Mekelle University

Ethiopian Institute of Technology –Mekelle

Faculty of Civil and Environmental Engineering

MSc in Civil Engineering (Irrigation and drainage Engineering)

Evaluating the Response of Teff (*Eragrostis* ***tef (Zucc***) to Irrigation Water Level and Type of Surface Irrigation Methods

In Meles kebelle, Mekelle Zone of Tigray, Ethiopia

M.Sc. Thesis

By

Berhanu Haile Hadera

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Co-Advisor: Gebremeskel Aregay (Ass.Prof)

February, 2026.
Mekelle, Ethiopia

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A Master's Thesis Submitted to the Faculty of Civil and Environmental Engineering in
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In
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Advisor: Gebremdhin Gebremeskel Haile (Ph.D.)
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Board of Examiners' Approval

We, the undersigned members of Board of Examiners for the final open defense of **Berhanu Haile Hadera**, have read and evaluated the thesis entitled **"Evaluating the Response of Teff to Irrigation Water Level and Type of Surface Irrigation in Meles Kebele Mekelle zone of Tigray, Ethiopia"** and assessed the candidates performance. We hereby certify that the thesis has been accepted in in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, with specialization in Irrigation and Drainage Engineering.

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Declaration

This is to certify that this thesis entitled **"Evaluating the Response of Teff to Irrigation Water Level and Type of Surface Irrigation in Meles Kebele Mekelle Zone of Tigray, Ethiopia"** submitted in partial fulfillment requirement for the award of the Degree of M.Sc., in irrigation and drainage engineering, Mekelle University through the department of civil and environmental engineering. I seriously declare that this thesis has not been presented in any other institution anywhere for the award of any academic degree, diploma, or certificate. The undersigned, hereby declare that this thesis is my original work and all sources of materials used for the thesis have been acknowledged.

Name of student: Berhanu Haile

Signature: ____________

Date: Feb, 2026

Dedication

I dedicate this study to my dearest family, who supported and encouraged me throughout the period of this study.

Biographical Sketch

The author, Berhanu Haile, was born on August 26, 1993, to his father Haile Hadera and his mother Mitslal Meresa in Adigudem town, Southeastern Zone Tigray Region. He completed his primary education at Arena Elementary School from 1998 to 2005. After completing his elementary education, he attended Adigudem Senior Secondary and Preparatory Schools from 2006 to 2009 for his high school and preparatory studies.

In November 2010, he joined Arba Minch University and graduated a Bachelor of Science (B.Sc.) Degree in Water Resources and Irrigation Engineering on July 03, 2014. After graduation, he joined the Hintalo Woreda Water Resource Bureau, where he served as water Resource Engineering Expert for one year and six months.

In May, 2017 he joined Tigray Region Agricultural Research Institute (TARI) and worked at the Humera Agricultural Research Center (HuARC) as a researcher in irrigation, drainage and water harvesting for 2 years. In October 2020 he joined the School of Graduate Studies at Mekelle University to pursue of the Master of Science (M.Sc.) degree in Irrigation and Drainage Engineering.

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List of Abbreviations

ANOVA	Analysis of Variance
Ea	Application Efficiency
CSA	Central Statistics Agency
CWR	Crop Water Requirement
CV	Coefficient of Variance
Kc	Crop Factor
DAP	Di Ammonium Phosphate
ETc	Crop Evapotranspiration
FAO	Food Agricultural Organization
FC	Field Capacity
GIWR	Gross Irrigation Water Requirement
HI	Harvest Index
IWMI	International Water Management Institute
LSD	Least Significance Difference
MoA	Ministry of Agriculture
MoWR	Ministry of Water Resource
NIWR	Net Irrigation Water Requirement
PWP	Permanent Wilting Point
ETo	Reference Evapotranspiration
TAW	Total Available Water
UN	United Nation
USDA	United States Department of Agriculture

Abstract

Water scarcity is the major limiting factor for crop yield production. In this case, the need to use the available water economically and efficiently is indisputable. Both the irrigation water level and the type of surface irrigation are very important to manage the poor irrigation water management practices. The field experiment was carried out at Mekelle Agricultural Research site in Mekelle zone, Tigray, Ethiopia, during the 2024 irrigation season with the objective of evaluating the response of Teff to irrigation water level and type of surface irrigation on yield, some yield components, and water productivity of Teff. The experiment was laid out in split plot design with three replications. The experiment contains three irrigation water levels of application (100% CWR, 75% CWR, and 50% CWR) and two methods of irrigation (furrow and basin). Soil depth at 0-30cm was conducted using the gravimetric method. Data on growth and yield components were recorded and subjected to ANOVA using GenStat 16th edition software. Analysis of variance indicated that the treatment interactions of irrigation interval with irrigation water level were significantly ($p<0.05$) affected on water productivity, yield, and yield components of Teff. The highest grain yield (30.63q/ha), biomass yield (119.58q/ha), and water productivity (1.0392kg/m^3) of Teff were obtained under the furrow irrigation method with 75% crop water requirement. Therefore, the deficit irrigation technique reduces irrigation water application and improves water productivity. If water saving is a major issue, then some yield reduction must be accepted, as shown by the trade-off in this study between water saving and yield loss. Farmers, water managers, water users' associations, and decision makers can save irrigation water and improve crop productivity using deficit irrigation, and increase their agricultural production by expanding irrigable land with the same amount of water in a given irrigation scheme.

Key words: irrigation level, water productivity, irrigation type, GenStat, Teff

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CHAPTER 1: INTRODUCTION

1.1 Background and Justification

The global population, which was approximately 7 billion in 2015, is expected to reach around 9 billion by 2050 (UN, 2015). This rapid population growth, particularly in the least developed countries, presents a significant challenge to global food systems. At the same time, the standard of living in many emerging economies, home to nearly 75% of the world's population is rising rapidly. These dual trends of population growth and rising living standards are driving unprecedented demand for food, which in turn requires a substantial increase in agricultural production to ensure sustainable food security (Yihun, 2015).

Irrigation is an age–old practice, perhaps as ancient as human civilization. It has long been a fundamental component of agriculture systems, enabling consistent crop production in regions with unreliable rainfall. Irrigated lands constitute only about 20% of the world's farm land, yet they contribute significantly to global food production (Yihun, 2015). As the global population continues to grow, the demand for food is rising sharply, encouraging the need for a rapid and sustainable expansion of irrigated agriculture to meet this challenge (Awlachew et al., 2005). Therefore, it is vital to bring large areas of Ethiopia's arid, semi-arid, and sub-humid regions, where rainfall is often uneven and unreliable, under effective irrigation systems. Irrigated agriculture plays a significant role in growing crops, maintaining the landscape, and vegetating disturbed soils in dry areas during periods of less rainfall. It provides the livelihood of an enormous part of the world's population and supplies a large portion of the world's food. Agriculture, which uses approximately 70% of the world's freshwater withdrawals for irrigation, is the largest consumer of water resources globally (Jaehak Jeong, 2020). This production sector is made by surface methods of irrigation, especially by furrow irrigation systems, which account for 97.8% of farmers' fields and the majority of commercial farms (Sleshi, 2011). Furrow irrigation is the most widely used surface irrigation method for water application to cropped fields. This type of irrigation is commonly used in arid and semi-arid areas to supply water for crops and requires a smaller initial investment; no more effort is required to keep improving its management and efficiency (Gelu, 2018).

In addition to increasing overall food production, improving irrigation water productivity is crucial to meet the growing water demands of the agricultural sector. With increasing competition for water from other sectors such as industry, hydropower, and domestic use, irrigated agriculture is under increasing pressure to use water more efficiently. Therefore, the challenge lies in producing sufficient food for a growing population while minimizing the share of water allocated to agriculture.

Ethiopia cultivates a wide variety of crops, vegetables, pulses, oil crops, cereals, fruits, tubers, and root (Yihun, 2015). Among these, Teff is the most important and stable food crop in the country. Traditionally, Teff was a rain-fed crop and harvested only once a year, it‘s production is limited by seasonal rainfall. Consequently, its supply often falls short of demand, contributing to a steady rise in market prices. To stabilize and potentially reduce the market price, there is a persistent need to increase the domestic supply of Teff, particularly through the introduction of irrigation. Teff holds a central place in Ethiopian culture and food. It is primarily used to make Injera a staple flatbread as well as porridge and various home-brewed alcoholic drinks (Divison & McKnight, 2004). Beyond its grain, Teff straw is highly valued by Ethiopian farmers, especially during dry seasons when other livestock feed sources become scanty. Cattle show a marked preference for Teff straw over other cereal straws.

Research indicates that Teff is well adapted to a wide range of environmental conditions ranging from drought-stressed to waterlogged soils (Roseberg et al., 2006). Despite originating and being widely cultivated in Ethiopia, where it has undergone significant diversification (Assefa et al., 2003) there has been relatively limited research on the crop’s agronomic and physiological responses to various environmental stresses, especially water availability. This knowledge gap highlights the need for further field-based research to determine the optimal water management practices for Teff and support its broader introduction into irrigated agricultural systems. In the study area, the lack of using proper irrigation methods and irrigation water level needs to be addressed to increase the productivity of Teff on a sustainable basis. There is a growing interest in irrigating with different levels of irrigation water to improve crop water productivity. Crop water productivity is increasing by reducing water use in water scarcity area (Hoekstra, 2017).

1.2 Statement of the Problem

The Ethiopian economy was heavily dependent on rain-fed agriculture. However, rainfall in most parts of the country is not only inadequate and erratic but also highly vulnerable to the effects of climate variability and drought. Moreover, traditional farming practices, undulating topography, and the widespread degradation of natural resources driven by both human activities and environmental factors have further exacerbated the situation. As a result, land productivity is declining at an alarming rate (Yihun, 2015) and the country struggles to meet the annual food requirements of its population.

In this context, it is essential to explore alternative strategies for improving agricultural productivity, particularly in the face of water scarcity. One such promising strategy is the application of deficit irrigation techniques, which involve applying less water than full crop water requirements at certain growth stages. These methods have been shown to enhance economic water productivity by producing acceptable yields with reduced water input, especially under drought-prone conditions.

In the study area, the farmers are not getting as much yield as expected due to various reasons. Limited knowledge of irrigation water level and the method of irrigation they used can be some of the reasons. They practice by the method of traditional flooding, which has poor irrigation water management. They applied based on observation and performance. That is when the land starts cracking and when the leaves of the cereals wilt, then the farmers decide to irrigate their cereals. This leads to water scarcity in the irrigation area. Consequently, number of farmers has been out of production in the irrigation area during the irrigation time.

Stage-wise deficit irrigation as defriend by (English et al., 1990) aims to increase water productivity (WP) and thereby enhance overall agricultural productivity. Studies have shown that stage-wise deficit irrigation has significantly increased grain yield, crop evapotranspiration, and water productivity as compared to the corresponding rain-fed productions (Oweis et al., 2000). However, the successful implementation of such techniques requires precise insights of crop response to water and methods of irrigation. Given its economic, nutritional, and cultural importance, Teff is a priority crop for such investigation. Despite its adaptability to a range of environmental conditions, there is limited field-based research on how Teff responds to various levels of irrigation and drought stress. Therefore, studying the effects of stage-wise deficit irrigation on the water productivity, growth, and yield performance of Teff is critical. Additionally, applying physiological approaches to assess Teff's drought tolerance will provide valuable understandings into its resilience and inform better water management strategies. This is particularly important for Ethiopia, where Teff holds significant economic, social, and food security value. Enhancing Teff productivity through efficient irrigation practices could play a vital role in improving national food security and promoting sustainable agricultural development.

1.3 Objectives

1.3.1 General Objective

Evaluating the effect of irrigation water levels and the type of surface irrigation methods on yield and water use efficiency of Teff under irrigated agricultural land.

1.3.2 Specific Objectives

- To evaluate the response of Teff for different irrigation water levels.
- To identify a better surface irrigation method for Teff cereal crop.
- To estimate water use efficiency, water productivities of Teff at different irrigation water levels.

