RESPONSE OF POTATO (*Solanum tuberosum* L.) TO WATER STRESS AT DIFFERENT GROWTH STAGES ON YIELD AND YIELD COMPONENTS AT SANKURA WEREDA, SILTE ZONE CENTRAL ETHIOPIA

MSc. THESIS

MOHAMMED AHMED SULE

HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

APRIL, 2024

RESPONSE OF POTATO (*Solanum tuberosum* L.) TO WATER STRESS AT DIFFERENT GROWTH STAGES ON YIELD AND YIELD COMPONENTS AT SANKURA WEREDA, SILTE ZONE CENTRAL ETHIOPIA

MOHAMMED AHMED SULE

ADVISOR: ABRAHAM WOLDEMICHAEL (PhD)

A THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCE AND IRRIGATION ENGINEERING, FACULTY OF BIOSYSTEM AND WATER RESOURCE ENGINEERING, INSTITUTE OF TECHNOLOGY, SCHOOL OF GRADUATE STUDIES, HAWASSA UNIVERSITY

IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN IRRIGATION AND DRIANAGE ENGINEERING

HAWASSA, ETHIOPIA

APRIL, 2024

ADVISORS' APPROVAL SHEET

SCHOOL OF GRADUATE STUDIES

HAWASSA UNIVERSITY

This is to certify that the thesis entitled "Response of Potato (*Solanum tuberosum* L.) to water stress levels at different growth stages on yield and yield components at Sankura Wereda, Silte Zone, Central Ethiopia " in Irrigation and Drainage Engineering, the Graduate Program of the Department/School of Bio-systems and Environmental Engineering, and has been carried out by Mohammed Ahmed ID. No GPIrDrR/0005/14, under my/our supervision. Therefore, I/we recommend that the student has fulfilled the requirements and hence here by can submit the thesis to the department.

Approved by

Abraham Woldemichael (PhD)	______________________	________________
Name of Major Advisor	Signature	Date

HAWASSA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
EXAMINERS'APPROVAL SHEET

We, the undersigned, members of the Board of Examiners of the final open defense by Mohammed Ahmed Sule, ID. No GPIrDrR/0005/14, have read and evaluated his/her thesis entitled "Response of Potato Solanum tuberosum L. to Water Stress Levels at Different Growth Stages on Yield and Yield Components at Sankura Wereda, Silte Zone, Central Ethiopia, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree.

____
Name of Major Advisor Signature Date

____
Name of Internal Examiner-I Signature
Date

____
Name of Internal Examiner-II Signature Date

Habtamu Hailu 30 April 2024
Name of External Examiner Signature Date

____
SGS Approval Signature Date

Final approval and acceptance of the thesis is contingent upon the submission of the final copy of the thesis to the School of Graduate Studies (SGS) through the Department/School Graduate Committee (DGC/SGC) of the candidate's department.

Stamp of SGS **Date: -__________________**

DEDICATION

I dedicate this thesis manuscript to my father Ahmed Sule, my mother Aysha Dedgeba , my wife Senya Tale and my brothers and sisters for nursing me with affection and love, and for their dedicate partnership in the success of my life.

STATEMENT OF THE AUTHOR

First, I declare that this thesis is my original work and that all sources of materials used for this thesis have been accordingly acknowledged. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

Brief quotations from this thesis are allowed without special permission provided that accurate acknowledgement of source is made. Requests for permission for extended quotation or reproduction of this manuscript in whole or in part may be granted by the Head of the Department of Bio-system and Environmental Engineering or the Dean of School of Graduate Studies when in his or her judgment the proposed use of the material is in the interest of scholarship. In all other instances, however, permissions must be obtained from the author.

Name: Mohammed Ahmed **Signature:** ________________

Place: Institute of Technology, Hawassa University, Hawassa

Date of submission:…………………………………………….

ACKNOWLEDGMENTS

Above all, I would like to honor and give glory to Allah who has been strengthening me throughout my research work. I want to express my heartfelt gratitude to my major advisor Dr. Abraham Woldemichael for his careful supervision, excellent guidance and assistance from the very beginning of the proposal initiation up to the final write up. I would like to pass my sincere thanks to the Southern Agricultural Research Institute (SARI) and Werabe Agricultural Research Center (WARC) for offering financial, technical and material assistance to conduct my thesis research work. I am thankful to the Hawassa National Meteorological Agency for providing me with necessary metrological data. I am highly indebted to the Werabe Agricultural Research Center Directors Mr. Seyfu Kemal and Kamil Temam and Natural Resource Management Work Process Mr. Tagese Bekele.

I also want to express my special thanks to my best friends those who I saw the meaning of friendship practically on Tamrneh K., Mohammed S., Bilal T., Mulugeta A. Mohammed D., Abdu S., Shimels M. and Mensur R. The last but not the least heartfelt thanks go to my beloved father; mother, wife, sisters and brothers who were anxious about and worried to my work during all the time.

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
BMC	Billion Meter Cube
CSA	Central Statistical Agency
CWR	Crop Water Requirement
CWUE	Crop Water Use Efficiency
DF	Degree of Freedom
D50%F	Days to 50% Flowering
DM	Days to Maturity
ETa	Actual evapotranspiration
ETc	Crop Evapotranspiration
ETm	Maxima mum Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organization
FC	Field Capacity
GIR	Gross Irrigation Requirement
Kc	Crop coefficient
Ky	Yield Response Factor
IAEA	International Atomic Energy Agency
LA	Leaf Area
LAI	Leaf Area Index
LN	Leaf Number
LSD	Least Significant Difference

m.a.s.l	Meter Above Sea Level
MoA	Ministry of Agriculture
MS	Mean Square
MTY	Marketable Tuber Yield
NIR	Net Irrigation Requirement
P	Manageable allowable level depletion fraction
Pe	Effective Rainfall
PH	Pant Height
pH	Soil Acidity
PWP	Permanent Wilting Point
RCBD	Randomized Complete Block Design
SARI	South Agricultural Research Institute
SAS	Statistical Analysis System
SSA	Sub-Saharan Africa
TAW	Total Available Water
TD	Tuber Diameter
TN	Tuber Number
TTY	Total Tuber Yield
USAID	United States Agency for International Development
UMTY	Unmarketable Tuber Yield
WARC	Werabe Agricultural Research Center
WP	Water Productivity
Ya	Actual Yield
Ym	Maximum Yield

TABLE OF CONTENTS Page

LIST OF TABLES

Tables Page

LIST OF FIGURES

LIST OF TABLES IN THE APPENDIX

LIST OF FIGURES IN THE APPENDIX

ABSTRACT

Water scarcity is one of the major challenges faced by the current agricultural systems worldwide, especially in arid and semi-arid areas. The objective of this study was to evaluate the response of potato (Solanum tuberosum L.) to water stress levels at different growth stages on yield and yield components under Sankura Wereda conditions. The field experiment was carried out in a randomized complete block design with four water stress levels and a total of thirteen treatments and three replications. The treatments were 100% ETc as a control and 85 ETc, 70 ETc, 55 ETc, and 40% ETc stress at each four growth stages of development stage of crop. Data on yield and yield components were collected and their responses to water stress were statistically tested using Analysis of variance (ANOVA)). The collected yield and growth parameters include plant height , leaf number, leaf area, leaf area index, tuber number, tuber diameter marketable yield , and total yiel. The results of the analysis of variance indicated that the different levels of water stress applied had a highly significant ($p<0.01$) effect on marketable tuber yield. The maximum marketable tuber yield of 41.52 tons/ha was achieved under full irrigation (100% ETc), and the minimum (32.86 tons/ha) was observed at 40% ETc at mid stage treatment. From the mean result of marketable tuber yield, it was observed that the control treatment (100% ETc) was significantly different from all treatments except the 85% ETc treatment water level. The highest water productivity (9.52 kg/m^3) was observed under 40% ETc at mid stage. The water saved at 40% ETc and 55% ETc treatment resulted in 22.76% and 17.07% at mid-stage, with yield reductions of 20.86% and 16.04, respectively. The marketable tuber yield obtained at 70% ETc was significantly higher than that obtained at 55% ETc and 40% ETc. From the result of the study, it was observed that the water stress levels on different growth stages when the water is a limitation ,70% ETc stress level give better result. Therefore, Irish potatoes could be irrigated at 70% ETc water stress level in limited water resource conditions.

Key words: Irrigation, water stress levels, growth stages, Potato, water productivity

1. INTRODUCTION

1.1. Background

Water scarcity is one of the most significant constraints on agricultural production. It is one of the major challenges faced by the current agricultural systems globally, especially in arid and semi-arid areas. Actually, it's thought that the lack of water in many countries is currently the biggest problem (Gohar and Ward, 2013). Water is becoming scarcer globally, and every indication is that it will become even more so in the future. As cities grow and populations increase, the problem worsens since needs for water increase in households, industry, and agriculture (Fereres et al., 2007).The largest global consumer of freshwater is agriculture, and the major obstacle to sustainable agricultural output is the decreased freshwater supply caused by rapid population growth, industrialization, climate change, and unproductive water loss (Chareesri *et al*., 2020). Agriculture is the main water consuming sector; over 40% of the world's yearly food supply is produced on irrigated land, which accounts for up to 70% of the water withdrawals for irrigation purposes (Awulachew *et al.*, 2010; FAO, 2012; Rai *et al*., 2022).

Ethiopia is putting irrigation projects into action more than anything else to help its crops that are supplied by rain. It is planned to improve agricultural productivity, range and ensure that agriculture will play a major role in the country's economic growth by generating food and raw materials for the agroindustry (Ayana, 2011).

In the past, intensive irrigated agriculture has helped to meet the world's food demand due to population growth. However, the growth in food production has been hindered by urgent challenges related to limited water availability caused by climate change. Irrigation is one means of agricultural production that can be used to increase production to meet the growing demands in Ethiopia (Awulachew, S. 2007). For successful distribution of scarce water and other inputs to crops, agriculturalists will need to be adaptable in how they manage the rate, frequency, and duration of water supply. It seems that well-planned deficit irrigation methods, backed by cutting-edge irrigation technologies and adaptable, cutting-edge water distribution systems, are the most efficient ways to preserve water.

Potato (*Solanum tuberosum* L.) is one of the most important starchy vegetables that is globally cultivated and consumed (Obidiegwu *et al*., 2015). It ranks as the first highest-produced non-cereal food crop and the fourth-highest-produced crop after wheat, corn, and rice worldwide (FAOSTAT, 2019). It is cultivated in over 100 countries, and the global production of potatoes was estimated to be 370 million tons in 2019, feeding over a billion people worldwide. It is a crop with a short growing season, broad use, adaptability to many growing conditions, and fast growth in output. The contemporary potato is regarded as a crop that is sensitive to drought and is prone to yield loss as a result of drought stress. Effective irrigation management is seen as a key component in raising agricultural output (Alan, J. 2016). Improvement of irrigation management in areas subjected to periods of water scarcity requires good knowledge of system performance over long time periods. Better water management is becoming a critical issue as water scarcity worsens in many parts of the world (García-Vila *et al*., 2008). Enhancing water productivity through deficit irrigation, which uses less irrigation water than plants actually need, is gaining adhesion yield. The more widely accepted idea of "water productivity" and its assessment across multiple scales provides a reliable indicator of how well agricultural systems use water to produce food (Clement *et al.,* 2011).

Deficit irrigation methods therefore assist irrigated agriculture in minimizing output losses brought on by water scarcity (Rodrigues and Pereira, 2009). Additionally, it's a method of controlling water resources that allows for a little drop in output without endangering the plant in a significant way.

Deficit irrigation can increase water productivity in drought- and water stressed environments by increasing yield per unit of water delivered. Improved agricultural techniques, such as the introduction of drought tolerant cultivars, are most successful when paired with better water management techniques (FAO, 2020). Given that drought and water scarcity were the primary factors influencing agricultural productivity in the research areas, the study area's water scarcity problem may be solved by different water stress levels of irrigation to enhance water management.

In the current situation of water shortages and droughts, deficit irrigation can also lead to greater water productivity by improving the yield per unit of water applied. Water scarcity and drought were the main factors affecting agricultural production in the study area; therefore, improved water management practices using the deficit irrigation method would help manage the water scarcity problem in the study area. Enhancing the water productivity of irrigated crops through a water management option is crucial in a water-scarce area. Therefore, the use of deficit irrigation water management practices like water stress levels in deficit irrigation would be one option to improve the water productivity and Irish potato yield in the study area.

1.2. Statement of the problem

Water scarcity is one of the most crucial limitations of sustainable crop production under irrigation due to frequent droughts during the main cropping season. Increasing competition for water for irrigated agriculture and other uses, particularly in areas such as Sankura Wereda is one of the issues. It is currently increasing, possibly due to the growth of smallholder farmers, private investors, households, and other demands. The increasing population growth and their corresponding demand for food require increasing agricultural production.

Water scarcity for farming will become the standard rather than the exception, and the focus of irrigation water saving techniques (management) will change from maximizing yield per acre to yield per unit of water used, or water productivity (Abdyl-Razak *et al*., 2014).

The effective water application practice was used to alleviate the increased water demand and increase production per given amount of water in the future to increase water profitability (Blum,2009). Thus, an increase in the WP of agricultural crops and the saving of water resources are becoming of strategic importance for the area with limited water resources. Potato in the area produced under a limited scenario, and hence, the stress level where yield is not affected by the pin pointed. Therefore, there must be an irrigation strategy that tests water stress levels and different growth stages specific to the study area to improve potato yield and water productivity with limited water resources.

1.3. Objectives

1.3.1. General objective

To evaluate the response of yield and yield components of potatoes to water stress levels applied at different growth stages under Sankura Wereda conditions.

1.3.2. Specific objectives

1. To identify the critical water stress level that bring optimal water saving with minimum yield reduction potato under the study area
2. To determine the water productivity of potato under different water stress levels and growth stages

1.4. Research questions

- ✓ Which growth stages of potato are critical and optimal water saving with a minimum of yield reduction to water stress levels?
- ✓ What levels of water stress and growth stage has more water productivity?

1.5. Significance of the study

The study was specifically based on the efficient utilization of the limited available water resources by varying water stress levels at different growth stages. Around the study area, farmers are producing potatoes next to maize and wheat crops. Thus, studying water stress levels during irrigation is useful to increase water productivity and yield for the newly introduced potato crop in the study area. The research result of this study will benefit farmers in the study area by providing information on water stress levels to apply during production with a limited amount of water and the result will supply some recommendations to farmers on how to choose the appropriate irrigated water under actual water stress levels that improves yields as well as water productivity.

Furthermore, agricultural experts could use the result to advising farmers and water user associations in the study area to manage the limited water resources by practicing appropriate water stress levels and contribute ideas for further research.

2. LITERATURE REVIEW

2.1. Water resources potential

Water resources must be managed appropriately in a global context to promote agricultural development. By using water resources for agriculture, we can enhance global food security and promote sustainable development in the face of water scarcity and climate change. In regions with inconsistent or insufficient rainfall patterns, effective water management techniques and the application of irrigation technologies are essential to meeting the increasing global demand for food. Ethiopia is one of the numerous places in Africa where surface water offers enormous possibilities for irrigation. Irrigation could be beneficial for general economic growth, the eradication of poverty, and food security. To utilize surface water resources for irrigation sustainably and efficiently, one must, however, have a thorough understanding of their distribution, availability, and potential (Birhanu, 2023).

The continent of Africa has a vast surface water potential due to the quantity of its river basins. Water, which makes up more than two-thirds of the earth's surface, is a rare resource since the majority of it is inaccessible and too salty to be useful. Two-thirds of the 2.5% of freshwater on Earth that is not salty is trapped in icecaps and glaciers. A significant portion of fresh water, roughly 20%, is inaccessible and arrives during inclement weather, such as monsoons and floods. Less than 0.08% of the water on earth is usable by humans at this time. However, over two-thirds of this inadequate amount of water that is accessible is utilized for agriculture (Delilo, 2020). Ethiopia has twelve river basins. The mean annual flow from all 12 river basins combined is estimated to be 125 BMC. The country has 112 million hectares of land. The amount of arable land is estimated to be between 30 and 70 million hectares. Based on conservative estimates, only approximately 15 million hectares of land are under cultivation at the moment. Only 4 to 5 percent of this area is under irrigation, with the 640,000 hectares now covered by projects with appropriate irrigation systems (Awulachew *et al.,* 2010). This suggested that a large area of Ethiopia's arable land is not currently receiving irrigation. But the expansion of irrigation is essential to dependable and sustainable agricultural growth, which drives Ethiopia's overall development (Makombe *et al.,* 2011).

In developing nations, irrigation development is critical because it increases labor, water, and land productivity and optimizes the use of agricultural inputs. Using its 5.3 million hectares of potential for irrigation, 3.7 million of that may be used using surface water sources, and 1.6 million can be used with groundwater and rainwater management (Van Halsema *et al.,* 2011). Given the importance of agriculture to the Ethiopian national economy, the government of Ethiopia has deal with an agriculture led development programed with irrigation development a central component. It is estimated that only 5% of 3.5 million ha of land that could be irrigated is currently developed (Awulachew *et al.,* 2010). Ethiopia uses twelve basins to manage its surface water, which are part of four trans boundary basins: the Nile, Rift Valley, Shebelle-Juba, and North East Coast (El Bilali et al., 2020). With the exception of the Nile Basin, all river basins experience water shortages. Almost no perennial rivers can be found below 1,500 meters, leaving much of eastern Ethiopia without reliable surface water. Furthermore, Ethiopia lacks the water infrastructure necessary to utilize its surface water resources, and its groundwater resource potential has not received much attention or investigation. As compared to surface water resources, Ethiopia has lower groundwater potential. Groundwater resources are poorly understood and estimates of their potential range from 2.6 to 13.5 BMC. However, local experts suggest that, given their experience with other groundbreaking projects, the potential could be far greater (Awulachew et al., 2010).

2.2. Irrigation potential and development in Ethiopia

The development of irrigation and agricultural water management holds significant potential to improve productivity and reduce vulnerability to climactic instability in any country. The majority of rural people in Ethiopia are among the poorest in the country, with limited access to agricultural technology, limited possibilities to diversify agricultural production given underdeveloped rural infrastructure, and little to no access to agricultural markets and to technological innovations. These issues, combined with the increasing degradation of the natural resource base, especially in the highlands, aggravate the incidence of poverty and food insecurity in rural areas. Improved water management for agriculture has many potential benefits in efforts to reduce vulnerability and improve productivity. Specifically, primary rationales for developing the irrigation sector in Ethiopia include (Awulachew et al. 2010).

The main use of this global resource is irrigation, which accounts for around two-thirds of the freshwater diverted for human use and about four-fifths of the total consumed. Irrigation has changed the economy of many dry and semiarid regions and irreversibly altered the social structure of many other places around the world. It has increased earnings, maintained rural communities, and created a multitude of new opportunities for economic expansion. Human settlement is made possible where it would not be possible without irrigation, occasionally to a quite dense population. However, it is estimated that 60% of the world's population will be facing a water deficit by 2025 (Qadir et al., 2007).

In Ethiopia, the percentages of land classified as pastoralist zones, high rainfall areas, and moisture shortage areas are 24, 32, and 44%, respectively. High rainfall fluctuation and irregularity, particularly throughout the crop-growing season, aggravate the issue. Since Ethiopian rainfall is characterized by seasonal and regional variability, irrigation development is essential to enhancing the country's food supply and economy. In addition to the abundance of surface water resources found in various regions of the nation, a greater portion of the nation is classified as semi-arid or desert. This causes water stress to progress for agricultural growth in many parts of the nation, particularly in areas with low moisture content and pastoral areas. While there is significant potential to increase irrigation through various surface water schemes, there are many challenges as most of the surface water potential is located in pastoralist areas due to land availability and flow concentration in these low-lying areas. The Ethiopian government places a greater focus on small-scale irrigation development projects that involve farmers at various stages in order to improve the nation's food security. This indicates that plans for continuous irrigation-based development initiatives are in place for the country's growth to be accelerated and sustained in order to eradicate poverty (Awulachew et al., 2010).

2.3. Sustainable water resource management in irrigated agriculture

Water is widely regarded as the most important resource for the development of sustainable agriculture worldwide. Since irrigation accounts for the majority of agricultural water usage, its availability can be negatively impacted. For agriculture in arid regions, conserving irrigation water is essential. Irrigated agriculture will occur in an environment of water scarcity both now and in the future, with inadequate water supplies for irrigation becoming the rule rather than the exception (Ruiz-Sanchez et al., 2010).

Technologies for agricultural water management have been recognized as crucial instruments to reduce poverty and the negative consequences of climate variability. Numerous developing nations, like Ethiopia, devote significant resources to the development and promotion of various low-cost water technologies (Hagos et al., 2012).

2.4. Water scarcity

Water is a limited resource, and scarcity results from its distribution across different geographic areas and from variations in seasonal distribution within the hydrologic cycle. Water scarcity is the lack of fresh water resources to meet the standard water demands. One of the most significant issues facing many communities around the world is a lack of water. The amount of water that is available in these places is insufficient to produce enough food to end hunger and poverty. In addition, population expansion is increasing the capacity for sustainable natural resource consumption. Because of this, the development of the industrial, urban, and tourism sectors cannot progress without limitations on the use of water and rules for allocating it to other user sectors, especially agriculture (Santos et al., 2009).

