervals and removed immediately when it appears.

Crop type and crop growing stages are factors that determine of crop water requirement, and hence the irrigation water requirement. The crop coefficient varied from on crop to other crops, and varies in growth stages of one crop. Because of the reason that no crop Kc values for garlic in the study areas, it was derived from FAO irrigation and drainage paper No. 56 (Allen *et al.*, 1998). The growth stage was fixed as 30, 40, 50, and 30 days, and the rooting depth of garlic was set as in the range of 0.25 up to 0.5cm. The allowable water depletion of garlic was 0.30 of total available water ($P = 0.30$) during the completely growing cycle as suggested in FAO 56 (Allen *et al.*, 1998).

3.6. Soil sampling and analysis

3.6.1. Soil physical and chemical properties

Composite soil sample was collected from the experimental area randomly in diagonal fashion from the top, middle, and bottom portion of the experimental field before planting by auger at a depth of 0-20, 20-40, 40-60, 60-80, and 80-100cm (Li *et al.*, 2022). This is because the plant may extract moisture from the 1 m depth and the soil is of clay soil type. The soil physical and chemical characteristics that affect irrigation regimes including field capacity, permanent wilting point, bulk density, infiltration rate and textural classes, FC, PWP, EC, PH, N and OC was determined at Debre Zeit and Debre Birhan Agricultural Research Centers soil laboratories. Soil pH was determined from saturation pest extract using pH meter. Total nitrogen was determined by treating the sample with a mixture of concentrated sulfuric acid and digestion catalysis following the modified Kjeldhal method (Okalebo *et al.*, 2002). Available phosphorus was determined using sodium bicarbonate as extraction solution according to the Olsen method.

3.6.2. Soil texture

The textural analysis of the soil was done by collecting soil samples by soil auger at three locations along the diagonal of the experimental area. Hydrometer method was employed for analyzing particle size distribution. The textural class was determined based on percent of sand, silt and clay in textural triangle. The soil type influences the maximum amount of water stored in the soil per meter depth of the soil.

3.6.3. Infiltration rate

The infiltration rate test was done near to the sampling point for other parameters from three locations and averaged out the results. The infiltration rate depends on physical properties of

the soil, such as texture, structure, porosity, moisture content of the soil, degree of compaction, organic matter etc. It decreases gradually with time and reach constant final rate, the so-called final or steady infiltration state. Knowledge of the soil infiltration rate is a prerequisite for efficient soil and water management, to determine the period of irrigation in one cycle. The infiltration rate of the soil was determined by double ring infiltrometer with 30cm and 60cm diameter for inner and outer ring respectively.

3.6.4. Bulk density

The soil bulk density was determined from undisturbed soil samples using core sampler for collection of the samples at similar location with sample collected for textural analysis. The core sample volume is known and the oven dry weight was computed divided to volume of core sample to determine the bulk density as (Hillel, 2000):

$$\rho_b = \frac{W_s}{V_c} \text{-----Equation 1}$$

Whereas: ρ_b is soil bulk-density (g/cm^3)

W_s is mass of dry soil (g)

V_c is volume of soil in the core (cm^3).

3.6.5. Field capacity and permanent wilting point

Field capacity is the state of soil moisture, which attained one day after irrigation or rainfall. Permanent wilting point is lower limit of water holding capacity of the soil that the plants cannot extract moisture sufficiently. The determination of moisture content at FC and PWP from the respective five depths 200g of samples was collected from three locations of the experimental area at similar locations where the soil is collected for texture and bulk density. Moisture content at field capacity and permanent wilting point was determined using pressure plate apparatus to adjust the suction force at field capacity (1/3 bar) and permanent wilting point (15 bar) and oven dry to determine the weight of water.

3.7. Determination of crop evapotranspiration and irrigation water requirement

Reference evapotranspiration was determined from climatic parameters with CROPWAT software version 8.0 based on Penman Monthieth approach. The empirical equation can be determined with the following formula (Allen *et al.*, 1998).

$$ET_o = \frac{[0.048\Delta(R - G) + \gamma - \left(\frac{900}{T} - 273\right) * U2(es - ea)]}{\Delta + \gamma(1 + 0.34U2)} \text{-----Equation 2}$$

Whereas: ET_o is reference evapotranspiration (mm/day)

R_n is net radiation at the crop surface (MJ/m²/day)

G is soil heat flux density (MJ/m²/day),

T is mean daily air temperature at 2 m height (°C)

U_2 is wind speed at 2 m height (m/s)

e_s is saturation vapor pressure (kPa),

e_a is actual vapor pressure (kPa)

$e_s - e_a$ is saturation vapor pressure deficit (kPa)

Δ is slope of vapor pressure curve (kPa/°C)

γ is psychometric constant (kPa/ °C) for altitude of 2860 m=0.049.

The manual calculation of ET_o with the above formula is too long and tedious, and high risk of making error. For this reason, FAO was developed the CROPWAT software to speed up the calculation and reduce the arithmetic error. The daily Evapotranspiration of the crop (ET_c) was determined by multiplying the estimated reference evapotranspiration and the crop coefficient. The crop coefficient for each crop growth stage and the respective ET_o are used to calculate ET_c by (Allen *et al.*, 1998): as 0.7 for the initial stage, $0.7 < K_c < 1.05$ for the crop development stage, 1.05 for the mid stage and $0.7 < K_c < 1.05$ for the late season stage.

$$ET_c = ET_o \times K_c \text{-----Equation 3}$$

Whereas: ET_c is the crop evapotranspiration (mm day⁻¹)

ET_o is the reference crop evapotranspiration (mm day⁻¹)

K_c is the single crop coefficient.

Then daily ET_c is multiplied with the number of days the crop is to be irrigated, to find out the amount of net seasonal evapotranspiration of crop. Irrigation water to be applied to garlic was determined at field capacity state of the soil for 100 % ET_c treatment. The other stressed treatment was received based on the deficit percentage of the control treatments (100 % ET_c). Rainfall that effectively used by the crop after rainfall losses due to surface run off and deep percolation was considered. The method given by Allen *et al.*, (1998) to determine effective rainfall (p_{eff}) as;

$$P_e = 0.6 \times P - \frac{10}{3}, \text{ for } P \leq \frac{70}{3} \text{ mm-----}$$

Equation 4

$$P_e = 0.8 \times P - \frac{24}{3}, \text{ for } P > \frac{70}{3} \text{ mm} \text{-----Equation 5}$$

Whereas: P_{eff} is effective rainfall
 P is total precipitation

3.8. Determination of soil available water

The moisture content in weight and volumetric base was determined by the equations:

$$\theta_{\text{FC}} \left(\frac{v}{v} \right) = \theta_{\text{FC}} \left(\frac{w}{w} \right) * \rho_b \text{-----Equation 6}$$

$$\theta_{\text{PWP}} \left(\frac{v}{v} \right) = \theta_{\text{PWP}} \left(\frac{w}{w} \right) * \rho_b \text{-----Equation 7}$$

The total available water (TAW) was calculated based on the data of FC, PWP and root depth as using the following equation.

$$TAW = 1000 \sum (\theta_{\text{FC}} - \theta_{\text{PWP}}) D_{\text{eff}} \text{-----Equation 8}$$

Whereas: TAW is the total available water in the root zone (mm/m),

D_{eff} is effective root zone depth (cm)

θ_{FC} is volumetric moisture content at field capacity (m^3/m^3)

θ_{pwp} is volumetric moisture content at field capacity (m^3/m^3)

ρ_b is the bulk density of the soil

The readily available water (RAW) was calculated by multiplying the TAW with the crop maximum allowable deficit factor, p . This fraction of TAW is the amount that the crop can extract from the root zone without suffering water stress. This is the full irrigation depth (100% ET_c) amount.

$$RAW = P * TAW \text{-----Equation 9}$$

3.9. Soil moisture monitoring

Soil moisture measurement method was used to determine the irrigation schedule by measuring soil moisture in the field. When the soil moisture content has dropped to a certain critical level, irrigation water is applied. The volumetric soil water content (m^3/m^3) was continuously monitored with gravimetric methods or the oven-dry method, which is the

commonest method of determining soil moisture content. It consists of taking a soil sample, weighting, and drying the sample in an oven at a temperature of 105⁰C for 24 hours, then weighing the sample and determining the moisture loss.

Soil samples were taken with a screw auger at planting, before each irrigation event, 2 days after each irrigation event both the ridge and bottom of the furrows (Awad, 2013). In this experiment, soil sampling for moisture determination was performed with three days' interval. The gravimetric method was used to determine the soil moisture content and calculated as a dry weighed fraction by the following (Michael, 2008).

$$\Theta_m (\%) = \frac{\text{weight of wet (gm)} - \text{weight of dry (gm)} * 100}{\text{Weight of dry soil (gm)}} \text{----- Equation 10}$$

$$\Theta_v (\%) = \Theta_m (\%) * \rho_b * D_{\text{eff}} \text{-----Equation 11}$$

Whereas: Θ_m and Θ_v are gravimetric and volumetric water content

ρ_b -----bulk density

D_{eff} ----- effective root zone depth

3.10. Determination of deficit irrigation regimes

The effect of soil moisture stress on crop ET was described by reducing the value of Kc, by multiplying the Kc by the water stress coefficient, Ks. Readily Available Soil Moisture /Allowable Soil Moisture Depletion, RAM - portion of the total available water, which is most easily extracted by the plant roots without suffering stress. Management Allowable Deficiency, MAD, was used to compute the amount of water that used without adversely affecting the plants and expressed as a fraction of TAW. The average ranges of furrow irrigation application efficiency vary from 50 to 70% (Bakker *et al.*, 1999). According to (Kassa and Fekadu, 2003); with furrow irrigation methods, application efficiency of 64% was achieved. However, in this experiment, the E_a was taken as 0.70, because of the clay loam soil and the water is directly fed in to furrows.