1.4 Research Hypothesis

The use of different irrigation water levels combined with the method of surface irrigation has significant effect on water productivity, yield, and yield components of Teff.

The use of different irrigation water levels combined with the method of surface irrigation has no significant effect on water productivity, yield, and yield components of Teff.

1.5 Significance of the Study

In regions where water supply is scarce and drought is recurrent, deficit irrigation has occurred as a practical and economically possible approach to increasing agricultural productivity. Stage-wise deficit irrigation has the fundamental goal to enhance water productivity (WP) by applying water strategically. This study, which examines the effect of different irrigation water levels and types of surface irrigation methods on the yield, yield components, and water productivity of Teff, is practically important given the crop's central role in Ethiopian agriculture and food security. By identifying the efficient irrigation methods and optimal water application levels for Teff, this provided valuable understanding into how to increase Teff productivity under water-limited conditions. The results of this study can be used as fundamental for future research on Teff agronomy and irrigation practice.

It additionally offers practical benefit to farmers, those operating in water-scarce areas, by guiding how to improve water use efficiency and crop yield. Furthermore, the findings can support policymakers and agricultural planners in making informed decisions about water allocation, irrigation infrastructure development, and sustainable land water resource management. The study underlines the importance of adapting irrigation practices to local environmental conditions and resource constraints, particularly for a staple crop like Teff that is both economically and culturally significant in Ethiopia.

1.6 Scope of the Study

This study was conducted at Mekelle Agricultural Research Center, specifically at the Illala site, over a single growing season from February 23, 2024, to June 07, 2024, covering a total of 105 days. The study was mainly focused on evaluating the effects of different irrigation water levels and methods of surface irrigation on yield and yield components and water productivity of Teff.

CHAPTER 2: LITERATURE REVIEW

2.1 Concepts and Definitions Related to Irrigation

Irrigation is the artificial application of water to soil primarily for crop production. It supplements the natural water supply from rainfall and groundwater contributions to maintain adequate soil moisture for plant growth (Michael, 1997). Irrigation is also defined as an artificial application of water to soil for the purpose of supplying the moisture essential in the plant root-zone to prevent stress that may cause reduced yield and/or poor quality of harvest of crops (Reddy, 2010). This is an intentional action made by humans to apply water for growing crops, especially during dry seasons where there is a shortage of rainfall (Reddy, 2010).

2.2 Irrigation History in Ethiopia

Different scholars have explored the historical perspectives of irrigation in Ethiopia. Yet there remains some ambiguity regarding its origins and development. For instance, (Sulas et al., 2009) found in a study investigating whether irrigation was a key factor in state formation and urban development in the ancient Axum civilization of, Northern Ethiopia, found in-sufficient information regarding of water managements of rain-fed agriculture. However, traditional irrigation in Ethiopia was practiced for centuries (Bekele Y, 2012). In the Ethiopian highlands, an irrigation practice has been practiced since ancient times, primarily to produce subsistence food crops (Awulachew SB, 2007). (Hagos, 2009) Emphasized that supplementary irrigation has been employed by smallholder farmers of Ethiopia for centuries to solve their livelihood challenges. Additionally, Spate irrigation, a method involving the diversion and management of flood waters, has traditionally been used in Ethiopia, particularly in Southern Tigray and in some semi-arid areas in Oromia region (Mehari A, 2011). This irrigation system captures water from flash floods originating from upper catchments, allowing for seasonal irrigation in water-scarce areas.

The development Irrigation in Ethiopia, especially small-scale irrigation, has a long-standing history. Modern irrigation practices however, started in the 1950s through collaboration between the Ethiopian Government and foreign companies, concentrating mainly on the commercial irrigated farms in the Awash Valley (Yalew, 2010). Historical records suggest that irrigation in Ethiopia was introduced with the arrival of Semitic immigrants from Yemen and, possibly, agriculturalists from Sudan. Seed cultivation involving irrigation was practiced in Northern Ethiopia during the era of the Axum Empire around 1000 B.C., introduced by these groups (Eliyas, 2011). This indicates that irrigation in Ethiopia though ancient, cannot be classified scarcely as a modern practice.

From the above discussions, the exact date when irrigation was started in Ethiopia remains uninvestigated, regardless of regularly saying "irrigation was started in Ethiopia during ancient times" (Awulachew SB, 2007) (Hagos, 2009) . Most of the traditional irrigated lands in Ethiopia are dominantly supplied by surface water sources, while groundwater uses has just been started on a pilot basis in the East Amhara region (MoA, 2011a).

In1970, modern Small-Scale Irrigation (SSI) practices and management were introduced by the Ministry of Agriculture as a response to recurrent droughts, which caused widespread crop failures and consequently hunger and starvation (Awlachew et al., 2010). According to (MoA, 2011a) pressurized sprinkler irrigation system were implemented on farms such as Fincha State Farm, in Eastern Amhara, Southern Tigray, and on some private farms in the Rift Valley. The Rift Valley is a place where modern irrigation in Ethiopia starts especially in the Awash River Basin at which adoption of pump-irrigation commences.

Surface irrigation methods, including furrow and basin irrigation were predominantly practiced for the cultivation of cotton, wheat, and commercial fruits such as bananas. Meanwhile, similar reports such as (Awlachew et al., 2007) explained that irrigated agriculture was started in Ethiopia in the upper Awash Valley with the objective of producing industrial crops such as sugarcane, cotton, and horticultural crops on a large-scale basis, explaining the remarkable emergence of irrigation development and establishment of agro-industrial centers. This was due to taking an advantage of the construction of Koka dam, aimed as a reservoir irrigation water supply, flood control, and hydropower generation. During the mid-1970s, windmills and hand pumps were introduced to lift water from groundwater for drinking water supply, domestic and gardening purposes (MoA, 2011a).

Irrigation practices in Ethiopia have played a crucial role in reducing the risk of crop failure due to drought. The government has increasingly focused on developing the sector to its full potential by supporting local farmers to improve irrigation techniques and promoting modern irrigation methods (Awlachew et al., 2005).

2.3 Ethiopia Irrigation Potential

According to (FAO, 1997) irrigation potential refers to a combination of factors including gross irrigation water requirements, the area of soil suitable for irrigation, available water resources by basin and consideration of environmental and socio-economic constraints. Various studies estimate Ethiopia's irrigation potential, ranging from 1.0 to 3.5 million hectares of irrigable land. Currently only about 160,000 to 190,000 hectares are under formal irrigation, while an additional 65,000 hectares of land are estimated to be irrigated using traditional methods (IWMI, 2002)

Estimation of the irrigation potential of Ethiopia varies from one source to the other. This variation is due to lack of standard or conventional criteria for estimating irrigation potential in the country. The irrigation potential of Ethiopia is estimated as 4.3million hectares (WorldBank, 1973). There have also been different estimates of the irrigation potential in Ethiopia. The total irrigable land in Ethiopia accounted for 2.3 million hectares (MoA, 1986), while (IFAD, 1987), on the other hand, gave 2.8milion hectare and a total of 3.7 million hectare potentially irrigable land (MoWR, 2002). An estimated the total irrigable land potential in Ethiopia. According to their estimation, the value was figured out as 5.3 million hectare assuming the use of existing technologies like rainwater harvesting and groundwater exploration, which accounts for 1.6 million hectares of land. However, Ethiopia accounts as 112 million hectares of land. From this coverage of land, the estimated cultivable land is ranges from 30 to 70 million hectares. Estimates show that only 15million hectare of land is under cultivation, from 30 to 70million hectares of land currently (Silesh B, 2010). Only about 4 to 5% of land is irrigated with the existing irrigation schemes from the existing cultivated land. This ground indicates that only a few portions of potentially cultivable land are under cultivation, while a few portions of potentially irrigable land are under irrigation. The implication shows that there are still an opportunities to increase the amount of irrigable land in the country.

Overall Ethiopia's irrigation potential is estimated at around 5.3 million hectares, with about 3.7 million hectares developable through surface water sources and 1.6 million hectares via groundwater and rainwater management (Awulachew & Mekonen, 2011).

2.3.1 Surface Water Resources: River Basins

Ethiopia endowed with 12major river basins, which serve as the primary sources of the country's surface water resources. The combined mean annual flow from these basins is estimated at approximately 122 billion cubic meters (MoWR, 1999). These basins vary widely in terms of size, hydrology, and potential for irrigation development. These river basins collectively offer immense potential for expanding irrigation infrastructure, hydropower generation, and water supply systems, contributing significantly to Ethiopia’s socio-economic development.

Table 1: Irrigation potential in river basin Ethiopia

Basin	catchment area (km^2)	Irrigation potential (Ha) (respective recent master plan studies)				Irrigation potential (WAPCOS 1995)		
		Small-scale	Medium-scale	Large-scale	Total	Total Drainage Area(km^2)	Irrigable Area(Ha)	Irrigable Area (%)
Abbay	198,890.7	45,856	130,395	639,330	815,581	201,346	1,001,000	27
Tekeze	83,475.94	N/A	N/A	83,368	83,368	90,001	317,000	8.5
Baro-Akobo	76,203.12	N/A	N/A	1,019,523	1,019,523	74,102	985,000	26.5
Omo-Ghibe	79,000	N/A	10,028	57,900	67,928	78,213	445,000	12
Rift Valley	52,739	N/A	4,000	45,700	139,300	52,739	139,000	3.7
Awash	110,439.3	30,556	24,500	79,065	134,121	112,697	205,000	5.5
Genale Dawa	172,133	1,805	28,415	1,044,500	1,074,720	117,042	423,000	11.4
Wabi Shebele	202,219.5	10,755	55,950	171,200	237,905	102,697	200,000	5.4
Denakil	63,852.97	2,309	45,656	110,811	158,776	74,102	-	-
Ogaden	77,121	-	-	-	-	77,121	-	-
Ayisha	2,000	-	-	-	-	2,000	-	-
Gulf of Aden	-	-	-	-	-	-	-	-
Total	1,118,074.53				3,713,222	982,060	3,715,000	100

Source (Awulachew & Mekonen, 2011)

2.3.2 Surface Water Resources: Lakes and Reservoirs

Ethiopia has a total surface area of about 7,500km^2 coved by natural and artificial lakes (MCE, 2001). These include a variety of water bodies such as fresh and saline lakes, crater lakes, as well as swamps or wetlands.

2.3.3 Groundwater Resources System

Compared to surface water resources, Ethiopia's groundwater potential is relatively lower. However, by international standards, the country's total exploitable groundwater resource is still considerable. Based on limited data, the annual rechargeable groundwater potential is estimated at approximately 2.6 Billion Cube Metric (Bm^3) (Tadesse, 2004). It is further estimated that about 13.2 billion cubic meters (Bm^3) of water infiltrates into the groundwater system annually, of which nearly 50% could be sustainably extracted.

2.4 Use of Irrigation Water in Ethiopia

Water is mankind's most vital and versatile natural resource (Nata T, 2008) and has always played an essential role in Ethiopian society, as it is an essential input to almost all production systems (MoWR, 2006) Water is also considered as an essential resource for irrigation. Irrigation can be defined as an artificial application of water to soil to supply the moisture necessary in the plant root-zone to prevent stress that could reduce yield and or quality is key use of water (Reddy, 2010). This human-driven practice is especially important during dry seasons when rainfall is insufficient for crop growth.

There are various methods of applying water to crop fields. The most commonly used and oldest method is surface irrigation, which relies on gravity to distribute water. This traditional technique has been practiced particularly in riverside areas and does not require mechanized equipment (FAO, 2002). In recent years, modern irrigation systems have become more prevalent, using pressurized energy to deliver water efficiently. Sprinkler and drip irrigation systems are examples of such technologies (FAO, 2001). In Ethiopia, irrigation is considered a fundamental strategy to improve poverty and hence food security. It facilitates the transformation from purely rain-fed agricultural to a combined rain-fed and irrigated farming system, which is considered essential for sustainable development in the country. However, the history and development of irrigation practices in Ethiopia need further investigation to better understand their emergence and its progress over time.