The availability of water below 1000 m3/person/year in a country or region is generally referred to as water shortage. Though it may be argued that extreme water scarcity exists in many parts of the world, where annual water availability is less than 500 m3 per person. A region is thought to be under water stress when its annual per capita water consumption falls below 2000 m3. In order to make up for the shortage of renewable water, desalination, non-renewable groundwater resources, and wastewater reuse are used in addition to renewable resources (Santos et al., 2009).The scarcity of water creates serious challenges for nations and populations. In these locations, where population expansion frequently exceeds the capacity for sustainable resource use, there is insufficient water available for food production, hunger relief, and poverty alleviation. Because of water scarcity, development in the industrial, urban, and tourism sectors cannot take place without regulations limiting water usage and allocating resources for other user sectors, especially agriculture. The ability of naturally occurring freshwater basins to handle growing demand and absorb the pollution caused by the effluents from growing urban, industrial, and agricultural usage is restricted. Water resources in dry areas are most likely already damaged or undergoing processes of degradation in terms of both quantity and quality (Santos *et al*., 2009).

The capacity of natural fresh water bodies are limited to supply the ever increasing demand and pollutant effluents from expanding urban, industrial and agricultural uses. In water scarce areas, water resources are already degraded or subjected to processes of degradation in both quality and quantity. Beyond the shortage of water for desired purpose, health problems are commonly associated with water scarcity due to water borne diseases. Water scarcity for farming will become the standard rather than the exception, and the focus of irrigation management will change from maximizing yield per acre to yield per unit of water used, or water productivity (Santos *et al.*, 2009)

For the purpose of allocating the limited water resources in an equitable manner, new equilibriums between supply and demand within the water-consuming sector are therefore required. To deal with water scarcity, innovative modern technology and management strategies that adjust to social, economic, and environmental conditions should be accessible. Water is plentiful in some areas, but accessing it for human use is hampered by a lack of infrastructure, access restrictions, political unrest, and sociocultural problems. In other regions, not everyone has guaranteed access to water, and human needs exceed what the basis of natural resources can support (Awulachew, S. 2007). These water scarcities are often classified as physical and economical water scarcities.

2.4.1. Physical water scarcity

The physical scarcity of water is insufficient to meet all requirements, including environmental flows. Water scarcity may occur in rich water places as well, despite the fact that physical water shortages are often associated with arid regions. This is because excessive water resources are dedicated to many uses owing to overdevelopment of hydraulic infrastructure, mostly for agriculture. In these conditions, the ecosystem's requirements and human consumption simply cannot be met by the available water (Awulachew, S. 2007).

2.4.2. Economic water scarcity

Economic water scarcity resulted from a lack of water investment, human capability, institutional and financial capital limitations, and restricted access to water, despite the fact that locally accessible natural water supplies satisfy human needs. In water scarce basins, home to some 1.6 billion people, there is likely to be inadequate human or financial ability to create sufficient water resources. Limited infrastructure development, whether on a local or large scale, is one sign of economic water scarcity, making it difficult for people to obtain adequate water for drinking and cultivation. Economic scarcity is a prevalent feature throughout most of sub-Saharan Africa. Water development might thereby significantly lessen poverty (Awulachew et al., 2010)

2.5. Deficit irrigation (water stress) and management

Deficit irrigation offers water savings potential and is becoming popular in arid and semi-arid regions, reducing freshwater use over time. The method of conserving water known as "water stress" involves purposefully using irrigation water in quantities that are less than what the plant needs. Throughout the growing season of the crop, or at specific times within it, stressed water up to the full amount might be applied. The crop's reaction to water stress is also dependent on a number of agronomic parameters, including location, climate, stress patterns, and other factors.

Deficit irrigation is one of the strategies for increasing yields per unit of applied irrigation water, which maximizes water use efficiency. This method involves subjecting the crop to a specific degree of water stress for a portion of the growing season or the entire time, with the expectation that any yield reduction will be negligible in comparison to the benefits of using the saved water to irrigate other crops (Rodrigues and Pereira, 2009). Water requirements are not entirely met during deficit irrigation, which permits soil water levels to drop to a point where the crop is subjected to only minor water stress. The crop's response is contingent upon the degree of soil dryness, crop characteristics, and timing of the water deficit. It may or may not involve a decrease in the rate of water usage and yield. It is commonly believed that storing water has less of an effect on final yields during the vegetative stage than it does during the blooming or yield-forming stages (Yoo et al., 2009).

Deficit irrigation management is frequently used to conserve irrigation water or in areas with insufficient water supply to meet full crop seasonal consumption. It requires careful attention to both strategic and logistical decisions for successful implementation. Compared to full irrigation, deficit irrigation involves more control over the quantity and timing of water supply. Compared to full irrigation, it is one of the solutions that saves 12% of the total water input and improves water yield (Tsakmakis et al., 2018).

According to Rodrigues and Pereira (2009), a water deficit slows down the growth and development of potatoes, which lowers yield. Depending on the cultivar, these growth phases have different lengths when subjected to water stress. One way to maximize irrigation water during dry periods might be to control the quantity and timing of irrigation at various phases of crop growth. In accordance with the migration law of production attributes during crop growth, deficit irrigation makes use of limited water resources to achieve the desired crop yield (Zou et al., 2021).

The water-saving irrigation technique that is gaining popularity in arid and semi-arid areas is deficit irrigation. When deficit irrigation techniques are used correctly, irrigation water application can be significantly reduced. Groundnuts, soybeans, common beans, and sugar cane exhibit comparatively lower output reductions among field crops when compared to the relative evapotranspiration deficit imposed during specific growth phases. Deficit irrigation techniques are distinct from conventional methods of giving water in that the manager must be aware of the maximum amount of transpiration deficiency that can be achieved without noticeably lowering crop output, as stated by Kang et al.(2000). Water productivity is increased under deficit irrigation because irrigation water is applied in smaller amounts than the total amount needed for crop evapotranspiration. According to certain theories, the amount of irrigation water provided under water stress (DI) should range from 60% to 100% of evapotranspiration (Mpandeli and Senzanje, 2019).

Water scarcity and food safety are strongly connected because agricultural systems are probably the first and direct victims of climate change-mediated groundwater depletion. These demands finding water-saving methods to decrease water use in agriculture while increasing yield to assist a rising population (Li et al., 2019). According to Santos et al. (2009), deficit irrigation can help deal with situations when supply is limited because it uses less irrigation water. A strategy and irrigation water management technique known as deficit irrigation permits a crop to withstand a certain amount of water stress in order to reduce irrigation expenses without appreciably lowering output and maybe increasing advantages.

The crop is subjected to a set amount of water stress either for a specific amount of time or for the complete developing phases. This is one method of increasing water productivity for higher yields per unit of irrigation water applied. According to conventional wisdom, deficit irrigation techniques aim to boost a crop's water production by removing irrigation that has minimal effect on output, as stated by (Kirda *et al.*, 1994). When weighed against the advantages of using the saved water to irrigate other crops for which conventional irrigation methods would typically prove insufficient, the yield reduction that results may be negligible. Deficit irrigation is essentially used in situations where there is a scarcity of water or high water expenses in order to optimize earnings. In this situation, crop values are strongly correlated with marketability, yield, and crop grade. In these situations, where water resources are limited, the farmer's objective is to supply water through practices. The amount of transpiration must be known by the irrigation management. Given the high opportunity cost of water, the water saved by deficit irrigation can be utilized to irrigate more area on the same farm or in the neighborhood of the water user, which could more than make up for the financial loss resulting from yield reduction. Three elements contribute to the potential benefits of deficit irrigation: lower irrigation costs, higher irrigation efficiency, and opportunity costs associated with water (Ali *et al*., 2007).

Water stress is the main factor limiting agricultural output in dry areas. As stated differently, the goal of deficit irrigation is to achieve maximum water productivity rather than maximum yields and to stabilize yields (Ekunsanmi, 2012). The primary benefit of deficit irrigation is that it increases water productivity. While a certain production drop is seen with deficit irrigation, the yield's quality, such as sugar content and grain size, is typically on par with or even better than that of full irrigation or rain-fed systems (Liu et al., 2019). In order to effectively manage crop water requirements at critical phonological stages, deficit irrigation techniques would require accurate assessment of vegetable crop growth stage-specific stress tolerances and optimal water management enabled by state-of-the-art irrigation technologies (Evans and Sadler, 2008).

2.6. The response of water stress on potato at different growth stages

Irish potato is a food security crop grown for its tubers as a main food source. The Irish potato tuber is a low fat source of carbohydrates and is formed from the differentiation of the stolon tissue (Muthoni and Shimelis, 2020). Irish potatoes show high sensitivity to water stress, either waterlogged or drought stress, especially during the growing seasons, for it reduces the number of tuber bulkings and can inhibit future bulking, decreasing the potato grade in terms of tuber sizes and quality, and generally lowers the potato yields. The Irish potato responds to water stress differently in timing, severity, and length of the deficits also vary. A slight water deficit inhibits the growth of stems and leaves, which lowers the leaf area index, photosynthetic efficiency, and dry matter content (Banik et al., 2016). The potato crop's vegetative development and tuber formation stages are the most crucial since metabolic activity peaks during these phases (Willem et al., 2006). Because of the high rate of photosynthesis, water scarcity has a severe impact on tuber start and bulking (Onder et al., 2005). Since the tuber is the section of the crop that can be harvested and stores nutrients, it is an essential component of the crop. While leaves are crucial to photosynthesis, roots and shoots provide nutrients and maintain the crop (Willem et al., 2006).

Growth stage-based deficit irrigation is an essential technique, which means determining which development stages are the most sensitive and supplying the required amount of water for irrigation. The starchy, tuberous Irish potato (Solonaum tuberosum L.) belongs to the solanaceae family of crops (Spooner et al., 2014). Therefore, it is essential to have sufficient knowledge about the connections between yield and the timing and severity of water shortages before implementing deficit irrigation techniques (García-Vila et al., 2008). However, the sensitivity to water deficits varies among each growth stage. The bulking of the growing potato tuber takes place alongside other growth or developmental processes in the plant, such as flowering, the initiation of new tubers, leaf expansion, and foliage development. To facilitate growth and development, these various plant tissues exchange carbon molecules in the form of sugars throughout the growing season. The growth and development of potatoes are influenced by various factors such as air temperature, soil temperature, light intensity and duration, growing season length, and humidity (Khan et al., 2011).

2.7. Determination of the growth stages

The total growing period (in days) is divided into four growth stages. These growth cycles of Irish potatoes include the initial, development, mid, and maturity (late) stages (Brouwer and Heibloem, 1986).

1. The initial stage: this is the period from sowing or transplanting until the crop covers about 10% of the ground.
2. The development stage: this period starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70–80%); it does not necessarily mean that the crop is at its maximum height.
3. The mid-season stage: this period starts at the end of the crop development stage and lasts until maturity; it includes flowering and tuber setting.
4. The maturity (late) stage: this period starts at the end of the mid-season stage and lasts until the last day of the harvest; it includes ripening.

2.8. Water productivity

Water productivity, defined as crop production per unit volume of water, is a term used in agricultural production systems to describe the link between the amount of water required in crop production and the crops produced (Smith et al., 1998).

Water productivity is defined as the ratio of agricultural output to the amount of water consumed (“more crops per drop"), and this has also been used to relate water use in agriculture. The value that is obtained per unit of water used has also been used to link the environment, jobs, welfare, and nutrition to the use of water in agriculture. Either water supply or water depletion is used as the denominator in the water productivity calculation. When water travels to a place where it cannot be easily recycled, it is eaten by evapotranspiration, which is combined with another substance. Water productivity is becoming increasingly recognized as a critical concern for regional and global food security (Molden et al., 2010).

Water productivity under water stress (DI) improves considerably compared to full irrigation because small amounts of irrigation raise crop evapotranspiration linearly up to a point optimizing production, but greater irrigation does not further increase yield. Actually, in an effort to boost yields, farmers are used to over-irrigating their crops, which exacerbates unproductive water loss and adds to the global freshwater deficit (Zou et al., 2021). Experiments with varying irrigation levels have also demonstrated that the water yield of deficit irrigation is typically higher than that of full irrigation. Early in the twenty-first century, one of the most significant issues will be finding a solution to the water shortage.

Large quantities of money have been invested in enhancing water for agricultural use in an effort to provide more access to water and enhance food security. But we also know that future water availability for agriculture will be reduced because of environmental problems, growing urban and industrial water demands, and other considerations. For instance, two-thirds of full irrigation enhanced water production by 19–28% for wheat and 8% for maize. They also came to the conclusion that deficit irrigation can be used to increase the productivity of water in semi-arid environments since it results in higher water productivity than can be achieved with full irrigation (Kijne et al., 2003).

2.9. Yield response of crops to water stress levels

Crop yield response functions were fitted to crop yields at various reduced crop water requirements (Geerts et al., 2010). The crop's ability to withstand water stress is shown by the crop yield response factor. The response factor larger than unity signifies that the relative decrease in evapotranspiration is proportionately smaller than the projected decrease in yield for a given ET deficit. Crop sensitivity to water differs from crop to crop and from growth stages to growth stages. Water stress levels practice requires knowledge of crop sensitive stages (Steduto et al., 2007).

The response of a crop to its soil moisture environment is quantified through Ky. Thus, the Ky-approach provides an efficient, time-effective, and reliable means of simulating crop yield in response to water stress for a specific region (Shrestha et al., 2010). As values of Ky represent a crop sensitivity factor to drought, existing crop water productivity function's and Ky values for specific crops are non-transferable since they are influenced by localized climatic conditions (Geerts et al., 2010). On the other hand, stress may affect fruit or tuber set during stages of reproductive development, resulting in decreased yields. Numerous studies have looked at the complex effects of stress on yields, which might differ depending on the species, cultivar, and stage of growth. In-depth field research is required to gain a greater knowledge of the biological and physical mechanisms controlling crop responses to moisture stress. Thus, the primary determinants of crop response to water scarcity include phonological stage, climate, edaphic impacts of an environment, and intrinsic crop character (Zwart and Bastiaanssen, 2004).

FAO and International Atomic Energy Agency (IAEA) research coordinated group studied yield responses of major field crops to deficit irrigation, including cotton, maize, potato, sugar cane, soybean, and wheat. The key values obtained from FAO data sets and from an IAEA coordinated research project (CRP) showed a wide range of variation for this parameter: $0.20 < Ky < 1.15$ (FAO, 2002a) and $0.08 < Ky < 1.75$ (IAEA). However, for many other crops, FAO recommendations of Ky values are more reliable and practical.

3. MATERIALS AND METHODS

3.1. Description of the study area

3.1.1. Location

The experiment was conducted at Sankura Wereda in the Silte Zone, Central Ethiopia, during the 2022–2023 seasons. Sankura wereda is located south of the silt zone, 42 km from the capital city of Werabe, 115 km from Hawassa, and 215 km from Addis Ababa. The study area is geographically located at an altitude of 1864 m.a.s.l., 7028′0″ N to 7037′30″ N latitude, and 3802′0″ E to 38^{0}18′30″ E longitude.

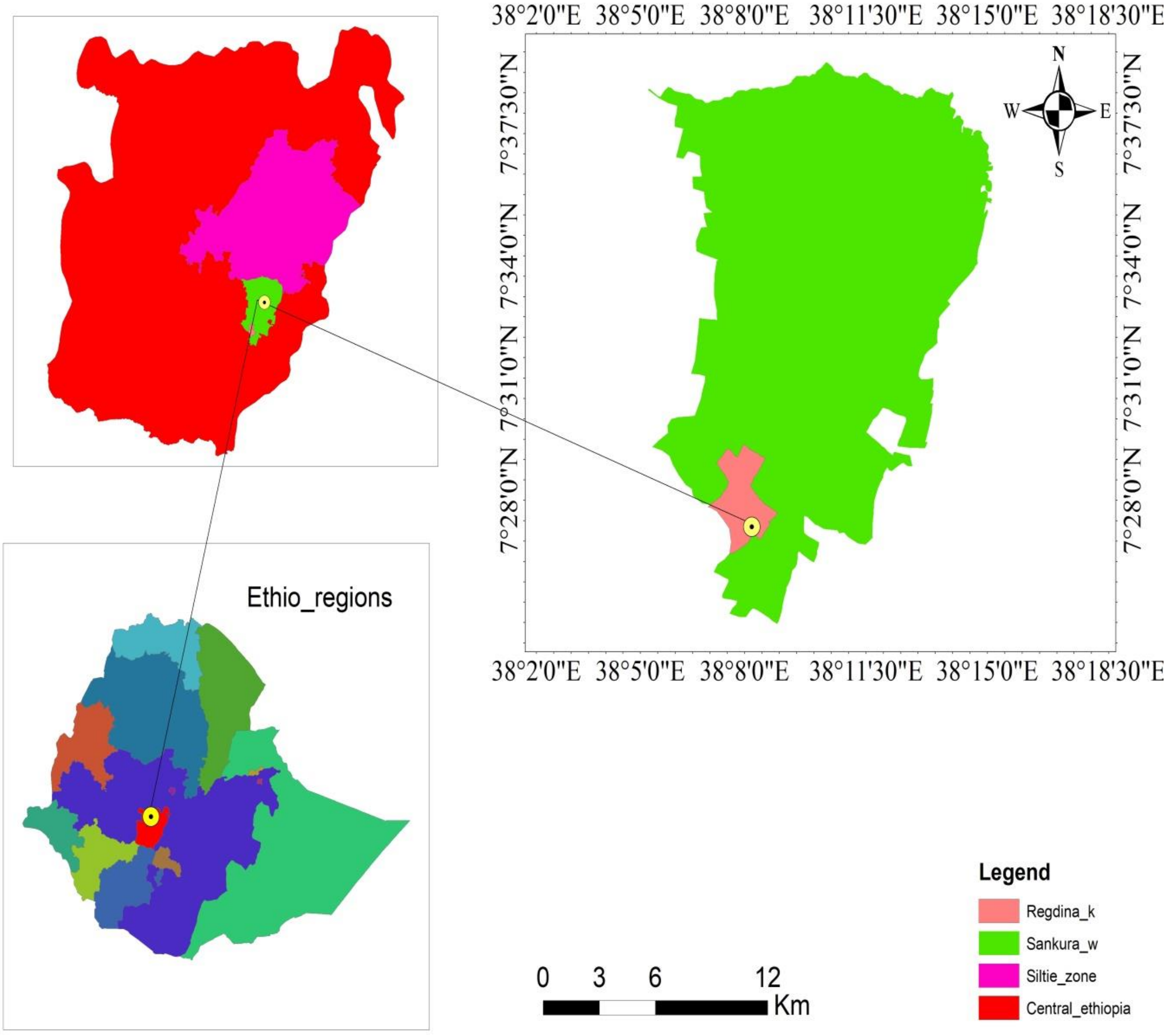

Figure 1: Map of Sankura Wereda , study area

3.1.2. Climate characteristics of experimental site

The climate of the study area was characterized by semi-arid conditions, and the rainfall distribution was erratic, with annual ranges from 600 mm to 1500 mm. The annual maximum temperature varies from 18°C to 29.8 °C, while the minimum temperature varies from 11.70 °C to 13.50 °C during dry months. The district has a long dry season from December to June, while July to September are the rainy seasons.

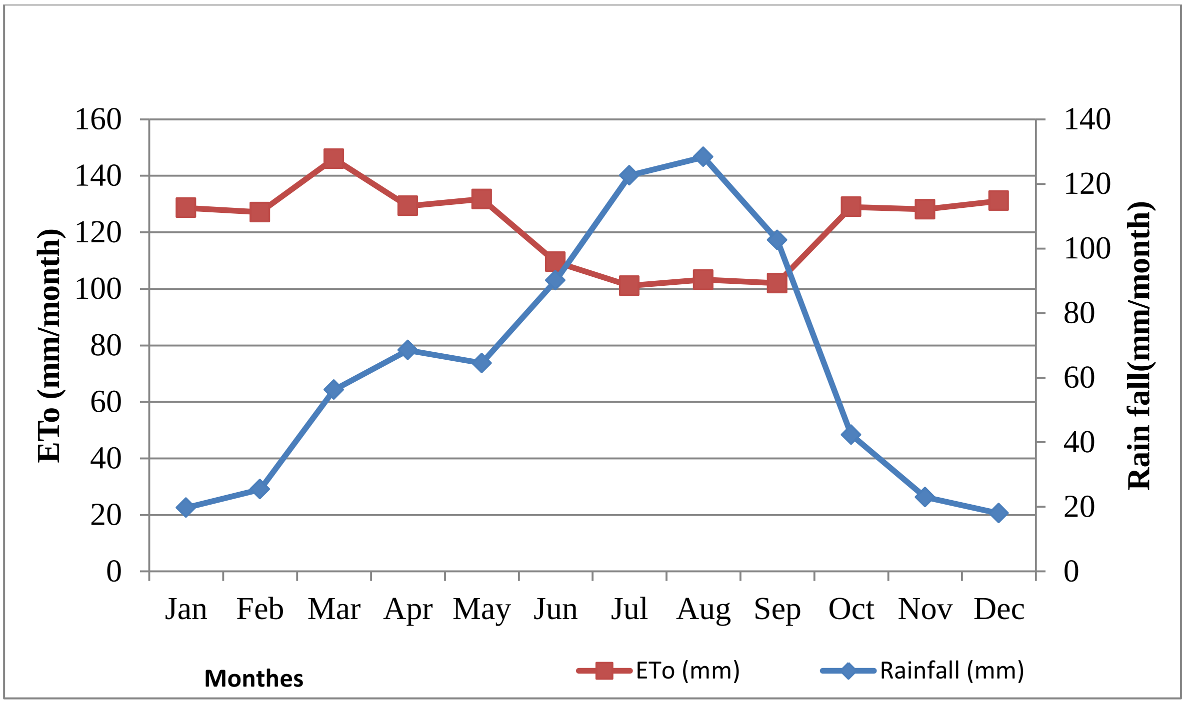

Figure 2: Average monthly Rainfall and temprarure distribution of the area

3.2. Methods

3.2.1. Land preparation

The experiment site was at Sankura Wereda farmer land on Jatta irrigation scheme during the 2022 dry season. The experimental field was ploughed on December 20, 2022, by Oxen. Then, the land was leveled so that it was suitable for laying the experiment. After the land was leveled, ridge preparation was done with each block.