As the crop grows and extracts water from the soil to satisfy its ETC requirement, the stored soil water is gradually depleted. In general, the net irrigation requirement is the amount of water required to refill the root zone soil water content back up to field capacity. This amount, which is the difference between field capacity and current soil water level, corresponds to the soil water deficit (D).When the ETC based crop water need is greater than the soil moisture balance (RAW), the former amount was applied accordingly for each

treatment. Irrigation applied as the soil water content falls below the design lower limit, and the required irrigation amount or the soil moisture depleted between irrigation should be determined using the equation (FAO, 2002).

$$\text{RAW} = \sum_{i=1}^n (\theta_{FC} - \theta_v) * \rho_b * D_{\text{eff}} \text{-----Equation 12}$$

$$P = \frac{\theta_{FC} - \theta_v}{\theta_{FC} - \theta_{\text{pwp}}} \text{-----Equation 13}$$

$$\text{In} = \frac{\text{RAW}}{\text{ETc}} \text{-----Equation 14}$$

$$\text{NIR} = \text{In} * \text{ETc} \text{-----Equation 15}$$

$$\text{GIR} = \frac{\text{NIR}}{\text{Ea}} \text{-----Equation 16}$$

Whereas: θ_v is the soil water content at current time before irrigation,

θ_{FC} ----- designed volumetric moisture content at field capacity (m^3/m^3).

NIR ----- irrigation requirement, GIR ----- Gross irrigation requirement

RAW ----- Readily available water, ETc ----- Crop evapotranspiration

In ----- irrigation interval, Ea ----- application efficiency

The crop evapotranspiration is adjusted by the soil moisture stress coefficient. Irrigation was applied when the depletion level of each stressed treatment is above the designed value of MAD level. The depletion factor, in which RAW is depleted, was considered as 100% ETc level at which the maximum crop production is achieved. The moisture stress coefficient k_s , for value of MAD less than RAW is one. However, for values of MAD greater than RAW, k_s would be determined by the formula given below:

$$k_s = \frac{\text{TAW} - \text{MAD}}{(\text{TAW} - \text{RAW})} \text{-----Equation 17}$$

Whereas: TAW ----- total available water

RAW ----- the recommended depletion level at Optimum Yield Threshold.

MAD ----- Management allowable depletion

The control treatment (100% ETc @ CFI) was irrigated based critical moisture deficit to refill back the soil to field capacity. However, stressed treatments were receiving lower amount based on the stress level with the same irrigation interval as control treatment. The depletion factor for each adjusted ETc coefficient was determined as 30%, 40.5%, 51%, 61.5% for 100% ETc, 85% ETc, 70% ETc, 55% ETc levels respectively.

3.11. Types of furrow irrigation systems

The water source used was from ponded water by pumping to 10,000 L containing storage tank. The mode of applying water was furrow irrigation methods with measuring device of a garden hose directly in to the furrow. The flow discharge into each plot using different furrow techniques and the time required to apply the desired depth of water was determined. Pre irrigation and three common irrigations at the early germination time were done for better establishment of the crop.

The gross Volumes of water applied to experimental plots were determined by multiplication of plot area and gross irrigation requirement. Since the discharge from storage tank vary at field condition as the water level decreases, calibration on water level of storage tank and the discharge released was done at field conditions, and the effective head was determined where the discharge change. Based on the discharge head relation, time required to irrigate each treatment was determined. The discharge rate from the storage, Q in L/s, was determined by the formula (Khurmi, 1984 and Michael, 1978):

$$Q = C * A\sqrt{2gh} \text{----- Equation 18}$$

Whereas: C is discharge coefficient of pipe, taken as 0.65.

A is area of pipe determined as πr^2 , r is internal radius of pipe

h is effective head of water level

g is the acceleration due to gravity.

The volume of water applied to each plot was calculated by multiplying the gross depth of irrigation water with the area of the plot. Irrigation was ceased two weeks before harvest to prevent bulb from rotting and sprouting (Kumar *et al.*, 2007). The time required to refill the soil moisture can be obtained from the following relationship:

$$T = \frac{GIR}{I} \text{-----Equation 19}$$

Whereas: T is time required to refill the soil moisture depleted in hrs.

GIR is Gross irrigation requirement in mm

I is infiltration rate of the soil in mm hr^{-1}

The discharge rate, Q in L/s, for a particular field was obtained from the equations:

$$Q \left(\frac{L}{s} \right) = \frac{A*d}{T*3600} \text{-----Equation}$$

200

Whereas: Q is discharge rate in L/s

A is plot area to be irrigated in m²

d is daily water need in mm

T is the time in hrs.

Time required to irrigate a particular plot was computed from:

$$T = \frac{A \cdot GIR}{6 \cdot Q} \text{-----Equation 21}$$

Whereas: A -----Area of one plot in m²

GIR----- Gross irrigation needs depth in cm

T-----Time required for irrigating one plot in min.

Q-----Discharge rate of hose in l/s

3.12. Agronomic data collection

Harvesting was done when the leaf tops begin to dry, discolor and bend towards the ground at 15/06/22. Samples of ten plants were taken from each plot to determine the significance difference among treatments for yield and yield components of garlic crop. It includes bulb diameter, marketable yield, and water use efficiency.

3.13. Irrigation water use efficiency, water saved and yield change

Crop water use efficiency is an indicator that determines the impact of irrigation scheduling decisions with regard to irrigation water management. CWUE refers to the ratio between the final dry bulb yields (Y) and cumulative crop evapotranspiration consumed by the crop during the growing season by the formula (Ali *et al.*, 2007 and Stanhill, 1986). Irrigation water use efficiency: was determined as the ratio of grain yield by total applied irrigation water as follows (Cabello *et al.*, 2009; FAO, 2003 and Michael 2008).

$$IWUE = \frac{Y(\text{kg})}{GIR(\text{m}^3)} \text{-----Equation}$$

223

Whereas: Y is bulb yield of garlic (kg ha⁻¹)

CWU is the crop water use or evapotranspiration of crop

GIR is gross irrigation applied water (m³ ha⁻¹)

The amount of irrigation water saved with AFI or FFI relative to CFI was determined by using the following formula.

$$\text{water saved}(\%) = \frac{100\% \text{ETc @CFI} - \text{ETC}(\%) \text{ @AFI or FFI}}{100\% \text{ETC @CFI}} \text{----- Equation}$$

234

Whereas, ETc (%) -----percentage of full ETc under AFI or FFI

The yield gain or loss due to deficit irrigation and irrigation techniques with reference to full irrigation was calculated by the formula (Jemal and Mukerem, 2017).

$$Y(\%) = \frac{Y_f - Y_{di}}{Y_f} \text{----- Equation}$$

245

Whereas: Y (%) -----Yield gain or loss

Y_f -----Yield of full-irrigated plot under CFI

Y_{di} -----Yield of other deficit plot under AFI, FFI, and CFI

3.14. Yield Response factor

In order to quantify the effect of water stress, driving the relation between relative yield decrease and relative crop evapotranspiration deficit is crucial. If K_y value is greater than unity, the plant is sensitive to water deficit and indicate large yield reductions. If K_y value is less than unity, the plant is tolerant to water deficit that is indication of less yield reductions. If k_y value is equal to unity, there is direct relation between yield reduction and water stress (Steduto *et al.*, 2012). The yield response factor was determined by using the equation (FAO, 2002 and Doorenbos & Kassam, 1979).

$$K_y = \frac{(1 - \frac{ET_a}{ET_m})}{(1 - \frac{Y_a}{Y_m})} \text{-----Equation}$$

256

Whereas: Y_a ----- actual yield (kg/ha)

Y_m ----- maximum yield (kg/ha)

K_y ----- yield response factor

ET_a ----- actual ETc (mm)

ET_m ----- maximum ETc (mm)

3.15. Statistical data analysis

Bulb yields, bulb diameter and water use efficiency data were analyzed using SAS 9.0 statistical software (SAS, 2002). ANOVA was subjected to evaluate the statistical effect of treatments for agronomic and irrigation parameters. Irrigation water amount and furrow irrigation techniques were interpreted with Fisher's LSD test at ($P \leq 0.05$) treatment means (Gomez and Gomez, 1984).

Regression analysis was conducted to determine the extent to which the how much the dependent parameters are explained with the independent one.

4. RESULTS AND DISCUSSIONS

4.1. Physical and Chemical Properties of Soils

From the result of the soil analysis, the soil textural class was found as clay loam to clay, based on USDA soil textural classification with composition of sand, silt and clay percentages as 16 %, 35.8 % and 49.0% respectively. Bulk density of the soil was found with an increasing fashion with the soil depth. This may be the compaction effect and the higher organic matter contents in the top soil surface. The average bulk density was 1.14g/cm^3 , which is considered as suitable for crop root growth. The results in line with Fikdu, (2003) reported that the average bulk density of the clay soil as 1.19 g/cm^3 and the total available water as 112.2 mm/m. As depth increases, the bulk density and clay content would increase.

The field capacity and permanent wilting data also shows an increasing trend down ward the soil depth. The average gravimetric soil water content at field capacity and permanent wilting point was 34.67% and 24.32% respectively. The mean value of total available water (TAW) which is the amount of water that a crop can extract from its root zone was 117.5mm/m depth of soil. According to Cornish *et al.*, (1990), the total available water of clay soil was 114 mm/m.

Soil pH was at the optimum value (6.1), which is suitable for garlic and other crops. This indicates slight acidity problem in the highland areas. The optimum soil pH for garlic is between 6 and 7 (Narendra *et al.*, 2011). The value of EC obtained was lower (0.17 dS/m). Generally based on to USDA soil classification, a soil with electrical conductivity of less than 2.0 dS/m at 25°C and pH of between 5 and 8.5 are classified as suitable soil for agricultural production. The weighted average organic matter content of the soil was about 1.41%. This value is categorized as low organic matter soil (Ghadami, 1992), which the yield of garlic was found as smaller in this experiment.

As depth increases, the organic matter content of the soil shows a decreasing trend. This indicates the top soil have higher organic matter that improve the soil water holding capacity in addition to provide the nutrient composition for crops. The basic infiltration rate of the experimental area was 5 mm/hr, which is in the range of clay soil (1-5 mm/hr) (Hillel, 2004). This means that a water layer of 0.5cm on the soil surface will take one hour to infiltrate. This result was in the range of infiltration rate of the soil, which was determined by Israelsen and Hansen, (1962) and classed as slow infiltration rate. The soil of the experimental area was

soil with low organic matter content and better water holding capacity, but with lower infiltration rate.

