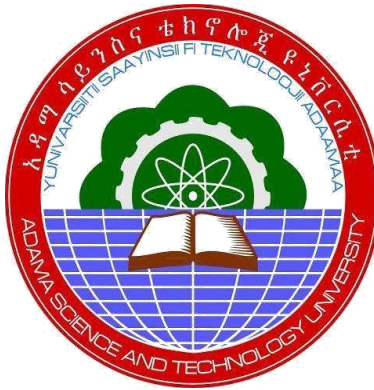


Effect of Furrow Irrigation Methods and Spacing on Yield and Water
Productivity of Wheat at Melkassa, Ethiopia



Aynalem Gurms Dinku

A Thesis Submitted to
The Department of Water Resources Engineering
School of Civil Engineering and Architecture
Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Water Resources Engineering (Specialization in Irrigation Engineering)

Office of Graduate studies
Adama Science and Technology University

February, 2024
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DECLARATION

I hereby declare that this Master Thesis entitled “**Effect of Furrow Irrigation Methods and Spacing on Yield and Water Productivity of Wheat at Melkassa, Ethiopia**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Aynalem Gurms Dinku

Name of student

Signature

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RECOMMENDATION

I, the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Effect of Furrow Irrigation Methods and Spacing on Yield and Water Productivity of Wheat at Melkassa, Ethiopia**” prepared under my guidance by **Aynalem Gurms Dinku** submitted in partial fulfillment of the requirements for the degree of Master's of Science in Water Resource Engineering, Specialization in Irrigation Engineering.

Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Mekonen Ayana (Prof.)

Major Advisor

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Date

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I, the advisor of the thesis entitled **“Effect of Furrow Irrigation Methods and Spacing on Yield and Water Productivity of Wheat at Melkassa, Ethiopia”** and developed by **Aynalem Gurms Dinku**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Mekonen Ayana (Prof.)

Major Advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by **Aynalem Gurms Dinku** have read and evaluated the thesis entitled **“Effect of Furrow Irrigation Methods and Spacing on Yield and Water Productivity of Wheat at Melkassa, Ethiopia”** and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resource Engineering, Specialization in Irrigation Engineering.

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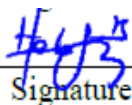
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LIST OF ABBREVIATIONS AND ACRONYMS

a.s.l	Above Sea Level
AFI	Alternate Furrow Irrigation
CFI	Conventional Furrow Irrigation
Cv	Coefficient Of Variance
CWR	Crop Water Requirement
FAO	Food And Agricultural Organization
Fc	Field Capacity
FFI	Fixed Furrow Irrigation
Ig	Gross Irrigation
In	Net Irrigation
Kc	Crop Coefficient
Ky	Yield Response Factor
LSD	List Significant Difference
PWP	Permanent Wilting Point
RAW	Readily Available Water
TAW	Total Available Water
WP	Water Productivity
Ya	Actual Yield
Ym	Maximum Yield

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ABSTRACT

Water availability is becoming a critical issue for irrigated crops in the Rift valley basin in Ethiopia. Therefore, enhancing water productivity of irrigated crops through water management is a vital option. The objective of this study was to evaluate the effect of furrow irrigation method and spacing on yield and water productivity of wheat. A field experiment was conducted at Awash Melkassa Agricultural Research Center on three types of furrow irrigation methods (Alternate furrow (AFI), fixed furrow (FFI) and conventional furrow (CFI)) and three furrow spacing (40 cm, 50 cm and 60 cm) with three replications. The design was split-plot design, in which furrow irrigation methods were used as the sub-plot while furrow spacing was used as main-plot and the data was analyzed using statistix10 software. The results of the analysis on yield, yield components, growth parameters and water productivity indicate that there was a significant difference ($p < 0.05$) in the furrow irrigation method and spacing. The interaction effect of furrow irrigation method and spacing was non-significant. The highest growth, yield and yield components including water productivity were obtained due to 50 cm furrow spacing. The highest grain yield (4630.3 Kg/ha) was observed under 50 cm furrow spacing which has no significance difference with 60 cm furrow spacing. The minimum grain yield (3837.4 Kg/ha) was recorded under 40 cm furrow spacing. The highest water productivity (2.1 kg/m^3) was obtained due to alternate furrow irrigation method which was statistically superior than conventional and fixed furrow irrigation method at ($P < 0.05$) and the lowest water productivity (1.25 Kg/ha) was observed under conventional furrow irrigation method. The interaction effect of furrow irrigation method and spacing on yield and water productivity of wheat was not significant at ($P < 0.05$). Alternate furrow irrigation method and 50 cm spacing can improve water productivity by saving 50% of irrigation water applied under conventional furrow irrigation method which is used to irrigate additional area. In economic analysis alternate furrow irrigation method showed the best benefit cost ratio results. Therefore, this study suggests that, for maximizing water productivity and water saved alternate furrow irrigation method and 50 cm furrow spacing is recommended in the study area without significant yield reduction than conventional furrow irrigation method.

Key word: furrow irrigation, furrow spacing, wheat, water productivity

1 INTRODUCTION

1.1 Background of the Study

Water is one of essential natural resources that can be considered as a core resource for social and economic development of every country (Abebe *et al.*,2013). Recently, due to the rapid growth of population throughout the globe, the pressure on different natural resources and existing environment is becoming a serious problem in many countries. From these natural resources, water is the most important element which faces huge pressure to provide most of essential services in order to live healthy life and increasing the life standard of the rapidly raising population among others (Yihun, 2015).

The global expansion of irrigated areas to feed the ever-increasing population and the limited availability of irrigation water is not balanced in different parts of the world. In arid and semi-arid areas where water scarcity is the main challenge for crop production, the spatial and temporal variations exacerbate the problem. Moreover, the design of irrigation schemes does not address the situation of moisture availability for crop production and the competition between different sectors. The main issue for both irrigated as well as rain-fed areas is to improve water use efficiency(Baye, 2011). Water use efficiency and agriculture production can be improved by improving soil and water management practices, and growing drought-tolerant and high yielding cultivars.

In low land areas of Ethiopia, irrigated agriculture is becoming main concern and strongly recognized to ensure the food security, which is taken as a means to increase food production and self-sufficiency of the rapidly increasing population of the country. Accordingly, Ethiopia has planned to irrigate over 5.3 million hectares of the land with existing water resources (Awulachew *et al.*, 2010, Lema, 2022). This expansion of irrigated agriculture to feed the ever-increasing population on one hand and the increasing competition for water due to the development of other water use sectors on the other hand necessitated the improvement of water use efficiencies in irrigated agriculture to ensure sustained production and conservation of this limited resource (Mekonen, 2011).