3.2.2. Experimental design and layout procedure

Treatments were arranged in Table 1 by a randomized complete block design (RCBD) with three replications, following the design by Gomez and Gomeze (1984). To minimize the effect of soil fertility differences on the treatment units, a randomized complete block design was used, and blocking was carried out across the slope following the gradient of the experimental site. The experiment had four water stress levels of treatments applied Treatments were arranged in each of the three replications randomly based on randomization. The treatments were levels of irrigation water applied to the growth stages of potatoes, one full irrigation as a control, and 12 treatments were water stress levels. In the initial stage, the irrigation application was commonly used for all treatments.

Table 1: Arrangement of treatments

Treatments	Irrigation and growth stage	Water stress levels explanation
T1	Full irrigation of 100%ETc	(Control)
T2	85%ETc at Development	(15% Water stress only at dev. stage)
T3	70%ETc at Development	(30% Water stress only at dev. stage)
T4	55%ETc at Development	(45% Water stress only at dev. stage)
T5	40%ETc at Development	(60% Water stress only at dev. stage)
T6	85%ETc at Tuber formation	(15% Water stress only at mid stage)
T7	70%ETc at Tuber formation	(30% Water stress only at mid stage)
T8	55%ETc at Tuber formation	(45% Water stress only at mid stage)
T9	40%ETc at Tuber formation	(60% Water stress only at mid stage)
T10	85%ETc at Maturity	(15% Water stress only at late stage)
T11	70%ETc at Maturity	(30% Water stress only at late stage)
T12	55%ETc at Maturity	(45% Water stress only at late stage)
T13	40%ETc at Maturity	(60% Water stress only at late stage)

Where: ETc = Crop evapotranspiration and T = Treatment

The layout of the experiment was prepared according to the experimental design. All the experimental area was subdivided into three replications, including free space between blocks and field channels, according to the dimensions provided in the layout of the experiment (Fig. 3). Each replication was subdivided into 13 experimental units, and the free space between each plot had the desired spacing. The plot size was 12 m^2 (4m length and 3m width) by taking into account the land availability in the experimental field. There were thirty-nine experimental units or plots. The distance between each plot and replication was 1.5m and 2m, respectively. The system of irrigation was the furrow (conventional) irrigation method. The boundary (bund) around which tides flow and the closed end of each plot would be provided to control the water movement across the plots.

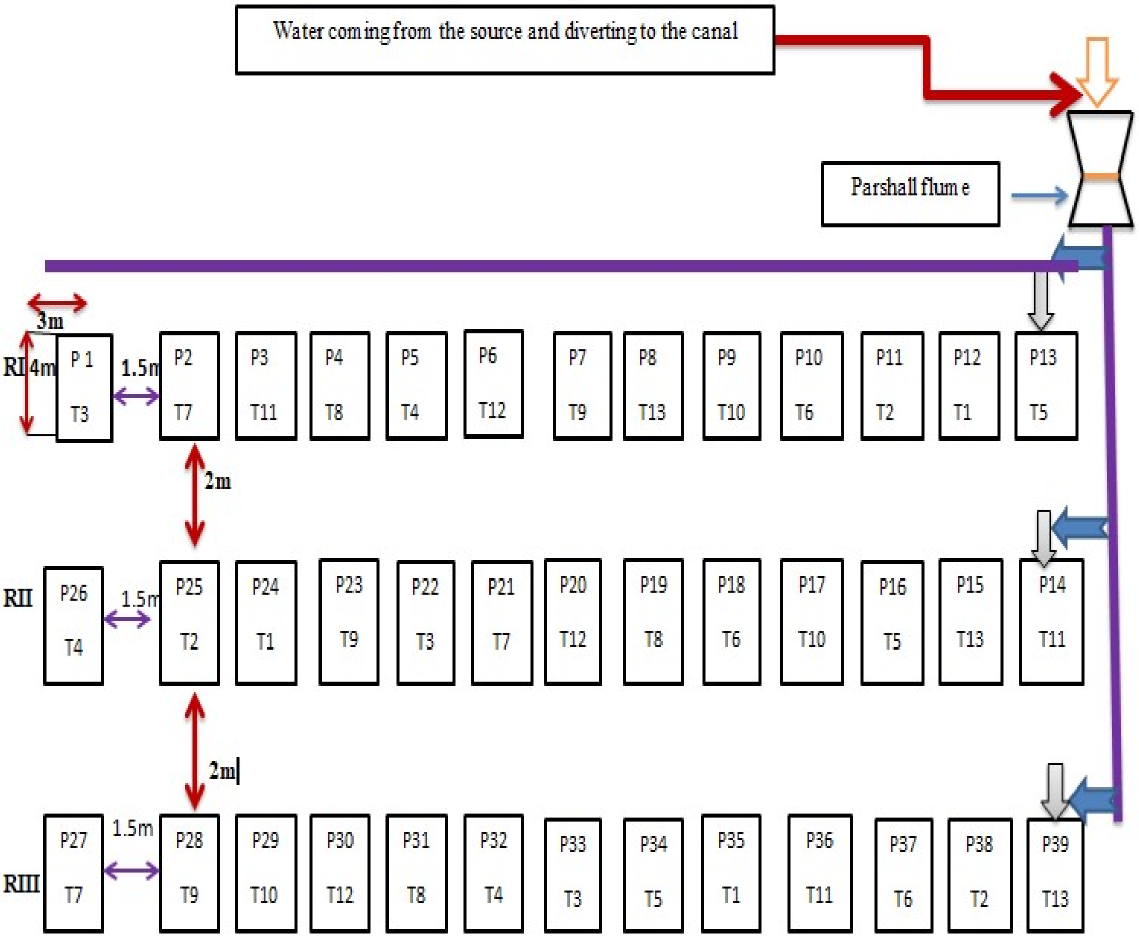

Figure 3: Layout of the study

3.3. Irrigation application

The irrigation application was done based on the optimum irrigation treatment and other treatments were receiving less water than the control treatment with their level of water stress. The control treatment was irrigated based on ETc of critical moisture stress for the crop irrigating to refill soil to field capacity. However, water-stressed treatments were receiving a lower amount based on the water stress levels at growth stages with a similar interval as the control treatment. Irrigation management was done based on the scheduling of metrological, soil, and crop data using the CROPWAT 8 model software, and the level of moisture depletion was detected by soil moisture determination using gravimetric soil sampling.

After all the field preparation, layout establishment, and planting of the Irish potato were undertaken and irrigated after plantation up to the initial stage uniformly for all plots established, and a Parshall flume with a 3-inch head was used to measure the amount of water applied for each treatment. The irrigation depth was converted to a volume of water by multiplying it by the plot area. Before starting the treatment, the water was wetted to manage the irrigation water loss. Then, after the water was applied to the experimental plot by small earthen water, it was distributed to each experimental plot based on the on the depths (water stress levels) of each treatment and started based on growth stages.

3.4. Agronomic practice

The land was ploughed three times according to the local practice of using Oxen before planting. After the land was ploughed leveling were done manually, and compacted to prevent water percolation, and sprouted tuber seeds of the Gudene variety. The experimental field was divided into 39 plots with 4m *3 m plot size having 4 Irish potato rows with 30 cm row spacing and distance between ridge was 45 cm. The distance between plots and blocks were 1 m and 2 m, respectively and the layout was presented in the above figure 3. The plantation of the sprouted Irish potato seed was one seed per hole, and the necessary activities were done after the plantation. NPS is a compound fertilizer containing a highly uniform granule of three important plant nutrients: nitrogen, phosphate, and sulfur, with a ratio of 19% N, 38% P2O5, and 7% S. The blanket recommended rate of NPS was 200 kg/ha used during planting time, and 150 kg/ha of urea was used in split application (Getaneh and Laekemariam, 2021). Total water requirement varies between 350 and 550mm depending upon soil type, climate, and crop duration (Reddy et al., 2018).

Being a short-duration crop, potatoes can be harvested at any time after about 60 to 70 days (early varieties) after planting until 100 to 110 days (late varieties). Until the emergence of sprouts, about 15 days, all plots were watered uniformly. Then, irrigation of the experimental plots was done based on water stress levels at growth stages, and treatments of deficit irrigation water were applied. The cultivation and weeding were done twice before harvesting. The Irish potato was matured for harvesting about 115 days after planting, and before harvesting, the necessary data was collected, and it was harvested by hand digging by manpower.

3.5. Data collection and analysis

3.5.1. Primary data

1. Soil data

Soil data were collected for the determination of the physical and chemical properties of the soil (texture class, bulk density, SMC, FC, PWP, pH, ECe, OC, and OM) and soil moisture content. Its sampling and analysis techniques were discussed below.

Composite soil samples were collected from 0–20 cm, 20–40 cm, and 40–60 cm depths in the experimental field. The soil samples were taken from the experimental field diagonally to avoid bias in the sampling, and they were taken before field preparation. The physical and chemical properties of the soil sample were carried out at the Werabe Agricultural Research Center soil laboratory. Field capacity and permanent wilting point analysis were done at the Ethiopian construction design and supervision work corporation research laboratory and training center in Addis Ababa.

3.5.2. Soil texture classes

Soil textural class was analyzed by using the hydrometer or sieve analysis method for undisturbed soil samples for each depth. The weighted soil samples were sieved through a screen, and the soil particles that had a diameter less than 2 mm were used for textural class determination. The amounts of sand, silt, and clay fractions were then calculated. The textural class was determined using the USDA textural triangle following the procedures indicated by Kebede and Ermias Birru (2011).

3.5.3. Bulk density

The soil bulk density is an indicator of soil compaction. It was determined from undisturbed soil samples collected by core samplers. Undisturbed soil samples were collected by using a soil core sampler with a known volume. The samples were dried in an oven at 105 °C for 24 hours, and the bulk density was calculated using the equation given by Hillel (2004).

$$\boldsymbol{\rho b = \frac{Ws}{Vc}} \qquad \mathbf{3.1}$$

Where: - ρb = is soil bulk density (g/cm^3)

Ws = is mass of dry soil (g)

Vc = is volume of soil in core (cm^3)

3.5.4. Soil moisture determination

The determination of the moisture content of the soil was carried out during the experiment using the gravimetric method since it was the only available method at the experimental site. The soil samples were collected using a soil auger at different depths based on root depth. The collected soil sample was weighted using a sensitive balance at field conditions, placed in an oven at a temperature of 105°C, and dried for 24 hours. Then and there, the oven-dried samples were weighed to determine the moisture content of the soil.

The moisture content in the soil was determined in terms of weight using the following equation (Estefan et al., 2013).

$$\boldsymbol{\theta m = \frac{(Wws - Wds)}{Wds} \times 100} \qquad \mathbf{3.2}$$

Where**:** - θm = is moisture content on weight basis (%)

Wds = is weight of dry soil (g),

Wws = weight of wet soil (g).

The volumetric moisture content was calculated using the following formula

$$\boldsymbol{\theta v = \theta m \times BD} \qquad \mathbf{3.3}$$

Where: - θv is volumetric moisture content in (%) and **BD =** is soil bulk density (g/cm3)

3.5.5. Soil infiltration rate

The infiltration rate of the soil in the experimental field was measured using a double-ring infiltrometer (Reynolds et al., 2007). The infiltrometer was attached with the help of a specially designed crossed-bar hammer, which set a circular driving cap on the device. Water was added gradually so as not to disturb the soil between the inner and outer rings. Observations were performed from the inner ring until a uniform pace was obtained. We recorded the scale readings minute by minute. The scale readings were recorded at time intervals of 1 minute. The difference in water level in mm recorded over an elapsed period of time divided by the time interval was expressed as the infiltration rate. The purpose of the data was in put for cropwat and to know the intake of soil infiltration

3.6. Determination of soil chemical characteristics

The soil chemical properties such as pH, electrical conductivity of soil saturated paste extract (ECe), organic matter content (OM), and organic carbon were analyzed in the laboratory. The ECe for the soil sample was determined by the ECe method of allowing soil saturated paste to stand for 24 hours (Kargas et al., 2018). Subsequently, the vacuum extracts were collected, and ECe was measured by a conductivity meter. The pH of the soil was measured by means of a pH meter in the supernatant suspension of 1:2.5, soil: liquid mixture, as described by (Batjes et al. 1992). To determine organic matter content, the titration method, which is oxidation under standardized conditions with potassium dichromate in sulfuric acid, was followed for organic carbon determination. Finally, the ratio of organic carbon to organic matter is, therefore, obtained by multiplying the percentage organic carbon by 1.724, as described by Nelson and Sommers (2018).

3.7 Secondary data

Climate data

Maximum and minimum temperature (0C), relative humidity (%), wind speed (m/s), sunshine hours (hours), and rainfall data (mm) of the study area were collected from the National Meteorological Station of Hawassa branch to determine reference evapotranspiration using the CropWat model.

Crop data

Crop coefficient, growth stages, root depth, and allowable depletion level fraction (p) were collected from FAO Irrigation and Drainage Paper 56 (FAO, 1998) for potato (Irish potato) to calculate crop water requirement using the CropWat model.

Table 2: Crop data for Irish potato

Crop	**Growth stages**			
Irish potato	Initial	Development	Mid	Late
Length of growing day	25	30	30	30
Crop coefficient (Kc)	-	-	1.15	0.75
Root depth (m)	0.4	-	-	0.6
Average depletion fraction (p)	0.65			

Source: FAO Irrigation and Drainage Paper 56(FAO 1998)

3.7. 1 Determination of crop water requirement

The depth of water needed by the crop to meet the amount of water loss through evapotranspiration of the crop requires climatic and crop input data. Crop water requirement refers to the water used by crops for cell construction and transpiration (Smith et al., 1998). The growth and yield of any crop are related to the amount of water used. The variable amount of water contained in a soil and its energy state are important factors affecting plant growth (Hillel, 2004). The accuracy of determining crop water requirements was largely dependent on the type of climatic data available and the accuracy of the method chosen to estimate evapotranspiration. According to Smith et al. (1998)., the crop water requirement (ETc) for the growing season of Irish potato was calculated from reference evapotranspiration (ETo) and crop coefficient (kc) values for each growth stage. The computation of crop water requirements (ETc) using CROPWAT software over the growing season was determined from ETo and crop coefficient (Kc).

$$\boldsymbol{ETc = ETo * Kc} \qquad \mathbf{3.4}$$

Where: - ETc = crop water requirement or crop evapotranspiration (mm/day)

ETo = reference evapotranspiration (mm/day)

Kc = crop coefficient (dimensionless)

3.7.2. Determination of reference evapotranspiration

Evapotranspiration is both the combined effect of water lost through evaporation and transpiration. Reference evapotranspiration (ETo) on a daily basis was computed by applying the modified FAO Penman-Monteith equation based on daily recorded climatic data (Smith et al., 1998) using FAO CROPWAT software version 8.0. Based on the comparative studies of the reference evapotranspiration methods and the recommendations of a panel of experts and researchers, the Penman Monteith equation has been adopted as the globally best-performing method of estimating evapotranspiration. The input data for the software includes location,

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{\mathrm{T} + 273} U2(es - ea)}{\Delta + \gamma(1 + 0.34u2)} \qquad 3.5$$

ETo = reference evapotranspiration (mm/day)

Rn = net radiation at the crop surface (MJ/m2/day)

G = soil heat flux density (MJ/m2/day

T = mean daily air temperature at 2m height

U2 = wind speed at2m height (m/s)

Es = saturation vapor pressure (kPa)

Ea = actual vapor pressure (kPa)

es-ea = saturation vapor pressure deficit(kPa)

$\boldsymbol{\gamma}$ = Psychometric constant (kPa)

3.7.3. Determination of irrigation water requirement

The amount of water needed (CWR) to compensate the amount of water lost through evapotranspiration. The irrigation requirement was computed using the CROPWAT computer based on (Smith *et al.*, 1998) as the following formula:

$$\boldsymbol{IR = ETc - Pe} \qquad \mathbf{3.6}$$

Where**:** - IR = irrigation requirement in (mm)

ETc = is crop water requirement or crop evapotranspiration (mm)

Pe = effective rainfall (mm).

3.7.4. Determination of soil available water

According to Smith et al. (1998), the amount of water that can be extracted by plant roots is held in the soil in an available form. The actual volume of water that can be obtained from the soil profile depends on the depth of the root system. Not all of the water found in the root zone will actually be taken up by roots. The total available water (TAW), which is stored in a unit volume of soil, is approximated by taking the difference between the water content at field capacity (FC) and at the permanent wilting point (PWP). This is the water available for plant use. The TAW is expressed as (Jaiswal 2003).

$$.TAW = 10(\theta\mathrm{vfc} - \theta\mathrm{vpwp}) * D \qquad 3.7$$

Where: TAW is the total available water in the root zone (mm)

θvfc = the volumetric moisture content at field capacity (%)

θvpwp = the volumetric moisture content at permanent wilting point (%)

D = the root depth of Irish potato in (m)

3.7.5. Determination of gross irrigation requirement

Gross irrigation usually requires more water than the net irrigation requirement, and it is applied during irrigation to compensate for unavoidable losses. GIR is the total amount of water applied to satisfy ET and losses. Furrow irrigation application efficiencies vary from 45 to 60% (Raine and Bakker, 1996. Gross irrigation usually requires more water than the net irrigation requirement, and it is applied during irrigation to compensate for unavoidable losses and satisfy ET. Based on the net irrigation depth and irrigation application efficiency the gross irrigation water requirement was calculated in the equation given as:

$$\boldsymbol{GIR = \frac{NIR}{Ea} \times 100} \qquad \mathbf{3.8}$$

Where: - GIR = gross irrigation requirement (mm)

NIR = net irrigation requirement (mm)

Ea = application efficiency (%)

3.7.6. Determination of effective rainfall

The effective rainfall (Pe) is estimated using the method given by (Smith *et al.*, 1998). Effective rainfall is the water retained in the root zone and obtained by subtracting the sum runoff, evaporation and deep percolation from total rainfall. If other information is not available like runoff, evaporation and deep percolation it can be calculated by using this equation.

$$\boldsymbol{Pe = 0.6 \times P - 10\ for\ P\ month \leq 70mm} \qquad \mathbf{3.9}$$

$$\boldsymbol{Pe = 0.8 \times P - 24\ \ for\ P\ month\ > 70mm} \qquad \mathbf{3.10}$$

3.7.7. Determination of irrigation application time

The Parshall flume was established straight from the canal and leveled in all directions in the converging parts of the instrument. The bottom of the converging and upstream sides was compacted, and stone riprap was put in the downstream side below the canal bottom level to minimize the erosion downstream of the Parshall flume. The gross irrigation depth-determined water was applied to the experimental plots based on the treatment. The volume of water applied for each treatment was the product of the area of the plot and the gross irrigation depth. The determined amount of irrigation water was applied to the experimental plot by using a 3-inch throat-width Parshall flume with a discharge rate. Since the discharge level may vary depending on the field condition, the time required to irrigate each treatment was calculated from 5 cm head levels. Before water irrigates the plot, the tertiary canal is wetted, and after that, the water is diverted into the furrows based on treatment. The time required to irrigate each plot was based on the discharge head relationships. Accordingly, the time required to deliver the desired depth of water into each plot was calculated using the equation by Kandiah (1981).

$$\mathbf{T} = \frac{\mathbf{L} * \mathbf{W} * \mathbf{GIR}}{\mathbf{60} * \mathbf{Q}} \qquad \mathbf{3.11}$$

Where: T = application time in minute

L = length of furrow in (m)

W = width of plot (m),

GIR = gross irrigation requirement (mm)

Q = flow rate in l/s at specific parshall flume head and 60 is unit conversion factor.