2.5 Deficit Irrigation

Water is as an essential resource for irrigation. Irrigation can be defined as an artificial application of water to soil for the purpose of supplying the moisture essential in the plant root-zone to prevent stress that may cause reduced yield and/or poor quality of harvest of crops (Reddy, 2010). Effective irrigation practices can improve yields and quality, minimize water productivity, and protect natural resources. Deficit irrigation is an irrigation practice whereby water supply is reduced below maximum level, and minor stress is allowed, during the growing season, without significant yield reduction.

According to (Kirda, 2002), deficit irrigation is a strategy that permits crops to endure some degree of water stress during growing season to save irrigation water. This means that total irrigation applied is not proportional to the crop's full water requirement throughout the growth cycle. While these inevitable leads to some drought stress and consequently in production loss, deficit irrigation aims to maximizes water productivity, which is critical where water is limited (English et el., 1990). In this method, the crop experiences a controlled level of water stress during the entire growing season (Bekele & Ketema, 2007) Crop water production functions are used to quantify the effects of water deficit on crop yield.

Deficit irrigation is increasingly recognized as an effective solution to water scarcity. It maximizes water productivity achieving higher yields per unit of irrigation water applied, and serves as a vital strategy to reduce agricultural water use, especially in arid and semi-arid regions (Bekele & Ketema, 2007).

2.6 Surface Irrigation Methods

Surface irrigation is the oldest and most common method of applying water to croplands. Also referred to as flood irrigation, the essential feature of this irrigation system is that water is applied at a specific location and allowed to flow freely over the field surface, and thereby apply and distribute the necessary water to refill the crop root zone. This can be contrasted to sprinkle or drip irrigation where water is distributed over the field in pressurized pipes and then applied through sprinklers or drippers to the surface. Surface irrigation has evolved into an extensive array of configurations that can broadly be classified as basin irrigation, border irrigation, furrow irrigation and wild flooding.

2.6.1 Furrow Irrigation Method

Furrow irrigation is a surface irrigation method in which water flows through small channels, known as furrows, which are made between crop rows. The water moves by gravity along the furrows and infiltrates into the soil to reach the plant roots. The furrow irrigation method has several advantages. It reduces water contact with plant stems, which helps minimize disease. It is suitable for row crops and can be used on gentle slopes. In addition, it has lower construction costs compared to pressurized irrigation systems.

However, furrow irrigation also has some disadvantages. Water distribution can be uneven, especially between the upper and lower parts of the field. There is a risk of water loss through runoff and deep percolation. The method requires good land leveling and careful management. It is not suitable for very sandy soils, and small-seeded crops, may suffer from seed wash.

2.6.2 Basin Irrigation Method

Basin irrigation is a surface irrigation method in which the field is divided into level basins surrounded by bunds. Water is applied to each basin and allowed to pond and infiltrate uniformly into the soil. This method offers several advantages. It provides uniform water distribution and is simple to operate and manage. It is particularly suitable for small-seeded crops and works well on flat land. Additionally, it requires relatively low labor during irrigation events.

Despite its advantages, basin irrigation also has some disadvantages. It requires excellent land leveling to function effectively. There is a risk of waterlogging, and it can promote increased weed growth. Furthermore, it is not suitable for sloping land.

2.6.3 Teff Response to Surface Irrigation Methods

Irrigation method is a critical factor influencing Teff (Eragrostis tef) productivity, as it affects soil moisture distribution, water use efficiency, and biomass partitioning. In smallholder farming systems in Ethiopia, basin (or traditional flat) irrigation is commonly practiced. While this method is simple and requires minimal labor, it often results in uneven water distribution, leading to localized waterlogging in some areas and moisture stress in others, which can reduce both biomass and grain yield (Mengistu et al., 2018). On the other hand, furrow irrigation, which directs water through small channels along crop rows, improves infiltration uniformity and reduces water loss through surface runoff and evaporation. Although studies specifically on Teff are limited, research on related cereals such as wheat and barley indicates that furrow irrigation tends to enhance biomass accumulation, grain yield, and water productivity compared to basin methods (Kebede et al., 2024; Amare & Abebe, 2020). By extension, Teff is likely to show similar advantages under furrow irrigation, particularly under controlled water application.

Despite these insights, there is a notable gap in literature comparing Teff productivity under different surface irrigation methods, particularly when combined with varying irrigation water levels. Few studies have quantified how Teff grain yield, biomass, and harvest index respond under basin versus furrow irrigation at full, moderate, or deficit water supply.

2.7 Description of Teff Crop

Teff (*Eragrostis tef* (Zucc.) Trotter) belongs to the family Poaceae, subfamily Eragrostoideae, tribe Eragrosteae, and genus *Eragrostis*. The genus *Eragrostis* includes about 300 species (Demissie, 2001). Of those species, approximately 43% are believed to have originated in Africa. 18% In South America, 12% in Asia, 10% in Australia, 9%in Central America, 6% in North America, and 2% in Europe (Costanza, 1979). Ethiopia is home to 54 Species of Eragrostis of which 14(or 26%) are endemic (Cufodontis, 1974).The genetic diversity of Teff is unique to Ethiopia with identifying the country center of origin and diversity of this crop (Vavilov, 1951).

Among Ethiopia’s major staple crops are cereals, pulses, oilseeds, and coffee. Cereals constitute the primary field crops and are the backbone of the Ethiopian diet, with Teff being the principal grain. Teff is an important food source used predominantly to make *Injera,* a traditional Ethiopian pancake. The word ‘Teff’ is thought to have been derived from Ethiopian Amharic word *teffe,* which means lost reflecting the grain's tiny size and how easily it can be lost if dropped. Teff is the smallest grain in the world, measuring only about 1/32 of inch in diameter. It takes approximately 150 grains of Teff to equal the weight of one wheat grain. Due to its small size, the bulk of Teff grain consists of bran and germ, making it highly nutrient-dense (http://chetday.com/teff.html).

2.7.1 Teff Production

Teff [*Eragrostis tef (Zucc*.) Trotter] is an indigenous staple cereal crop of Ethiopia, cultivated on approximately 2.6 million hectares, accounting for about 23% of the country’s grain crop area, more than any other major cereals such as maize (16%), sorghum (14%), and wheat (13%) Central Statistical Agency (CSA, 2008). Ethiopia is recognized as the center of origin and genetic diversity for Teff, with Ethiopians being the first to domesticate this unique cereal (Seyfu, 1997).

Teff is favored by farmers due to its low risk profile (Minten B, 2016). Among the 12 million smallholder farmers in Ethiopia, around 6.2 million cultivated Teff between 2004 and 2014 (Bachewe F, 2015). The crop has a short growing period, maturing in two to five months after sowing (Crymes, 2015). It is relatively resistant to various biotic and abiotic stresses (Assefa et al., 2015). Allowing it to adapt to a wide range of growing conditions where major crops may fail (Zhu, 2017). Despite its significance, Teff production in Ethiopia remains at an elementary stage, with considerable potential for improvement.

2.7.2 Environmental Requirements for Teff Growth

Teff is a highly adaptable crop capable of growing in diverse environments, with altitudes ranging from sea level to 3,200 meters (Tefera, 2011). However, it is sensitive to frost and doses not tolerate freezing temperatures. Optimum yields are achieved when Teff is cultivated between 1,800 to 2,100 m, with an annual rainfall between 450 and 550 mm, and daily temperatures ranging from 15 to 27 °C. Yields reductions occur when annual rainfall drops below 250 mm or when the average temperature during pollination exceeds 22 °C. (Cheng et al., 2017) Despite having a shallow root system, Teff demonstrates notable drought resistance due its ability to rapidly regenerate following moderate water stress and complete its fruiting stage in a relatively short period of time. The crop is also photoperiod-sensitive, flowering best under approximately 12 hours of daylight.

According to (Seyfu, 1997), in Ethiopia, Teff can be cultivated from sea level up to 2,800 meters above sea level, under various rainfalls, temperatures, and soil conditions. For optimal performance, however, Teff requires an altitude between 1,800 and 2,100 meters above sea level, annual rainfall of 750 to 850 mm, and a temperature ranging of 10 to 27°C. The crop is predominantly grown on sandy loam to black clay soils.

2.7.3 Importance of Teff Crop

In recent years, Teff has gained global attention as a valuable cash crop, increasingly recognized in export market for its nutritional and health-related benefits (Provost & Jobson, 2014), one of the key health advantages of Teff is the absence of gluten in its grain, making it suitable for people with celiac disease (fikadu, 2019). Most Ethiopian farmers are motivated to cultivate Teff due to its relative merits over other cereals regarding husbandry, utilization, and economic benefits (Assefa et al., 2011). Teff grains are nutritionally superior, containing higher amounts of fiber, minerals, vitamins, and bioactive phenolic compounds compared to other cereals (Gebremariam et al., 2012). The protein content of Teff ranges from 9% to 11%, which is slightly higher than that found in sorghum (*Sorghum bicolour*), maize (*Zea mays* L.) or oats (Avana *sativa* L.) (NRC, 1996).

Economically, Teff is superior commodity in Ethiopia. It typically commands a market price two to three times higher than maize, which is country's most widely produced cereal (Assefa et al., 2015). This price premium makes Teff an important cash crop for producers. Urban affluent consumers tend to consume more Teff compared to rural populations, with estimates of average annual consumption at 61 kg per capita in urban areas versus 20 kg in rural areas. (Zhu, 2017) (Crymes.A, 2015). Globally, Teff is gaining traction as a "super food," with consumers willing to pay premium prices for Teff-based products (Zhu, 2017). A variety of value-added products, including bread, porridge, muffins, biscuits, cakes, casseroles and puddings, have been developed to capture these markets. Additionally, Teff's potential as a thickener for soups, stews, gravies, and baby foods has been explored (AgriFuture, 2017).

Despite its promising attributes, Teff faces challenges that limit its potential as a global income-generating commodity for Ethiopian producers (Cheng et al., 2017). These include relatively low yields compared to the other major cereals, high labor-input requirement, inadequate infrastructure, and limited or inefficient market access) (Abay et al., 2011).

2.8 Reference Evapotranspiration

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics.

The reference crop evapotranspiration is defined as the rate at which evapotranspiration would occur from a short green crop, completely shading the ground, uniform height, and having adequate water supply (Allen, 1998). The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development, and management practices.

There are four main methods for estimating reference crop evapotranspiration: Blaney-Criddle, radiation, pan evaporation, and modified Penman Monteith (Allen, 1998).

Among these, Modified Penman-Monteith Method is generally considered the most accurate, producing results with minimum error when compared to actual evapotranspiration from a living grass reference crop. The pan evaporation method can provide acceptable estimates depending on the pan's location, while the radiation method is suitable in regions where climatic data on temperature and sunshine or radiation are available, but wind speed and humidity data are missing. The Blaney-Criddle method, which requires only temperature data, is recommended for areas with limited climatic information (Smith, 1992).

Penman-Monteith method integrates multiple weather variables that influence reference evapotranspiration, such as air temperature (maximum and minimum), air relative humidity, wind speed, and sunshine hours. However, in many locations, especially in developing countries, these data are not always available or reliable. Since air temperature data are more recorded worldwide, while the remaining variables are only collected at relatively few locations and those recordings are not always very reliable. This lack of reliable weather data led to the suggestion of using a simple reference crop evapotranspiration estimation equation, comparing and calibrating the same with standard Penman-Monteith equation. A relationship of other methods which require limited data, with Penman-Montieth method will facilitate increasing the accuracy of those methods (Smith, 1992).

The FAO Penman-Monteith equation used for calculating reference evapotranspiration is expressed as follows (Allen, 1998).

$$ETo = \frac{0.408\Delta(Rn-G)+y+\frac{900}{T+273}u2+es-ea)}{\Delta+Y)1+0.34u2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where

ETo = reference evapotranspiration [mm/day],

Rn = net radiation at the crop surface [MJ/m^2/day],

G = soil heat flux density [MJ/m^2/day],

T = air temperature at 2 m height [°C],

u2 = wind speed at 2 m height [m/s],

es = saturation vapor pressure [kPa],

ea = actual vapor pressure [kPa],

es – ea = saturation vapors pressure deficit [kPa],

Δ = slope vapor pressure curve [kPa/C°],

γ = psychometric constant [kPa /C°].