4.2. Crop evapotranspiration and irrigation water requirements

4.2.1. Reference evapotranspiration

From the figure below, the maximum reference evapotranspiration (3.9 mm/day) was observed in May and the lowest ETo of 2.94 mm/day was found in January. CWR is a function of crop coefficient, crop type, crop growth stage and the weather conditions. The maximum crop evapotranspiration of garlic (3.84 mm/day) was determined at mid growth stage of garlic and the minimum ETc of 2.08 mm/day was found in January. The average daily crop water requirement of garlic was 3.06mm/day.

4.2.2. Crop evapotranspiration

The seasonal garlic CWR was found as 463 mm in the growing season by using FAO 56 recommended Kc value and the exact climatic parameter for calculating. This results matches with (Hamid *et al.*, 2011); who found garlic water requirements as 546.5 mm and 519.2 mm for two growing season with lysimetric experimentation respectively. However, James, (2008) found that the crop water use at 100% ETc for the lysimetric experimentation as 425 mm, including 108 mm of rainfall. These differences may be due to the variation in climatic conditions, soil variability and management differences in controlling the water balance. The total amount of effective rainfall happened in the growing season was about 49 mm. The value of CWR was increased exponentially at development stage and reaches the maximum, finally shows a decreasing rate when the crop becomes mature.

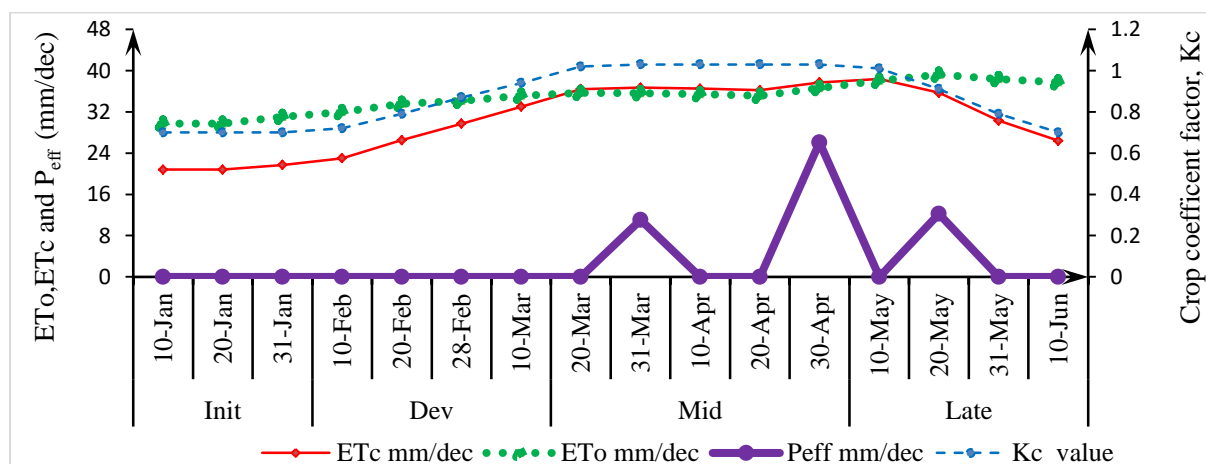


Figure 4. Reference Evapotranspiration, crop coefficient and Crop water demand of garlic.

4.2.3. Irrigation water requirement

Seasonal irrigation water requirement determined based on the seasonal water application depth in the growing period was determined for each treatment. Common irrigation depth of 59 mm was applied for all treatments until ground cover. Since irrigation water requirement is a function of weather, crop type, soil properties, rain fall, irrigation method, and water table of ground water, the gross application depth should consider these factors. The highest and minimum seasonal irrigation water requirement obtained was 483 mm and 233 mm with 100% ETC under CFI techniques.

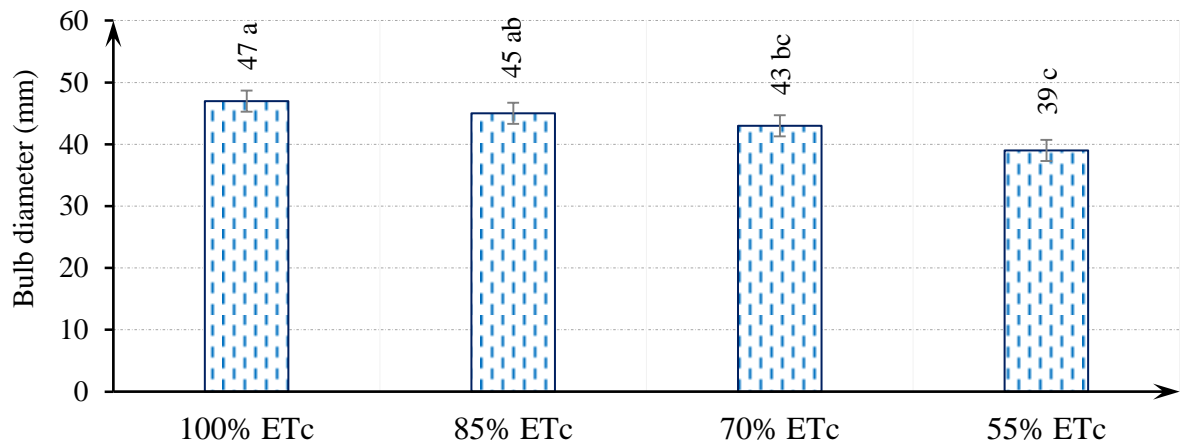
In line with this result, James (2008) found that the irrigation water use of garlic for 100% ETC as 425 mm depth. Abdeilatif and Abdelshafy (2017) were found that seasonal values of applied irrigation water for the surface irrigation system as 785 mm. The ranges of irrigation water levels of their experimentation were 394 mm to 490 mm (Fabeiro *et al.*, 2003). Garlic yield was independent of applied water for conditions where a deep fine textured soil is initially at field capacity. Applied water varied from about 100 mm to 325 mm, no yield response was found (Marita *et al.*, 2000).

4.3. Effect of deficit levels on yield and water use efficiency

4.3.1. Bulb diameter

ANOVA results revealed that there was significance difference at ($P < 0.05$) in bulb diameter of garlic among deficit irrigation levels (Table 2). The largest bulb diameter (47 mm) was obtained with the application of 100% ETc, which had insignificance difference with treatment that received 85% ETc; whereas the least bulb diameter (39 mm) was recorded with the application of 55 % ETc, which is statistically similar with 70% ETc (Figure 5).

This shows a small change in irrigation would not brought significance change in bulb diameter and thereby on bulb yield and total biomass. The decrease in irrigation level from 100% ETC to 55% ETC reflects a decrease of 17% of bulb diameter of garlic. But, the decrease in irrigation level from 100% ETC to 85% ETC reflects nearly no change in bulb diameter (4.2% decreases). This indicates a small reduction in irrigation levels resulted in no reduction on bulb diameter and consequently on yield.



Means with different letters in a labels differ significantly and means followed by the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 5. Effects of irrigation water levels on bulb diameter of garlic.

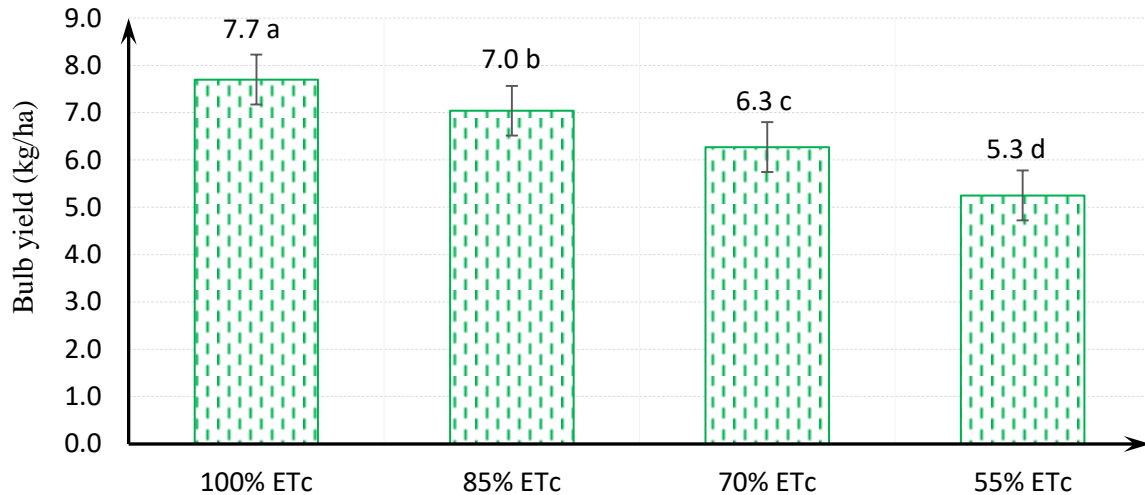
4.3.2. Bulb yield of garlic

ANOVA result revealed that marketable bulb yield, total bulb yield, and total biomass were highly significantly influenced ($P < 0.01$) by water deficit levels (Table 2). The maximum total bulb yield was obtained by 100% ETc (8 t/ha) and the minimum yield of 5 t/ha was found with irrigating 55% ETc. This finding is in close agreement with that of Lellis *et al.*, (2022), found bulb yield of garlic as 9.9 t/ha with 100% ETc water application garlic bulb yield was reduced as water stress level increased from 100% ETC to 55% ETC (Figure 6). The decrease in irrigation level from 100% ETC to 55% ETC reflects a decrease of 37.5 % of bulb yield of garlic. However, the decrease in irrigation level from 100% ETC to 85% ETC reflects nearly small change in bulb diameter (9% decreases). This indicates a small reduction in irrigation levels resulted in little reduction on bulb yield.