3.8. Response of Irish potato to irrigation

3.8.1. Yield response factor

The relationship between crop yield and water supply can be determined when crop water requirements and crop water stress level, on the one hand, and maximum and actual crop yield, on the other, can be quantified. Yield response factor (ky) was quantified empirically from the relationship between relative yield decrease and relative evapotranspiration deficit

(Doorenbos and Kassam, 1979). The purpose of this relationship was in which growth stage and moisture stress sensitive and resistance the water stress levels on Potato crop.

$$\left(1-\frac{\mathbf{Ya}}{\mathbf{Ym}}\right)=ky\left(1-\frac{ETa}{ETm}\right) \qquad 3.12$$

Where: ky = yield response factor

Ya = actual marketable yield (t/ha)

Ym = maximum marketable yield (t/ha)

ETa = actual evapotranspiration (mm)

ETm = Maximum evapotranspiration (mm)

3.8.2. Water productivity

The crop water productivity was determined based on the ratio of marketable tuber yield produced (kg/ha) to the seasonal amount of water (m3/ha) used by Irish potatoes. Water productivity in agriculture (WP) (kg/m3), also known as water use efficiency, is generally expressed as the ratio between the actual crop yields produced and the corresponding total water use expressed. Crop water use efficiency (CWUE) was computed as the ratio of yield obtained to the seasonal evapotranspiration of the crop (Howell, 2001).

$$WP=\frac{Tuber\ yield(\frac{kg}{ha})}{ETC(\frac{m3}{ha})} \qquad 3.13$$

Where: WP = water productivity (kg/m3)

Y = tuber yield of Irish potato (kg/ha)

ETc = Seasonal crop water need (m3/ha)

3.9. Data collection on yield and yield components

3.9.1. Agronomic Data collection

Samples of five plants were selected randomly from each experimental plot and measured using the following agronomic parameters: The growth parameters and yield components were collected from the middle rows. The data was taken from the central two rows and the net area of each plot; this is to avoid border effects. The data includes plant height, number steam, number leaf, leaf area, leaf area index, tuber number, marketable yield, The sum of marketable and unmarketable tuber yields per plot at harvesting from the net area was recorded and summed up to estimate yield per hectare.

3.9.2. Phonological parameters

Days to flowering: It was determined by counting the number of days forgotten from days to planting to the time when 50% of the plants in each plot started to flower through visual observation and the mean count days were used for further analysis.

Days to maturity: It was determined by counting the number of elapsed days from days to planting to the days when more than 90% of the plants in a plot attained physiological maturity, i.e. when 90% of the haulm of the plants dried.

3.9.3. Growth parameters

Plant height (cm): The plant heights of five randomly selected plants from the net plot area at physiological maturity were measured from the ground level to the tip of the main stem using rulers and the mean values used for further analysis.

Leaf number per plant (No.): The numbers of leaf was from randomly selected five plants and counted at 50% flowering and the average was taken for further analysis.

Leaf area (cm^2): The leaf area was determined by the product of the leaf width (w) and length (L) from randomly selected five plants of leaves and multiplied constant (0.674). That means leaf area

$$LA = Width * LENGTH * 0.674 \qquad 3.15$$

Where 0.674 is the correction factor according to (Sadik et al., 2018).

Leaf area index: Was determined by the average leaf area with the respective leaf number of the plant and obtained total leaf area. Then, dividing total leaf area to the respective land area occupied by plants.

$$LAI = \frac{LA(cm2pp) * Leaf\ number}{Ground\ area(cm2pp)} \qquad 3.16$$

Number of Irish potato tubers per plant: Was recorded as counting of the actual number of tubers collected from randomly selected five plants at harvesting time in the plot of the middle rows and taken the average number of tubers per plant.

Tuber diameter: At harvesting time tubers were collected from two central rows in each plot, and categorized into small medium and large size, then after each tuber measured by caliper ruler and the average of three size used for further analysis.

Marketable Irish potato yield (t/ha): was obtaining from the harvested potato yields from the middle rows that were not affected by pest, digging materials, rotten and under size.

Unmarketable Irish potato yield (t/ha): was obtaining from the harvested potato yield that was affected by pest, digging materials, rotten and under size.

Total yield (t/ha): the sum marketable and unmarketable) Irish potato tuber yields per plot harvested from the net area was recorded and summing up to estimate yield per hectare.

3.10. Statistical analysis

The collected data, like growth parameters, yield, and yield components of Irish potatoes, were analyzed using the statistical analysis system (SAS) version 9.3 using the procedure of general linear model (SAS) for the variance analysis. Mean comparisons were carried out to estimate the differences between treatments. The least significant difference (LSD) at the 5% probability level was used to compare the treatments.

4. RESULTS AND DISCSSUIONS

4.1. Soil physical and chemical properties

The results on the physical and chemical properties of the studied soil at the experimental site were presented in Table 2.

The result of the soil textural class analysis showed that the relative proportions of sand, clay, and silt were 37, 35, and 28, respectively. Thus, according to the USDA soil textural classification, the soil texture could be classified as clay loam soil.

The soil bulk density analysis result of the experimental site indicates that the bulk density increases with soil depth. It varied from 1.19 g/cm^3 at the upper root zone (0.20) cm to 1.26 g/cm3 at the lower root zone layer (40–60 cm), respectively. This could be because of a slight decrease in organic matter with depth and compaction due to the weight of the overlying soil layer (McCauley et al., 2005). The critical value of bulk density for restricting root growth varies with soil type (Hunt and Gilkes, 1992), but bulk density greater than 1.6 g/cm3 tends to restrict root growth (McTainsh et al., 2006). The average bulky density of the experimental site soil was 1.23 g/cm^3, which was less than the ideal bulky density (1.4 g/cm^3) for plant root growth and was suitable for crop root growth.

The average soil moisture content at field capacity and the permanent wilting point of the experimental soil were 34% and 19%, respectively. The total average available water (TAW) of 186 mm/m and the TAW range of 170–220 mm/m are characteristic of clay loam soil (Brouwer and Heibloem, 1986). The average pH value of the experimental site through the analyzed depth was found to be slightly acidic, with an average value of 6.43. The pH of the soil is moderately acidic (Hazelton and Murphy, 2019).

With values ranging between 6 and 6.62, Irish potatoes can be grown on a wide range of soil, but a well-drained soil with a pH of 5 to 7 is preferred (Reddy et al., 2018). The pH value of the study area soil is suitable for Irish potato production. The result of electrical conductivity for soil saturated paste extract (ECe) varied from 1.7 to 1.5 (dS/m), with an average value of 1.64 (dS/m) at 25 °C, which indicates a non-salinity effect on the experimental soil (Kargas et al., 2020). The soils of the study area resulted in OC ranges from 1.7% to 1.45%, with an average value of 1.55% throughout the soil depths. This indicates a medium fertility range (Musinguzi et al., 2016). The average organic matter content of the soil in the study area was 2.68% through the soil profile, which indicates the organic matter of the soil is within the range of clay loam soil (Thinking, H. 2022).

Table 3: Physical and Chemical characteristics of the soil at the study area

Soil parameters	**Soil depth (cm)**			**Average**
	(0-20)	(20-40)	(40-60)	
Particle size distribution				
Sandy (%)	40	38	33	37
Clay (%)	32	35	37	34.6
Silt (%)	28	27	30	28.33
Textural class	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Bd (g/cm^3)	1.19	1.23	1.26	1.23
FC (vol %)	32.9	33.8	34.6	33.76
PWP (vol %)	18.2	18.9	19.5	18.86
TAW (mm/m)	174.9	183.3	200.4	186.2
pH	6.3	6.5	6.5	6.43
Ece (ds/m)	1.58	1.65	1.7	1.64
OC (%)	1.7	1.52	1.45	1.55
OM (%)	2.93	2.62	2.49	2.68

4.1.2. Infiltration characteristics of soil for the experimental site

The data collected in the field using a double-ring infiltrometer was used to generate the cumulative infiltration and infiltration rate curves, as shown in Fig. 4. The basic infiltration rate for the experimental field was found to be 7.8 mm/hr., which is within the range of clay loam soil (5–10) mm/hr. (FAO, 1990). This means that a water layer of 7.8 mm/hr on the soil surface will take one hour to infiltrate. Cumulative infiltration is the time integral of the infiltration rate, and it is an increasing function of time. As can be seen from the figure on the on the next page, the cumulative infiltration increased sharply at the beginning of the infiltration process, after which the rate decreased. This is because at the beginning of the process, though irregular, the initial infiltration rate was relatively high, resulting in the absorption of a large quantity of water. The decrease in rate of increase of the cumulative infiltration might be related to the monotonic decrease in infiltration rate with time due to a decrease in the matric suction gradient and the gradual deterioration of the surface soil structure by water. The total amount of water infiltrated with less than four hours of the basic infiltration process was 4.5cm of water.

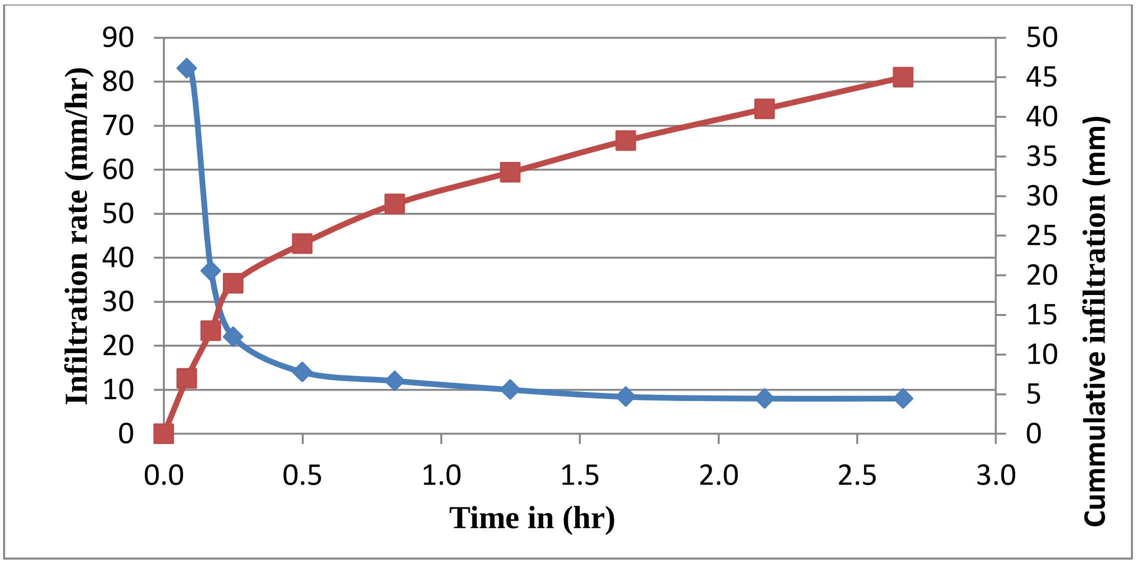

Figure 4: Infiltration rate and Cumulative Intake depth of soil for experimental site

4.2. Crop Water requirement of Potato

The value of the reference evapotranspiration was computed from the meteorological data of the study area by the CROPWAT 8.0 model using the FAO56 Penman Montieth method on a daily basis. The reference evapotranspiration (ETo) value of the study site was found to range between 4.54 mm/day in February, 4.69 mm/day in March, 4.46 mm/day in April, 4.25 mm/day in May, and 3.65 mm/day in June, with an average of 4.32 mm/day for the whole growth period. In the absence of rainfall and considering Irish potato with crop coefficient (Kc) at initial stage 0.5, development stages 0.75, mid stage 1.15, and late stage 0.6, root depth 0.3 to 0.6 m, allowable critical depletion of 0.35%, clay loam soil with total soil available moisture of 186 mm/m, the seasonal irrigation requirement was found to be 446.9 mm. This amount is needed for full irrigation through the growing season.

The results of daily crop water need (ETc) values showed variation with growth stages. It started small during the initial stage and then increased gradually from development up to the mid-stage and then declined at the maturity stage. The highest value was recorded in the mid-season growth stage, followed by development and the late-season stage; the lowest value was recorded in the initial stages. The highest value of daily crop water need (5.02 mm/day) was obtained during the mid-stage, while the lowest value of daily crop water need (2.3 mm/day) was obtained during the initial stage. In the mid-season stage, the crop is physiologically capable of the highest water need and has the highest crop coefficient value (FAO, 1998). During the late season, the rate of crop water need decreased due to the lower leaves of the plants drying, and the rate reached its minimum value during harvesting time due to plant maturity.

The seasonal crop water requirement computed was affected by the water stress levels through the growth stages of the Irish potato. The result revealed that the average seasonal values of ETc decreased as the percentage of water stress level increased (more available water was extracted). It is clear that increasing the available water deficit level in the Irish potato crop caused a significant decrease in the seasonal water consumption of the potato. The result indicated that the highest seasonal water requirement value was recorded under full irrigation conditions, while the lowest one was recorded at 40% ETc at mid-stage. The other treatments seasonal ETc values were between the two treatments levels and their corresponding water stress levels. The seasonal crop water requirement was determined based on seasonal water application depth from establishment to harvest and varied based on treatments under different water stress levels of growth stages. Water stress in the early stage of the yield formation period increases the occurrence of spindle tubers. Water stress during this period, followed by irrigation, may result in tubers cracking or tubers with black hearts. Because of this, at the initial stage, common irrigation was applied. The common irrigation depth of 52.3 mm was applied for all treatments after germination. The highest and minimum seasonal crop water requirements were 446.9 mm and 345.2 mm at 100% ETc and 40% ETc, respectively.

Table 4: Seasonal net irrigation depth applied each growth stage (mm)

Treatments	Initial	Development	Mid	Late	Total
100%ETc at all	52.3	139.6	169.5	85.5	446.9
85%ETc at dev.	52.3	118.66	169.5	85.5	426.0
70%ETc at dev.	52.3	97.72	169.5	85.5	405.0
55%ETc at dev.	52.3	76.78	169.5	85.5	384.1
40%ETc at dev.	52.3	55.84	169.5	85.5	363.1
85%Etc at tuber	52.3	139.6	144.1	85.5	421.5
70%ETc at tuber	52.3	139.6	118.7	85.5	396.1
55%ETc at tuber	52.3	139.6	93.2	85.5	370.6
40%ETc at tuber	52.3	139.6	67.8	85.5	345.2
85%ETc at late	52.3	139.6	169.5	72.7	434.1
70%ETc at late	52.3	139.6	169.5	58.9	420.3
55%Etc at late	52.3	139.6	169.5	47.0	408.4
40%ETc at late	52.3	139.6	169.5	34.2	395.6

4.3. Response of Potato to water stress on phonological stage and growth parameters.

Table 5: Mean comparison of water stress levels at different growth stages on days to 50% flowering, days to maturity and plant height

Treatments	Days to 50% flowering	Days to maturity	Plant height (cm)
100%ETc at all	68^{a}	113^{a}	122.80^{a}
85%ETc at dev.	61^{defg}	107^{bc}	116.10^{c}
70%ETc at dev.	56^{h}	103^{e}	115.13e
55%ETc at dev.	52^{i}	103^{e}	113.60^{f}
40%ETc at dev.	51^{ij}	97^{f}	110.46g
85%Etc at tuber	62^{cdef}	109^{bc}	118.60^{c}
70%ETc at tuber	61^{cd}	105^{de}	116.06^{d}
55%ETc at tuber	62^{bcd}	105^{de}	113.73^{f}
40%ETc at tuber	62^{bcd}	106^{dc}	110.80^{g}
85%ETc at late	65^{abc}	111^{ab}	120.47^{b}
70%ETc at late	63^{bcde}	105^{de}	116.07^{d}
55%Etc at late	64^{bcd}	105^{de}	113.83^{f}
40%ETc at late	66^{ab}	108^{c}	113.77^{f}
CV (%)	3.43	1.39	0.42
LSD (5%)	3.52	2.48	0.825

*Means followed by different letters in column differs significantly and those followed by the same letters are not significantly different at $p<0.05$ level of significance. NS: non-significant at $p<0.05$.

4.3.1. Days to 50% flowering and maturity

The analysis of variance showed that the number of days to 50% of flowering of Irish potato was highly significantly ($p < 0.01$) affected by different water stress levels of irrigation at different growth stages. This could be due to varying water stress levels between Irish potato growth stages. It was discovered that different moisture stress levels influenced the results of days to 50% flowering in Irish potato production in the research area. The average number of days from planting to 50% flowering and maturity existed in Table 5. Days to 50% of the flowering Irish potato were affected by water stress levels, irrigation water applied, and growth stages. Days to 50% flowering were varied during the study period. Treatment under 40% ETc and 55% ETc applications at the development (vegetative) growth stage attained the shortest number of days to flower, while experimental plots applied with full irrigation application took the longest days of flowering. The longest days to 50% flowering were statistically not highly significant with treatments that received 40% ETC at the late growth stage. Similarly, (Ahmed et al., 2008) discovered that the number of days to 50% flowering and maturity in fababean plants tries to escape unfavorable stress conditions by ending their life a few days earlier than those under normal or high soil moisture conditions.

4.3.2. Days to maturity

The analysis of variance showed that the number of days to maturity of the Irish potato was highly significantly ($p < 0.01$) affected by different water stress levels of irrigation at different growth stages. This might have been due to varying water stress levels between Irish potato growth stages. It suggests that different moisture stress levels affect the maturity of Irish potato production in the study area. The days to maturity of the Irish potato varied from 113 to 97, with an average value of 105 days (Table 5). Days to maturity of Irish potatoes were affected by water stress levels, irrigation water applied, and growth stages. The study shows that the increased water stress irrigation level leads to early maturity, whereas full irrigation treatment matures later. This showed that the higher the water stress (deficit), the earlier the day to maturity. A similar result has been reported: stressed treatments in wheat lead to early maturity (Li et al., 2011).

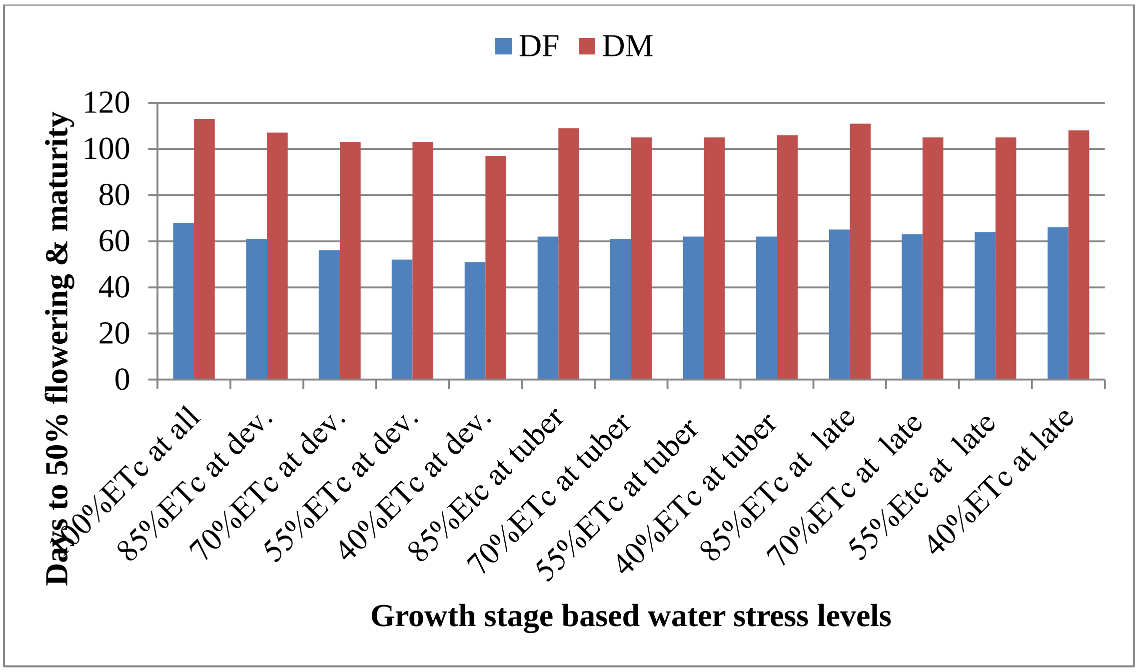

Fig. 5: Responses of Potato water stress levels at growth stages on days to 50% flowering and days to maturity

4.3.3. Plant height

The analysis of variance indicated that the plant height of Irish potato was highly significant ($p<0.01$) due to different water stress levels applied at different growth stages. It might have been due to various amounts of water stress in Irish potatoes at different growth stages. It suggests that different levels of moisture stress influence the plant heights of Irish potatoes at different growth stages in the study area. The mean value of plant height varied from 122.8cm to 110.47 cm, with an average value of 115.65cm (Table 5). The maximum plant height of 122.8 cm was obtained from the control treatment, which gained 100% ETc at all growth stages, and the lowest plant height of 110 cm was recorded on experimental plots, which received 40% ETc at the development and tuber formation stages. The mean results showed that plant height was directly related to the amount of irrigation water applied and inversely related to water stress level. When the water stress level increases, plant height also becomes shorter. The highest plant height was statistically similar with treatments that received 85% ETc at the late growth stage, which obtained 120.47 cm, and also statistically significant with treatments 2 and 6 that received 85% ETc at the development and tuber formation growth stages, which obtained 118.1 cm and 118.6 cm, respectively. At 70% ETC, treatment received at the development stage was significantly different from the late stage and tuber information stage. When compared to the 55% ETc treatment received at the late stage, it was significantly different with development and tuber information stage, while a minimum plant height of 110.47 cm was obtained from the treatment that received 40% ETc at the development growth stages and 110.80 cm from the tuber formation growth stage.

Plant height was reduced under water stress levels, which might be due to the difference in stress levels among different growth stages that influences plant height with the availability of moisture stress. Some of the research results that support the current finding were, according to Maqbool et al. (2015), reported to indicated that when water stress is imposed at the growth stage, it decreases the growth of plant height. Similarly, plant height in potatoes is very sensitive to moderate water stress conditions (Deblonde and Ledent, 2001).