This method is widely used globally due to its reliability and comprehensive use of climatic parameters that affect evapotranspiration.

2.9 Crop Water Requirement (CWR)

Crops need a continuous and the right amount of water from the time of sowing to maturity. The rate of use of water is not the same for all crops. The rate of use of water varies with the kind of crop grown, time taken by the crop to mature, and the weather conditions such as temperature, wind, solar radiation, and relative humidity. The amount of water used in producing a crop is commonly referred to as consumptive use or evapotranspiration. It includes the water transpired by the leaves of the plants and evaporated from the wet soil. Part of the consumptive use requirement may be satisfied by rainfall during the growing season or precipitation before planting and retained in the soil. The amount of water needed in addition to effective rainfall to satisfy the consumptive use requirement of the crop is referred to as the consumptive use of applied water. This is the amount that must be supplied by irrigation (Sahasrabudhe, 1996). The water requirement of a crop is the total amount of the water required to sustain the normal growth of the plant. This includes the amount of water required to meet losses through evaporation, losses through transpiration, plant metabolism needs, application losses, and special needs (Sahasrabudhe, 1996).

2.10 Previous Researches on Teff under Irrigation

Effective irrigation practices play a crucial role in improving crop yields, enhancing water productivity, and conserving natural resources. One such approach gaining attention is deficit irrigation, a strategy aimed at optimizing the use of limited water resources by intentionally applying water below full crop water requirements while allowing mild water stress to crops (Geerts & Raes, 2009). This technique helps maximize yield per unit water applied, thereby improving overall water use efficiency (Abdel-Aziz, 2017). Deficit irrigation involves reducing water supply below the maximum level, permitting controlled water stress during non-critical growth stages without severely impacting final yields (yenesew & Ketama, 2009).

In Ethiopia, several studies have been conducted to evaluate the effect of different irrigation levels on Teff (*Eragrostis teff*), which is stable cereal crop in the region. (Yihun,2015), Was conducted at Melkasa, Genchi watershed in Central Ethiopia during the 2010-2012 growing season, aiming to optimize agricultural water productivity for irrigated Teff (*Eragrostis tef*). The study employed four irrigation levels, 25%, 50%, 75% and 100% of crop evapotranspiration (ETc) in a randomized complete block design with three replications. The result indicated that the highest average Teff yield of 3.3t/ha was achieved under full irrigation (100%ETc), meanwhile, the lowest yield (0.45t/ha) was recorded under the most sever water deficit (25%ETc). At 75% ETc, the yield was 2.45t/ha, and the crop water productivity was found to be 1.24kg/m^3. Based on these findings, the study recommended adopting 75%ETc irrigation when water is scarce, but irrigable land is relatively abundant, as is typical in Ethiopia, to balance water saving and reasonable yields.

Similarly, a study carried out in 2010-2012 in the Central Rift Valley of Ethiopia investigated the crop water requirements of irrigated Teff in water-stressed environment (Yihun et al., 2013). This research also evaluated four different levels and reported yields of 3.12t/ha at 100%ETc, 2.45t/ha at 75%ETc and 0.69t/ha at 25%ETc. Interestingly, the study observed that yield and water productivity differences between full irrigation 25% deficit irrigation applied throughout the growth period were statistically insignificant. This suggests that a 25% water deficit irrigation strategy can be recommended in contexts where water resources are limited but there is sufficient irrigable land, allowing farmers to save water without substantial yield loss.

These studies collectively emphasize the potential of deficit irrigation as a water-saving strategy that can sustain Teff production in semi-arid and water-scarce regions of Ethiopia. Optimizing irrigation levels according to local water availability and crop water needs could significantly enhance water use efficiency, ensuring food security while conserving precious water resources.

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Geographical and Administrative Location

The research was conducted in Meles kebele, located Semen Woreda of the Mekelle Zone, Tigray region, northern Ethiopia. The experiment was conducted from February 23 to June 7, 2024. The study site situated 183km away from Addis Ababa, the capital city of Ethiopia. The research study site is located in the north direction of Mekelle town specifically at the Mekelle Agricultural Research Station, which serves as a key center for agricultural research in the region. Geographically, the study area is situated between 13° 28' 30" and 13° 32' 00" North latitude and between 39^{o} 27' 30" and 39° 30' 30" East longitude and at an elevation of 2014m.a.s.l (Figure 1).

The primary source of irrigation water for this research site is natural spring water, which provides a reliable and sustainable water supply critical for the irrigation experiment. The use of spring water helps minimize dependence on surface water sources and supports consistent irrigation scheduling for Teff production under the local climatic and soil conditions.

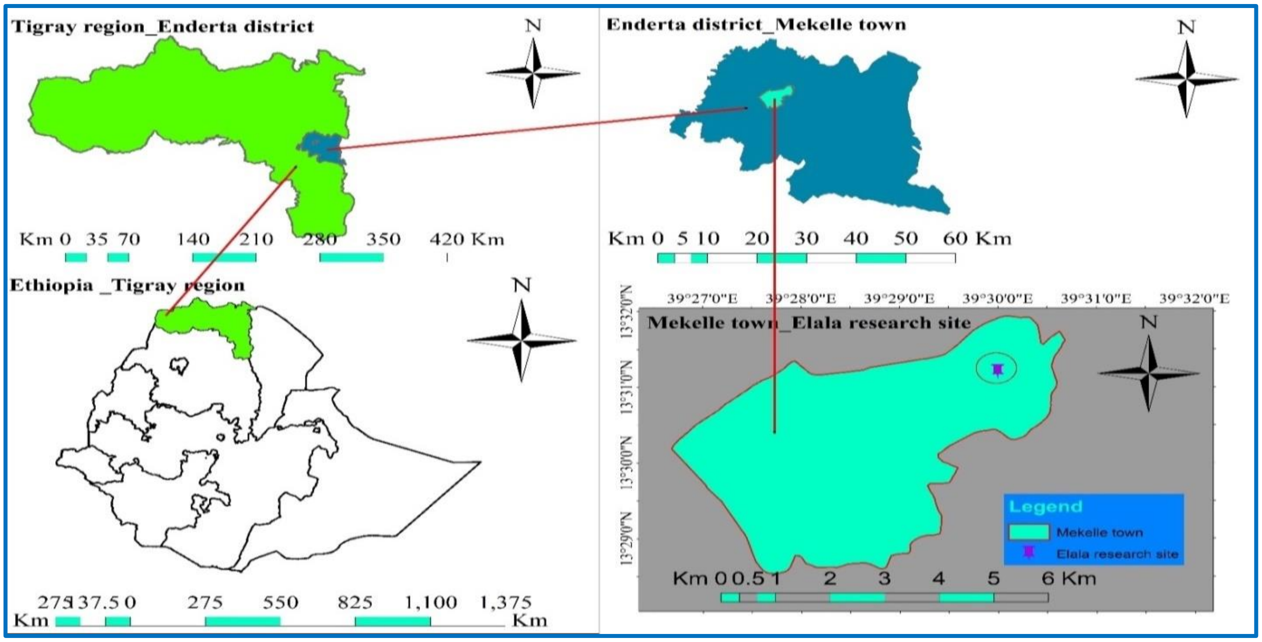

Figure 1: Location of study area

3.1.2 Climate

Long term Climatic data of the study area were obtained using the New-LocClim-1.10 application and subsequently exported to the FAO CROPWAT software version 8.0 (see Appendix A1). The data shown that the average maximum temperature was 27.7°C while the average minimum temperature was 8.6°C, reflecting a moderate temperature range favorable for Teff cultivation.

The area experiences an average relative humidity 88%, and the average wind speed was recorded at 266km/day, contributing to atmospheric moisture loss and affecting the microclimate around the crops. Additionally, the region receives an average of 8.4 hours of daily sunshine, which supports photosynthesis and crop growth. Together, these climatic parameters provide essential inputs for calculating crop water requirements and scheduling irrigation effectively to optimize Teff yield under the local environmental conditions.

3.1.3 Soil

The soil at the experimental site is characterized by its clay loam texture, consisting of approximately 28% sand, 44% silt, and 32% clay. This textural class provides a balance between water retention and drainage, making it suitable for teff cultivation. The soil pH was measured at 7.76, indicating a slightly alkaline condition, which is generally favorable for nutrient availability and crop growth. Such soil properties influence water holding capacity, nutrient dynamics, and root development, all of which are critical factors for determining irrigation requirements and crop performance.

3.1.4 Land Preparation of the Experimental Site

Land preparation using a tractor was performed for establishing a well-structured and uniform experimental field. The process begins by clearing the area of weeds, stones, and crop residues. A tractor was then used for primary tillage, typically with a moldboard or disc plow, to break up the soil, improve aeration, and facilitate root penetration. After plowing, secondary tillage was performed using tractor-mounted implements like harrows to level the soil, resulting in a fine gradient ideal for planting. The use of a tractor not only saves time and labor but also ensures consistent soil conditions across all plots.

The land was leveled by daily workers. After the land is leveled, ridge preparation had been done with three block replications. Then, after based on the experimental design, layout of the experiment was prepared. Then, the experimental site was divided into three block replications, including free space about 2m between blocks and field channels, according to the dimensions provided in the layout of the experiment. Each block was then subdivided to plots and within 1.5m free space between each plot.

Before sowing, the field is measured and marked into equal experimental plots using measuring tapes and stakes to maintain uniformity and accuracy. This mechanized land preparation ensures better germination, uniform crop growth, and reliable data collection throughout the experimental period.

3.2 Experimental Field layout, Design and Treatment Combination

The field experiment was conducted at Meles kebelle, specifically with in the sites of Mekelle Agricultural Research Center. A split-plot design was employed for the experimental layout. The main plot treatments consisted of two surface irrigation methods, furrow irrigation and basin irrigation. The subplot treatments involved three level of crop water requirement (CWR), (100%CWR, 75%CWR and 50%CWR); the setup resulted a total six treatment combinations (Table 3), F100% CWR, F75% CWR, F50% CWR, B100% CWR, B75% CWR and B50% CWR. Each treatment was replicated three times, giving a total of 18 plots for the entire experiment. The layout of the plots was arranged in a radial pattern at 90° angles from each corner of the field and the plots the treatments are placed using randomized complete block design. A Parshall flume was installed 10 meters upstream from the experimental field to measure the water flow rate into the plots accurately.

3.2.1 Plot Size and Field Characteristics

The total experimental area was 315m² (10m × 31.5m). Each individual plot measured 4m × 2m, with a ridge-to-ridge spacing of 0.4 m for furrow irrigation treatments (Jabesa & Abrham, 2016). Each plot in this treatment had five ridges and six furrows. All six furrows in each plot were used for irrigation and data collection to ensure accurate measurement of water use and crop performance. The average slope of the field along the direction of the irrigation site was approximately 0.3%, which falls within the acceptable range for surface irrigation systems.

According to (Cuenca, 1989), a slope of up to 0.3% is close to the upper limit at which the irrigation systems flowing at full capacity will not cause serious soil erosion.

The experimental layout was designed with appropriate spacing to minimize the effects of external factors and to prevent water movement between plots. A spacing of 2 meters was maintained between replications to ensure clear separation and reduce the possibility of treatment interference. Additionally, a spacing of 1.5 meters was provided between individual plots within each replication to avoid cross-contamination of irrigation water and to facilitate easy movement for field operations and data collection.