According to the investigation of Elaman, (2001) for major horticultural crops, with a reduction of 10 % water supply would have brought a reduction of 2% agricultural product. Similarly, James (1988) found as there was no significance difference of yield with the reduction of 125% ETc to 100% ETc. Irrigation of garlic on weekly basis would have produced the maximum yield (Blaine *et al.*, 2002). Olalla *et al.*, (2004) reported that plots which received the greatest volumes of water yields with higher percentages of large-size bulbs whereas water shortages lead to higher percentages of small size bulbs.

The maximum total biomass (10t/ha) was observed with the application of 100% ETc and followed by 85% ETc. This indicates that the higher biomass reflects the higher total bulb

yield of garlic. Garlic crop tolerate moderate water deficit imposed by optimized regulated deficit irrigation and recover physiological performance, water limitation did not produced reduction in growth performance and yield (Sanchez *et al.*, 2020).

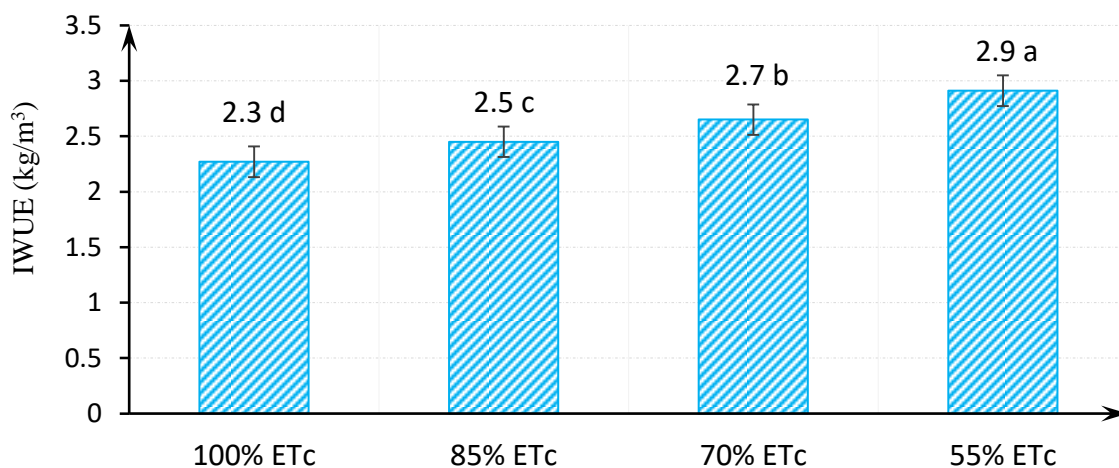


Means with different letters in a labels differ significantly and means followed by the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 6. Effects of irrigation water levels on marketable bulb yield, TY and TB yield.

4.3.3. Irrigation water use efficiency

As the ANOVA result (Table 2), IWUE was highly significantly ($P < 0.001$) influenced by the water stress levels. The range of IWUE in this study was 2.27- 2.91 kg/m^3 (Figure 7). As the applied amount of water increases, the IWUE would decrease. The obtained IWUE in this study was in agreement with that of (Fabeiro *et al.*, 2003), they found within the range of 1.8 to 2.5 kg/m^3 . For the reduction of water levels from 100% ETc to 55% ETc, the increase in irrigation water productivity was by 28 %.



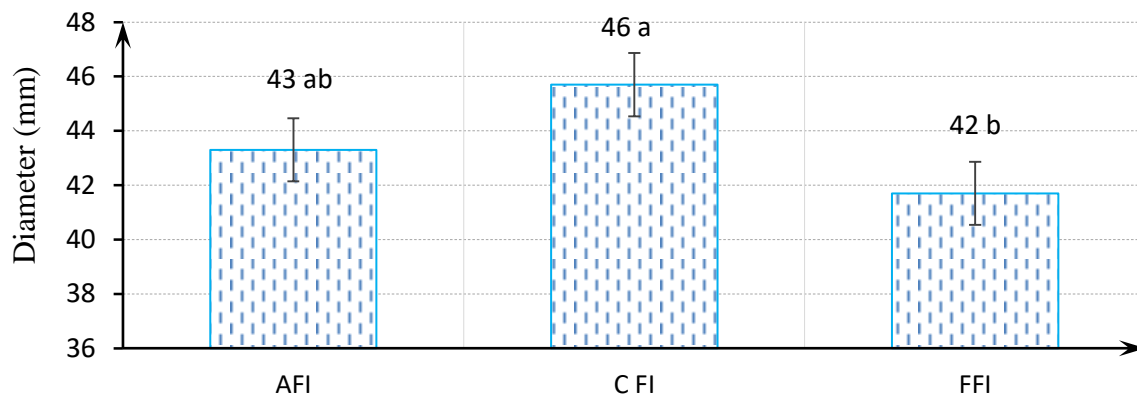
Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 7. Effects of irrigation water levels on CWUE and IWUE of garlic

4.4. Effect of furrow irrigation techniques on yield and water use efficiency

4.4.1. Bulb diameter

Highly significant variation ($p < 0.01$) in the bulb diameter was observed at different furrow irrigation techniques (Table 2). The widest diameter of garlic bulb of 46 mm was recorded under CFI and followed by AFI system (43 mm). Whereas the narrowest diameter of bulb was obtained under FFI system (Figure 8). This might be due to the moisture distribution variation problem in FFI. When the RAW is depleted above the threshold, the plant experiences water stress, the crop evapotranspiration falls below evaporative MAD demand of the atmosphere. According to the results of (Abdelhady and Ebtisam, 2016), mean diameter of 44 to 58 mm.

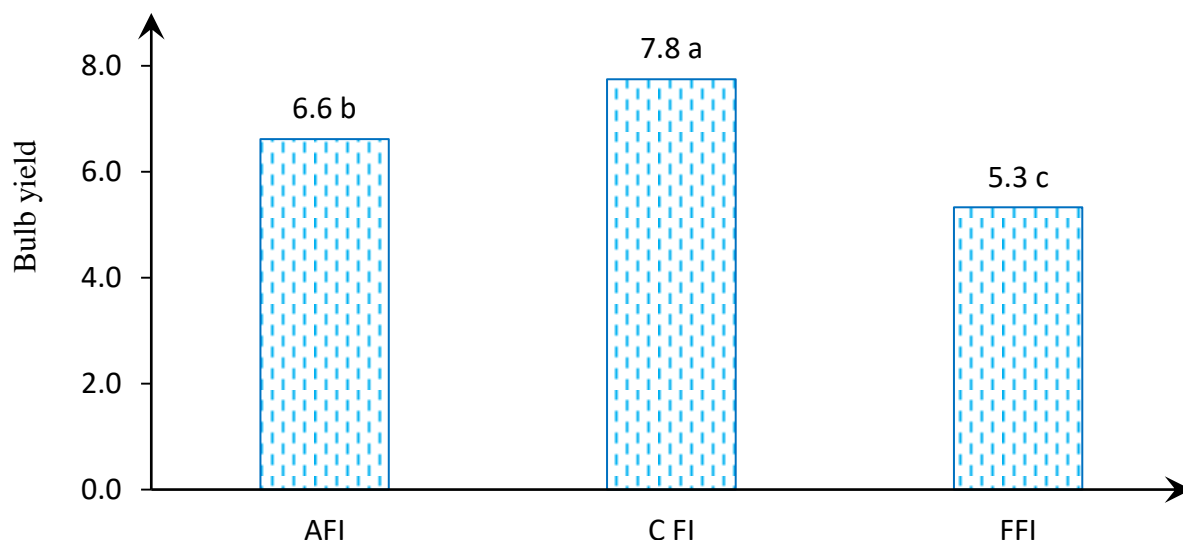


Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 8. Effects of furrow irrigation techniques on bulb diameter of garlic

4.4.2. Bulb yield of garlic

A high statistical difference ($P < 0.01$) was observed in furrow irrigation techniques on marketable yield, total yield and total biomass production (Table 2). The maximum yield (8 t/ha) was observed in CFI and followed by AFI (Figure 9). The bulb yield obtained with AFI was significantly differing from FFI, but the amount of water applied to them was equal. Similarly, the maximum biomass (10 t/ha) was obtained under CFI system, and followed by treatments that was irrigated under AFI.

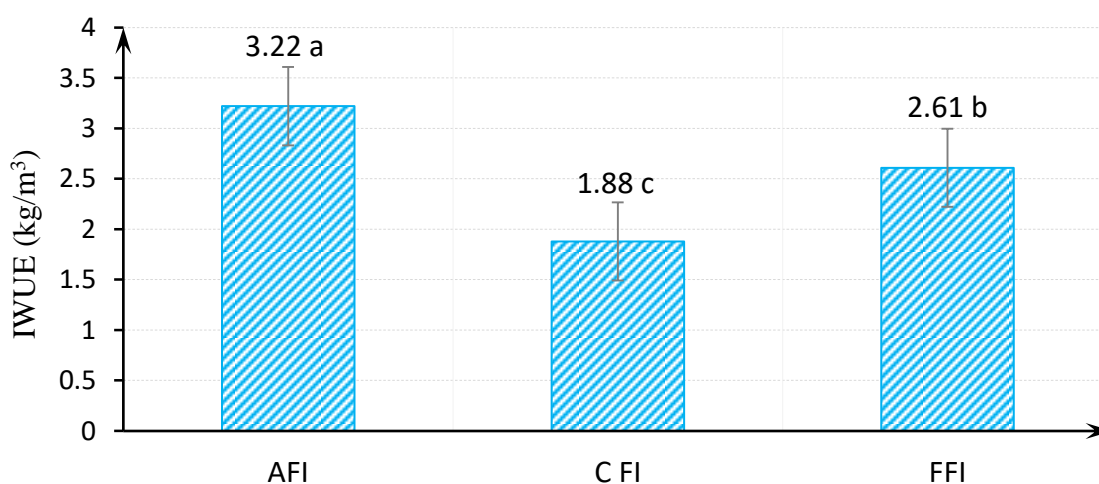


Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 9. Effects of furrow techniques on marketable, total yield and total biomass.