Irrigation is widely practiced in different parts of the world and the expansion is alarming especially in developing countries. Therefore, due to the limited water availability for irrigation, there is a need to optimize water application and enhancement of water productivity similar to maximizing the crop yields by improving soil and water management practices, such as mulch management and different irrigation water application methods (Biswas, 1997).

Furrow irrigation is the common surface irrigation method for water application to cropped fields (Kannan et al., 2015); however, furrow irrigation as practiced by farmers in Ethiopia results in large deep percolation losses and uneven water application (Eba et al., 2018). These are not only result in large losses of limited water but also create problems of waterlogging and salinity (Belay et al, 2022). Therefore, the development of efficient furrow irrigation method and furrow spacing practices are essential for higher water productivity and yield production.

In Ethiopia, most irrigators allocate irrigation water to their field below the maximum crop water requirement for maximum yield because of the limited water and high level of competition at tail of scheme (Lorite et al., 2007). Most of irrigation in Ethiopia (97.8%) is done by surface irrigation methods, especially by furrow system in farmer's fields and majority of the commercial farms (FAO, 2001, Lemma, 2017). The furrow irrigation water application systems include conventional furrow irrigation (CFI), fixed furrow irrigation (FFI) and alternative furrow irrigation (AFI). CFI is where every furrow is irrigated during consecutive watering, is known to be less efficient particularly in areas where there is shortage of irrigation water. The development towards optimum utilization of irrigation to irrigate alternate furrows during each irrigation time is known as alternate furrow irrigation (Zhang et al., 2000). By irrigating alternative furrows, half of root is exposed to wet soil condition and the other half is exposed to dry soil condition. FFI is a means of selection some furrows for irrigation while other adjacent furrows were not irrigated for the whole season.

Wheat (*Triticum aestivum* L.) is one of the first domesticated food crops and has been the basic stable food of the major civilization in most part of the world. It is the most important grain worldwide based on grain acreage and is ranked second when it comes to the total production volume and it is an essential source of calories in human diet. Statista.com reported that the wheat consumption has been increased by 16.72 million metric tons from 2017/2018 to

2020/2021 which measures 775.8 million metric tons. Ethiopia is ranked second among sub-Saharan African nations in terms of total wheat area coverage and production. Wheat (*Triticum aestivum* L.) is one of the main cereal food crops grown extensively in Ethiopia. With 13.25% of all grain crops cultivated in the nation, wheat is the fourth most important crop among cereals in terms of area coverage, after teff, maize, and sorghum (Ketema et al., 2019). Other report from U.S department of agriculture said that the domestic demand of the nation couldn't be covered even though other reports mentioned that Ethiopia is one of in the top three wheat producer in Africa (worldgrain.com). Hodson et al., (2020) also reported that though Ethiopia is the largest producer of wheat at the same time wheat importing by the government is taking billions of dollars every year just to fill the gap between the demand and supply. Therefore, in order to be self-sufficient in wheat supply, the government of Ethiopia has started new program related to expanding irrigated wheat production in different places through enhancing of productivity of irrigation schemes and adding of varies inputs (Ketema *et al.*, 2019). As irrigation of cereal crops like wheat is a new initiative in Ethiopia, the irrigation demand and management needs of the crop is not well researched. Therefore, evaluation of the impacts of different furrow spacing and water application methods on yield and water productivity of wheat (*Triticum aestivum* L.) is urgently required. The results of such assessment will have a great importance to enhance irrigated wheat productivity and developing effective furrow irrigation application system with specific furrow space practices for Melkassa area.

1.2 Statement of the Problem

Water has been identified as one of the scarce inputs, which can severely restrict agricultural production and productivity unless carefully conserved and managed (Jemal, 2018). Irrigation expansion together with inefficient water use in agriculture will exacerbate pressure on available water. Currently irrigated agriculture take place under water scarcity and insufficient water supply for irrigation due to these the crop and the water productivity are low (Belachew *et al.*, 2022). Enhancing water productivity (WP) for sustainable crop production and water savings is a major challenge for current irrigated agriculture (Mubarak & Hamdan, 2018). The lack of irrigation water management had significantly impacted the sustainability of crop production and productivity (Belachewu *et al.*, 2022). The furrow irrigation method is the most

widely used in Ethiopia in almost all large and small irrigation schemes. The furrow irrigation method practiced in our country is traditional. It is less efficient, particularly in areas where there is a shortage of irrigation water usually causing excessive deep percolation at the upper part of the furrow, insufficient irrigation at the lower part and considerable runoff, resulting in low application efficiencies and distribution uniformities. Proper furrow irrigation practices can minimize water application and irrigation costs, save water, control soil salinity, and result in higher crop yields (Michael, 2008). In furrow irrigation, the spacing between furrows can vary based on the specific requirements of the crop, soil characteristics, and equipment capabilities. The determination of the best possible furrow spacing used for the dominant type of soil is important. Ethiopia is the largest producer of wheat at the same time wheat importing by the government is taking billions of dollars every year just to fill the gap between the demands and supply (Hodson *et al.*, 2020). Therefore, to be self-sufficient in wheat supply, the government of Ethiopia has started a new program related to expanding irrigated wheat production in different places through enhancing of productivity of irrigation schemes and adding of various inputs (Ketema *et al.*, 2019). Numerous academicians and scientists conducted studies on, furrow irrigation systems that enhance crop yield and water productivity (Hussain, *et al.*, 2018, Yigezu *et al.*, 2021)). However, the impacts of furrow irrigation method and spacing on yield and water productivity of wheat in our study area are not well evaluated and documented.

1.3 Objectives

1.3.1 General objective

The general objective of this research was to evaluate the effects of furrow irrigation methods and spacing on yield and water productivity of wheat crop.

1.3.2 Specific Objectives

- To evaluate the effect of furrow irrigation methods on yield and water productivity of wheat crop.
- To identify appropriate furrow spacing for irrigation of wheat crop.
- To evaluate the combined effects of furrow irrigation methods and spacing on yield and water productivity of wheat crop.

1.4 Research Questions

- Which furrow irrigation method has productivity and water saving effect on irrigated wheat?
- What is the optimum furrow spacing for irrigated wheat?
- What is the extent of the combined effect of furrow irrigation method and spacing on yield and water productivity of wheat?