Table 2: Randomized placement of treatments across replicated plots

	Furrow				Basin		
Rip -I	P1 T1	P2 T3	P3 T2	2m	P4 T4	P5 T5	P6 T6
	Basin				Furrow		
Rip-II	P12 T5	P11 T4	P10 T6	2m	P9 T1	P8 T2	P7 T3
	Furrow				Basin		
Rip-III	P13 T3	P14 T2	P15 T1	2m	P16 T5	P17 T4	P18 T6

The upper case is plot number and the lower case is treatment number

Where, P = plot, T = treatment, Rip = replication

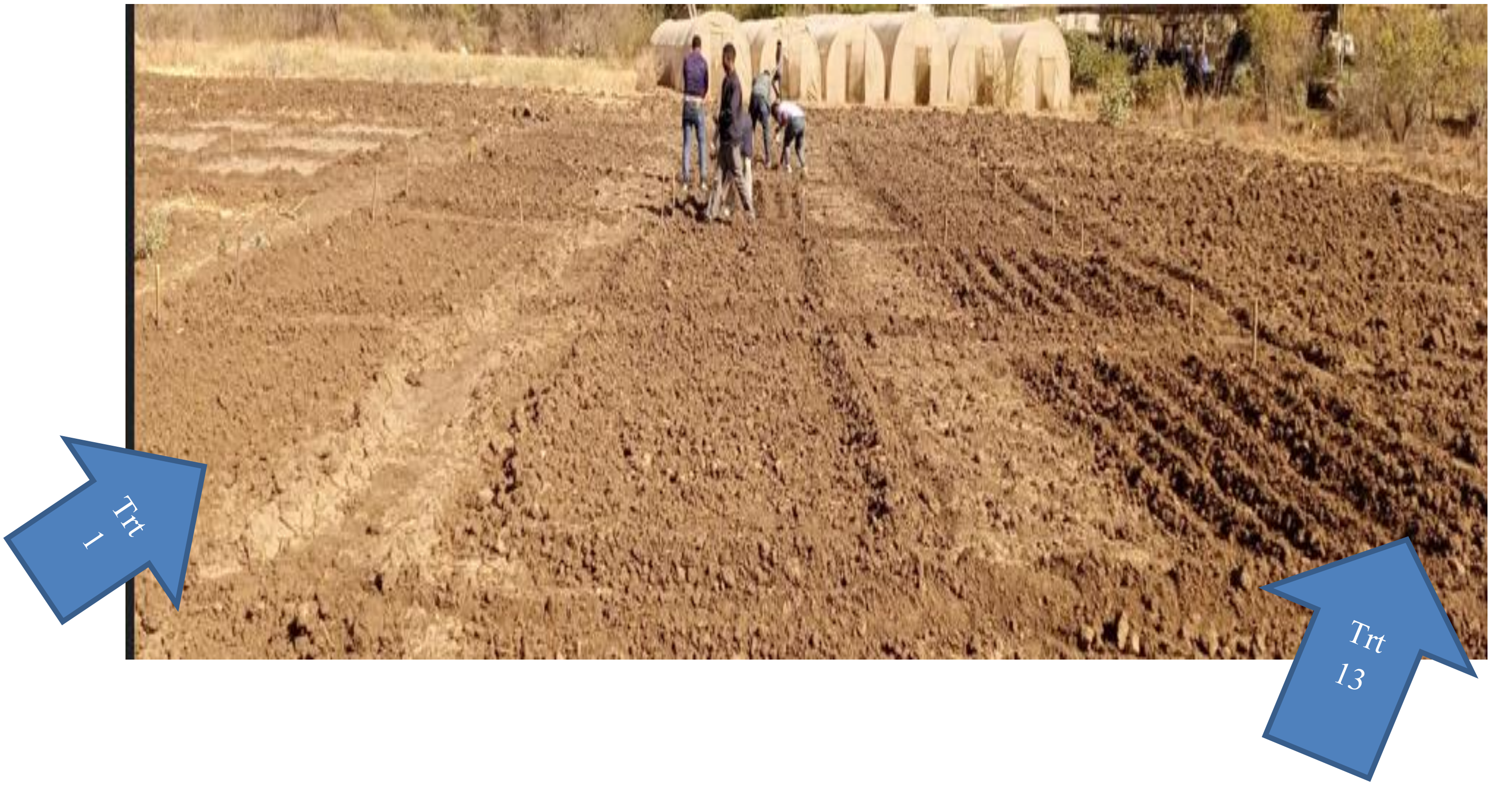

Figure 2: The experimental plots preparation

The experiment was conducted using six different treatments, which were arranged based on two main factors: the method of surface irrigation and the amount of irrigation water applied used throughout the growing season. The two irrigation methods employed in the study were furrow irrigation and basin irrigation, and each method was tested at three different water application levels: 100%, 75%, and 50% of the crop water requirement (CWR)**.**

Table 3: description of irrigation water level and type of surface irrigation

Water level (% of CWR)	Irrigation type	Treatment code	Description
100% CWR	Furrow irrigation	T1	100% of the crop water requirement applied using furrow irrigation
75% CWR	Furrow irrigation	T2	75% of the crop water requirement applied using furrow irrigation
50% CWR	Furrow irrigation	T3	50% of the crop water requirement applied using furrow irrigation

100% CWR	Basin irrigation	T4	100% of the crop water requirement applied using basin irrigation
75% CWR	Basin irrigation	T5	75% of the crop water requirement applied using basin irrigation
50% CWR	Basin irrigation	T6	50% of the crop water requirement applied using basin irrigation

3.3 Experimental Management Practice

3.3.1 Crop Establishment

The Teff variety used in this study was Kora (DZ-Cr-438 (RIL No.133B), which was released from Debre Zeit Agricultural Research Center as Ethiopian Tef variety named “Kora” in 2014 (MoA M. , 2014,). Kora is white seeded high yielding potential variety resulting from a simple cross, and released as an alternative variety to Quncho. The grain yield performance on the research station ranged from 2.5-3.2 ton ha^{-1} and farmers’ fields, the grain yield ranged from 2-2.8 ton ha $^{-1}$. Kora takes 46 days to emerge panicles (head) and 102.5cm tall total plant height with average panicle length of 37.3cm. It has variegated (yellow and red) lemma color, purple anther color, loose panicle form, and very white seed color. It got an immense farmers attention due to its yielding potential, very white seed color and good straw yield (straw yield is no less important than grain yield) at participatory variety selection trials. The seed which was used for the experimental trail was taken from Mekelle Agricultural Research Center. Sowing was carried out on 23 February 2024, using different seedling rates depending on the irrigation methods, thus for the furrow irrigation method, 15kg/ha and for the basin irrigation method, 20kg/ha. The rates were chosen based on researchers’ recommendations from the Mekelle Agricultural Research Center.

3.3.2 Fertilizer Application

Fertilizers were applied 100 kg/ha of DAP (Di-Ammonium Phosphate) at sowing time, and 50 kg/ha of Urea was applied in two split as half of it at sowing and the remaining half during the vegetative growth stage, when the plants had fully established. The rates and application timings were based on agronomist recommendations from Mekelle Agricultural Research Center and the

Semen Woreda Agricultural Office. The grown plants were also protected from diseases and pests and from frost by spraying them with 2-4 D and Farate regularly at a rate of 1 liter/ha.

3.4 Data Collection Techniques

Primary and secondary data were collected and utilized in this study to ensure comprehensive analysis and reliable results. The primary data collected during the field experiment includes various soil, water, and crop parameters. The soil parameters include field capacity (FC), Permanent wilting point (PWP), textural class (Tx), moisture content, pH, and bulk density (Pb). The water-related data are volume of water supplied to each treatment, irrigation duration, and frequency, and application method. The crop-related parameters are growth and yield components of Teff. These growth and yield parameters of Teff were measured at different stages of the crop development to assess the impact of irrigation water levels and application methods.

Secondary data were obtained to support the estimation of crop water requirements and to simulate reference evapotranspiration using standard models. These include rainfall (mm), maximum and minimum air temperature (°c), sunshine hours (hours/day), wind speed (km/d), and relative humidity (%). The climatic variables were obtained using the New Loc-Clim 1.10 software, a local climate estimation tool. These climate parameters were particularly important as inputs for the CROPWAT 8.0 software, which was used to estimate crop evapotranspiration (ETc), net irrigation water requirements, and scheduling for the Teff crop. By combining both primary field measurements and secondary climatic data, the study was able to perform a robust analysis of the irrigation efficiency, water productivity, and crop response under varying irrigation levels and surface irrigation methods.

3.4.1 Soil Sample Collection and Analysis

Before starting the irrigation experiment, key physical properties of the soil at the experiment site were analyzed to inform the water management and irrigation scheduling decisions. The analysis was conducted at the Mekelle Agricultural Soil Center in accordance with the standardized procedures described in the manual of Soil Sampling and Analysis (Dharmakeerthi, 2007).

The soil particle size distribution was determined using the Bouyoucos hydrometer method (Bouyoucos, 1962). This method quantifies the proportions of sand, silt, and clay in the soil, which is then, classified using the USDA soil textural triangle to identify the soil texture class. Field capacity (FC), permanent wilting point (PWP) and bulk density (pb) of the study site were determined using 1 undisturbed soil sample per plot collected using core samples from the soil pit (Elshamly, 2013) at the depth of 0 – 30 cm from the surface (based on the maximum root of the crop) (Araya, 2011). The average field capacity and permanent wilting points of the root zone profile was determined using pressure plate apparatus in the laboratory. Soil samples were saturated for one day and, a pressure of 1/3 bar (filed capacity) and 15 bars (for permanent wilting point) were exerted until no more change in weight of sample was observed. From the result total available water (TAW) for experimental field was computed using equation 2(Allen, 1998).

$$TAW = \left(\frac{(FC-PWP)\times Bd\times Dz}{100}\right)\frac{1}{\rho}\text{…………………………}2$$

Where:

TAW is total available soil water content (mm),

FC is soil water content at field capacity (%),

PWP is soil water content at permanent wilting point (%),

B_d is soil bulk density (g /cm^3),

Dz is maximum effective root depth of teff (mm)

ρ is density of water (assumed as 1g/cm^3)

The bulk density (Bd) of the soil was determined from the same undisturbed soil samples using the core sampling method, following the procedure outlined by (Jury, 1991). The soil samples were oven-dried at 105°C for 24 hours, and bulk density was calculated using the following equation (Blake, 1965).

Bulk density is the weight of oven dry soil per unit total volume

$$Pb = \frac{Wd}{Vc}\text{ ……………………………………..}3$$

Where

ρ_b = soil bulk density, g/cm^3

Wd = mass of dry soil, g

Vc= volume of soil sample, cm

Readily available soil water content (RAW) refers to the portion of the total available water that can be used by plants without harmfully affecting the plants growth and can be expressed as a fraction of the total available soil water content. The allowable depletion factor (P) varies by crop type; for teff, this factor was taken as 40%, based on values reported by (Araya, 2011)

$RAW=P\times TAW$

Where: RAW is readily available soil water content (mm),

TAW is total available soil water content (mm) and

P=Allowable soil water depletion (fraction).

3.4.2 Soil Moisture Content Determination

Oven drying was employed to determine the soil moisture content of the experiment. This method is a standard and reliable approach for assessing the water content of soil samples under field conditions.

Soil samples were collected from center of each experimental plot at depths ranging from 0 to 30cm using a soil auger. According to the procedure described by (Elshamly, 2013) samples were extracted before each irrigation event to assess the depleted soil moisture and determine the amount of water to be re filled. The collected soil samples were immediately packed in to tin core samplers to preserve their original moisture content and were then transported to the Mekelle Soil Research Center laboratory. In the laboratory, the samples were oven-dried at 105°C for 24 hours, after which they were weighted to determine the dry mass. By comparing the weight of the fresh sample with the oven-dried sample, the gravimetric water content was calculated for each soil depth. Sampling was carried out as follows: one sample was taken per plot (depth-wise), totaling six samples per block and 18 samples from the entire experimental field for each measurement period. The gravimetric soil water content was calculated using equation (4) as outlined by (Topp, 1993).

$\theta dw = \frac{Wws-Wds}{Wds} * 100$……………………………….4

θ_{dw} = gravimetric water content (%)

W_{ws}= weight of fresh soil (g)

W_{ds}= wright of dry soil (g)

To convert gravimetric water content into volumetric soil moisture content, the gravimetric value was multiplied by the bulk density of the soil profile at the corresponding depth. The volumetric moisture content was calculated using equation (5) as described by (Jaiswal, 2003).