4.4.3. Irrigation water use efficiency

As the ANOVA table shows IWUE was significantly affected by furrow irrigation methods at ($P < 0.01$) (Table 2). The maximum IWP was obtained in treatments that irrigated with AFI and followed by FFI as shown (Figure 10). Whereas the lowest IWP was observed under CFI. This indicates that AFI would improve water productivity with a significance difference compared with FFI, with the same amount of irrigation water. The moisture availability in AFI was greater than FFI, provided that the plant gets water and nutrient with lower energy.



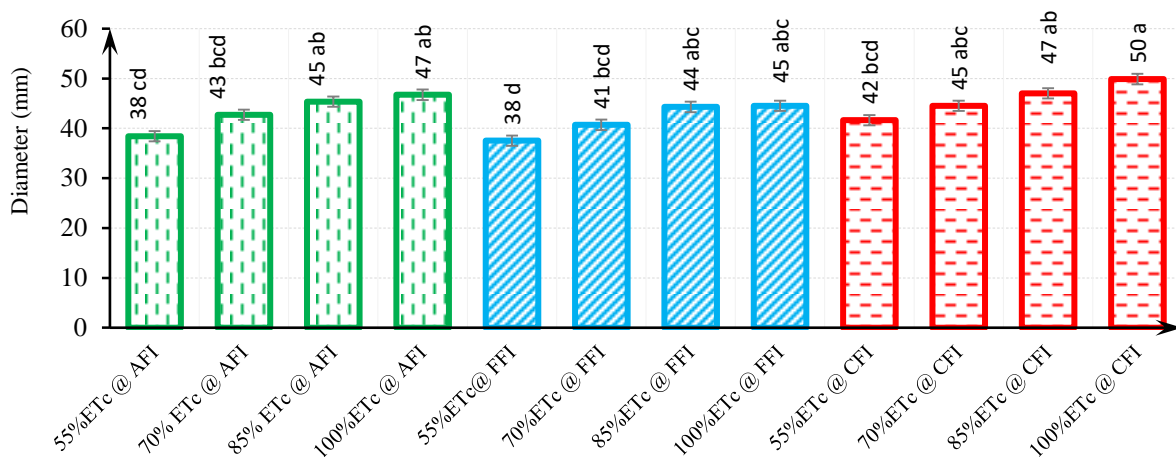
Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 10. Effects of furrow irrigation techniques on CWUE and IWP of garlic

4.5. Effect of deficit levels and furrow techniques on yield and water use efficiency

4.5.1. Diameter of bulb

ANOVA results revealed that there was higher significance difference at ($P < 0.01$) in bulb diameter of garlic (Table 2). The largest bulb diameter (50mm) was obtained with the application of 100% ETc under CFI, which had insignificance difference among treatments that received 85% ETc under CFI, 70% ETc under CFI, 100% ETc under AFI, 85% ETc under AFI (Figure 11). However, the least bulb diameter (38mm) was recorded for FFI under 50% ETc under AFI and FFI, which they were statistically similar with 70% ETc under AFI and FFI. These results are close agreement with (Abdelhady and Ebtisam, 2016), they found a diameter of 44 to 58 mm.



Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

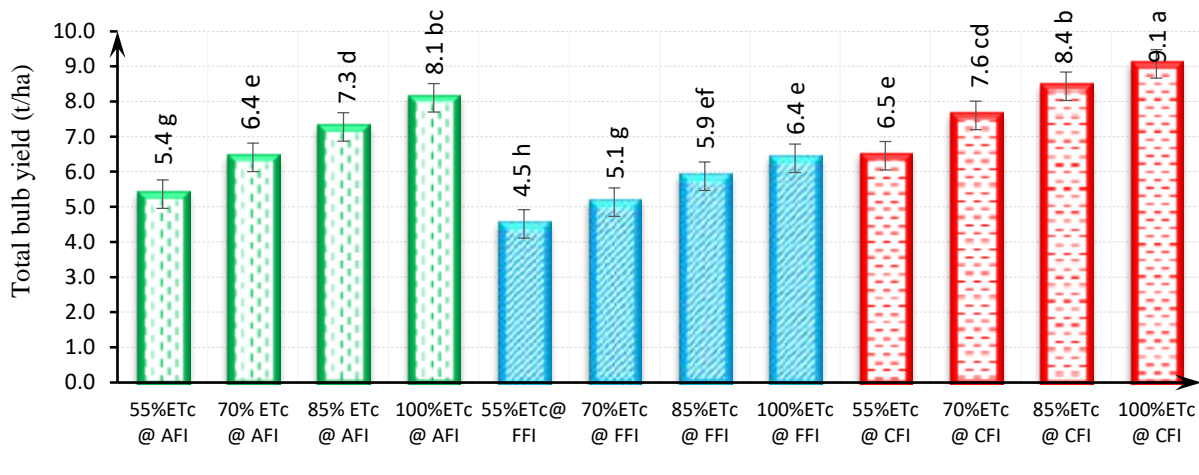
Figure 11. Effects of deficit levels and furrow techniques on diameter.

4.5.2. Total bulb yield

Analysis of variance revealed that total bulb yield was highly significantly influenced ($P < 0.01$) by both furrow irrigation techniques and water application levels (Table 2). The maximum total bulb yield was obtained by 100% ETc under CFI (9.1 t/ha) and the minimum yield of 4.5 t/ha was found with irrigating 55% ETc under FFI (Figure 12). This results are supported by others authors, Ahmed *et al.*, (2009) and Sankar *et al.*, (2008); whose they were found a total bulb yield of garlic within the range between 7.05 to 8.5 t/ha and 7.5 to 12.9 t/ha respectively.

The yield of garlic was in the range of 5 to 8.5 t/ha with different fertilizer rate under irrigation practices (Workat *et al.*, 2018). Gupta *et al.*, (2017) obtained similar results; the

maximum bulb yield of garlic was obtained as 11.5 t/ha with 100% CPE treatment. The bulb yield obtained under 70% ET with AFI, 85% ETc with FFI, 100% ETc with FFI and 55% ETc with CFI had no statistically significance difference. Garlic bulb yield was reduced as water stress level increased from 100% ETC to 50% ETC and in order of CFI, AFI and FFI. The range of garlic under absence of moisture stress was 12.5 t/ha (Baiq *et al.*, 2020).



Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 12. Effects of deficit irrigation levels and furrow techniques on total yield.

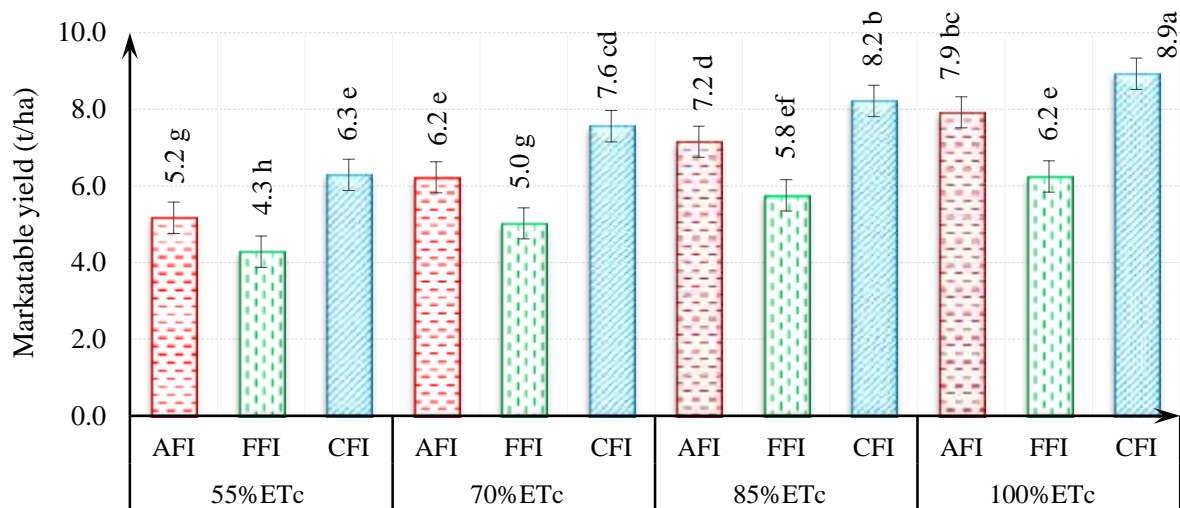
4.5.3. Marketable bulb yield

Analysis of variance showed that marketable bulb yield of garlic was highly significantly ($P < 0.01$) influenced by both furrow irrigation techniques and irrigation water levels (Table 2). The maximum marketable yield (8.9 t/ha) was observed with the application of 100% ETc under CFI and followed by 85% ETc under CFI (8.2 t/ha) (Figure 13). According to Mohammad *et al.*, (2013) and Abdelhady & Ebtisam, (2016); the marketable yield was found as 6.1 t/ha with drip irrigation and within the range of 5 up to 6.1 t/ha.

This difference in yield might be due to soil variability, climate difference, management difference and variety difference. The highest marketable yield was recorded when plants received 14 days' irrigation interval (Ahmed and Kasem, 2019). The maximum marketable bulb yield (7.5 t/ha) and WUE were observed from applying irrigation water at 20% more of the recommended ASMDL (Ashebir *et al.*, 2021). Whereas, the minimum marketable yield (4.3 t/ha) was obtained with application of 55% ETc under FFI and followed by 70% ETc under FFI and 55% ETc under AFI.

As shown (Figure 13), the yield obtained was statistically significant for furrow irrigation techniques at all irrigation levels. The minimum yield was obtained under FFI and the

maximum was obtained at CFI. The highest marketable bulb yield of garlic was found as 14.7t/ha under 100% ETc (Rajesh *et al.*, 2020). Highest yields are probable with soil moisture depletion of as little as 25 to 30% depletion, certainly lower than 50%. The yield obtained at 85% ETc under CFI and 100% ETc was statistically similar each other. The application of 80% ETc could be suggested to generate comparable garlic yield to that of full irrigation (Mandefro and Shoeb, 2015).



Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 13. Effects of irrigation levels and furrow irrigation techniques on marketable yield.