1.5 Significance of the Study

At present situation water is a scarce resource due to use of water for different purposes. However, attention given to agricultural water management by the irrigators as well as the irrigation experts is very low. Therefore, efforts should be put in a place to develop water saving mechanisms which can minimize water lost during application of irrigation water. If the amount of water lost due to poor water application method can be saved, irrigation command area of the scheme can be increased and accommodate the increased number of farmers. Saving unproductive losses creates opportunity for optimized use of a limited supply of irrigation water. Improving furrow irrigation methods are among the means of cutting losses and increasing efficiency. Alternate furrow irrigation is considered to be one of the most effective tools to minimize water application and irrigation costs and produce a higher crop yield. The AFI method is a way to save irrigation water, improve irrigation efficiency, and increase yield. Using the appropriate furrow irrigation method with spacing can save irrigation water without yield reduction. It can be more profitable for a farmer to maximize crop water productivity instead of maximizing the harvest per unit of land. Additional plots of land can be irrigated using the water that was saved. The findings of these studies could promote studies by universities, water institutes, research centers, and other academics in the areas of irrigation, conservation agriculture and agricultural water management. The results of this study was also be used as a source of information for irrigation water managers and policymakers in their assessment as well as an understanding of furrow irrigation method with spacing to improve water and agricultural productivity.

1.6 Scope of the Study

The study focused on evaluating the effects of furrow irrigation methods and spacing on yield and water productivity of wheat. The study was containing two factors which is furrow irrigation methods and spacing. The study can involve field experiments conducted on wheat crops, where furrow irrigation methods and spacing configurations are implemented. The choice of irrigation methods (such as conventional furrow irrigation, alternate furrow irrigation, and fixed furrow irrigation) and furrow spacing can be explored as independent variables. The study can evaluate the effect of furrow irrigation methods and furrow spacing on various crop performance parameters. This can include assessing the wheat yield, dry biomass, plant height, spike length and other relevant agronomic characteristics. In this study, the single effects of furrow irrigation method and spacing on yield and water productivity of wheat and the interaction effects of irrigation method with spacing on yield and water productivity of wheat were evaluated during the experiment. Wheat water productivity, growth and yield component parameters, and yield data were collected and analyzed. The experiment was conducted in 2023 for one irrigation season (dry season) of wheat crops at plot level in Melkassa agricultural research center experimental site.

1.7 Expected Output of the Study

At the end of this experimental study the following parameters will be identified

- The effect of furrow irrigation method on yield and water productivity of wheat crop was evaluated.
- The optimum furrow spacing for irrigated wheat crop was identified.
- The combined effect of furrow irrigation method and spacing was evaluated.

2 LITRATURE REVIEW

2.1 Furrow Irrigation

The most commonly used and most ancient type is surface irrigation methods (FAO,2002) through using gravity forces. Furrow irrigation system is the most popular surface irrigation, as it requires a smaller initial investment compared to pressured irrigation systems like sprinkler and drip irrigation systems. For furrow irrigation systems, the important hydraulic variables are inflow rate, length of water run over the field, time of irrigation water cut-off, surface resistance of water flow, field slope and the infiltration characteristics of the soil. The combination of these variables may result in non-uniformity from varying intake opportunity time and infiltration rate throughout the irrigated field. Furrow irrigation method is the most widely used in Ethiopia in almost all large and small irrigation schemes. In Ethiopia, surface irrigation methods predominantly furrow irrigation and basin irrigation methods were practiced for crop production in Ethiopia (Michael et al., 2007, Eba, 2018).

Furrow irrigation is considered one of the main types of surface irrigation methods and consists of furrows and ridges. The water is applied by means of small channels or furrows, which follow a uniform longitudinal slope. The method is best suited to row crops such as maize, potatoes, onions, tomatoes, etc. The principal advantage of furrow irrigation is the less irrigated area compared with other surface irrigation methods, especially basin irrigation, which irrigates the total cultivated area. The furrow irrigation method is the one that has the lowest application efficiency among irrigation methods as a result of water losses in the form of runoff, evaporation from water in the furrow, evaporation from the soil surface, and percolation below the root zone. Losses due to runoff can be significant if tail water is not recovered and reused (Adisu, 2017).

2.2 Advantage of Furrow Irrigation

Furrow irrigation is a type of surface irrigation method in which water is distributed across the field through small, regular channels. For crops grown in rows like vegetables, maize, cotton, tomato, and potatoes, etc., the furrow irrigation method is best suited to deep, moderately

permeable soils. Since water ponding and contact with plant parts can be avoided, furrows are especially well suited for irrigating crops that are susceptible to fungal root rot(Michael, 2008).Furrow irrigation may be adapted on a wide range of natural slopes without causing erosion by designing the furrows across the slope rather than down the slope. The method reduces labor requirements in the land preparation and irrigation. Compared to check basin method, there is no wastage of land in field ditches. Most crops can be irrigated by furrow method except those grown in ponded water such as rice. The furrow method is particularly suitable for irrigating crops subject to injury if water covers the crown or stem of the plants, as the crops may be planted on beds between furrows(Michael, 2008 , Eba, 2018).

Moderate to high application efficiency can be obtained if good water management practices are followed and the land is properly prepared. Different kinds of crops can be grown in sequence without major changes in design layout or operating procedures. The initial capital investment is relatively low on lands not requiring extensive land forming as the furrow are constructed by common farm implements (FAO, 2002). Soils, which form surface crusts when flooded, can readily be irrigated, because water moves laterally under the surface. This irrigation method is best suited to medium and moderately fine textured soils with relatively high available water holding capacity and hydraulic conductivity, which allow significant water movement in both the horizontal and vertical directions. The method is also suited to fine textured soils on level sites, where it permits water impoundment (Michael, 2008 , Jemal, 2018).

As compared to other methods of surface irrigation, furrow method has several distinct advantages: when the available irrigation streams are small, for land of uneven topography, water in the furrows contacts only one-half to one-fifth of the land surface, using furrows irrigation necessitates the wetting of only part of the surface (20% to 50%), thus reducing evaporation losses, lessening the puddling of heavy soils, earlier cultivation is possible which is a distinct advantage in heavy soils, adapted to use without erosion on a wide range of natural slopes by carrying the furrows across a sloping field rather than down the slope, reduces labor requirements in land preparation and irrigation, no wastage of land in field ditches compared to check basin method, Nearly all row crops can be irrigated using furrow method rather than flooding (Michael, 2008 , Teklu, 2022).