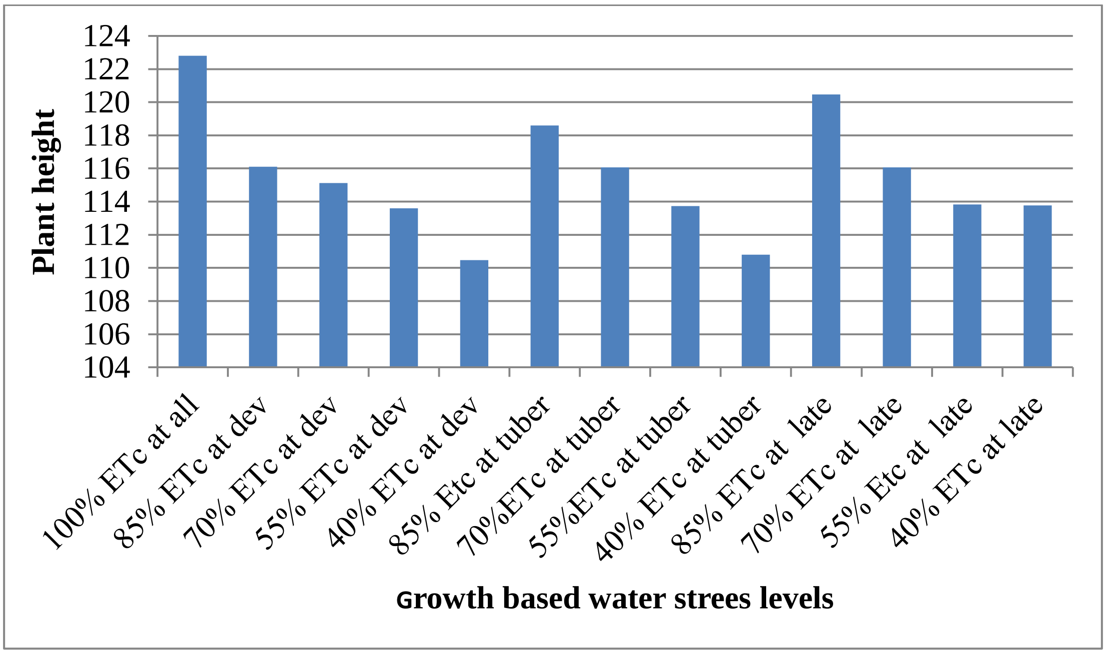

Figure 6: Responses of Potato to water stress levels and growth stages on plant height

Table 6: Mean comparison for leaf number per plant, leaf area and leaf area index response of potato to water stress levels and different growth stages

Treatment	Leaf number per plant	Leaf area (cm^2)	Leaf area index (%)
100%ETc at all	470.50^{a}	26.00^{a}	3.66^{a}
85%ETc at dev.	437.67^{a}	24.91^{a}	3.26^{b}
70%ETc at dev.	374.00^{bc}	21.00^{b}	2.35^{c}
55%ETc at dev.	336.00^{defg}	16.25^{cd}	1.64^{de}
40%ETc at dev.	327.67^{defgh}	14.30^{e}	1.40^{g}
85%Etc at tuber	440.33^{a}	24.09^{a}	3.31^{b}
70%ETc at tuber	406.67^{ab}	20.71^{b}	2.50^{c}
55%ETc at tuber	344.00^{cde}	16.77^{c}	1.73^{de}
40%ETc at tuber	320.00^{defghi}	15.19^{de}	1.45^{fg}
85%ETc at late	446.00^{a}	25.93^{a}	3.45^{b}
70%ETc at late	374.00^{cd}	21.47^{b}	2.40^{c}
55%Etc at late	350.7^{cd}	17.08^{c}	1.79^{d}
40%ETc at late	337.05^{def}	15.27^{d}	1.55^{e}
CV (%)	5.21	4.10	4.77
LSD (5%)	33.56	1.38	0.19

*Means followed by different letters in column differs significantly and those followed by the same letters are not significantly different at $p<0.05$ level of significance. NS: non-significant at $p<0.05$.

4.3.4. Leaf number per Plant

The analysis of variance indicated that leaf number per plant was highly significant ($p<0.01$) due to different application irrigation and water stress levels at different growth stages. The result could be due to various water stress levels between Irish potato growth stages. It was discovered that different moisture stress levels impacted the results of leaf number per plant of Irish potato in the experiment's area. The mean number of leaves per plant increased with decreased water stress and irrigation levels. The different water stress levels of irrigation water application at different growth stages showed that it affected the number of leaves per plant (Table 6). The maximum average number of leaf 470.5 leaves was obtained from the control treatment that gained 100% ETc at irrigated water at all growth stages, and the lowest average number of leaf 320.0 was gained from the treatment that received 40% ETc at tuber formation stage growth stages.

The mean result showed that leaf number per plant was directly related to the amount of irrigation water applied and inversely related to water stress level. The highest leaf number showed no significant difference with treatments that received 85% ETC at all growth stages of Irish potatoes. Treatment 70% ETc received at the development stage was significantly different with late growth stage and tuber information growth stage compared with each growth stage and significantly different compared with the control. Treatment (55% ETC) received at the late stage was significantly different with development and tuber information stage compared with each growth stage and significantly different compared with the control. The lowest leaf number was obtained from the treatment that received 40% ETC at all growth stages, and it was statistically less than all other treatments. The number of leaves was reduced as stress levels increased from 15% EC to 60% EC on the treatments that were stressed at different growth stages. Some of the research results which support the current finding were, (Shaterian *et al.,* 2008) when the water stress level increase number of leaf per plant also becomes lower.

Leaf number and leaf length are very sensitive to moderate water stress conditions (Deblonde and Ledent, 2001). According to Schittenhelm et al. (2006) reported that the stem type of potato plant exhibits less self-shading of leaves than the leaf types, and thus might be able to better use their aerial environment. Water stress causes premature leaf shedding. Older leaves and fallen leaves became affected first. Leaf shedding is detrimental to plant growth as it reduces the plant assimilation area.

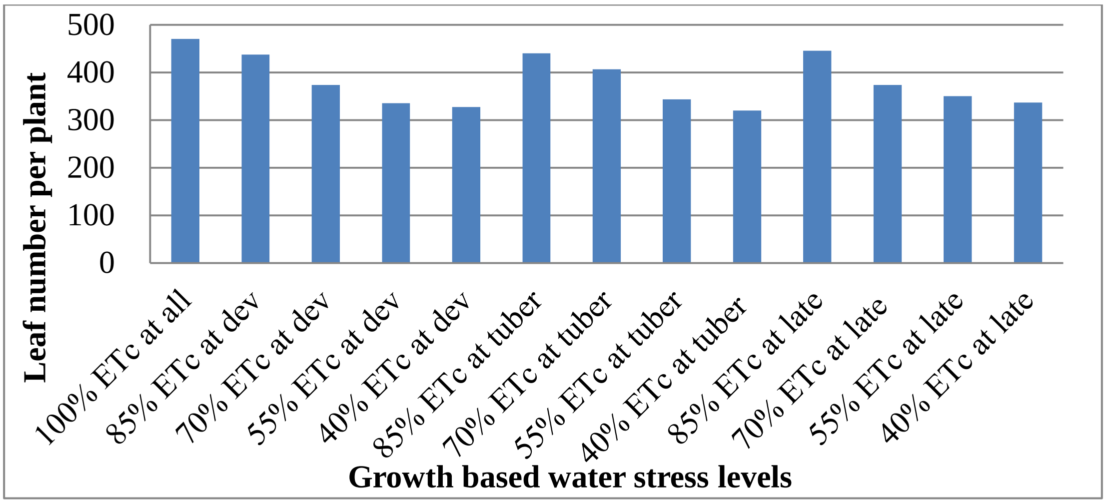

Fig. 7: Responses of Potato to water stress levels at different growth stages on leaf number

4.3.5. Leaf area

The analysis of variance has indicated that leaf area was highly significant ($p<0.01$) due to different water stress levels and growth stages. This could be due to various amounts of water stress during the Irish potato growth cycle. It indicates that different moisture stress levels contribute to the results of leaf area in Irish potato production in the research area. The maximum average leaf area of 26 cm2 was obtained from the control treatment that received 100% ETc irrigated water at all growth stages, and the minimum average leaf area was 14.3 cm2 obtained from the treatment that received 40% ETc irrigated water at development growth stages. The water stress levels of irrigation water application at different growth stages showed that it affected the leaf area of the Irish potato (Table 6).

The mean result showed that leaf area was directly related to the amount of irrigation water applied and inversely related to water stress level. When the water stress level increases, the leaf area also becomes narrower. The highest leaf area was gained from the control treatment that irrigation water applied 100% ETc at all growth stages, and there was no significant difference from treatments that received 85% ETc at all growth stages for Irish potatoes. The treatment that 70% ETC received at all growth stages was statistically not significantly different compared with each growth stage. The treatment that 55% ETC received at all growth stages was statistically not significantly different compared with each growth stage and significantly different compared with the control.

On the other hand, statistically, there is no significant difference between those who received treatment at 40% ETC at all growth stages and those who were statistically significantly different compared with the control. The lowest leaf area was obtained from the treatment that received 40% ETC at all growth stages, and it was statistically less than all other treatments. Leaf area was reduced as stress levels increased from 15% ETc to 60% ETc on the treatments that were stressed at different growth stages. Water stress causes premature leaf shedding. Older leaves and fallen leaves became affected first. Leaf shedding is detrimental to plant growth as it reduces the plant engagement area. Some of the research results that support the current finding, according to Kumar et al. (2007) reported that reduced leaf growth by affecting leaf photosynthesis by chlorophyll reduction, leaf area index, or leaf area duration reduction, and accelerated leaf senescence are common responses to water stress. This reduction in leaf area ultimately delays photosynthesis and other physiological activities, which reduce the ultimate plant productivity (Journal and Engineering, 2021).

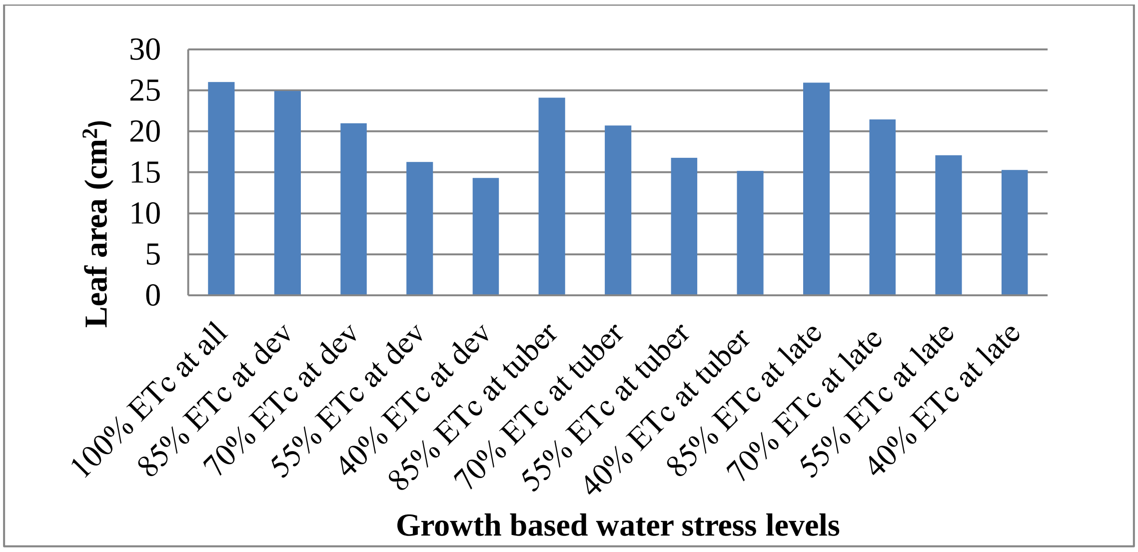

Figure 8: Responses of Potato to water stress levels at different growth stages on leaf area

4.3.6. Leaf area index

The analysis of variance indicated that the leaf area index was highly significant (p<0.01) due to different water stress levels and different growth stages. This might be caused by differing water stress levels between Irish potato growth stages. It revealed that different moisture stress levels affected the leaf area index of Irish potato production in the research area. The maximum average leaf area index of 3.66% was obtained from the control treatment that gained 100% ETc irrigated water at all growth stages, and the minimum average leaf area index of 1.4% was obtained from the treatment that received 40% ETc at development growth stages. The different water stress levels of irrigation water application at different growth stages showed that it affected the leaf area index of potatoes (Table 6).

The mean result showed that leaf area index was directly related to the amount of irrigation water applied and inversely related to water stress level. When the water stress level increases, the leaf area index also becomes lower. The highest leaf area index was gained from the control treatment, in which irrigation water was applied at 100% ETc at all growth stages, and there was no significant difference from treatments that received 85% ETc at all growth stages for Irish potatoes. Treatment that received 70% ETC at all growth stages was statistically not significantly different compared with each growth stage and significantly different compared with the control. The treatment that 55% ETC received at all growth stages was statistically not significantly different compared with each growth stage and significantly different compared with the control. The lowest leaf area index was obtained from the treatment that received 40% ETC at all growth stages, and it was statistically less than all other treatments. The leaf area index was reduced as stress levels increased from 15% EC to 60% EC on the treatments that were stressed at different growth stages.

This result indicates that due to the adverse response of water stress levels on plant growth, development, and yield, which lead to a loss of turgidity leading to cell enlargement and little growth, there is a there is a decrease in photosynthesis due to decreased diffusion of CO2 with the closure of stomata to conserve water and a reduced leaf area index. Water stress in the vegetative stage decreased leaf area index due to more transpiration from the plant canopy and evaporation from the soil surface. Besides vegetative growth, drought may affect the reproductive stage of potatoes by shortening the growth cycle (Nasir and Toth, 2022). They investigated that leaf area index is decreased by water stress in vegetative stages. The results of the present study clearly indicated an increase in leaf area index with increased irrigation determination methods. However, the increase in leaf area was more expressed, which is probably associated with the highest water use efficiency of plants, which promoted the growth and development of potato plants. The increase in leaf area of potato plants was also observed with an increase in less water stress levels of deficit irrigation, as indicated by the findings of various researchers, which are generally in line with the findings of the present study (Geremew et al., 2008).

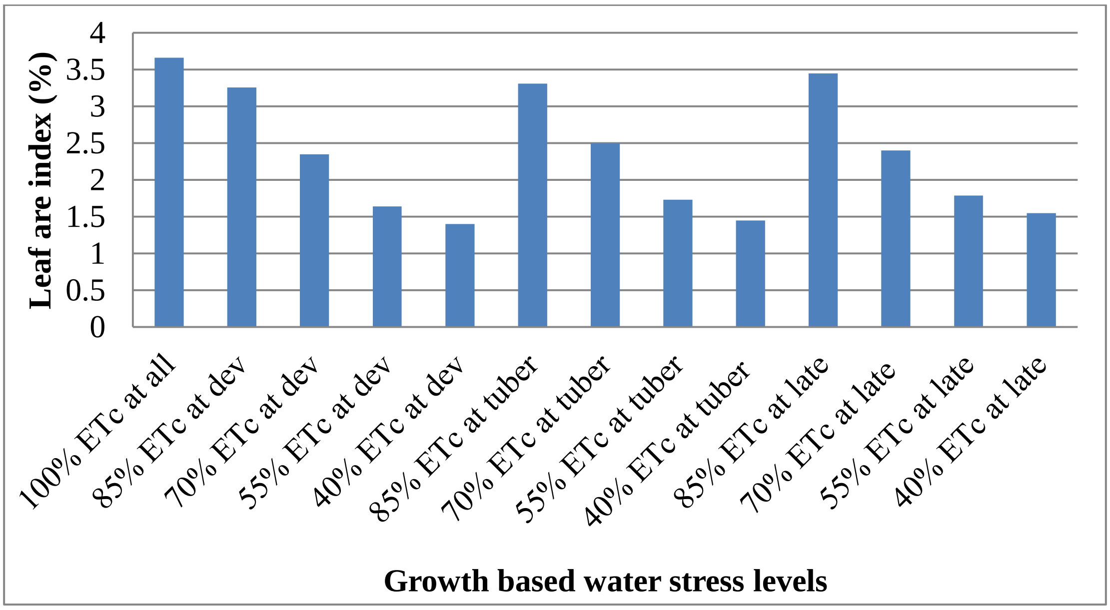

Fig.9: Responses of Potato to water stress levels at different growth stages on leaf area index

4.4. Response to water stress levels of different growth stages on yield and yield component Potatoes

Table 7: Mean comparison of yield and yield components Potato response to water stress levels at different growth stages

Treatments	Tuber number	Tuber diameter (cm)	Marketable tuber yield (t/ha)	Unmarketable tuber yield (t/ha)	Total yield (t/ha
100% ETc at all	15.87^{a}	24.73^{a}	41.52^{a}	3.78^{a}	45.30^{a}
85% ETc at dev	14.23^{bc}	22.20^{bc}	39.85^{ab}	3.04^{bc}	42.89^{b}
70% ETc at dev	13.13^{cde}	20.60^{de}	37.7^{cd}	2.96^{bc}	40.66^{cd}
55% ETc at dev	12.33^{def}	18.60^{fg}	35.43^{fg}	2.83^{bc}	33.48^{de}
40% ETc at dev	12.40^{def}	17.00^{h}	33.01^{j}	3.25^{abc}	38.26^{e}
85% Etc at tuber	14.47^{b}	22.86^{b}	40.01^{ab}	2.74^{c}	42.86^{b}
70%ETc at tuber	13.53^{bcd}	20.80^{cd}	37.15^{de}	2.92^{bc}	40.07^{d}
55%ETc at tuber	11.87^{ef}	19.13^{ef}	34.86^{ghi}	3.26^{abc}	38.12^{e}
40% ETc at tuber	11.27^{f}	17.07^{gh}	32.86^{jk}	3.37^{ab}	35.97^{f}
85% ETc at late	14.27^{bc}	23.60^{ab}	40.44^{a}	3.35^{ab}	43.79^{b}
70% ETc at late	12.31^{def}	18.80^{f}	38.45^{c}	2.84^{bc}	41.30^{c}
55% Etc at late	12.5^{def}	18.93^{f}	36.46^{ef}	3.21^{abc}	39.67^{d}
40% ETc at late	12^{ef}	16.27^{h}	35.23^{gh}	2.85^{bc}	38.08^{e}
CV (%)	5.96	4.59	1.85	11.41	1.75
LSD (5%)	1.32	1.55	1.16	0.59	1.19

*Means followed by different letters in column differs significantly and those followed by the same letters are not significantly different at $p<0.05$ level of significance. NS: non-significant at $p<0.05$.

4.4.1. Tuber number

The analysis of variance has indicated that tuber number per plant was highly significant ($p<0.01$) due to different water stress levels at different growth stages. This could be because of differences in moisture stress levels between Irish potatoes at different growth stages. It implies that there was an optimum water stress level for sustainable potato production in the research area. The maximum average tuber number per plant was 15.87 obtained from the control treatment that gained 100% ETc irrigated water at all growth stages, and the minimum average tuber number per plant was 11.27 obtained from the treatment that received 40% ETc at tuber formation growth stages, and 12.4 and 12.0 obtained from the development growth stage and late growth stage, respectively. The responses of different water stress levels to irrigation water application at different growth stages showed that it affected tuber number per plant (Table 7).

The mean result showed that tuber number was directly related to the amount of irrigation water applied and inversely related to water stress level. When the water stress levels increase, the number of tubers per plant also decreases. The highest tuber number per plant was gained from the control treatment, which was statistically not significantly different with treatments that received 85% ETc at the tuber formation growth stage that obtained 14.47 and also statistically significant different with treatments that received 85% ETc at the development and late growth stages that obtained 14.2 and 14.27, respectively. Treatment 70% of ETc received irrigated water at the tuber formation growth stage, which was significantly different with development and late growth stage compared with each growth stage and significantly different compared with the control. Treatment (55% ETC) received irrigated water at tuber formation was statistically significant different with development and late growth stage. The lowest tuber number per plant was obtained from the treatment that received 40% ETC at all growth stages, and it was statistically less than all other treatments. Tuber number per plant was reduced as stress levels increased from 15% ETc to 60% ETc on the treatments that were stressed at different growth stages. The application of water stress levels during tuber formation (40% ETc and 55% ETc) and development and maturity (55% ETc and 40% ETc) growth stages leads to a reduction in the number of tubers per plant.

Some of the research results that support the current finding were, according to Kumar et al. (2007), that the size and number of tubers and, by affecting leaf photosynthesis by chlorophyll reduction, leaf area index, or leaf area duration reduction, irrigation started at an early stage of growth had little effect on the total number of tubers produced by the plant (Kar and Verma, 2005).