$\theta v = \frac{Pb}{Pw} * \theta dw$………………………………........5

Where

θ_v = volumetric moisture content (%)

ρ_b = soil bulk density (g/cm^3)

P_w = water bulk density (g/cm^3)

θ_{dw} =Gravimetric water content

3.5 Determination of Crop Water Requirement of Teff

Water requirement of Teff in this study was computed for a total growing season of 105 days using CROPWAT 8.0 computer program. This computer-based model, developed by the Food Agricultural Organization (FAO), allows for estimation of crop water requirements using the experimental site climatic data, crop data, and soil data. To calculate the crop water requirement accurately, the reference evapotranspiration (ETo) of the study area was first computed using the FAO Penman-Monteith Method as recommended by (Allen, Pereira, Raes, & Smith, 1998). This method requires long-term climatic parameters like maximum and minimum temperatures, rainfall, relative humidity, wind speed, and sunshine hours. These parameters were collected from the nearby metrological station and processed using New-Loc Clim 1.10 (Appendix Table A2).

The crop-specific parameters required by CROPWAT model were obtained from previous studies on Teff particularly from (Araya, 2011). These parameters include the crop coefficient

(Kc) values for different growth stages, Teff growth duration, rooting depth, and yield response factor to water stress. The crop coefficient values used in this study were 0.9 for the initial stage, 0.975 for the development stage, 1.025 for the mid-season stage and, 0.45 for the late stage. Similarly, the duration of growth stages was 20-days for the initial stage, 35-days for the development stage, 30-days for the mid-season stage, and 20-days for the late stage. Thus, the total growing period of the crop was considered to be 105 days, which reflects the typical phonological development of Teff under the environmental condition of the study area. In addition, the maximum rooting depth of Teff was taken as 0.3meters, after entering the climatic and crop parameters in the CROPWAT 8.0 software; the seasonal crop evapotranspiration (ETc) which represents the total water requirement of the crop, was calculated for the entire growing season (Allen, Pereira, Raes, & Smith, 1998). Based on the output generated by the software, the seasonal crop water requirement for Teff at the experimental site was found to be 393 mm. (Appendix A2). This value represents the total depth of water needed over the 105-day growing period to reach optimal crop growth and yield under the given environmental conditions.

This method ensures that irrigation planning is based on realistic field and climatic conditions, and allows for precise scheduling of water applications throughout the crop's life cycle. The use of scientifically validated models like CROPWAT helps in optimizing water resources, particularly in regions like Ethiopia, where efficient water use is critical for sustainable agricultural development.

3.5.1 Determination of Net Irrigation Water Requirement of Teff

The amount of net irrigation water requirement of Teff was determined based on the water holding capacity of the experimental soil from the critical depletion up to the field capacity within the effective root depth. The amount of net irrigation water requirement was obtained using the CROPWAT 8.0 software (Allen, 1998) which considers the crop water demand and effective rainfall the net irrigation requirement was calculated using the following formula.

$IRn = ETc - Pe$……………………………………..….6

Where,

IRn =Net irrigation requirement (mm),

ETc=crop evapotranspiration in mm and

Pe = effective rainfall (mm) which refers to the portion of rainfall that infiltrates the soil and is available for crop use.

3.5.2 Estimation of Effective Rainfall

Effective rainfall is a critical factor in determining the net irrigation requirement. It refers to the part of total rainfall that infiltrates into the soil and is stored within the crop's root zone, thereby contributing to its water needs. Not all rainfall is effective; some is lost due to surface runoff, evaporation, or deep percolation beyond the root zone. Hence, accurate estimation of effective rainfall is essential for optimizing irrigation planning. In this study, effective rainfall was estimated using the empirical method recommended by, (Allen, 1998), which provides formulas depending on the total monthly rainfall (R). The formulas used are:

$Pe = 0.6 * R - 10/3$ For total monthly rainfall<=70mm……………….7

$Pe = 0.8 * R - 24/3$ For total monthly rainfall >70mm………………..8

Where: R = total monthly rain fall (mm)

These equations adjust the effective rainfall based on the likelihood of rainfall losses. When rainfall is low, a smaller portion is lost, while higher rainfall tends to result in greater losses due to runoff or deep drainage. The application of this method helps to provide a more realistic estimate of the water available for crop use, improving the reliability of irrigation planning and scheduling.

By using this approach, the net irrigation requirement for Teff was calculated for each growth stage, ensuring that the crop's water demand was met under different climatic conditions throughout the growing season. In the study area rainfall is rained once through the irrigation season, which measures 27mm (<70mm), then effective rain fall is calculated as follows

$Pe = 0.6 * R - 10/3$ (R=27mm)

$Pe = 0.6 * 27 - 10/3 = 12.867mm \approx 13mm$

3.5.3 Determination Gross Irrigation Water Requirement of Teff

Gross irrigation water requirement (GIWR) of Teff refers to the total amount of water needed for irrigation, considering conveyance and field application losses. It is calculated based on the net irrigation requirement efficiency of water application. The gross irrigation water requirement was determined based on the following formula.

$$GIWR = \frac{IRn}{Ea} \ldots\ldots\ldots\ldots\ldots\ldots 9$$

Where: GIWR is gross irrigation water requirement (mm)

IRn =Net irrigation requirement (mm)

Ea = application efficiency (%)

The irrigation application efficiency is defined as the ratio of volume of water effectively used by the crop to the volume of water delivered at the field inlet. When properly designed and managed, the field application efficiency can range 60%-70% for surface irrigation methods such as basin and furrow irrigation system. For this experiment, the irrigation application efficiency of 65% was used, which is common value for well-managed furrow and basin irrigation systems (Chandrasekaran, B.Annadurai, & Somasundaram, 2010)

3.6 Water Application Duration in Each Plot

The irrigation water was conveyed from the source to the experimental site through a pipeline and delivered to the plots via a two-inch partial flume installed at the entry point. The flow rate of irrigation water into each experimental plot was measured using the Parshall flume. To ensure accurate measurements, water was allowed to flow until a steady and constant flow rate was achieved in the flume. The water application duration for each treatment during each irrigation interval was calculated using crop water application depth (obtained from irrigation scheduling), discharge rate (from the Parshall flume table), furrow length, and furrow spacing, following the method described by (Birhanu, 2011) . The time was computed using the equation given below.

$$t = \frac{Dap*l*w}{6q} \ldots\ldots\ldots\ldots\ldots\ldots 10$$

t = water application time (mm)

Dap=gross water application depth (mm)

l= furrow length (m)

w= furrow width (m)

q=discharge rate from partial flume table (l/sec))

The time required to apply a calculated volume of water for each plot was measured with the help of a stop watch.

Figure 3: Two inch partial flume using for measuring flow discharge

3.7 Agronomic Data Collected

Agronomic data were collected at both plant and plot levels to assess yield and yield-components of Teff. Each trait was recorded following standard procedures, as described below:

Days to 90% emergency (DE): this refers to the number of days from the sowing date until 90% of the planted seeds had emerged from the soil surface and were visibly as seedlings. These parameters reflect the seedling emergence rate and establishment uniformity, which are essential for good crop stand and subsequent performance.

Days to 50% heading (DH): days to 50% heading denotes the number of days from sowing until 50% of the plants in a plot exhibited heading, i.e., the stage at which the tips of panicles become visible as they emerge from the flag leaf sheath. It serves as an indicator of the transition from vegetative to reproductive growth.

Days to maturity (DM): This is defined as the number of days from sowing until the crop reached physiological maturity stage. Physiological maturity was determined visually by observing the color change of the plant's vegetative parts (such as leaves and stems) from green to light yellow or straw color, the completion of grain filling, and cessation of dry matter accumulation.

Grain filling period (GFP): the grain filling period was calculated as the difference between days to maturity to days to heading (i.e., GFP=DM-DH). This parameter indicates the duration available for grain development and dry matter accumulation, and it has a direct influence on final grain yield and quality.

Shoot Biomass per plot (By): Total above-ground biomass was harvested from each experimental plot at the time of physiological maturity. The fresh biomass was weighed and recorded, with values adjusted to a standard moisture content of 8%–10% to ensure consistency. Biomass yield reflects the total vegetative productivity of the crop and is often used in evaluating forage value or assessing partitioning of assimilates.

Grain yield per plot (Y): Grain yield was determined as the total dry weight of threshed grains collected from each plot. The grains were dried and adjusted to a uniform moisture content of 12.5%, following standard grain yield evaluation protocols. A sensitive electronic balance was used to weigh the grain yield in grams.

To express grain yield on a per-hectare basis for standard comparison, the following formula was used (Zhang et al., 2019).

$$Grain\ yield\left(\frac{kg}{ha}\right) = \frac{grain\ weight\ of\ plot(kg)}{harvested\ sample\ area(ha)} \ldots\ldots\ldots\ldots 11$$

Harvesting index (HI): is a measure of crop′s efficiency in converting the total biomass (total dry matter) in to harvestable yield (usually grain). It tells that the proportion of total plant growth is actually contributing to the part that harvested.

$$\boldsymbol{HI}(\%) = \frac{grain\ yield(q/ha)}{biomass\ yield(q/ha)} \ldots\ldots\ldots\ldots 12$$

3.8 Crop Water Productivity

Crop water productivity is a measure of how efficiently a crop uses water to produce yield. It is particularly important for rain fed crops like Teff, which are commonly grown in water-scarce regions such as Ethiopia. In this study, the crop water productivity of Teff was determined by using the ratio of grain yield to the consumptive water used by the plant.

The concept of water productivity grounded in the principle of "**more crop per drop**," which emphasizes producing more food from the same amount water resources or producing the same amount of food from less water resources. In a broader sense, productivity of water refers to the value benefit derived from the use of water. Enhancing water productivity allows more water to be made available for other essential human and environmental needs (Molden & Rijsberman, 2001). In this study, crop water productivity (CWP) is defined as the amount or value of product per volume of water depleted or diverted (Molden, 2007).

It is expressed as kilograms of grain yield per cubic meter of water and calculated using the following formula (Zwart, 2004).

$$CWP = \frac{Y}{NIWR} \qquad \text{……13}$$

Where: CWP is crop water productivity (kg /m^3)

NIWR is seasonal net irrigation water requirement consumption (m^3/ha)

And Y is grain yield (kg/ha)

3.9 Statistical Data analysis

The collected data were subjected to the statistical analysis using analysis of variance (ANOVA). Since the study involved two independent variables (irrigation water level and type of surface irrigation) a two-way ANOVA was performed using GenStat 16th edition statistical software programme.

Genstat provides comprehensive tools for analyzing variance (Payne, 2012). To compare treatment means where more than five treatments were involved, Duncan's Multiple Range Test was employed (Gomez, 1984). Significant mean separation was computed using least significant difference method at 5% probability level for ranking the treatment means (Dahanayake, 2015). Before performing the analysis of variables, the assumptions of normality of variances were tested. Normality of the data distribution was assessed using the Shapiro-Wilk Test, method (Snedecor, 1989).

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Physical Properties of Soil

The physical properties of soil refer to the observable and or measurable characteristics that do not involve changes in the soil's chemical composition. These properties play a crucial role in determining how soil behaves under various conditions. They significantly influence the soil's ability to support plant growth by affecting root penetration, nutrient availability, and water retention. Additionally, they impact water movement through the soil profile, which is essential for irrigation, drainage, and groundwater recharge. From an engineering perspective, soil physical properties are critical in assessing the soil's load-bearing capacity, stability, and suitability for construction and other infrastructure projects.

Analysis of soil samples for the major physicochemical properties before planting was carried out at Mekelle Soil Research Center. The result of the soil analysis from the experimental sites (Table 4) showed that the average composition of sand, silt and clay percentages were 24%, 44% and 32% Thus, according to the USDA soil textural classification system (USDA, 1987), this percent particle size distribution indicates that the soil texture of the experimental site is classified as clay loam. The soil pH value of the experimental site was measured at 7.76. According to (Tekalign, 1991), and (Sad, 2009) soils with a pH value in this range are considered as a slightly alkaline in reaction, which can have implications for nutrient availability and crop performance.