2.3 Furrow Irrigation Method

2.3.1 Alternate furrow irrigation system

Alternate furrow irrigation (AFI) meant one of the two neighboring furrows alternatively irrigated during consecutive watering. It offers opportunity for reducing size of irrigation and permits irrigating the field in a shorter time with a given water supply. The reduced size of irrigation may not reduce yields appreciably and thus increase irrigation- water use efficiency. Besides this, alternate furrow irrigation (AFI) system is adopted where salt is a problem. This system saves quite a good amount of water and is very useful and crucial in areas of water scarcity and salt problems. Alternate furrow irrigation system may supply water in a manner that greatly reduces the amount of surface wetted leading to less evapotranspiration and less deep percolation (Hsiao *et al.*, 2007 , Adisu, 2017). Deep percolation can be reduced because the lower wetted surface with alternate furrow results in lower infiltration. It has been suggested that the reduced evapotranspiration in the alternate furrow irrigation method is due to a reduction wet soil surface and continuous regulation on stomatal opening by plant hormone (ABA) Absisic Acid (ABA) produced in roots in drying soil and transported by water to shoot (Farre and Faci, 2009). According to Luis and Lacovos, (2012) alternate furrow irrigation method uses less irrigation water but can maintain the same grain yield production as that of conventional furrow irrigation.

When the supply of water is limited, irrigation is applied through alternate furrows. Besides this, AFI system is adopted where salt is a problem. This system save quite a good amount of water and is very useful and crucial in areas of water scarcity and salt problems (Karajeh *et al.*, 2000).Alternate furrow irrigation (AFI) or Partial root-zone drying (PRD) which involves irrigating only one part of the root zone in each irrigation event, leaving another part to dry to certain soil water content before rewetting by shifting irrigation to the dry side. Therefore, alternate furrow irrigation is a novel irrigation technique that half of the root is placed in drying soil and the other half is growing in irrigated soil (Ahmadi *et al.*, 2011). Absisic Acid (ABA) is a plant hormone that is produced in the roots in drying soils and is transported by water flow in xylem to the shoot for regulating the shoot physiology. Therefore, in alternate furrow irrigation, roots sense the soil drying and induce ABA that reduce leaf expansion and stomatal

conductance and simultaneously the roots in wet soil absorb sufficient water to maintain a high-water status in the shoot. Roots in drying soil produce more ABA than under normal conditions and it is moved as an anti-stress root chemical signal to shoot through transpiration stream and limits the stomatal conductance (Kang, and Zang, 2004).

The studies of Du *et al.*, (2010) have been suggested efficiency of conventional furrow irrigation (CFI) or every furrow irrigation method can be improved by converting it to alternate furrow irrigation (AFI). The AFI method is essentially the same as CFI, except that instead of irrigating every furrow, irrigation is applied to alternate furrows. This means each ridge receives water from only one side, and the side receiving irrigation water could be changed with each irrigation event if the field set up is facilitating this change. Irrigating just one side of the ridge means there is significant potential to save irrigation water compared to CFI. However, there is potential in some cases for a reduction in crop yield (Mashori, 2013). Alternate furrow irrigation (AFI) is considered to be one of the most effective tools to minimize irrigation water application and irrigation costs without yield reduction. The alternate furrow irrigation (AFI) method is a way to save irrigation water, improve irrigation efficiency and increase yield (Shayannejad *et al.*, 2009). Excessive soil moisture following planting can promote seed piece decay and an erratic emergence.

According to Karajeh *et al.*, (2000), application of alternate furrow irrigation system has improved irrigation water use. Under this furrow irrigation system, 56.7-72% of the water supply has been used to replenish soil moisture, 12-21.1% for infiltration within the temporary irrigation network and 11.3-17.8% for surface runoff. Working conditions of labors carrying out irrigation process were improved as this technology allowed them moving on the dry furrows.

2.3.2 Fixed furrow irrigation (FFI)

Irrigating fixed furrow and applying less water per irrigation may provide more storage space within the root zone for potential rainfall. Usually, this technique applies water to more area in a given amount of time than does irrigating conventional furrow irrigation. Benefit of irrigating every other furrow is the ability to store rainfall in a recently irrigated soil. Fixed furrow irrigation (FFI) should not be used on steep slopes or on soils with low intake rates. Research

indicates that fixed furrow irrigation results in yields comparable to those achieved when every furrow is irrigated. Irrigation water application may be reduced 20 to 30 percent by implementing fixed furrow irrigation (FFI) (Yonts *et al.*, 2007);(Jemal, 2018). Fixed furrow irrigation may reduce the volume of water used up to 50 percent and induce a decrease in growth and yield due to the water stress caused by the smaller amount of applied irrigation in same furrow(Masoud, 2012).

Fixed furrow irrigation (FFI) is a way to save water and showed a small improvement over the alternate furrow irrigation (Slatni *et al* ,2011). For economic and environmental benefit of using every-other furrow irrigation method is higher than any other irrigation methods, because less water is applied and a greater economic return can be obtained(Nelson and Kaisi, 2011). Fixed furrow irrigation (FFI) means that irrigation is fixed to one of the two neighboring furrows. Irrigating every other furrow (fixed furrow irrigation) means supplying water to one side of each furrow ridge throughout crop growing season. If water has been applied to every furrow, the entire root zone may have been refilled prior to rainfall.

2.3.3 Conventional furrow irrigation (CFI)

Conventional furrow irrigation (CFI) means irrigating all furrows during consecutive watering. The significant quantities of irrigation water losses by infiltration and surface runoff (about 40% of total water supply) and decreased the efficiency of agricultural production as well as the reliability of drainage systems. This irrigation system has speed up the processes of decomposition and removal of organic elements and mobile forms of nutrients in the root zone that eventually, brought to soil fertility losses (Karajeh *et al.*,2000). Conventional furrow irrigation (CFI) system, where every furrow is irrigated during consecutive watering, is known to be less efficient particularly where there is shortage of irrigation water. It usually causes excessive deep percolation at the upper part of the furrow, insufficient irrigation at the lower part and considerable runoff, resulting in low application efficiencies and distribution uniformities. Therefore, proper furrow irrigation practices have to be devised to minimize water application and irrigation costs and to save water at the same time maintaining higher crop yields.

According to Karaje *et al.*, (2000) under conventional furrow irrigation (CFI) option, irrigation water has been used as follows: 51-54% of the total water supply was used to moisten soil (saturation), 20-25% for infiltration within the temporary irrigation network and in the fields, 5-6% for the evaporation from water surface, and 18-21% for surface runoff. Significant quantities of irrigation water losses by infiltration and surface runoff is about 40% of total water supply which reduced water supply to the irrigated lands and decreased the efficiency of agricultural production as well as the reliability of drainage systems. This irrigation system has speed up the processes of decomposition and removal of organic elements and mobile forms of nutrients in the root zone that eventually, brought to soil fertility losses.