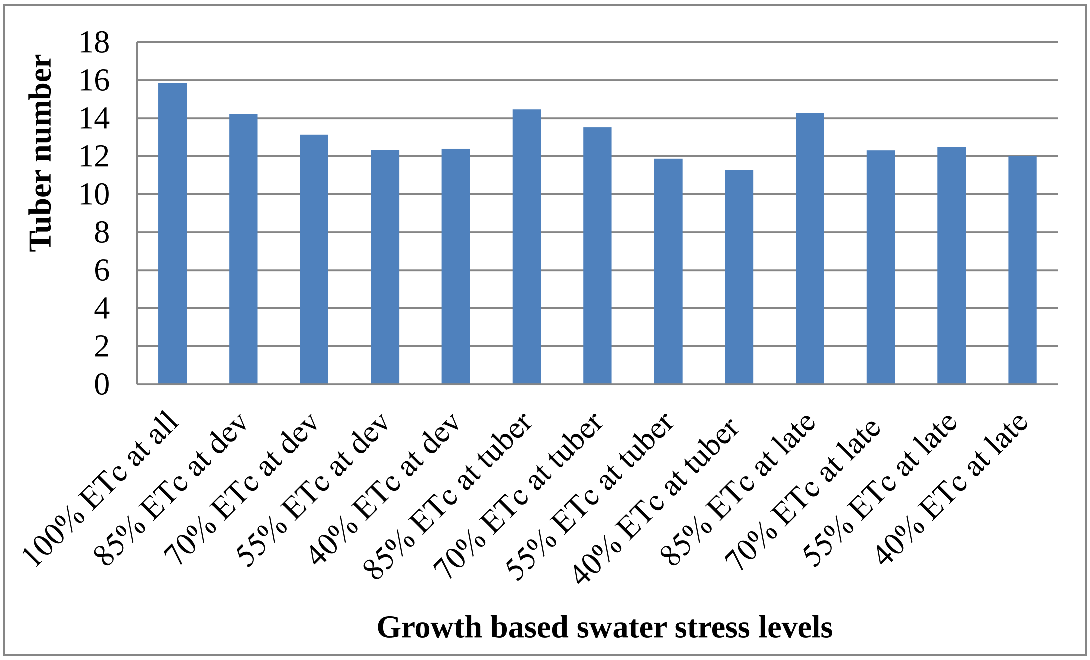

Fig.10: Responses of Potato to water stress levels at d/t growth stages on tuber number

4.4.2. Tuber diameter

The analysis of variance results indicated that tuber diameter was highly significant ($p<0.01$) due to water stress levels at different growth stages. This might be because of differences in water stress levels between potatoes at different growth stages. It implies that there was an optimum water stress level for sustainable potato production in the study area. The maximum average tuber diameter of 24.73 cm was obtained from the control treatment that gained 100% ETc irrigated at all growth stages, and the average minimum tuber diameter of 16.78 cm was obtained from the treatment that received 40% ETc at all growth stages. The water stress levels of irrigation water application at different growth stages showed responses that affected tuber diameter (Table 7).

The mean result showed that tuber diameter is directly related to the amount of irrigation water applied and inversely related to water stress level. The water stress level increases, and tuber diameter also decreases. The highest tuber diameter was gained from the control treatment that irrigation water applied 100% ETc at all growth stages, which was statistically not significant with treatments that received 85% ETc at the (maturity) late growth stage that obtained 24.73 cm and 23.60 cm, respectively, and also statistically significant with treatments that received 85% ETc at the tuber formation growth stage and development growth stages. At treatment, 70% of ETc received irrigated water at the late stage, which was significantly different with development and tuber information stage. At 55% ETc, treatment received irrigated water at the tuber formation growth stage, which was significantly different from the development growth stage. The lowest tuber diameter of 16.27 was obtained from the treatment that received 40% ETc at the late growth stage, and 17cm and 17.07 cm were obtained from the development growth stage and tuber formation growth stage, respectively. While the responses of the same treatments of water stress irrigation were at different stages, they were insignificant.

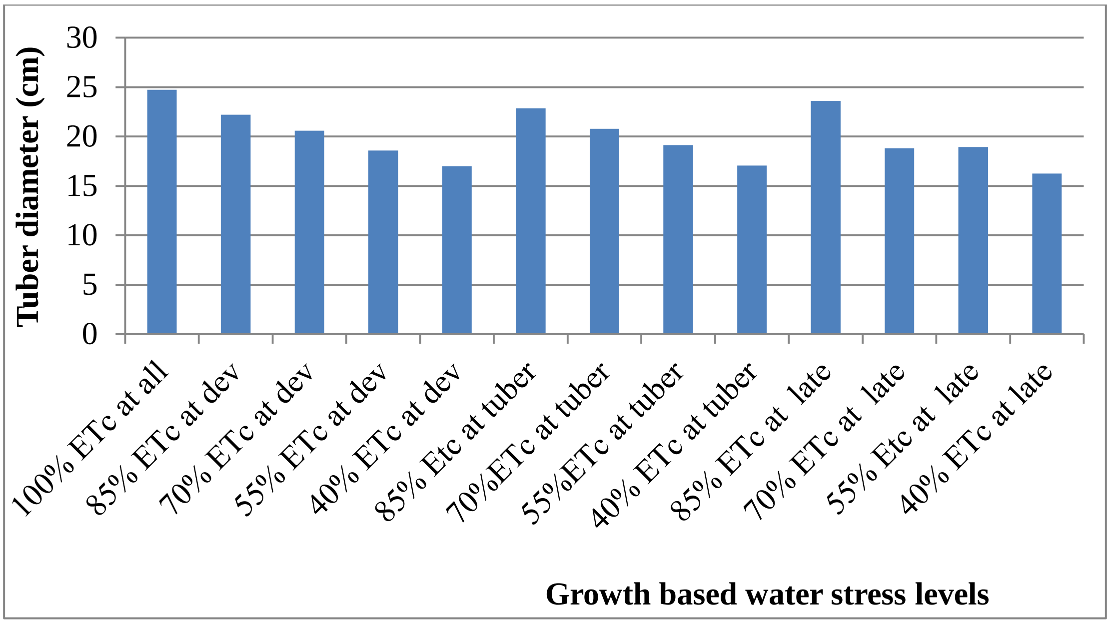

Fig.11: Responses of Potato to water stress levels at different growth stages on tuber diameter

4.4.3. Mark1etable tuber Yield

The analysis of variance results indicated that marketable tuber yield was highly significant (p<0.01) due to different water stress levels at different growth stages. This could be because moisture stress levels fluctuate between Irish potatoes at different growth stages. It signifies that there was an ideal water stress level for sustainable Irish potato production in the research area. This shows an outstanding chance for farmers and scientific communities to reduce water loss while growing potatoes underwater in inadequate conditions. The maximum average marketable yield of 41.52 t/ha was obtained from the control treatment that gained 100% ETc irrigated at all growth stages, and the minimum marketable yield of 32.86 t/ha was obtained from the treatment that received 40% ETc at the tuber formation growth stage. The different water stress levels of irrigation water application at different growth stages showed responses that affected marketable tuber yield (Table 7).

The mean result showed that marketable tuber yield is directly related to the amount of irrigation water applied and inversely related to the water stress level. The water stress level increases marketable tuber yield, which also decreases. The highest marketable tuber yield was gained from the control treatment that irrigation water applied 100% ETc at all growth stages, which was statistically not significant with treatments that received 85% ETc at tuber formation (mid) growth stage that obtained 40.01 t/ha and late stage 40.44 t/ha, respectively, and also statistically significant with treatments that received 85% ETc at development growth stage that obtained 39.85 t/ha. At treatment, 70% of ETc received irrigated water at the late stage, which was significantly different with the development and tuber information stages. At 55% ETc, treatment received irrigated water at the tuber formation growth stage, which was significantly different from the development growth stage.

The lowest marketable yield of 32.86 t/ha was obtained from the treatment that received 40% ETC at the tuber formation growth stage and 33.01 t/ha and 35.23 t/ha obtained from the development growth stage and late growth stage, respectively. While the responses of the same treatments of water stress irrigation were at different stages, they were statistically significant. Marketable tuber yield was reduced as stress levels increased from 15% ETC to 60% ETC on the treatments that were stressed at different growth stages..

Some of the research results that support the current finding indicated that a reduction in yield is a cause of deficit irrigation at different growth stages of the potato (Gultekin and Ertek, 2018). In another similar study, it was also shown that Irish potato yield was low, indicating that deficit irrigation should be avoided during tuber formation and in the middle of the maturity stage of potatoes to reach acceptable quality and quantity productivity (Hassan et al., 2002). According to Ustun (2006), water deficits have decreased the evapotranspiration and tuber yield of potatoes. These results of water stress levels showed that deficit irrigation had a significant impact on yield. The amount of irrigation water was reduced as yield significantly decreased.

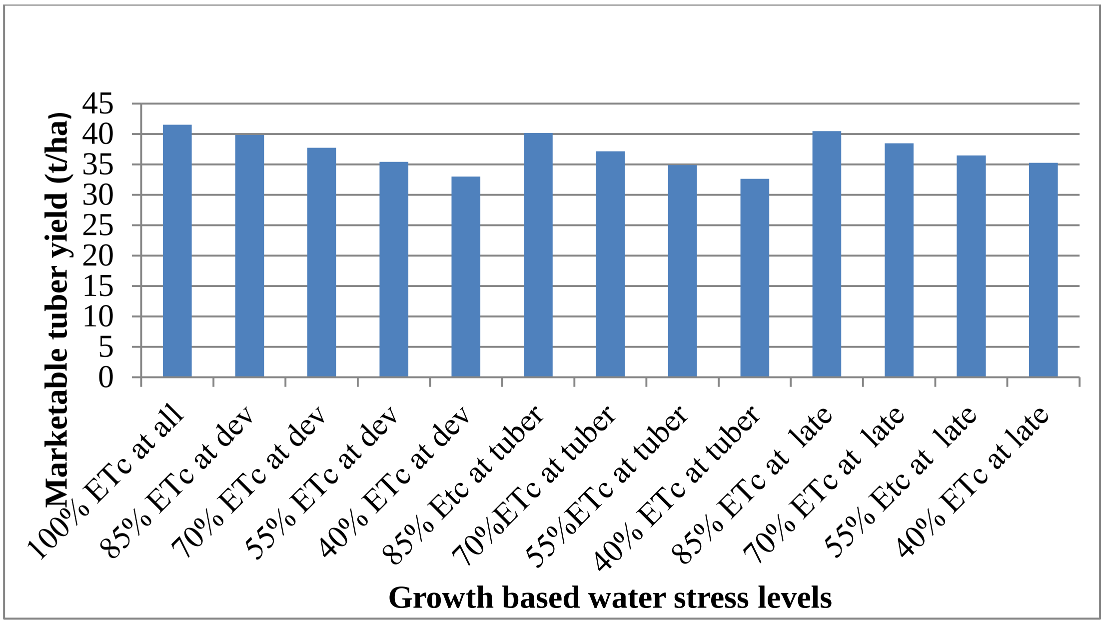

Figure 12: Responses of Potato to water stress levels and different growth stages on marketable tuber yield of Irish potato

4.4.4. Unmarketable tuber yield

The analysis of variance results indicated that unmarketable tuber yield was insignificant ($p<0.01$) due to different water stress levels at different growth stages. The maximum average unmarketable tuber yield of 3.85 t/ha was obtained from the treatment that gained 40% ETc and 70% ETc, which was statistically not significant with treatments that received all treatments, and the minimum unmarketable tuber yield of 2.7 t/ha was obtained from the treatment that received 85% ETc at the tuber formation growth stage. The different water stress levels of irrigation water application at different growth stages showed an unmarketable yield (Table 7). The maximum unmarketable tuber yield was gained from the treatment that irrigation water applied at 40% ETc and 70% ETc at development and tuber formation, respectively. There is no significant difference between all treatments received during the growth stages. The lowest unmarketable tuber yield was obtained from the treatment that received 85% ETc at tuber formation growth stages, and there was no statistically significant difference between all treatments.

4.4.5. Total Tuber yield

The analysis of variance results indicated that total tuber yield was highly significant ($p<0.01$) due to different water stress levels at different growth stages. The maximum average total tuber yield of 45.30 t/ha was obtained from the control treatment that gained 100% ETc at all growth stages, and the minimum total tuber yield of 32.6 t/ha was obtained from the treatment that received 40% ETc at the tuber formation growth stage. The different water stress levels of irrigation water application at different growth stages showed responses that affect marketable yield (Table 7).

The result showed that total tuber yield was directly related to the amount of irrigation water applied and inversely related to the water stress level. As the water stress level increases, total yield also decreases. The highest total tuber yield was gained from the control, which was statistically not significant with treatments that received 85% ETc at the development growth stage that obtained 43.79 t/ha and also statistically significant with treatments that received 85% ETc at the tuber formation growth stage and late stage that obtained 43.26 t/ha and 43.56 t/ha, respectively. At 70% ETc, treatment received at the tuber information stage was significantly different with development and late stage. At 55% ETC, treatment received at all growth stages was statistically not significantly different compared with each growth stage and significantly different compared with the control and the other treatments. The lowest total yield (32.6 t/ha) was obtained from the treatment that received 40% ETC at the tuber formation growth stage and 33.01 t/ha and 35.23 t/ha obtained from the development growth stage and late growth stage, respectively. Total tuber yield was reduced as stress levels increased from 15% ETC to 60% ETC on the treatments that were stressed during growth stages.

The result reveals that the maximum total tuber yield obtained was similar to the previous studies. According to Gultekin and Ertek (2018), potato yields were significantly affected depending on the water deficit (stress), and the best yield achieved (47.13 tons/ha) was recorded by the treatment receiving 100% of the water needs. According to Kumar et al. (2007), the potato's response to water scarcity indicated that deficit (water stress) irrigation increased potato water use efficiency.

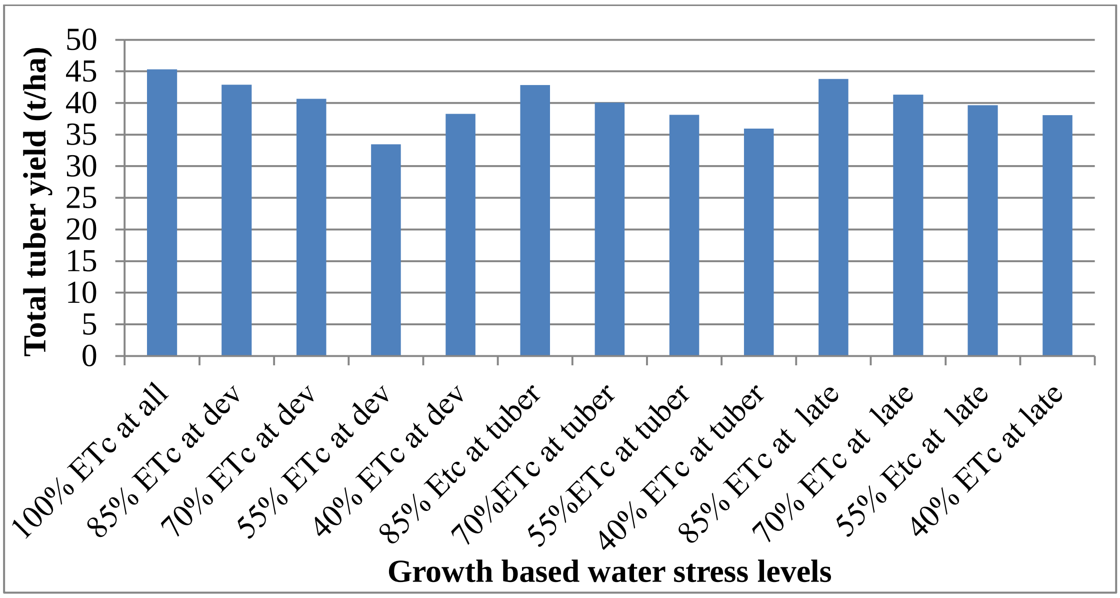

Fig. 13: Responses of Potato to water stress levels & growth stages on total tuber yield

4.5. Water Productivity

Crop water productivity values for marketable tuber yield responses to seasonal applied water were presented in Table 8 for different water stress levels of treatments. Water productivity values were varied with crop water stress levels applied at corresponding depths. Reducing the amount of irrigation water applied leads to improved water productivity. According to the results of the study, the highest water productivity (22.76%) was observed from the application of crop water stress level (60% ETc) at the tuber formation (mid) stage, while the lowest water productivity (2.86%) was observed from the application of 15% ETc at the tuber formation (mid) stage. The water productivity values for other irrigation treatments were in between these two irrigation water stress levels of treatments at different growth stages.

The results of the study indicated that the values of water productivity of Irish potato responses vary depending on the different growth stages of applied treatments throughout the season. From the results, the application of different water stresses at 15, 30, 45, and 60% lower than full irrigation saved 4.67, 9.38, 14.05, and 18.75% of irrigation water with relative yield reductions of 4.02, 10.88, 14.67, and 24.49% at the development stage; 5.69, 11.37, 17.07, and 22.76% of saved irrigation water with relative yield reductions of 3.37, 10.52, 16.04, and 21.48 at the mid sage; and 2.86, 5.95, 8.61, and 11.48% of saved irrigation water with relative yield reductions of 2.60, 7.39, 12.19, and 15.07% at the late stage, respectively. This indicates that using the saved amount of water to irrigate an additional area could compensate for any yield loss due to different water stress levels during irrigation. Since, from a different growth stage-based water stress level point of view, obtaining optimum marketable tuber yield relies on having relatively optimum water productivity, minimum yield reduction and comparable water savings were under consideration.

For instance, in treatment, 85% ETc at the development and late stages could compensate for the decrease in grain yield by producing 1940kg and 1188 kg more grain yield on an additional area of land. In addition, treatment with 70% ETc at the late stage could compensate for the yield reduction that occurred and resulted in an additional yield of 2471 kg on an additional area of land, respectively. From the deficit irrigation point of view, the more flexibility required to obtain optimum grain yield relies on having relatively optimum water productivity, minimum yield reduction, and comparable water savings. An acceptable level of water savings and WP that can be achieved without a significant reduction in yield was under consideration. Consequently, the use of deficit irrigation at 15% and 30% of full irrigation resulted in optimum water productivity observed without significant reduction and minimum reductions in yield in comparison to other deficit treatments.

An acceptable level of water saving and water productivity that can be achieved with a minimum yield reduction was under consideration. Consequently, the use of water stress levels at 15% and 30% of full irrigation resulted in optimum water savings observed with a minimum reduction in yield in comparison to other water stress levels.

From the results, the optimum average tuber yield was obtained from a 30% EC irrigation water stress level at the different growth stages of Irish potato, as shown below the figure.

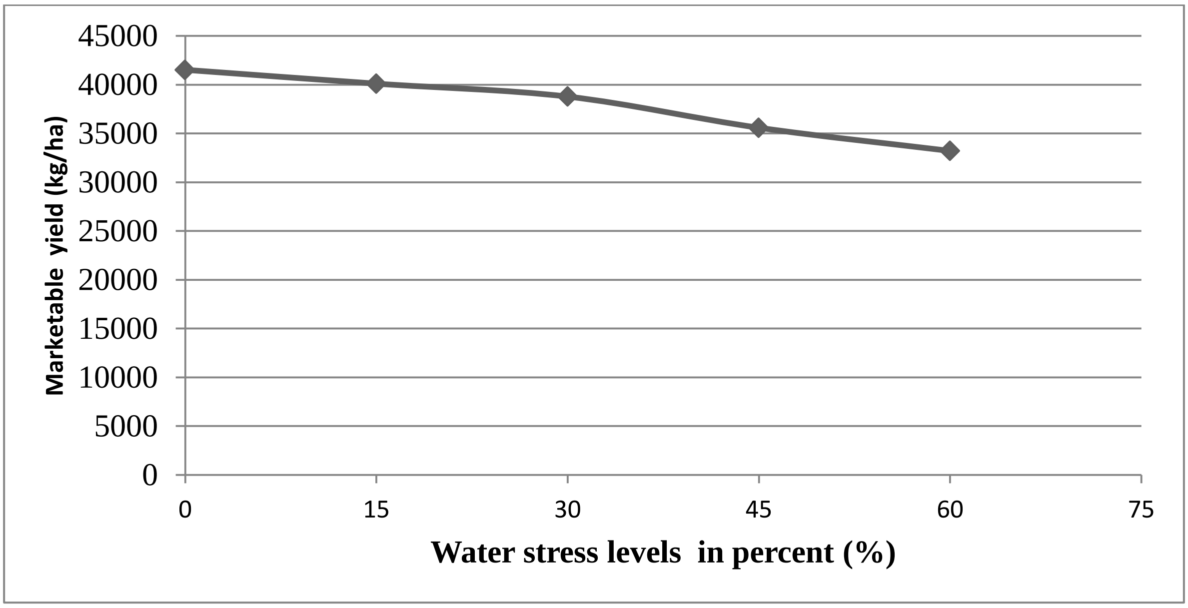

Figure 14: The optimization relationship of seasonal average water stress levels at different growth stages of marketable tuber yield of Irish potato

Table 8: Water productivity of deficit irrigation levels under different water stress levels and different growth stages of Irish potato

TRT	Seasonal Water (m^3/ha)	Marketable yield (Kg/ha)	WP (kg $m^{3)}$	Relative water saved (%)	Relative yield reduction (%)
100% ETc at all	4469	41520	9.29	0.00	0.00
85% ETc at dev	4260	39850	9.35	4.67	4.02
70% ETc at dev	4050	37700	9.30	9.38	10.88
55% ETc at dev	3841	35430	9.22	14.05	14.67
40% ETc at dev	3631	33010	9.09	18.75	20.49
85% Etc at tuber	4215	40010	9.49	5.69	3.64
70%ETc at tuber	3961	37150	9.37	11.37	10.52
55%ETc at tuber	3706	34860	9.41	17.07	16.04
40% ETc at tuber	3452	32860	9.52	22.76	20.86
85% ETc at late	4341	40440	9.32	2.86	2.60
70% ETc at late	4203	38450	9.15	5.95	7.39
55% ETc at late	4084	36460	8.93	8.61	12.19
40% ETc at late	3956	35260	8.91	11.48	15.07

Where: TRT = treatments, WP= Water productivity

4.6. Yield response factor

The yield response factor is one of the important parameters that indicate whether water stress due to reduced irrigation is advantageous or not in terms of enhancing water use efficiency. Any significant decrease in soil water storage has an impact on water availability for a crop and, subsequently, on actual yield and actual evapotranspiration.