Pooled marketable yield of garlic bulb had a positive strong relation ($P < 0.01$) with the total amount of water applied with R^2 value of 0.76 and the linearly association were explained as marketable yield = $0.001 * \text{water} + 3.78$ (Figure 14). The yield variability of treatments is well expressed in terms of water amount variability. Similarly, (Abdellatif and Abdelshafy, 2017) was found a positive relation between yield and water applied with coefficient of determination, R^2 value of 0.89.

Soil moisture content data showed that garlic extracted soil moisture deeper than 1.07 m to compensate for deficit irrigation, garlic yield decreased linearly with applied water in sandy loam (Hanson *et al.*, 2003). Despite in this study because of the soil is clay textured, soil moisture regimes for each deficit irrigations can occur without reducing much on yield. The application of 372 mm of seasonal water with 10 days' interval resulted with the highest bulb yield of 10.48 t/ha (Mohammed and Rokon, 2017). As investigated by many researchers, direct relationship between yield and yield components of bulb with available moisture was observed (Singh *et al.*, 2007; Ahmed *et al.*, 2009).

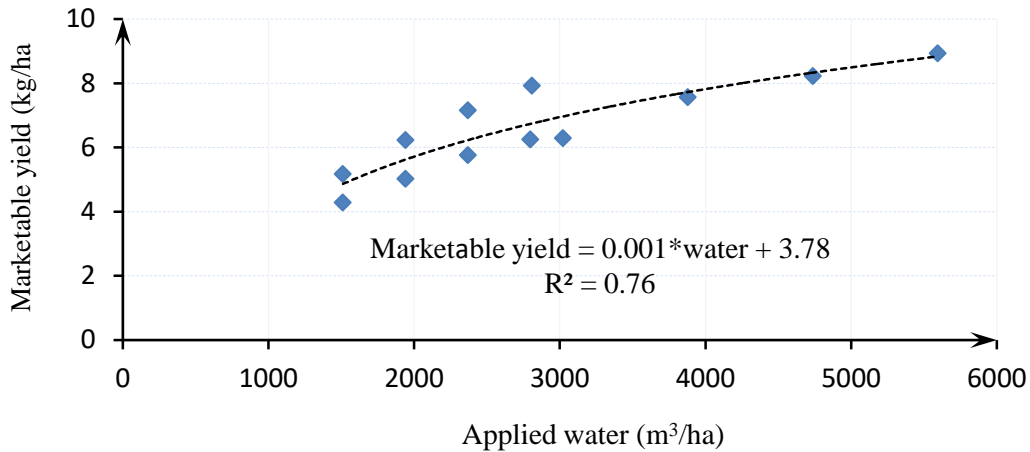
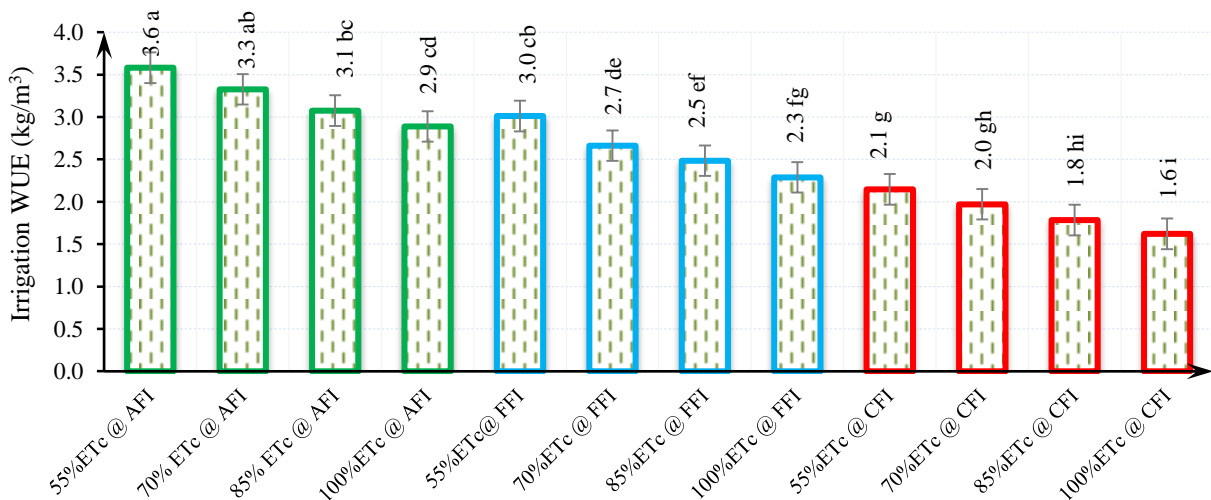


Figure 14. Effect of applied total season water on marketable bulb yield.

4.5.4. Irrigation water use efficiency

Irrigation water productivity was highly statistically significantly ($p < 0.001$) affected by the interaction effect of furrow irrigation methods and irrigation water levels (Table 2). The obtained IWP in this study was in agreement with that of (Mandefro and Shoeb, 2015); Fabeiro *et al.*, (2003), they found within the range of 1.8 to 2.5 kg/m^3 (Figure 15). In line with these, Lellis *et al.*, (2022); found water productivity from 2.53 to 3.72 kg/m^3 with the application of 3382 m^3/ha water. IWUE was lower in farmer's irrigation practices due to lower local garlic yield responses to over irrigation and greater water application variability (Sisay *et al.*, 2019). Maximum value of WUE was 3.29 kg garlic per m^3 of irrigation water as recorded with the treatment 100% ETc (Tayel *et al.*, 2010).



Means with different letters in a labels differ significantly and means labeled with the same letter are similar at ($p < 0.05$) level of significance. Means not labeled with letters: - non-significant at $p < 0.05$.

Figure 15: Effects of deficit irrigation levels and furrow irrigation techniques on IWP.

Conventional furrow irrigation gives highest yield and low water production following alternate furrow irrigation with equivalent yield of CFI and higher water productivity and fixed furrow irrigation with lower yield and high water productivity. Alternate furrow irrigation gives optimum yield and water productivity. The combined effect of AFI system and 100% ETc was superior in terms of improving growth characters, producing high marketable garlic yield, water use efficiency, water productivity than CFI and FFI system with 100% ETc. As the amount of water applied increased over conventional irrigation the yield also increased, but high water productivity of water was gained in Fixed and Alternate furrow irrigation. Clearly, water productivity depends on total applied water and the yield.

The regression analysis was statistically significant with coefficient of determination, $R^2=0.77$, indicates that all the variability in IWUE is explained in the variability of applied water. As the applied water increases, the garlic IWUE would decrease (Figure 16). These results in line with the findings of Hanson *et al.*, (2003), they found a decreasing trend of garlic IWUE as the applied water increased with the coefficient of determination of 0.91 value. In area where water is the limiting factor for crop production, it is more important to improve IWP rather than increasing yield (Geerts and Raes, 2009).

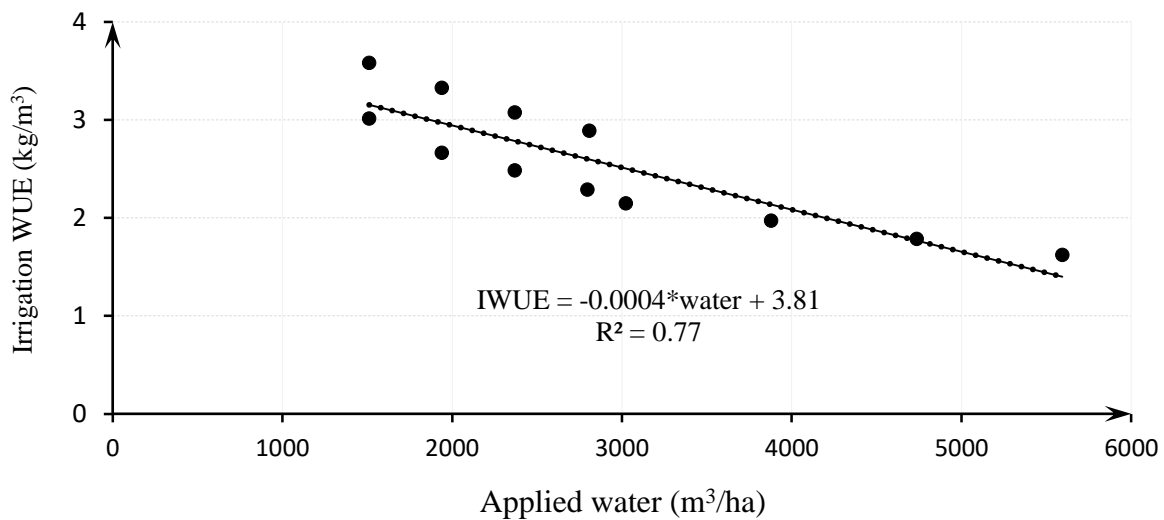


Figure 16. Effect of applied water on irrigation water productivity.

The relationship between IWP and CWUE was found as a positive strong linear relation with R^2 value of 0.97. Abdellatif and Abdelshafy, (2017), supported this result linear regression analysis between the applied irrigation water and water-consumed water with R^2 value of 0.98 under the surface irrigation methods was obtained (Figure 17).