Mintesinot *et al.*, (2000) made a comparative study that has been undertaken over two irrigation seasons (1998/1999 and 1999/2000) between the traditional furrow irrigation management and scheduling; and alternative water management options (furrows-scientific scheduling and every furrow-scientific scheduling) on maize plots in northern Ethiopia. Results were compared on the basis of yield, water productivity and economic productivity concepts. Yield-based comparison has shown that every furrow-scientific scheduling generates the highest yield levels followed by alternate furrows-scientific scheduling. The yield increase by every furrow-scientific scheduling over the traditional management was found to be 54%. Water productivity-based comparison has shown that alternate furrows-scientific scheduling generates the highest water productivity values followed by every furrow-scientific scheduling. The increase by alternate furrow irrigation, scientific scheduling over the traditional irrigation management was 58%. Economic productivity-based comparison has shown that the highest economic return was obtained from every furrow-scientific scheduling followed by alternate furrows-scientific scheduling. The increase in income by every furrow scientific scheduling over the traditional irrigation management was 54%.

2.4 Effect of Furrow Irrigation on Yield

Selamawit & Oli, (2020) revealed that maize grain yield at $p < 0.05$ significantly influenced by furrow irrigation method. But there is no significant difference between mean grain yields obtained from conventional furrow irrigation and alternate furrow irrigation treatments but there is significant difference between mean grain yields obtained from conventional furrow

irrigation and fixed furrow irrigation treatments. Application of conventional furrow irrigation and alternate furrow irrigation gives a higher grain yield of 9284.6k g/ha and 8768.3k g/ha respectively. non-significant yield reduction relative to the conventional furrow irrigation at $P < 0.05$, while fixed furrow irrigation had a significant grain yield reduction of 16.84 % as compared to conventional furrow irrigation.

According to Mehamed, (2019) Furrow methods showed significant effect in maize grain yield ($P < 0.05$). Conventional furrow irrigation method was produced the highest grain yield with the value of 5.7 tone/ ha followed by alternative furrow irrigation methods. In the other hand fixed furrow irrigation methods were recorded the lowest maize grain yield with the value of 4.33 t/ha. Conventional furrow irrigation method was recorded 15.78% superior to alternative furrow irrigation method and 24.03% of fixed furrow irrigation method.

According to Pradhan *et al.*, (2013) though crops such as wheat grain yield increase with amount of irrigation water increase, it could be grown with irrigation to replenish only 60% soil moisture depletion to field capacity to achieve higher water productivity without any significant reduction in crop yield. Moreover, moisture stress could be applied to enhance the utilization of scarce water in irrigation.

Meskelu *et al.*, (2018) showed that maize biomass yield was significantly affected ($P < 0.05$) by the different level of furrow methods. Higher biomass yield was recorded when convectional furrow irrigation method applied that gave 14.5 t/ha and followed by alternative furrow irrigation method with the value of 13.26 t/ha. The lowest biomass yield of maize was obtained from the treatment of fixed furrow irrigation method with the value of 12.28 t /ha.

Jemal *et al.*, (2018) declared that grain yield was significantly ($P < 0.05$) affected by irrigation methods (IMs). The largest mean value of 64.88 t/ha were produced under CFI, but statistically the yield recorded by AFI and FFI were not significantly different.

2.5 Effect of Furrow Irrigation on Water Productivity

According to Selamawit & Oli, (2020) application furrow irrigation method had a significant effect on water productivity of maize. Also, alternate furrow and fixed furrow irrigation application gives the higher water productivity value with less water application as compared

to conventional furrow irrigation. Alternate furrow application had a significant water productivity increment as compared to both fixed furrow and conventional furrow irrigation by 12.18 % and 47.6 % respectively.

Mehamed, (2019) revealed that the different types of furrow irrigation water management methods on maize have shown a significant ($p < 0.05$) influence on water productivity. Water productivity of maize was higher under alternate furrow irrigation method as compared with conventional and fixed furrow method. The highest water productivity (1.75 kg/m³) was recorded at alternate furrow irrigation method and statically superior to both conventional and fixed furrow methods. The minimum water productivity (1.1 kg/m³) was observed at conventional furrow method and this was statistically inferior to both alternate and fixed furrow method during growing seasons.

Similarly Meskelu *et al.*, (2018) reported that water use efficiency was significantly ($p < 0.01$) influenced due to different types of irrigation water management methods. Results indicated that the water use efficiency of maize was higher under alternate furrow irrigation method during both seasons as compared with conventional and fixed furrow method. Maximum water use efficiency (1.69 kg/m³) observed at alternate furrow method was statistically superior to both conventional and fixed furrow methods. The minimum water use efficiency (1.15 kg/m³) was observed at conventional furrow method and this was statistically inferior to both alternate and fixed furrow method during both seasons.

2.6 Furrow Spacing

Furrow spacing refers to the distance between individual furrows in an irrigation system. In furrow irrigation, crops are grown in rows, and furrows are created between the rows to deliver water to the plants.

Furrow spacing varies usually from 45 to 150 cm (for sugar cane) depending on crops, crop spacing and their cultural practices, soil characteristics allowing the lateral movements of water to wet the soil below the ridges and machinery used. Furrows are spaced wider up to 180 cm for orchard crops on soils with greater permeability. Usually, the spacing between furrows is narrower in sandy soils and wider in heavy soils. This is to ensure that water spreads laterally into the soil below ridges and downwards in the effective rooting depth uniformly. The cross

section of furrows is designed to carry sufficient water to wet the whole length of the furrow and the soils between furrows by capillary. In high rainfall areas drainage provision is necessary at the end of the furrows. Length of furrows varies from 45 to 300 m. they are shorter in coarse soils and longer in heavier soils. When the slope is from 0.05 to 0.3 percent, furrows are 200 to 250 m long in medium (loam) soils and 300 to 450m long in heavy soils (Majumdar, 2004).

Furrow spacing affects how evenly water is distributed across the field. If the furrow spacing is too wide, there may be gaps between furrows where water does not adequately reach the crop roots. This can result in uneven water distribution, leading to variations in soil moisture levels and potential water stress for some plants. On the other hand, if the furrow spacing is too narrow, it may result in excessive water accumulation and poor drainage, which can also negatively impact crop growth. Finding the optimal furrow spacing that ensures uniform water distribution is crucial for maximizing crop yield and water productivity.