The result indicated that the yield response factor ranges from 0.56 to 1.15 for stressed treatments (Table 9). A lower yield response factor is associated with lower stressed treatments, and higher values are associated with highly stressed treatments.

The study shows that a lower yield response factor was associated with lower stressed treatments, in which a statistically similar yield was obtained with that of the optimum irrigation of 100% ETc treatments. Yield response factors of 85% ETc, 70% ETc, 55% ETc, and 40% ETc were 0.8, 0.91, 1.07, 1.15 at the development stage, 0.56, 0.95, 0.94, 1.13 at the midst age, and 0.86, 0.94, 1.1, and 1.08 at the late stage, respectively.

The result reveals that yield sensitivity increased as moisture stress increased. The variation of a yield response factor at different stress levels showed that yield reductions were not similar for the same amount of water saved due to a reduction in irrigation amount from the optimum application depth of 100% ETC treatment. Different studies reveal that the yield response factor varies for different crop types and stress conditions. The result indicated that the that the yield response factor ranges from 0.56 to 1.15 for stressed treatments. The lower yield response factor is associated with lower stressed treatments, and higher values are associated with highly stressed treatments. The higher Ky values of 1.15 could be an indication of severe water stresses. This implies that the rate of relative yield decrease resulting from water stress is proportionally the same as the relative evapotranspiration water stress.

From the result, the lowest was 0.56 observed at 85% ETc at mid-stage, which indicates the tolerance of the crop to water stress level. The lowest Ky values of 0.56 could be an indication of medium water stress. The yield response factor of different crops and different stress conditions varies from 0.20 for tolerant crops to 1.15 for sensitive crops. A response factor greater than unity indicates that the relative yield decrease for a given evapotranspiration deficit (water stress) is proportionately greater than the relative decrease in evapotranspiration (FAO, 2002).

Table 9: Yield response factor for deficit irrigation treatments of different water stress levels on yield response factor of Irish potato

Treatments	1 - (Ya/Ym	1 - (Eta/ETm)	Ky = (1 - Ya/Ym) /(1- Eta/ETm)
100% ETc at all	0	0.00	-
85% ETc at dev	0.04	0.05	0.80
70% ETc at dev	0.09	0.098	0.91
55% ETc at dev	0.15	0.14	1.07
40% ETc at dev	0.21	0.182	1.15
85% Etc at tuber	0.034	0.06	0.56
70%ETc at tuber	0.105	0.11	0.95
55%ETc at tuber	0.16	0.17	0.94
40% ETc at tuber	0.15	0.19	1.13
85% ETc at late	0.026	0.03	0.86
70% ETc at late	0.074	0.078	0.94
55% Etc at late	0.11	0.10	1.10
40% ETc at late	0.13	0.12	1.08

Ya = actual yield, Ym = maximum yield, ETa = actual evapotranspiration and ETm = maximum evapotranspiration

4.7 Correlation of Yield and Yield Components

The analysis for the association between yield and its contributing variables was examined using the Pearson correlation coefficient (r) method. The crop water stress levels applied had a significant effect on the yield and yield components of Irish potatoes, according to the correlation coefficient analysis results. These associations were favorable and had comparable magnitudes. This implies that a decrease in one variable is associated with a decrease in another, and an increase in one is associated with a rise in another.

From the total correlation analysis, most of the yield components, such as days to maturity (r = 0.71**), plant height (r = 0.51**), leaf number (r = 0.39**), leaf area (r = 0.42**), leaf area index (r = 0.43**), tuber number (r = 0.27**), tuber diameter (r = 0.31**), and marketable tuber yield (r = 0.42**), had a positively strong and moderate correlation relation range except leaf number and a highly significant ($p < 0.01$) association with total tuber yield (Table 10).

This indicates that the application of crop water stress levels and irrigation treatments on Irish potatoes positively affects its yield and yield components. Days to 50% flowering were positively strongly correlated from days to maturity, and plant height, leaf number, leaf area, leaf area index, and marketable tuber yield were positively moderately correlated, while tuber number and tuber diameter were lowly positively correlated. Similarly, from days to 50% flowering, all the recorded growth parameters, yield, and yield components were positively correlated with each other.

Some of the research results that support the current finding indicated that yield is positively associated with yield and yield components (Meskelu et al., 2017). This shows that an increase in these parameters might lead to an enhancement of tuber yield.

Table 10: The correlation coefficient matrix results of growth parameters yield and yield components of Irish potato responses under different water stress levels of deficit irrigation

	DF	DM	PH	LN	LA	LAI	TN	TD	MY
DF	1								
DM	0.714**	1							
PH	0.513**	0.74**	1						
LN	0.39**	0.67**	0.89**	1					
LA	0.42**	0.63**	0.91**	0.85**	1				
LAI	0.43*	0.68**	0.94**	0.95**	0.97**	1			
TN	0.27ns	0.51*	0.75**	0.75**	0.81**	0.82**	1		
TD	0.31**	0.65**	0.87**	0.89**	0.87**	0.91**	0.79**	1	
MY	0.42**	0.63**	0.94**	0.89**	0.91**	0.93**	0.73**	0.85**	1

**= statistically highly significant ($p<0.01$), *= statistically significant ($p<0.05$) and ns= statistically not significant ($p>0.05$). DF: days to 50% flowering, DM: days to maturity, PH: plant height, LN: leaf number, LA: leaf area, LAI: leaf area index, TN: tuber number, TD: tuber diameter, MTY: marketable tuber yield and TTY: total tuber yield

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Efficient use of scare water with an appropriate irrigation water management strategy is an important consideration in the moisture-stress areas. Strategies such as water management techniques like deficit irrigation, which is considered optional, can help recover the problem and improve agricultural water productivity. Through deficit irrigation, significant water savings can be achieved, and larger areas are served with the available water. The study was practiced by covering up the crop water requirement below the full level throughout the growing season.

This study was aimed at evaluating the response of potatoes to water stress levels at different growth stages in water-scarce areas. Water stress levels were reduced during the growth stages by reducing the amount of irrigation water applied to the crop. The optimum irrigation water application was determined based on the CropWat model, and the irrigation water applied to each stressed treatment was based on their stress levels. Accordingly, seasonal water demand for Irish potato (Solanum tuberosum L.) under the study area and for the specified planting date could be 446.9 mm net irrigation depth for the non-stress condition (100% ETc). However, in stressed situations, the net irrigation depth is reduced based on the growth stage and the water stress levels. At 85% ETc, 70% ETc, 55% ETc, and 40% ETc, seasonal net irrigation depths were 426 mm, 405 mm, 384.1 mm, and 3613.1mm on the development stage, 421.5 mm, 396.1 mm, 370.6mm, and 345.1mm on the mid-growth stage, and 434.1mm, 420.3mm, 408.4 mm, and 395.6mm on the late-growth stage, respectively.

The results showed that water stress levels affect the phenology of the Irish potato, whose physiology is varied. Reducing irrigation water from 100% ETc to 40% ETc leads to earlier flowering and physiological maturity of potatoes by a week. Moreover, crop growth parameters like plant height, leaf number, leaf area, and leaf area index were significantly reduced. Plant height was shortened from 122.8 cm to 110.46 cm at the development stage and from 122.8 cm to 110.8 cm at the midstage due to the reduction of irrigation water from 100% ETC to 40% ETC. The growth parameters like leaf number and leaf area per plant were reduced from 470.5 to 320, 327.67 to 337.05 and 26 cm2 to 14.3 cm2, 15.19 cm2, and 15.27 cm2 as the irrigation water was reduced from 100% to 40% during mid-stage, development stage, late stage, and development, mid- and late stage, respectively.

Yield components like the number of tubers per plant were significantly reduced due to the reduction in irrigation water amount. The number of tubers per plant was reduced from 15.87 to 11.27, 12 and 12.4 as the irrigation water was reduced from 100% ETc to 40% ETc at mid-stage, late-stage, and development stages, respectively. Marketable yield and total yield production were significantly affected by water stress levels. The maximum marketable yield of Irish potato was 41.52 t/ha at 100% ETC, and the minimum marketable yield of 32.6 t/ha was obtained at 40% ETC.

From the results, the application of different water stresses at 15, 30, 45, and 60% lower than full irrigation saved 4.67, 9.38, 14.05, and 18.75% of irrigation water with relative yield reductions of 4.02, 10.88, 14.67, and 24.49% at the development stage; 5.69, 11.37, 17.07, and 22.76% of saved irrigation water with relative yield reductions of 3.37, 10.52, 16.04, and 21.48 at the midstage; and 2.86, 5.95, 8.61, and 11.48% of saved irrigation water with relative yield reductions of 2.60, 7.39, 12.19, and 15.07% at the late stage, respectively. This indicates that using the saved amount of water to irrigate an additional area could compensate for any yield loss due to different water stress levels during irrigation.

Generally, the study showed that water stress below 60% during development and mid-stages affected tuber yield significantly, especially when compared with other stages. In addition to the responses on yield and yield components, reducing irrigation water leads to improving water productivity.

1. The maximum yield and yield components of Irish potato were observed on T1 (100% ETc), while the minimum was under (40% ETc) water deficit level at the development stage. It was observed that the application of 85% ETc was not significantly different from the control treatment; however, there was a significant difference observed with 70% crop water stress levels in the deficit water application.
2. Application of 85%ETc and 70%ETc of full crop water requirement without significantly reduces yield and with minimum significantly reduces yield respectively and enhance the water productivity in comparison to control treatment. It was also concluded that more positive results could be obtained by imposing a water stress deficit level of less than 85% ETc and 70% ETc at the development and late growth stages, while the other treatments (55% ETc and 40% ETc) have greater water saved than 85% ETc and 70% ETc with higher yield reduction.
3. Water saved increased with increased water stress levels from deficit irrigation applications. The highest water saved was observed under the most stressed treatment, while the lowest was under full irrigation.
4. The yield response factors were between 0.56< Ky < 1.15, which means at 15% water stress at the mid stage, it was tolerant of water stress, and at 60% water stress at the development and mid (tuber formation) stages, the results indicated a high sensitivity to water stress levels.

5.2. Recommendations

1. For a non-stressed condition, Irish potatoes should be irrigated with a net seasonal irrigation depth of 446.9 mm for maximum marketable yield attainment (100% ETc) at all growth stages.
2. Under limited water resource conditions on study area 70% ETc to enhance yield and water productivity irrigation water stress level applications.
3. The study should be repeated in other areas under similar agro-ecological conditions in order to confirm the validity of the present findings since the research is done in one location for a single season.

6. REFFERENCES

Abdyl-razak, M. M. A., Hamzah, I. A., Alag, M. K., and Ahmed, S. A. H. (2014). *Influence of Irrigation Method , Weed , and Splitting Nitrogen Fertilizers on Water Use Efficiency and Productivity of Sunflower*. 136–141.

Ahmed, A. K., Tawfik, K. M., Zinab, A. A. E.-G., and El-Gawad, A. (2008). Tolerance of seven faba bean varieties to drought and salt stresses. *J. Agric. Biol. Sci*, *4*(2), 175–186.

Alan Walters, S., and Jha, A. K. (2016). Sustaining chili pepper production in Afghanistan through better irrigation practices and management. *Agriculture (Switzerland)*, *6*(4), 1–10. https://doi.org/10.3390/agriculture6040062.

Ali, M. H., Hoque, M. R., Hassan, A. A., and Khair, A. (2007). Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. *Agricultural Water Management*, *92*(3), 151–161. https://doi.org/10.1016/j.agwat.2007.05.010.

Awulachew, S. Teklu E, and Regash E. (2010). Irrigation potential in Ethiopia: Constraints and opportunities for enhancing the system. Research Report, International Water Management Institute, Addis Ababa. *International Water Management Institute*, *July*, 1–59.

Awulachew, S. (2007). Water Resources and Irrigation Development in Ethiopia. In *Iwmi: Vol. Working Pa* (Issue June 2015).

Ayana, M. (2011). Deficit irrigation practices as alternative means of improving water use efficiencies in irrigated agriculture: Case study of maize crop at Arba Minch, Ethiopia. *African Journal of Agricultural Research*, *6*(2), 226–235. https://doi.org/10.5897/AJAR09.118.

Banik, P., Zeng, W., Tai, H., Bizimungu, B., and Tanino, K. (2016). Effects of drought acclimation on drought stress resistance in potato (Solanum tuberosum L.) genotypes. *Environmental and Experimental Botany*, *126*(February), 76–89. https://doi.org/10.1016/j.envexpbot.2016.01.008.

Batjes, N. H., Bridges, E. M. (Edwin M., Clabaut, M.-B., Netherlands National Research Programme on Global Air Pollution and Climate Change., and International Soil Reference and Information Centre. (1992). *World inventory of soil emission potentials : proceedings of an International Workshop held at Wageningen, the Netherlands (24-27 August 1992)*.

Birhanu, E. (2023). *GSJ : Volume 11 , Issue 10 , October 2023 , Online : ISSN 2320 - 9186*. *October*. https://doi.org/10.13140/RG.2.2.16151.75686.

Blum, A. (2009). *Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress.* Field Crops Research,112:119–123.

Brouwer, C., and Heibloem, M. (1986). Irrigation Water Needs: Irrigation Water Management. Training manual no. 3. *Training Manual No. 3*. http://www.fao.org/3/u3160e/u3160e04.htm#2.1.1.

Chareesri, A., De Deyn, G. B., Sergeeva, L., Polthanee, A., and Kuyper, T. W. (2020). Increased arbuscular mycorrhizal fungal colonization reduces yield loss of rice (Oryza sativa L.) under drought. *Mycorrhiza*, *30*(2–3), 315–328.

https://doi.org/10.1007/s00572-020-00953-z.

Clement, F., Haileslassie, A., Ishaq, S., Blümmel, M., Murty, M. V. R., Samad, M., Dey, S., Das, H., and Khan, M. A. (2011). Enhancing water productivity for poverty alleviation: Role of capitals and institutions in the ganga basin. *Experimental Agriculture*, *47*(S1), 133–151. https://doi.org/10.1017/S0014479710000827.

Deblonde, P. M. K., and Ledent, J. F. (2001). Effects of moderate drought conditions on green leaf number, stem height, leaf length and tuber yield of potato cultivars. *European Journal of Agronomy*, *14*(1), 31–41. https://doi.org/10.1016/S1161-0301(00)00081-2.

Delilo, G. (2020). Fisheries production and aquaculture development: Current status and future directions in Ethiopia. *Global Journal of Fisheries Science*, *2*(2), 14–29. https://doi.org/10.31248/gjfs2020.017.

Doorenbos, J., and Kassam, A. H. (1979). Paper 33. Yield Response to water. In *FAO Irrigation and Drainage Paper* (p. 203).

Ekunsanmi, T. (2012). Journal of Life Sciences. In *Journal of life sciences* (Vol. 6, Issue 3). https://www.researchgate.net/publication/240613280_A_Note_on_the_Current_Status_of_Arin_a_Yoruba_Traditional_Game_Played_with_the_Seeds_of_Dioclea_reflexa.

El Bilali, H., Bassole, I. H. N., Dambo, L., and Berjan, S. (2020). Climate change and food security. *Agriculture and Forestry*, *66*(3), 197–210. https://doi.org/10.17707/AgricultForest.66.3.16.

Estefan, G., Sommer, R., and Ryan, J. (2013). *Methods of Soil , Plant , and Water Analysis :*

A manual for the West Asia and North.

Evans, R. G., and Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water Resources Research, 44*(7), 1–15. https://.

FAO, (1990). Irrigation Water Management: Irrigation Water Needs Training manual no.3. Rome, Italy: FAO.

FAO, (1998a). Crop evapotranspiration: Guidelines for computing crop water requirements. By: Richard Allen, Luis Pereira, Dirk Raes and Martin Smith. FAO Irrigation and Drainage Paper 56. Rome, Italy.

FAO, (2000). State of food security and agriculture. World water development report. FAO, Rome, Italy.doi.org/10.1029/2007WR006200.

FAO, (2002. Deficit irrigation practices. FAO Water reports, 22. FAO, Rome, Italy.

FAO (2012). Coping with Water Scarcity: An Action Framework for Agriculture and Food Security. Water Reports 38, Rome, Italy.

FAO, 2020. (2020). The State of Food and Agriculture 2020. In *The State of Food and Agriculture 2020*. https://doi.org/10.4060/cb1447.

FAOSTAT (2019). Available online at: http://www.fao.org/faostat/en/#data/QC (accessed July 07, 2021).

Fereree E., T.C. and Gonclaves D. A.(2007). Crop-yield/water-use production functions of potatoes(Solanum tuberosum, L.) grown under differential nitrogen and irrigation treatments in a hot, dry climate. Agricultural Water Management, 90, 45-55.

García-Vila, M., Lorite, I. J., Soriano, M. A., and Fereres, E. (2008). Management trends and responses to water scarcity in an irrigation scheme of Southern Spain. *Agricultural Water Management*, *95*(4), 458–468. https://doi.org/10.1016/j.agwat.2007.11.009.

Geerts, S., Raes, D., and Garcia, M. (2010). Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management*, *98*(1), 213–216. https://doi.org/10.1016/j.agwat.2010.07.003.

Geremew, E. B., Steyn, J. M., and Annandale, J. G. (2008). Comparison between traditional and scientific irrigation scheduling practices for furrow irrigated potatoes (solanum tuberosum L.) in Ethiopia. *South African Journal of Plant and Soil*, *25*(1), 42–48. https://doi.org/10.1080/02571862.2008.10639893.

Getaneh, L., and Laekemariam, F. (2021). Response of Potato (Solanum tuberosum L.) to NPS Fertilizer Rates and Inter-Row Spacing in Kechi District, South Western Ethiopia. *Applied and Environmental Soil Science*, *2021*. https://doi.org/10.1155/2021/5582066.

Gohar, A. A., and Ward, F. A. (2013). Mitigating impacts of water shortage on Egyptian agriculture: A catchment scale analysis. *Water Policy*, *15*(5), 738–760. https://doi.org/10.2166/wp.2013.091.

Gomez, A. A., and Wiley, J. (1984). Gomez and Gomez. *IRRI*, *6*, 594.

Gültekin, R., and Ertek, A. (2018). Effects of deficit irrigation on the potato tuber development and quality. *International Journal of Agriculture Environment and Food Sciences*, *2*(3), 93–98. https://doi.org/10.31015/jaefs.18015.

Hagos, F., Jayasinghe, G., Awulachew, S. B., Loulseged, M., and Yilma, A. D. (2012). Agricultural water management and poverty in Ethiopia. *Agricultural Economics (United Kingdom)*, *43*(SUPPL. 1), 99–111. https://doi.org/10.1111/j.1574-0862.2012.00623.x.

Hassan, A. A., Sarkar, A. A., Ali, M. H., and Karim, N. N. (2002). Effect of Deficit Irrigation at Different Growth Stages on the Yield of Potato. *Pakistan Journal of Biological Sciences*, *5*(2), 128–134. https://doi.org/10.3923/pjbs.2002.128.134.

Hazelton, P., and Murphy, B. (2019). Interpreting Soil Test Results. *Interpreting Soil Test Results*. https://doi.org/10.1071/9781486303977.

Hillel, D. (2004). *Hillel Daniel. (2004). Introduction to Environmental Soil Physics. Elsevier science, USA.PP494*.

Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, *93*(2), 281–289. https://doi.org/10.2134/agronj2001.932281x.

Hunt, N., and Gilkes, B. (1992). Soil Structure and Drainage. *Farm Monitoring Handbook*, 13–62.

Journal, E., and Engineering, S. (2021). *Effect of Deficit Irrigation and Potassium on Leaf Area , Chlorophyll and Photosynthesis in Potatoes*. *2*(2), 62–68.

Kandiah, A. (1981). *Guide for measurement of irrigation water using Parshall flumes and siphons*. Institute of Agricultural Research.

Kang, S. Z., Liang, Z. S., Hu, X. T., Pan, Y. H., Shi, P. Z., and Zhang, J. (2000). Soil water distribution, uniformity and water-use efficiency under alternate furrow irrigation in arid areas. *Irrigation Science*, *19*(4), 181–190. https://doi.org/10.1007/s002710000019.

Kar, G., and Verma, H. N. (2005). Phenology based irrigation scheduling and determination of crop coefficient of winter maize in rice fallow of eastern India. *Agricultural Water Management*, *75*(3), 169–183. https://doi.org/10.1016/j.agwat.2005.01.002.

Kargas, G., Chatzigiakoumis, I., Kollias, A., Spiliotis, D., and Kerkides, P. (2018). *An Investigation of the Relationship between the Electrical Conductivity of the Soil Saturated Paste Extract ECe with the Respective Values of the Mass Soil/Water Ratios 1:1 and 1:5 (EC1:1 and EC1:5)*. *5*, 661. https://doi.org/10.3390/proceedings2110661.

Kargas, G., Londra, P., and Sgoubopoulou, A. (2020). Comparison of soil EC values from methods based on 1:1 and 1:5 soil to water ratios and ECe from saturated paste extract based method. *Water (Switzerland)*, *12*(4), 1–12. https://doi.org/10.3390/W12041010.