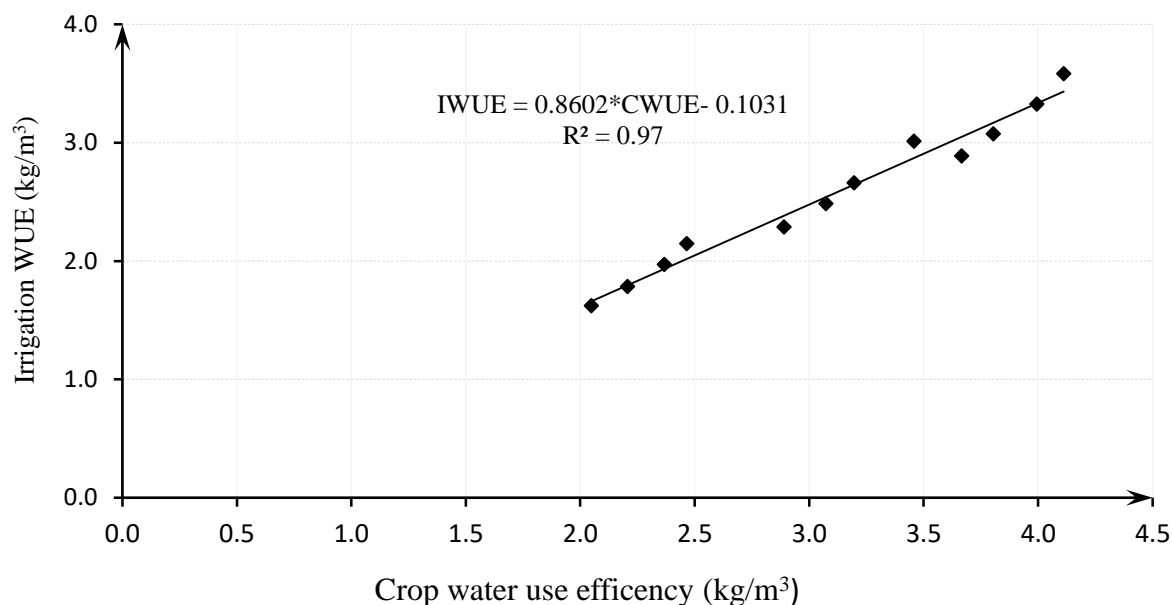


Figure 17. The relationship between CWUE and IWUE of garlic.

Table 2. Combined ANOVA on effects of deficit levels and furrow techniques on yield and irrigation water use efficiency

Source of variations	Statistical indicators	D (mm)	MKY (t/ha)	IWUE (kg/m ³)
	Mean	43.6	6.57	2.60
Irrigation levels	LSD _{5%/1%}	3.7**	1.06**	0.17**
	C.V (%)	9	17	17
	Mean	43.6	6.6	2.6
Furrow techniques	LSD _{5%/1%}	ns	0.29**	0.15**
	C.V (%)	11	22	7
Irrigation levels*	Mean	43.6	6.6	2.6
furrow techniques	LSD _{5%/1%}	6.72*	0.28**	0.3**
	C.V (%)	9.14	5.12	10.44

**-----highly significance difference, *----- significance difference, ns-----not significance, D--- Bulb diameter, MKY-marketable bulb yield, IWUE----- Irrigation water use efficiency.

4.6. Yield reduction and water saved with reference to the control treatment

The amount of water saved and yield reduction with reference to 100% ET_c under CFI is presented as shown below (Figure 18). The higher yield reduction (50%) was observed in plots irrigated with 55% ET_c under FFI, and followed by 70% ET_c under FFI (43%) and 55% ET_c under AFI system (41%). However, the amount of water saved was 73%, 65% and 73%

respectively. It can be observed that in AFI, irrigating with 100% ETc accounts 11% yield reduction with saving 50% water; but in FFI for 100% ETc about 30% yield reduction occurred with saving 50% water. With nearly the same yield reduction for 55% ETc under CFI, 100% ETc under FFI, 70% ETc under AFI; the amount of water saved was 46%, 50% and 65% respectively.

Therefore, alternate furrow irrigation increases water use efficiency as compared with fixed and conventional furrow irrigation techniques. The minimum yield reduction (7%) was observed under plots irrigated with 85% ETc under CFI. This indicates that application of smaller deficit irrigation levels would avoid yield penalty in garlic production.

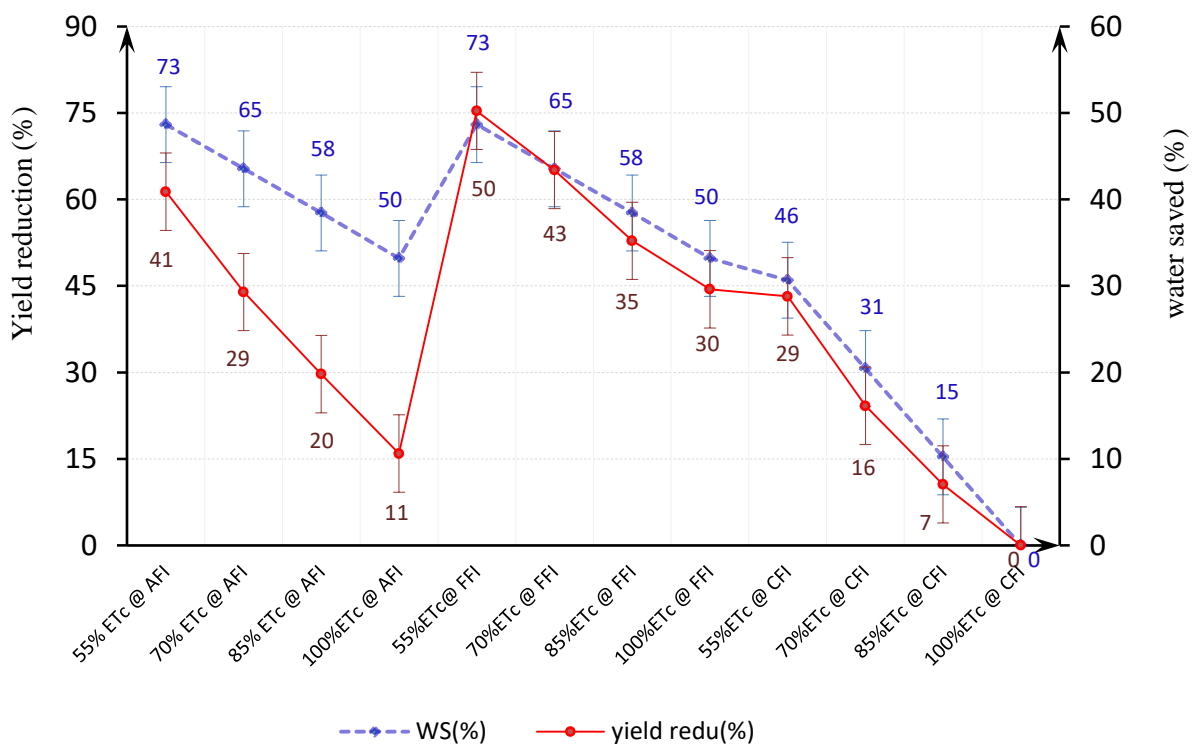


Figure 18. Yield reduction and water saved in reference to control treatment.

4.7. Additional area irrigated with the saved water and possible yield advantages

It is obviously known that the water saved by deficit irrigation levels and alternative furrow irrigation techniques in reference to full irrigation under conventional furrow irrigation used to irrigate extra land and produce additional benefits. Alternate furrow and fixed furrow irrigation saved the same amount of water, but AFI significantly improved the possible additional yield from the same extra area. For instance, with irrigating 1 ha of extra land in treatments of 55% ETc under CFI, 100% ETc under AFI and FFI would give 5495 kg, 8037 kg and 6330 kg respectively (Figure 19).

In areas where water availability and quantity are a main limiting factor for irrigated agriculture (un-irrigated area due to absence of water), water saving strategies like AFI and DI are of a mandatory option. Thus, the water saved would irrigate other extra area, produce yield, and generate a higher income for the farmers. Therefore, the application of 85 % ETc under AFI accounts 20 % yield reduction, in which the 58 % of the saved water could irrigate extra 1.4 ha land and produce a garlic bulb yield of 9.9 t/ha.

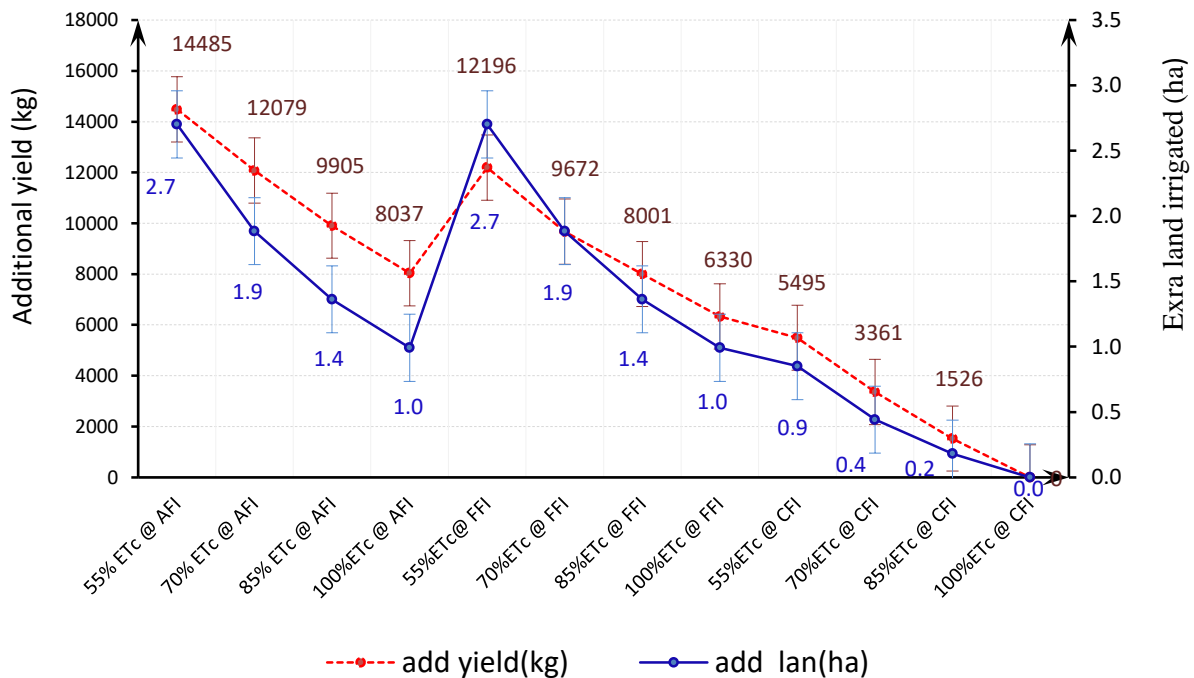


Figure 19. Additional area irrigated with the saved water and yield obtained

4.8. Yield response factor

Yield response factor is used to quantify the decrease in irrigation levels and crop water use efficiency. The higher K_y values indicate that the crop would have a greater yield loss and inversely the lower the K_y values indicate the smaller the yield reduction because of the water stress. Crop ET and bulb yields reduced when soil water become a limiting problem. When the available water in the root zone becomes below the design MAD level, there may be reduction of crop evapotranspiration and there by yield reduction.