Furrow spacing influences soil moisture dynamics within the field. Narrow furrow spacing can result in smaller wetted soil areas around each furrow, leading to relatively higher soil moisture levels. This can be beneficial in areas with low water-holding capacity, as it helps maintain sufficient soil moisture for the crop. On the other hand, wider furrow spacing can result in larger wetted soil areas, potentially reducing soil moisture levels. This configuration may be more suitable in areas with high water-holding capacity soils or regions where excess soil moisture can lead to waterlogging issues. Proper furrow spacing selection can help optimize soil moisture management, ensuring adequate water availability for the crop without excessive drainage or water stress. It also affects the spatial arrangement of crops within the field. Narrow furrow spacing can result in denser planting configurations, leading to more intense crop competition for resources such as water, nutrients, and sunlight. This competition can influence crop growth and yield potential. Alternatively, wider furrow spacing allows for more individual space for each plant, potentially reducing interplant competition. Understanding the relationship between furrow spacing and crop competition is important for optimizing plant density and achieving the desired crop yield.

2.7 Wheat Production around the World

Wheat is one of the first domesticated food crops and has been the basic stable food of the major civilization in most part of the world. It is successful at the area of latitude between 30° and 60° N and 27° & 40°S; of course, it can be produced beyond this limit too. The optimal growth temperature is about 25°C which is between minimum and maximum temperature of 30°C & 40°C and 30°C & 32°C respectively (FAO- wheat in the world by Curtis) and (Bouras *et al.*, 2019). Wheat is the most important grain worldwide based on grain acreage and is ranked second when it comes to the total production volume and it is an essential source of calorie in human diet. Statista.com reported that the wheat consumption has been increased by 16.72 million metric tons from 2017/2018 to 2020/2021 and is the second grain type produced in the world which measures 775.8 million metric tons. This indicates that the demand for this particular crop will continue increasing for the next coming times too.

2.8 Wheat Production and Productivity in Ethiopia

Wheat (*Triticum aestivum*,) is one of the most important food security crops in Ethiopia. It is cultivated on a total area of 2.1 million (1.7 million ha rain fed and 0.4 million ha irrigated) hectares annually with a total production of 6.7 million tons of grain at an average productivity of 3.0 and 4.0 t/ha under rain-fed and irrigated conditions (Tadesse *et al.*, 2022). As U.S department of agriculture report the domestic demand of the nation couldn't be covered even though other reports mentioned that Ethiopia is one of in the top three wheat producer in Africa (worldgrain.com). According to (Ketema *et al.*, 2019), it is commonly grown in the highlands at altitudes ranging from 1500 to 3000masl. Major wheat production areas in the country are Arsi, Bale, Shewa, Ilubabor, Western Harerghe, Sidama, Tigray, Northern Gonder, and Gojam regions.

Hodson *et al.*, (2020) reported that Ethiopia is the largest producer of wheat at the same time wheat importing by the government is taking billions of dollars every year just to fill the gap between the demand and supply. Even if the reports indicated the need of wheat production increment in the future, the parameters which limit its productivity and production are not well studied and irrigation practices are still traditional (Fitsume *et al.*, 2017).

2.9 Water productivity

The concept of water productivity in agricultural production systems is focused on ‘producing more food with the fewer water resources’ or ‘producing the same amount of food with less water resources’. Water productivity (WP) mainly refers to the ratio between output derived from water use and the water input (volume or value of water depleted or diverted)(Clement et al., 2011). The more commonly used concept of ‘water productivity’ and its measurement at various scales is a robust measure of the ability of agricultural systems to convert water into foods. Crop water productivity (WP) expressed in kg/m^3 is an efficiency term, expressing the amount of marketable product (e.g. kilograms of grain) in relation to the amount of input needed to produce that output (cubic meters of water) (Kijne *et al.*, 2003). The water used for crop production is referred to as crop evapotranspiration. This is a combination of water lost by evaporation from the soil surface and transpiration by the plant, occurring simultaneously. Except by modeling, distinguishing between the two processes is difficult. Representative values of WUE for cereals at field level, expressed with evapotranspiration in the denominator, can vary between 0.10 and 4 kg/m^3 (Zwart and Bastiaanssen, 2000). In crop production system, water productivity is used to define the relationship between crops produced and the amount of water involved in crop production, expressed as crop production per unit volume of water (Kassam, A. and Smith, 2001). Increasing the WP of irrigated and rain fed agriculture is thereby seen as the critical element in increasing agricultural production without a major increase in fresh water diversion to agriculture particularly in regions facing increasing water scarcity (FAO, 2012).

3 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The study was conducted at Melkassa Agricultural Research Centre during the dry season of 2023. This area is located in Ethiopia's Central Rift Valley. Geographically, it is located latitudes 8°24' and longitudes 39°12'. The area's mean altitude is 1550 m.a.s.l (Figure 3.1). It is located 17 km southeast of Adama and 107 km east of Ethiopia's capital, Addis Ababa. The two major soil types in the area are loam and clay loam.