Kebede, H., and Ermias Birru. (2011). Guideline on irrigation agronomy. *Ministry of Agriculture Natural Resource Sector, September*.

Khan, A. A., Jilani, M. S., Khan, M. Q., and Zubair, M. (2011). Effect of seasonal variation on tuber bulking rate of potato. *Journal of Animal and Plant Sciences*, *21*(1), 31–37.

Kijne, J. W., Barker, R., and Molden, D. (2003). *Improving Water Productivity in Agriculture : Editors ' Overview*.

Kirda, C., Kanhi-r, R., and Tuiuco, K. (1994). *"the Use of Nuclear and Related Teciinbiques in Assessment of Irrigation Schedules of Crops To Increase the*

Effective Use of Water in Irrigation Projects" Progres Report, 1994. *July*.

Kumar, S., Asrey, R. A. M., andMandal, G. (2007). Effect of differential irrigation regimes on potato (Solanum tuberosum) yield and post-harvest attributes. *Indian Journal of Agricultural Sciences*, *77*(6), 366–368.

Li, C., Carrijo, D. R., Nakayama, Y., Linquist, B. A., Green, P. G., and Parikh, S. J. (2019). Impact of Alternate Wetting and Drying Irrigation on Arsenic Uptake and Speciation in Flooded Rice Systems. *Agriculture, Ecosystems and Environment*, *272*(February), 188–198. https://doi.org/10.1016/j.agee.2018.11.009.

Li, P., Chen, J., and Wu, P. (2011). Agronomic characteristics and grain yield of 30 spring wheat genotypes under drought stress and nonstress conditions. *Agronomy Journal*, *103*(6), 1619–1628. https://doi.org/10.2134/agronj2011.0013.

Liu, H., Li, H., Ning, H., Zhang, X., Li, S., Pang, J., Wang, G., and Sun, J. (2019). Optimizing irrigation frequency and amount to balance yield, fruit quality and water use efficiency of greenhouse tomato. *Agricultural Water Management*, *226*(January 2021). https://doi.org/10.1016/j.agwat.2019.105787.

Makombe, G., Namara, R., Hagos, F., Awulachew, S. B., Ayana, M., and Bossio, D. (2011). A comparative analysis of the technical efficiency of rain-fed and smallholder irrigation in Ethiopia. *IWMI Working Papers*, *143*(1). https://doi.org/10.5337/2011.202.

Maqbool, M. M., Ali, A., ul Haq, T., Majeed, M. N., and Lee, D. J. (2015). Response of Spring Wheat (Triticum aestivum L.) to Induced Water Stress at Critical Growth Stages. *Sarhad Journal of Agriculture*, *31*(1), 53–58.

McCauley, A., Jones, C., & Jacobsen, J. (2005). Basic Soil Properties. *Soil and Water*, 1–12. http://landresources.montana.edu/SWM/PDF/Final_proof_SW1.pdf.

McTainsh, G. H., Leys, J. F., Carter, D., Butler, H. J., McCord, A., Wain, A., and Al., E. (2006). Monitoring soil condition across Australia Recommendations from the Expert Panels. *Canberra, Australia: National Committee on Soil and Terrain for the National Land and Water Resources Audit.*, 1–81.

Meskelu, E., Woldemichael, A., & Hordofa, T. (2017). Effect of moisture stress on yield and water use efficiency of irrigated wheat (Triticum aestivum L.) at Melkassa, Ethiopia. *Academic Research Journal of Agricultural Science and Research*, *5*(2), 90–97. https://doi.org/10.14662/ARJASR2016.055.

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

Mpandeli, S., and Senzanje, A. (2019). *Options for Improving Agricultural Water Productivity Under Increasing Water Scarcity in South Africa*. *September*. https://www.researchgate.net/publication/335835026.

Musinguzi, P., Ebanyat, P., Tenywa, J. S., Basamba, T. A., Tenywa, M. M., and Mubiru, D. N. (2016). Critical soil organic carbon range for optimal crop response to mineral Fertiliser nitrogen on a Ferralsol. *Experimental Agriculture*, *52*(4), 635–653. https://doi.org/10.1017/S0014479715000307.

Muthoni, J., and Shimelis, H. (2020). Heat and drought stress and their implications on potato production under dry African tropics. *Australian Journal of Crop Science, 14*(9), 1405–1414. https://doi.org/10.21475/ajcs.20.14.09.p2402.

Nasir, M. W., and Toth, Z. (2022). Effect of Drought Stress on Potato Production: A Review. Agronomy, 12(3). https://doi.org/10.3390/agronomy12030635

Nelson, D. W., andSommers, L. E. (2018). Total carbon, organic carbon, and organic matter. *Methods of Soil Analysis, Part 3: Chemical Methods*, *5*, 961–1010. https://doi.org/10.2136/sssabookser5.3.c34.

Obidiegwu, J.E., Bryan, G.J., Jones, H.G., Prashar, A., (2015). Coping with drought: stress and adaptive responses in potato and perspectives for improvement. Frontier in Plant Science, 6: 542.

Onder, S., Caliskan, M. E., Onder, D., and Caliskan, S. (2005). Different irrigation methods and water stress effects on potato yield and yield components. *Agricultural Water Management*, *73*(1), 73–86. https://doi.org/10.1016/j.agwat.2004.09.023..

Qadir, M., Sharma, B. R., Bruggeman, A., Choukr-Allah, R., and Karajeh, F. (2007). Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. *Agricultural Water Management, 87*(1), 2–22. https://doi.org/10.1016/j.agwat.2006.03.018.

Rai, A., Sarkar, S., and Jha, P. K. (2022). *Deficit Irrigation: An Optimization Strategy for a Sustainable Agriculture* (Issue December). Springer International Publishing. https://doi.org/10.1007/978-3-031-12059-6_9.

Raine, S. R., and Bakker, D. (1996). Increased Furrow Irrigation Efficiency through Better Design and Management of Cane Fields. *Proceedings of the Australian Society of*

Sugar Cane Technologists, *January*, 119–124.

Reddy, B. J., Mandal, R., Chakroborty, M., Hijam, L., and Dutta, P. (2018). A Review on Potato (Solanum Tuberosum L.) and its Genetic Diversity. *International Journal of Genetics*, *10*(2), 360. https://doi.org/10.9735/0975-2862.10.2.360-364.

Reynolds, S. P., Borkowski, K. J., Hwang, U., Hughes, J. P., Badenes, C., Laming, J. M., and Blondin, J. M. (2007). A Deep Chandra Observation of Kepler's Supernova Remnant: A Type Ia Event with Circumstellar Interaction . *The Astrophysical Journal*, *668*(2), L135–L138. https://doi.org/10.1086/522830.

Rodrigues, G. C., and Pereira, L. S. (2009). Assessing economic impacts of deficit irrigation as related to water productivity and water costs. *Biosystems Engineering*, *103*(4), 536–551. https://doi.org/10.1016/j.biosystemseng.2009.05.002.

Ruiz-Sanchez, M. C., Domingo, R., and Castel, J. R. (2010). Introduction. *Spanish Journal ofAgriculturalResearch*,*8*(2),5http://repositorio.upct.es/bitstream/handle/10317/1554/dif.pdf sequence=1 isAllowed=y

Sadik, E., Hussien, M., and Tewodros, A. (2018). Effects of seed tuber size on growth and yield performance of potato (Solanum tuberosum L.) varieties under field conditions. *African Journal of Agricultural Research*, *13*(39), 2077–2086. https://doi.org/10.5897/ajar2018.13405.

Santos Pereira, L., Cordery, I., and Iacovides, I. (2009). Coping with water scarcity: Addressing the challenges. In *Coping with Water Scarcity: Addressing the Challenges* (Issue January 2009). https://doi.org/10.1007/978-1-4020-9579-5.

Schittenhelm, S., Sourell, H. and Löpmeier, F.J. (2006). Drought resistance of potato cultivars with contrasting canopy architecture. *European Journal of Agronomy, 24*(3), pp.193-202.

Shaterian, J., Waterer, D. R., de Jong, H., and Tanino, K. K. (2008). Methodologies and traits for evaluating the salt tolerance in diploid potato clones. *American Journal of Potato Research*, *85*(2), 93–100. https://doi.org/10.1007/s12230-008-9003-9.

Shrestha, N., Geerts, S., Raes, D., Horemans, S., Soentjens, S., Maupas, F., and Clouet, P. (2010). Yield response of sugar beets to water stress under Western European conditions. *Agricultural Water Management*, *97*(2), 346–350. https://doi.org/10.1016/j.agwat.2009.10.005.

Smith, M., Allen, R., and Pereira, L. (1998). Revised FAO methodology for crop-water requirements. *International Atomic Energy Agency (IAEA)*, 51–58.

Spooner, D. M., Ghislain, M., Simon, R., Jansky, S. H., and Gavrilenko, T. (2014). Systematics, Diversity, Genetics, and Evolution of Wild and Cultivated Potatoes. *Botanical Review, 80*(4), 283–383. https://doi.org/10.1007/s12229-014-9146-y.

Steduto, P., Hsiao, T. C., and Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrigation Science*, *25*(3), 189–207. https://doi.org/10.1007/s00271-007-0064-1.

Thinking, H. S. (2022). Soil health management. *Advances in Legumes for Sustainable Intensification*, 245–246. https://doi.org/10.1016/b978-0-323-85797-0.00048-3

Tsakmakis, I. D., Zoidou, M., Gikas, G. D., and Sylaios, G. K. (2018). *Impact of Irrigation Technologies and Strategies on Cotton Water Footprint Using AquaCrop and*

CROPWAT Models Impact of Irrigation Technologies and Strategies on Cotton Water Footprint Using AquaCrop and CROPWAT Models. *November*. https://doi.org/10.1007/s40710-018-0289-4.

Ustun, S. (2006). *The_Effect_of_Deficit_Irrigation_on_Pota*.

van Halsema, G. E., Keddi Lencha, B., Assefa, M., Hengsdijk, H., and Wesseler, J. (2011). Performance assessment of smallholder irrigation in the central rift valley of Ethiopia. *Irrigation and Drainage*, *60*(5), 622–634. https://doi.org/10.1002/ird.613.

Willem, J., Fao, K., and Havard, M. (2006). *All about Potatoes A Handbook to the Ecology and Integrated Management of Potato International Potato Center (CIP-ESEAP Region) & FAO Regional Vegetable IPM Program in South and Southeast Asia In cooperation with : Lembaga Pengembangan Teknologi Pedesaa*.

Yoo, C. Y., Pence, H. E., Hasegawa, P. M., and Mickelbart, M. V. (2009). Regulation of transpiration to improve crop water use. *Critical Reviews in Plant Sciences*, *28*(6), 410–431. https://doi.org/10.1080/07352680903173175.

Zou, Y., Saddique, Q., Ali, A., Xu, J., Khan, M. I., Qing, M., Azmat, M., Cai, H., and Siddique, K. H. M. (2021). Deficit irrigation improves maize yield and water use efficiency in a semi-arid environment. *Agricultural Water Management*, *243*(August 2020). https://doi.org/10.1016/j.agwat.2020.106483.

Zwart, S. J., and Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, *69*(2), 115–133. https://doi.org/10.1016/j.agwat.2004.04.007.

7. APPENDIX

Appendices table

Table1: Metrological data of the study area

Climate Month	Max.temp (^{o}c)	Min.temp (^{o}c)	Sunshine (hr)	Wind speed (m/s)	Relative Humidity (%)	Rainfall (mm)
Jan	27.6	12.1	8.1	1.4	57	19.7
Feb	28.1	12.7	8.2	1.4	54	25.4
Mar	28.5	13.2	8.5	1.4	59	56.2
Apr	27.8	12.9	8.1	1.3	63	68.5
May	29.6	13.0	8.6	1.2	74	64.48
Jun	25. 3	12.3	6.5	1.1	75	90.1
Jul	23.5	11.5	5.3	1.1	78	122.6
Aug	23.8	11.8	5.4	0.9	77	128.3
Sep	25.1	12.5	5.2	1.3	77	102.6
Oct	26.6	11.6	8.2	1.4	71	42.3
Nov	27.1	10.5	8.8	1.5	58	23
Dec	27.8	11	8.3	1.6	53	18

Table 2: Reference evapotranspiration (ETo) by Penman-Monteith method

Climate Month	Min Temp (^{o}c)	Max Temp (^{o}c)	Humidity %	Wind speed (m/s)	Sunshine hours	Rad MJ/m²/day	ETo mm/day
Jan	27.6	12.1	8.1	1.4	57	19.9	4.15
Feb	28.1	12.7	8.2	1.4	54	21.1	4.54
Mar	28.5	13.2	8.5	1.4	59	22.5	4.7
Apr	27.8	12.9	8.1	1.3	63	22	4.46
May	29.6	13.0	8.6	1.2	74	20.6	4.25
Jun	25. 3	12.3	6.5	1.1	75	18.5	3.65
Jul	23.5	11.5	5.3	1.1	78	16.9	3.26
Aug	23.8	11.8	5.4	0.9	77	17.5	3.33
Sep	25.1	12.5	5.2	1.3	77	17.3	3.4
Oct	26.6	11.6	8.2	1.4	71	21.3	4.16
Nov	27.1	10.5	8.8	1.5	58	21	4.27
Dec	27.8	11	8.3	1.6	53	19.7	4.23

Table 3: Average infiltration rate of the experimental field soil

Time	Time difference (min)	Cumulative time	Av reading	Av difference	Infiltration rate mm/min	Infiltration rate mm/hr	Cumulative Intake depth (mm)
4:30	0	0	113	0	0	0	0
4:35	5	5	106.1	6.9	1.38	82.8	7
4:45	10	15	104.8	6.2	0.62	37.2	13
5:00	15	30	106.5	5.5	0.36	21.6	19
5:20	20	50	104	5	0.25	15	24
5:45	25	75	107.2	4.8	0.19	11.4	29
6:10	25	100	105.7	4.3	0.17	10.2	33
6:40	30	130	107.8	4.2	0.14	8.4	37
7:10	30	160	107	4	0.13	7.8	41
7:40	30	190	105	4	0.13	7.8	45

Table 4: Time calculated to irrigated for Irish potato experimental trial

Date	Stage	IRn(mm)	Irg(mm)	Q(l/s)	Area (m2)
3-Mar	Init	32.8	54.7	1.7	12
10-Mar	Init	19.5	32.5	1.7	12
17-Mar	Dev	20.4	34	1.7	12
24-Mar	Dev	23.8	39.7	1.7	12
31-Mar	Dev	26.3	43.9	1.7	12
7-Apr	Dev	33.1	55.1	1.7	12
14-Apr	Dev	36	60.1	1.7	12
21-Apr	Mid	35	58.3	1.7	12
28-Apr	Mid	34.7	57.8	1.7	12
5-May	Mid	33.9	56.5	1.7	12
12-May	Mid	33.3	55.6	1.7	12
19-May	Mid	32.6	54.4	1.7	12
26-May	End	30.9	51.5	1.7	12
2-Jun	End	29.1	48.5	1.7	12
9-Jun	End	25.5	42.5	1.7	12
14-Jun	End	446.9	745.1		

T1 mint	T2 mint	T3 mint	T4 mint	T5 mint	T6 mint	T7 mint	T8 mint	T9 mint	T10 mint	T11 mint	T12 mint	T13 mint
6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44	6.44
3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82
4.00	3.40	2.80	2.20	1.60	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
4.67	3.97	3.27	2.57	1.87	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67
5.16	4.39	3.62	2.41	2.07	5.16	5.16	5.16	5.16	5.16	5.16	5.16	5.16
6.48	5.51	4.54	3.57	2.59	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48
7.07	6.01	4.95	3.89	2.83	7.07	7.07	7.07	7.07	7.07	7.07	7.07	7.07
6.86	6.86	6.86	6.86	6.86	5.83	4.80	3.77	6.86	6.86	6.86	6.86	6.86
6.80	6.80	6.80	6.80	6.80	5.78	4.76	3.74	6.80	6.80	6.80	6.80	6.80
6.65	6.65	6.65	6.65	6.65	5.65	4.65	3.66	6.65	6.65	6.65	6.65	6.65
6.54	6.54	6.54	6.54	6.54	5.56	4.58	3.60	6.54	6.54	6.54	6.54	6.54
6.40	6.40	6.40	6.40	6.40	5.44	4.48	3.52	6.40	6.40	6.40	6.40	6.40
6.06	6.06	6.06	6.06	6.06	6.06	6.06	6.06	6.06	5.15	4.24	3.33	2.42
5.71	5.71	5.71	5.71	5.71	5.71	5.71	5.71	5.71	4.85	3.99	3.14	2.28
5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.25	2.98	2.75	2.00

T1 = treatment 1, T2 = treatment 2, T3 = treatment 3, T4 = treatment 4, T5 = treatment 5, T6 = treatment 6, T7 = treatment 7, T8 = treatment 8, T9 = treatment 9, T10 = treatment 10, T11 = treatment 11, T12 = treatment 12 and T13 = treatment 13.

Table 5: Free flow discharge values for different size of Parshall flumes

Head (cm)	Throat width (inches)				
	1	2	3	6	9
	Discharge (l/s				
2	0.140	0.281			
3	0.263	0.526	0.772	1.496	2.504
4	0.411	0.822	1.206	2.357	3.889
5	0.581	1.162	**1.705**	3.354	5.471
6	0.771	1.541	2.261	4.473	7.232
7	0.979	1.957	2.872	5.707	9.155
8	1.205	2.407	3.532	7.047	11.231
9	1.446	2.889	4.239	8.489	13.448
10	1.702	3.402	4.991	10.027	15.801
11	1.973	3.943	5.786	11.656	18.281
12	2.258	4.513	6.621	13.374	20.855
13	2.557	5.109	7.496	15.177	23.605
`14	2.868	5.731	8.408	17.062	26.440
15	3.191	6.377	9.358	19.027	29.383
16	3.527	7.048	10.342	21.070	32.433
17	3.875	7.743	11.361	23.188	35.585
18	4.234	8.460	12.413	25.38	38.837
19	4.604	9.200	13.499	27.643	42.186
20	4.985	9.961	14.616	29.976	45.630
21	5.376	10.744	15.764	32.379	49.167
22		11.547	16.942	34.848	56.510
23			18.151	37.384	56.510
24			19.389	39.984	60.312

Table 6: Analysis of variance for all phonological growth parameters and yield and yield components of Irish potato response to water stress levels at different growth stages

Mean square values of Potato

SV	DF	D50%F	DM	PH	LN	LA	LAI	TN	TD	MTY	UMTY	TTY
REP	2	10.2	11.1	0.4	1825.9	5.4	0.03	1.9	3.2	2.1	0.5	0.7
TRT	12	76.2	41.7	38.7	8128.2	58.8	2.1	5.2	21.6	24.5	0.3	24.9
Error	24	4.4	2.2	0.2	396.5	0.7	0.01	0.6	0.9	0.5	0.1	0.5
P-value	-	<0.01**	0.01**	0.01**	0.01**	0.01**	0.01**	0.01**	0.01**	0.01**	0.06ns	0.01**

NB. **= highly significant at p<0.01 level of probability, and *= significant at p<0.05 level of probability and ns = not significant at p<0.05 at level of probability. SV = source of variation, REP = replication, TRT = treatments, DF = degree of freedom, D50%F = days to 50% flowering, DM = days to maturity and PH = plant height, LN = leaf number, LA = leaf area, LAI = leaf area index TN = tuber number, TD = tuber diameter, MTY = marketable tuber yield, UMTY = unmarketable tuber yield, and TY = total tuber yield.

Appendix figure 1: Soil sample collecting before layout preparation and planting Irish potato

Appendix figure 2: Irrigation water source coming canal and division box.

Appendix figure 3: Layout and furrow preparation

Appendix figure 4: Seed planting hole and fertilizer sowing place preparation

Appendix figure 5: Fertilizer NPS and Urea application and mixing with soil

Appendix figure 6: Sprouted Gudene variety of Irish potato seed and planting on the prepared hole

Appendix figure 7: After plantation common irrigation and irrigation process through growth stage cleaning furrow siltation and first round cultivation status

Appendix figure 8: Second round cultivation and plant height measurement

Appendix figure 9: Flowering stage and maturity stage status with plant height measurement

Appendix figure 10: During harvesting status of image and measuring the necessary data

BIOGRAPHY

The author Mohammed Ahmed was born on September 18, 1993 G.C in Meskan district, now East Gurage zone, SNNPR (now Central Ethiopia Region), Ethiopia from his father **Ahmed Sule** and his mother **Aysha Dedgeba**. He attended his elementary education (1-8) at Dobo Tuto primary school from (1999 to 2008); his junior high school education (9-10) at Mekicho Millennium Secondary School from 2009 to 2010); and pursued his preparatory education (11-12) at Butajira preparatory School from 2011 to 2012.

Then, he joined Dilla University Collage of Agricultural and Natural Resource Management in 2012 and was awarded a BSc degree in Water resource and Irrigation Management in August 2015. Soon after graduation, he was employed by Werabe Agricultural Research Center of Southern Agricultural Research Institute as irrigation Agronomy researcher. He joined the School of Graduate Studies, Hawassa University, in October 2021 to pursue his **Master of Science** (MSc.) study in Irrigation and Drainage Engineering.

.