Additional soil physical properties were also assessed, including field capacity (FC), permanent wilting point (PWP), bulk density, and total available water (TAW). The field capacity and permanent wilting point were found to be 30% and 15% by weight, respectively. The bulk density was recorded as 1.3 g/cm^3, and the total available water was calculated to be 180 mm/m, indicating a moderate water-holding capacity typical of clay loam soils.

These results provide essential baseline information for evaluating the soil's suitability for crop production and understanding how different soil management practices may influence productivity.

Table 4: Physical properties of soil for the experimental area

Soil depth(cm)	Particle size (%)			Textural class	FC (%wt)	PWP (%wt)	Bulk density (g/cc)	TAW (mm/m)
	sand	silt	clay					
0-30	24	44	32	Clay loam	30	15	1.3	180

4.2 Testing Normality of Variances

A normality test is used to determine whether sample data has been drawn from a normally distributed population (within some tolerance). A number of statistical tests, such as the one-way and two-way analysis of variance (ANOVA), require a normally distributed sample population.

The collected yield and yield components of Teff were checked before doing the data analysis using the Genstat 16th edition statistical software program weather the assumptions of normality are satisfied or not. The normal distribution of water productivity, yield and yield components of Teff was checked by THE Shapiro-Wilk test. According to (Shapiro.S.S & Wilk.M.B, 1965) assumptions test if the probability (p) of the available data is greater than significance level (0.05), the data is normally distributed whereas the data is not normally distributed (Table 5).

Table 5: Checking for normal distribution of data using the Shapiro-Wilk test

Data variables	Test statistics W.	Probability	Remark
DE	0.9241	0.153	P>0.05, then the DE data is normally distributed
DTH	0.8649	0.065	P>0.05, then the DTH data is normally distributed
GFP	0.9297	0.192	P>0.05, then the GFP data is normally distributed
DM	0.9714	0.823	P>0.05, then the DM data is normally distributed
BY	0.9838	0.981	P>0.05, then the BY data is normally distributed
GY	0.9602	0.605	P>0.05, then the GY data is normally distributed
CWP	0.9548	0.505	P>0.05, then the CWP data is normally distributed

Note: DE=date of emergency (days), DTH=Date to heading (days), GFP=Grain filling period (days), DM=Days to maturity (days), BY=Biomass yield (Q/ha), GY=Grain yield (Q/ha), CWP=Crop water productivity (kg/m^3), P=Probability

4.3 Seasonal Crop and Irrigation Water Requirement of Teff

Crop water requirement is the quantity of water, regardless of its source, required by a crop in a given period of time for its normal growth under field conditions at a place. Estimation of the water requirement of a crop is one of the basic needs for irrigated crop production planning. The values of ETo estimated using CROPWAT model based on climate parameters need to be adjusted for actual crop ET. The crop water requirement of the tested crop is calculated by multiplying the reference ETo with crop coefficient (Kc) as presented (Appendix Table 2).

Both crop and irrigation water requirement of Teff were determined from planting to harvesting date. According to Table 6 The highest Crop water requirement (288mm/season), Net Irrigation requirement (275mm/season) and Gross Irrigation Requirement (393mm/season) of Teff were recorded. This amount of water was needed for 100%ETc, in the findings the treatments which get the full irrigation requirements are T1 (furrow irrigation with 100%CWR) and T4 (basin irrigation with 100%CWR) of irrigation water level application whereas the lowest Crop water requirement (144mm/season), Net Irrigation requirement (131mm/season) and Gross Irrigation Requirement (196.5mm/season) of Teff were obtained at T3 (furrow irrigation with 50%CWR) and T6 (basin irrigation with 50%CWR) of irrigation water level application (Table 6). The rainfall (27.5mm) and effective rainfall (13mm) were recorded at the experimental site. Then, after, the calculated effective rainfall was subtracted from the net irrigation water requirement for the next irrigation treatment water application.

Table 6: Seasonal amount of crop and irrigation water requirement of Teff

Treatment combination	CWR (mm)	Rain (mm)	Pe (mm)	NIWR(mm/ season)	NIWR(m^3/ha /season)	GIWR (mm/season)	GIWR (m^3/ha/season)
T1	288	27.5	13	275	2750	393	3930
T2	216	27.5	13	203	107	294.75	2947.5
T3	144	27.5	13	131	166	196.5	1965
T4	288	27.5	13	275	2750	393	3930
T5	216	27.5	13	203	223	294.75	2947.5
T6	144	27.5	13	131	223	196.5	1965

Note: CWR=Crop water requirement, Pe=Effective rainfall, NIWR=Net irrigation water requirement and GIWR=Gross irrigation water requirement

4.4 Effect of Treatments on Yield Components of Teff.

The effect of treatment interactions of irrigation methods (furrow vs. basin) with irrigation water application levels (100%, 75%, and 50% of crop water requirement-CWR) on selected yield components of Teff has shown significant difference ($p<0.05$) for several parameters. These parameters include, days to emergency, days to heading, and number of tillers per plant. However the interaction effects were shown non significance difference at grain filling period and days to maturity (Table 7).

In this findings, the fastest to emerge of the Teff crop, 7 days was found from the treatments T1 (furrow irrigation with 100%CWR), T4 (basin irrigation with 100%CWR), and T5 (basin irrigation with 75%CWR), whereas the latest to emerge recorded at 9.33 days, which observed in T6 (basin irrigation with 50%CWR). This suggests that both the irrigation method and the adequacy of water supply play an important role in the germination speed. Days to heading were also significantly influenced by the interaction between irrigation method and irrigation water level. Treatments T4 and T5, both under basin irrigation with higher water levels (100% and 75%CWR, respectively), reached earlier approximately 50 days compared to T2 (furrow irrigation with 75%CWR) and T3 (furrow irrigation with 50%CWR), which showed delayed heading (~57 days). This shows that adequate water availability, particularly under basin irrigation, accelerates crop development.

Although the grain filling period (GFP) was longest in T4 (basin irrigation with 100%CWR) and T5 (basin irrigation with 75%CWR), both under basin irrigation. These treatments had GFP durations of 36–37 days, longer than T3 (furrow irrigation with 50%CWR) and T6 (basin irrigation with 50%CWR) (28 days). Extended GFP likely contributed to higher grain yields in well-irrigated treatments. No significant difference was found in days to maturity (DM) among treatments, though T4 (basin irrigation with 100%CWR) exhibited the longest duration (87.67 days) and T6 (basin irrigation with 50%CWR) had the shortest (83 days). This suggests that maturity may be relatively stable under different irrigation levels, with only minor acceleration under water stress.

Overall, these findings highlight the importance of both irrigation method and water application level in influencing Teff growth and yield components. Basin irrigation with higher water levels enhanced early development stages. The choice between irrigation strategies may thus depend on the target yield component and available water resources.

Table 7: Effect of treatments on yield components of Teff (Duncan's multiple range tests).

Treatment interaction	90%DE	DTH	GFP	DM
T1 (furrow irrigation with 100%CWR)	7.00^{b}	53.67^{ab}	32.33	86.00
T2 (furrow irrigation with 75%CWR)	8.333^{ab}	57.00^{a}	29.00	86.00
T3 (furrow irrigation with 50%CWR)	8.667^{ab}	57.00^{a}	28.00	85.00
T4 (basin irrigation with 100%CWR)	7.000^{b}	50.33^{b}	37.33	87.67
T5 (basin irrigation with75%CWR)	7.000^{b}	50.00^{b}	36.00	86.00
T6 (basin irrigation with 50%CWR)	9.333^{a}	55.00^{ab}	28.00	83.00
Average	7.89	53.83	31.80	85.61
LSD(0.05)	1.683	6.018	NS	NS
CV (%)	12.70	6.30	20.50	4.60

Note: DE=days to emergency (days), DTH=Days to heading (days), GFP= Grain filling period (days), DM=Days to maturity (days), PL= Panicle length (cm), TPH=Total plant height (cm), NS=non-significant, LSD =Least Significant Difference, CV=Coefficient of Variance

4.5 Effect of Treatments on Water Productivity and Yields of Teff.

Teff grain yield and biomass yield was collected from each plots, weighed and converted to hectare basis with intention of comparing the yield performance of the two surface irrigation methods with different levels of water application. The grain and biomass yield of the plot was collected from the $8m^2$area of a 2*4m plot for the basin irrigation method, for the furrow irrigation method the area of furrow is subtracted from the total area of the plot which was 2*4m ($8m^2$) - ((2m*0.4m*6 furrors-5rows*0.2m spacing)) = $4.2m^2$. The mean values of biomass yield (BY), grain yield (GY) and crop water productivity (CWP) are presented in Table 8.

The interaction between surface irrigation method (furrow vs. basin) and irrigation water level (100%, 75% and 50% of crop water requirement) had a significant impact on both biomass yield (BY) and grain yield (GY) of Teff. Analysis of variance shown statistically significant differences among treatments ($p<0.05$), for these parameters.

The highest biomass yield (119.58 q/ha) was recorded under furrow irrigation with 75% crop water requirement (T2), which was significantly higher than basin irrigation treatments at all water levels (T4, T5 and T6). Biomass yields obtained under furrow irrigation at 100% CWR (T1) and 50%CWR (T3) were statistically comparable (100.56 q/ha and 103.7q/ha respectively), indicating that 25% reduction in irrigation water did not significantly affect biomass production under furrow conditions. On the contrary, biomass yield declined sharply under basin irrigation at 50% CWR (T6) which is recorded 58.25q/ha.

Grain yield followed a similar pattern. The highest grain yield (30.63 q/ha), was recorded in T2 (furrow irrigation with 75%CWR), closely followed by T1 (furrow irrigation with 100%CWR) which was produced 28.46 q/ha. The lowest grain yield (16.40q/ha) was observed in under basin irrigation with 50%CWR). These results are consistent with those results of (Yihun M. , 2015), who reported the highest Teff yield (33q/ha) at 100%ETc and slightly lower yield but statistically comparable yield at 75%ETc (24.5q/ha) in Melkasa and Genchi Watersheds of Central Ethiopia. Similarly (Yihun et al., 2013) found Teff yields of 31.2q/ha at 100% ETc and 24.5 q/ha at 75%ETc in Central Rift Valley. Importantly, both studies concluded that the yield differences between 100% and 75% irrigation levels were not statistically significant, supporting 75% ETc as an efficient strategy for water saving without substantial yield loss.

These findings suggest that furrow irrigation at 75% CWR is capable of maintaining high grain yield levels while reducing overall water use, making it a promising strategy for water-limited environments.

Crop water productivity is usually a seasonal value defined as yield in an area per water used to produce the yield (Gregory, 1998). So, under this experiment, to evaluate furrow and basin irrigation systems and water application levels in terms crop water productivity were considered. As the objectives of doing this experiment was to assess how much water could be saved by comparing these irrigation methods.

Crop water productivity (CWP), is also defined as the grain yield per unit of water applied, showed an inverse relationship with the volume water used. The highest crop water productivity (1.0392 kg/m³) was recorded under furrow irrigation with 75% crop water requirement (T2), while the lowest value (0.5440 kg/m³) was observed under basin irrigation with 100% crop water requirement (T4). This trend demonstrates the potential of deficit irrigation, particularly under furrow irrigation to enhance water use efficiency. Although higher water productivity was achieved under severe water limitation, this came at the cost of reduced yields, highlighting the need for an optimal balanced between water savings and crop productivity. Overall, the results indicate that water productivity in Teff improves as irrigation levels decreased from 100% Crop water requirement to 50%Crop water requirement. However, furrow irrigation at 75% crop water requirement provided the best balance between grain yield (30.63q/ha), biomass yield (119.58q/ha), and crop water productivity (1.0392kg/m$^{3)}$, making it the most efficient and sustainable irrigation strategy under the conditions this study. These findings are in agreement with (Yihun M. , 2015) who reported maximum crop water productivity of Teff 1.24 kg/m³ and grain yield of 24.5q/ha at 75% crop water requirement and leading the author to recommend 75% ETc as the most efficient strategy under limited water availability.