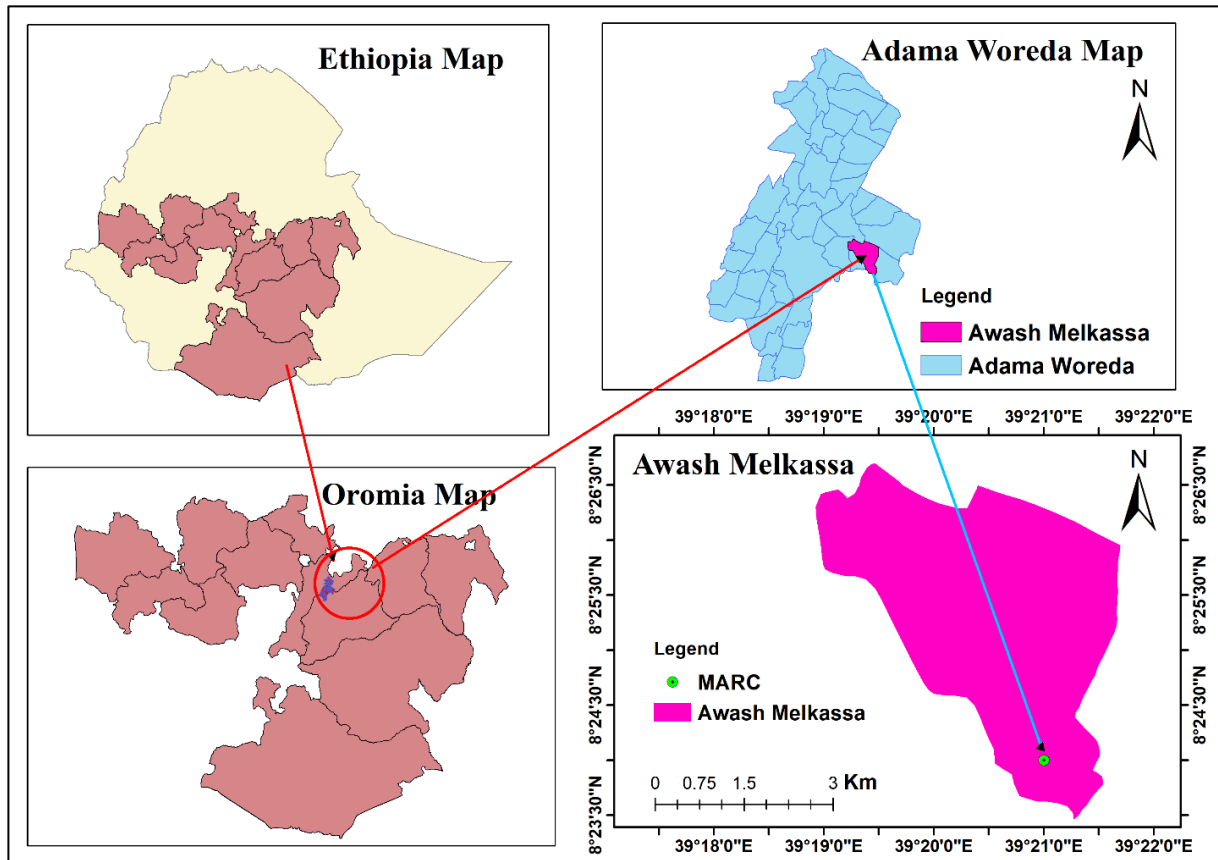


Figure 3-1: Map of the study area

3.1.2 Climate

Long-term (1977 – 2017) climatic record from station, average annual rainfall in the area is 824.9 mm. The climate of the area is characterized as semi-arid with uni-modal low and erratic

rainfall pattern. Kiremt season have got more rainfall about 67.4% of the total rainfall of the area occurs from June to September, with peak month of July and August. The mean maximum and minimum monthly rainfall is 191.4 and 9.1 mm occurs in the month of August and November, respectively. The mean maximum temperature varies from 26.3 to 30.9 °C while the mean minimum temperature varies from 11.1 to 16.5 °C, with the average of 20.12 °C (Table 3.1).

Table 3-1: Mean annual climate data at melkassa station (1977-2017)

Month	Tmax(°C)	Tmin (°C)	RH (%)	Wind speed (m/sec)	Sunshine hour(hr.)	Rainfall (mm)	Eto (mm/day)
January	27.97	11.66	51	8.6	9.05	15.64	7.3
February	29.21	13.41	48.7	9.1	9.04	24.20	8.2
March	30.5	15.10	49.2	8.6	8.55	47.56	8.4
April	30.5	15.49	50.8	7.8	8.25	61.32	8.1
May	31.3	15.57	51.2	7.5	8.74	60.58	8.1
June	30.17	16.39	53.1	9.0	8.35	67.93	8.1
July	26.88	15.67	66.4	9.1	6.95	200.95	5.9
August	26.34	15.37	69.2	7	7.02	185.52	5.3
September	27.67	14.45	65.8	4.9	7.44	100.71	5.4
October	28.79	11.65	50	6.6	8.66	38.89	7.2
November	28.34	10.81	46.7	8.3	9.58	13.76	7.8
December	27.57	10.36	46.8	8.9	9.44	9.52	7.5

Source: MARC agro Metrological observation station

3.1.3 Farming practices

In the area, farmers grow crops three times a year: twice in the wet (September to January) and again in the dry (February to May) seasons, respectively, using traditional furrow irrigation; while the third time, in the rainy season (June to September), they use supplemental irrigation and rainfall. The crops grown include pepper, tomato, onion, potato, shallot, haricot beans, sweet potato, papaya, wheat, maize and teff. Most of the time, vegetable crops grow during dry season and cereal crops during rainy season(Scholten,, 2007). In the study area Awash River is used as the source of irrigation water.

3.2 Experimental Design and Layout

3.2.1 Experimental design

The experiment was arranged in a split-plot design with three replications. The treatment includes two factors which are three furrow irrigation methods (CFI, AFI and FFI) and three furrow spacing (40 cm, 50 cm and 60 cm). CFI with 60 cm spacing were used as control. The treatments were randomized in split plot arrangement. The furrow spacing was in the main plot while the furrow irrigation method was assigned to the subplots. The amount of irrigation water to be applied at each irrigation application was measured using the Parshall flume. The details of the experimental treatments are presented in Table 3.2.

1. Conventional furrow irrigation (CFI): In this case, each furrow received watered throughout a series of irrigation events.
2. Alternate furrow irrigation (AFI): During each irrigation event, one of the two neighboring furrows was irrigated alternately.
3. Fixed furrow irrigation (FFI): During successive irrigation events, irrigation was in this case fixed to one of the two neighboring furrows.

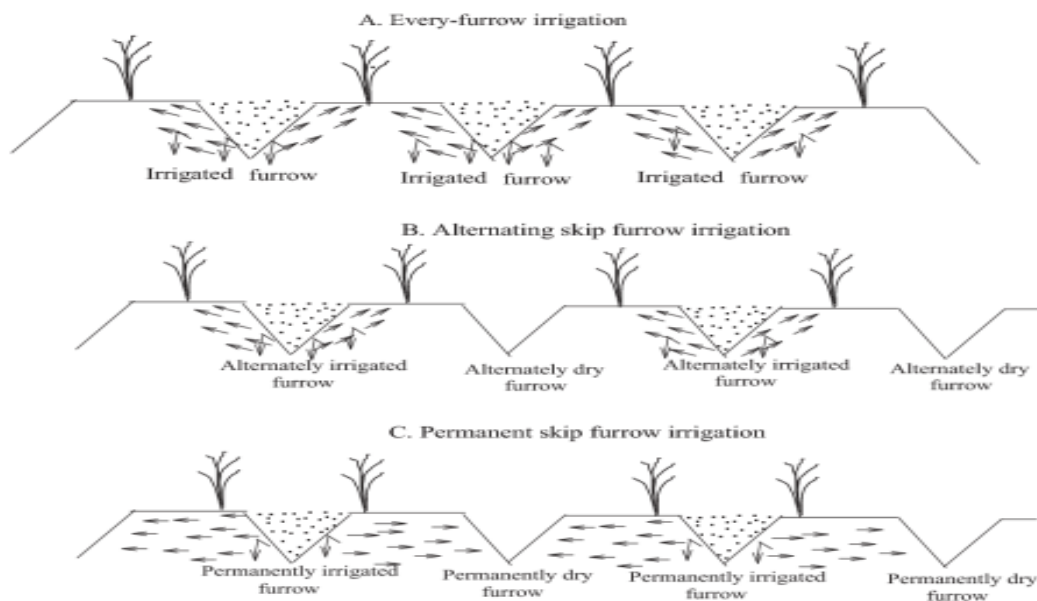


Figure 3-2 layout of furrow irrigation system (Source:(Devkota et al., 2015))

The treatment combination of the experiment was totally nine and showed in table 3.2 below.