From the result, the range of yield response factor was between 0.72 and 0.98. The maximum yield response factor was obtained in plots irrigated with 100% ETc under FFI and followed by 100% ETc under AFI system. Whereas, the minimum K_y value was obtained in plot that was irrigated with 85% ETc under CFI system (Figure 20). This indicates that the smaller value of K_y shows smaller deficit levels and higher yields, and vice versa. When garlic crops

irrigated with 55% ETc and 70% ETc, the value of K_y is approached to 1, indicates that garlic is sensitive for water stress.

When irrigating garlic with full or 85% ETc, the value of K_y is relatively smaller indicates that garlic crops tolerate that level of moisture and produce satisfactory yield. Since all K_y values are smaller than unity, the rate of yield reduction is smaller than crop evapotranspiration deficit. The rate of relative yield reduction was proportionally linear to the relative evapotranspiration deficit with coefficient of determination of 0.99.

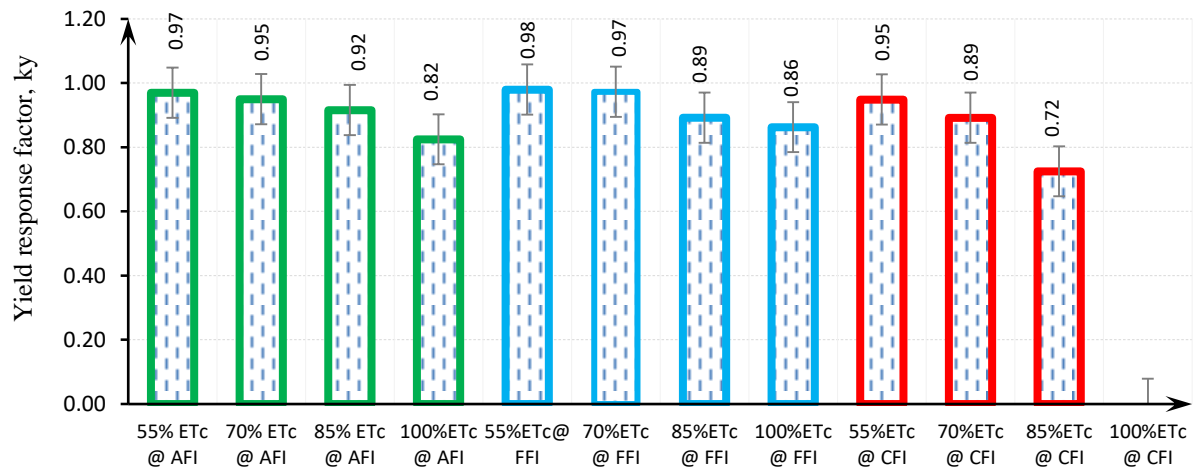


Figure 200. yield-water production function for garlic crop.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In the study area where rainfall is erratic and uneven, water is unavailable for gravity irrigation and farmers have not any information regarding how to irrigate, how much to irrigate and when to irrigate; adoption of the right water management is very important issue. This study was investigated by comparing different furrow techniques and irrigation levels and their interaction effects on growth parameters, bulb yield and yield components, crop water use efficiency and irrigation water productivity of garlic. The optimum irrigation water application was determined based on the CROPWAT software for windows 8.0 and the irrigation water applied to each treatment was determined based on the management allowable depletion levels. The depth of water that was supplied was different based on the designed MAD levels and the type of furrow irrigation techniques.

The season water requirement of garlic crop for full ET_c in the growing season was found as 463mm. As the result, confirmed deficit irrigation levels (100% ET_c, 85% ET_c, 70% ET_c and 55% ET_c) and furrow irrigation techniques (AFI, FFI, and CFI) significantly influenced growth parameters, yield and yield components, and water use efficiency and water productivity of garlic crop. Analysis of variance shows that plant growth parameters, yield and yield components, and water use efficiency has highly affected ($P < 0.01$) by the deficit levels and furrow irrigation techniques. The maximum value of bulb diameter (47mm) and bulb yield (8 t/ha) were obtained in 100% ET_c under CFI, while the minimum value of 39 mm and 5 t/ha were obtained under 55% ET_c application respectively. However, the maximum IWUE (3.6 kg/m^3) under 100% ET_c with AFI and the minimum IWUE (1.6 kg/m^3) in 100% ET_c with CFI were obtained.

The higher value of the bulb diameter and yield was found due to the higher photosynthetic apparatus developed in the plant and there by better blurbification of garlic was observed. Mean values of yield showed that 100% ET_c and 85% ET_c irrigation levels provided higher values of total and marketable yield, which was significantly different from 70% ET_c and 55% ET_c levels. Thus, the application irrigation water with small reduction of ET_c would not brought a significance change on yield and yield components of garlic. The result also confirmed that different furrow irrigation techniques significantly at ($p < 0.01$) affected bulb and yield of garlic. The maximum value of different parameters was observed in CFI, while

the minimum values in FFI. However, AFI and FFI could save 50% of water used in CFI and irrigate an extra area. However, AFI increases water use efficiency when compared with CFI and FFI without significant yield reduction. This is due to the fact the moisture distribution in the root zone to be uniform and evenly distributed. From the standpoint of garlic crops, the need of optimum moisture frequently because of shallow rooted vegetable crops, AFI holds to be effective. The use of FFI resulted in the deviation between better water use efficiency and low bulb yield.

The results also confirmed that the interaction effect of deficit irrigation levels and furrow irrigation techniques significantly affected growth parameters, yield and yield components, and water use efficiency of garlic. Correlation analysis confirmed that garlic yield had a strong positive association with bulb diameter. This means, the higher performance of garlic in growth stage would be resulted in higher garlic bulb yield. The application of 85% ETc under AFI techniques save irrigation water without having yield penalty or low risk of yield reduction (20 %), could produce an extra yield of 9.9 t/ha from 58% of the saved water; save water usage and attain optimum garlic production. Therefore, the application of 85% ETc levels under alternate furrow irrigation is the best choice under the conditions of the study area, where water is accessed by pumping, clay loam soil and humid to sub humid microclimate, erratic and uneven rainfall, traditional irrigation water management.

5.2. Recommendations

Based on the present finding on the effect of deficit irrigation levels and furrow irrigation techniques on yield and WUE of garlic, the following concluding remarks could be drawn: -

- ❖ In areas where absence of water shortage problem and no extra cost for pumping scenario, garlic crops could be irrigated with gross seasonal irrigation depth of 592 mm with 100% ETc under CFI techniques where the soil moisture at manageable depletion level of 30% to produce maximum bulb yield of garlic.
- ❖ In areas where water shortage is a problem and extra cost invested for pumping scenario, garlic could be irrigated either 100% ETc or 85% ETc under AFI techniques to achieve a maximum crop water use efficiency and irrigation water productivity by compromising 11% and 20% yield reduction.
- ❖ The study should be verified across different location of highlands of Debre Birhan and over season to validate present findings of irrigation water management strategies.

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7. APPENDICES

7.1. List of Tables in appendix

Tables 1. Infiltration rate test result from 3 location of the site

Time (hrs)	Time (min)	Cumulative time (min)	Cumulative time (hrs)	Reading (mm)	Infiltration (mm)	Infiltration rate (mm/hrs)	Cumulative intake (mm)
3:00	0	0	0.00	180.0	0	0	0
3:00	0.5	0.5	0.01	175.5	4.5	540	5
3:01	0.5	1	0.02	172.6	2.9	352	7
3:02	1	2	0.03	168.9	3.7	220	11
3:05	3	5	0.08	161.6	7.3	147	18
3:10	5	10	0.17	154.7	6.9	83	25
3:20	10	20	0.33	145.7	9.0	54	34
3:30	10	30	0.50	139.3	6.3	38	41
3:45	15	45	0.75	132.0	7.3	29	48
4:00	15	60	1.00	127.2	4.8	19	53
4:20	20	80	1.33	122.3	4.8	15	58
4:40	20	100	1.67	118.3	4.0	12	62
5:00	20	120	2.00	114.3	4.0	12	66
5:30	30	150	2.50	146.0	4.0	8	70
6:00	30	180	3.00	142.2	3.8	8	73
6:30	30	210	3.50	139.1	3.1	6	77
7:00	30	240	4.00	136.3	2.8	6	79
7:45	45	285	4.75	132.7	3.7	5	83
8:30	45	330	5.50	129.2	3.5	5	86

Tables 2. Analysis of Variance for yield and yield components of garlic.

Marketable bulb yield					
Source	DF	SS	MS	F Value	Pr >F
methods	2	35.3	17.6	148.5	<.0001
Irrigation levels	3	30.0	10.0	84.3	<.0001
replication	2	0.0	0.0	0.2	0.8324
Error	28	3.3	0.1		
Total	35	68.7			

Bulb diameter (mm)					
Source	DF	SS	MS	F Value	Pr >F
methods	2	97	49	20	<.0001
Irrigation levels	3	324	108	43	<.0001
replication	2	319	160	64	<.0001
Error	28	70	2		
Total	35	810			

Tables 3. Analysis of Variance for water use efficiency of garlic

irrigation water productivity					
Source	DF	SS	MS	F Value	Pr >F
methods	2	10.77	5.38	179.7	<.0001
Irrigation levels	3	2.09	0.69	23.3	<.0001
replication	2	1.02	0.51	17	<.0001
Error	28	0.84	0.03		
Total	35	14.72			

7.2. List of figures in appendix

Figure 1. Land preparation, pre irrigation and initial growth stage of garlic.



Figure 2. Performance of garlic in development stage





Figure 3. Performance of garlic at mid growth stage.



Figure 4. Moisture depletion level of the soil for 100% ETC (CROPWAT model).