Table 8: Effect of Treatments on Water Productivity and Yields of Teff

Treatment interaction	BY(Q/ha)	GY(Q/ha)	CWP(kg/m^3)
T1 (furrow irrigation with 100%CWR)	100.56^{ab}	28.46^{a}	0.7242^{cd}
T2 (furrow irrigation with 75%CWR)	119.58^{a}	30.63^{a}	1.0392^{a}
T3 (furrow irrigation with 50%CWR)	103.70^{ab}	19.16^{bc}	0.9751^{ab}
T4 (basin irrigation with 100%CWR)	87.83^{b}	21.32^{b}	0.5440^{d}
T5 (basin irrigation with75%CWR)	81.99^{b}	21.00^{bc}	0.7137^{cd}
T6 (basin irrigation with 50%CWR)	58.25^{c}	16.40^{c}	0.8343^{bc}
Average	92.00	22.83	0.8050
LSD(0.05)	23.67	4.465	0.1766
CV (%)	14.50	11.00	12.30

Note: BY=Biomass yield (Q/ha), GY=Grain yield (Q/ha), CWP=Crop water productivity (kg/m^3), LSD =Least Significant Difference, CV=Coefficient of Variation

4.6 Harvest Index

The highest Harvest Index was scientifically affected by the interaction between surface irrigation method and irrigation water level (Table 9). The highest harvest index (29.84%) was reordered under basin irrigation with 50% CWR (T6), which was significantly higher than furrow irrigation with 50% CWR (T3). Harvest index obtained under furrow irrigation at 100%CWR (T1), 75%CWR (T2) and under basin irrigation at 75%CWR (T5), 100%CWR (T4) were statistically comparable (28.27%, 25.58% , 25.77% and 24.67%respectively), while the lowest was occurred in furrow irrigation with 50% CWR (T3, 18.47%). High HI under low water conditions (T6) was due to reduced vegetative growth rather than higher grain yield, indicating that HI reflects biomass allocation efficiency rather than absolute yield. Treatments combining adequate water and good biomass partitioning, such as furrow irrigation with 100% and 75% CWR, achieved both high grain yield and reasonably high HI. In contrast, severe water stress under furrow irrigation with 50% CWR negatively affected biomass partitioning, resulting in the lowest harvest index among all treatments.

Table 9: harvest index

Treatment interaction	HI (%)
T1 (furrow irrigation with 100%CWR)	28.27^{a}
T2 (furrow irrigation with 75%CWR)	25.58^{a}
T3 (furrow irrigation with 50%CWR)	18.57^{b}
T4 (basin irrigation with 100%CWR)	24.67^{ab}
T5 (basin irrigation with75%CWR)	25.77^{a}
T6 (basin irrigation with 50%CWR)	29.84^{a}
Average	25.45
LSD(0.05)	6.395
CV (%)	14.40

Note: HI = Harvest Index (%)

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study was conducted to evaluate the response of Teff (*Eragrostis tef*) to different irrigation water levels and surface irrigation methods on the growth, yield, and water productivity of Teff (*Eragrostis tef*) under controlled field conditions. The results showed that both the surface irrigation methods (furrow and basin) and the irrigation water levels (100%, 75%, and 50% of crop water requirement) had significant impacts on the crop's performance. Key agronomic parameters such as days to emergence, days to heading, grain filling period, biomass yield, grain yield, and crop water productivity were all significantly influenced by the interactions of these treatments.

Among all the treatments, Teff showed the best overall performance under furrow irrigation method with 75% crop water requirement (T2). This treatment combination resulted in the highest biomass yield (119.58q/ha) and highest grain yields (30.63q/ha), while achieving the maximum crop water productivity (1.0392kg/m^3) and showed favorable crop growth responses, indicated that 25% deficit irrigation (75% crop water requirement), particularly when applied through furrow irrigation did not cause a significant reduction in yield. In contrast, basin irrigation treatments resulted in lower biomass and grain yields and water productivity at corresponding irrigation levels.

Severe water stress imposed by 50% crop water requirement significantly reduced both biomass and grain yields, particularly under basin irrigation (T6), which recorded the lowest biomass yield (58.25q/ha) and grain yield (16.40q/ha). Although crop water productivity tends to increase under deficit irrigation, excessive water reduction led to yield losses that may not be economically acceptable.

This indicates that applying 75% of crop's water requirement through furrow irrigation provides a balanced strategy that conserves water without causing a significant reduction in yield, and the land to be irrigated is increased. While the basin irrigation method was effective in early growth performance, it was generally less efficient in terms of total yield and water productivity compared to furrow irrigation method.

Furthermore, the results highlight the importance of matching irrigation depth with the appropriate method of surface irrigation to optimize both crop productivity and resource use. Shifting from full of irrigation (100% CWR) to a 75% CWR under furrow irrigation resulted in a substantial improvement in water use efficiency with minimal yield reduction. The gross irrigation water requirement (GIWR) decreased from 3930 m^3/ha in the 100% CWR treatment to 2947.5 m^3/ha at the 75% CWR treatment, saving 982.5 m^3 of irrigation water per hectare. With this saved water, the same volume that irrigates 1 hectare at full irrigation could irrigate approximately 1.33 hectares under the 75% CWR regime, representing a 33.3% increase in irrigated area.

In summary, the study concludes that 25% water reductions (75% crop water requirement), when coupled with an efficient irrigation method such as furrow irrigation, provide an optimal solution for improving the sustainability of Teff production in water-scarce environments. This approach not only helps in saving valuable irrigation water but also ensures stable crop yields, making it highly applicable for regions where resources are limited. Future efforts in irrigation planning for Teff should therefore prioritize both irrigation efficiency and strategic water management to achieve sustainable agricultural outcomes.

In conclusion, the adoption of efficient irrigation strategies-particularly furrow irrigation combined with optimized water application levels to ensure sustainable Teff production and promising solution for sustaining teff productivity while addressing the challenges posed by increasing water scarcity.

5.2 Recommendations

Based on the findings and outcomes of this study, several practical and research-oriented recommendations are proposed to enhance Teff production and water resources management under varying irrigation conditions:

1. **Adopt furrow irrigation as the preferred surface irrigation method:** furrow irrigation demonstrated superior performance in supporting early emergence, timely heading, prolonged grain filling, and ultimately higher grain and biomass yield. It is therefore recommended as the preferred surface irrigation method for Teff cultivation, particularly in areas where full or moderately reduced irrigation is available. Its efficiency in

delivering water evenly across the root zone makes it especially suitable for improving crop uniformity and productivity.

2. **Implement 25% deficit irrigation strategies (75% CWR)**; the study showed that applying 75% of crop water requirement, especially through furrow irrigation, maintained high yield levels while significantly enhancing crop water productivity This strategy represents a balanced approach to water savings and agricultural output. It is therefore recommended for water-scarce regions aiming to optimize irrigation efficiency without severely affecting crop performance.
3. **Avoid severe deficit irrigation (50% CWR) in Teff production :** Severe reductions in irrigation water (50% CWR) resulted in delayed crop emergence and heading, shorter grain filling periods, and reduced vegetative growth, all of which contributed to lower yields. Hence, it is recommended that such levels of water stress be avoided where possible, particularly in commercial or yield-focused production systems. The risks of reduced economic returns under these conditions outweigh the water savings.
4. **Farmers and irrigation planners:** should consider integrating soil type, rainfall patterns, and crop stage sensitivity into irrigation scheduling to maximize Teff performance under water-scarce conditions.

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Appendix of Tables and Figures

Table A1 Long-term average climatic data of and calculated reference evaporation (ETo) of the study area

Month	Minmum Tempratu re (°C)	Maximum teprature (°C)	Relative humidit y (%)	Wind speed (km/day)	Sunshine hours (hrs)	Radiatin (MJ/m²/day)	ETo (mm/day)
Junuary	8.8	12.6	88	346	4.9	7.9	1.03
February	8.6	12.6	89	346	5.9	10.9	1.31
March	9.3	13.6	89	302	7.1	15.3	1.89
April	11.1	16.1	86	277	9.0	20.7	2.86
May	14.3	20.1	91	216	10.6	24.8	3.76
June	18.0	24.0	86	190	12.0	27.4	4.83
July	21.2	27.5	86	190	12.4	27.5	5.34
Augoust	21.7	27.7	86	216	11.5	24.6	4.87
September	20.0	25.2	87	216	9.6	19.2	3.61
October	16.7	21.2	87	251	7.3	13.2	2.27
Nevember	13.1	17.2	88	302	5.8	9.1	1.39
December	10.3	14.0	88	346	4.5	6.9	1.02
Average	14.4	19.2	88	266	8.4	17.3	2.85

Table A2 predetermined irrigation schedule using CROPWAT version 8.0.

Date	Day	Stage	CWR (mm)	Rain (mm)	Pe (mm)	NIWR (mm)	NIWR (m^3/ha)	GIWR (mm)	GIWR (m^3/ha)
1 Mar	7	inti	9.6	0.0	0.0	9.6	96	13.8	138
8 Mar	14	inti	10.7	0.0	0.0	10.7	107	15.2	152
18 Mar	24	dev	16.6	0.0	0.0	16.6	166	23.8	238
28 Mar	34	dev	19.5	0.0	0.0	19.5	195	27.8	278
7 Apr	44	dev	22.3	0.0	0.0	22.3	223	31.9	319
7Apr	44	dev	25.3	27.5	13	22.3	223	31.9	319

17 Apr	54	dev	25.5	0.0	0.0	25.5	255	36.4	364
27 Apr	64	Mid	28.4	0.0	0.0	28.4	284	40.6	406
7 May	74	Mid	31.2	0.0	0.0	31.2	312	44.6	446
17 May	84	Mid	33.8	0.0	0.0	33.8	338	48.2	482
27 May	94	End	30.8	0.0	0.0	30.8	308	44.1	441
6 Jun	104	End	24.3	0.0	0.0	24.3	243	34.7	347
7 Jun	end	End	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total			288	27.5	13	275	2750	393	3930

Table A3 Irrigation water level applied for each treatment

Irrigation interval	Amount of irrigation water levels applied for each treatment					
	T1	T2	T3	T4	T5	T6
1-Mar	9.6	7.2	4.30	9.6	7.2	4.30
8-Mar	10.7	8.025	5.35	10.7	8.025	5.35
18-Mar	16.6	12.45	8.30	16.6	12.45	8.30
28-Mar	19.5	14.625	8.75	19.5	14.625	8.75
7-Apr	22.3	16.725	11.15	22.3	16.725	11.15
7-Apr	25.3	26.475	17.65	35.5	26.475	17.65
17-Apr	25.5	19.125	12.75	25.5	19.125	12.75
27-Apr	28.4	21.30	14.20	28.4	21.30	14.20
7-May	31.2	23.325	15.60	31.2	23.325	15.60
17-May	33.8	25.35	16.9	33.8	25.35	16.90
27-May	30.8	23.10	15.4	30.8	23.10	15.40
6-Jun	24.3	18.225	12.15	24.3	18.225	12.15
Total	288	216	144	288	216	144

Table A4 Free flow discharge values for different size of Parshall flumes (Samani, 2017)

Head (cm)	Through 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	20.885
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	52.794
23			18.151	37.384	56.510
24			19.389	39.984	60.312

Appendix figure 1 Prformance of the experiment at intial stage

At development stage (heading)

Appendix figure 2 performance of teff at development stage

Appendix figure 3 Performance of the experiment at mid stage

Appendix figure 4 Late stage

Appendix figure 4 Late stage

Appendix figure 5 Weighing the biomass yield

Appendix figure 6 threshing the grain of teff

Weighing the grain yield using sensitive balance

Appendix figure 7 weighing the grain yield of teff using sensitive balance