Table 3-2: Treatment combination

Treatments			
Main plot	Sub plot	Treatment	Treatment No
Furrow	Irrigation	Combination	
spacing(cm)	method		
40	CFI	CFI with 40 cm	T1
	AFI	AFI with 40 cm	T2
	FFI	FFI with 40 cm	T3
50	CFI	CFI with 50 cm	T4
	AFI	AFI with 50 cm	T5
	FFI	FFI with 50 cm	T6
60	CFI	CFI with 60 cm(control)	T7
	AFI	AFI with 60 cm	T8
	FFI	FFI with 60 cm	T9

Note. The control furrow spacing was selected based on conventional practice.

3.2.2 Experimental layout

The experimental field was split up into 27 plots, with a plot size of 4 m × 3.6 m=14.4 m² area. Different furrow spacing (40, 50, and 60 cm) exist in the plot. The distances between plots and blocks were 1.5 m and 3 m respectively. Block distance should be adequate to reduce the impact of lateral water flow into the plots, as this experiment used the furrow irrigation method. For the purpose of irrigating its field a field channel was built for every block. Using a 3-inch Parshall flume, the pre-calculated irrigation water was applied into each plot. The irrigation interval remained at the same interval as the control treatment. In order to replenish the soil moisture to the field's capacity, the treatment was irrigated according to the allowed moisture depletion level in the effective root depth. The Parshall flume was set up 10m away from the nearest plot in the main canal to the experimental field.

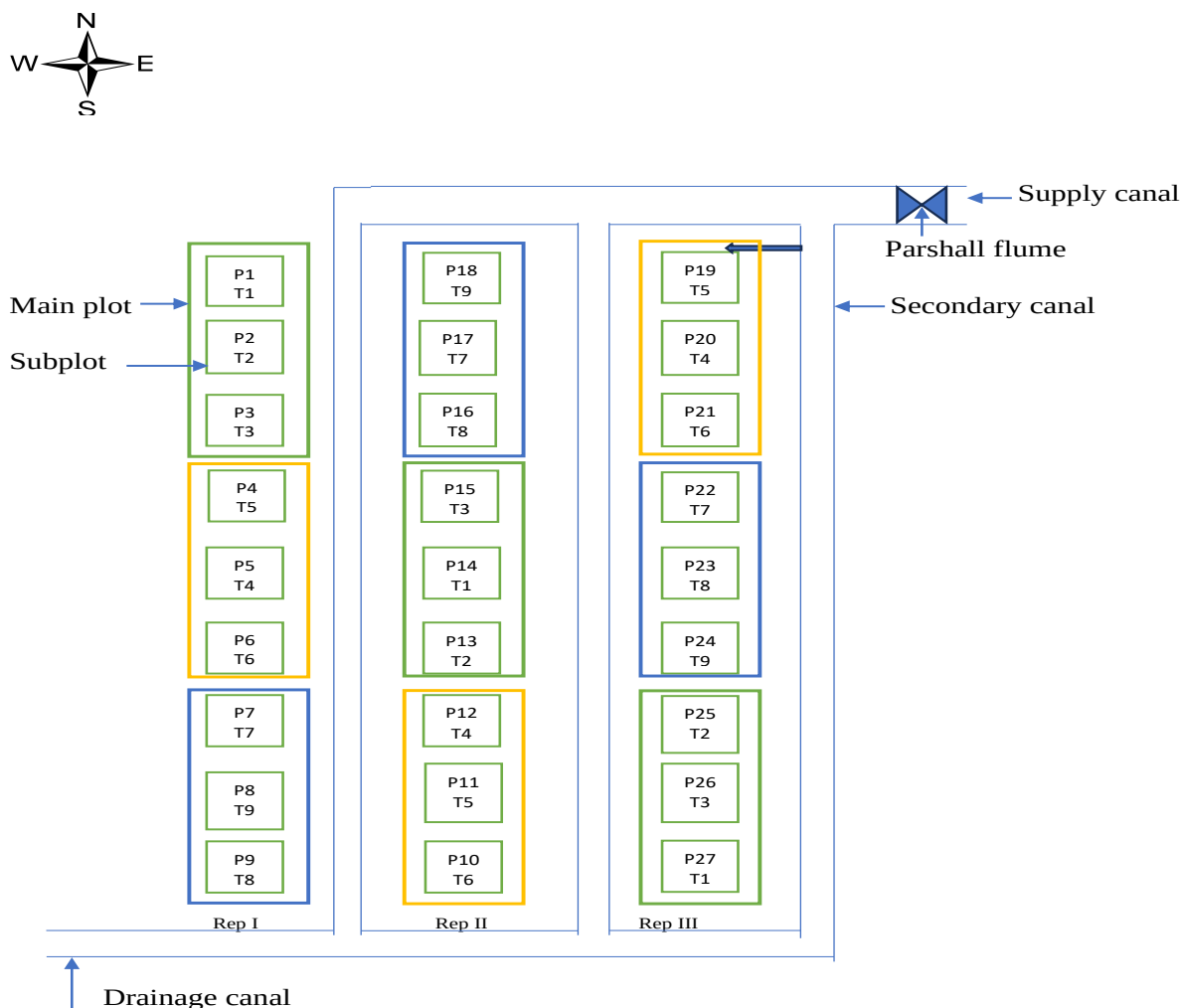


Figure 3-3: Layout of the experimental field

3.2.3 Agronomic practices of the experiment

The seed material utilized was King Bird variety wheat (*Triticum aestivum* L.). On February 17, 2023, the seeds were drilled into experimental plots. To grow the plant, the furrow irrigation method was employed. Based on the furrow spacing; every plot has a distinct number of furrows. There are 6 furrows at the control furrow spacing of 60 cm, 7 furrows at 50 cm, and 9 furrows at 40 cm. The seed rate for each treatment was 125 kg/ha (Meskelu *et al.*, 2017). The agronomic recommended rate of 125 kg/ha of NPS and 74 kg/ha of urea at the time of sowing and 45 days after sowing 74 kg/ha was applied to each treatment based on the recommend value in the experimental area. The experiment was protected from disease and pests through the use

of chemicals, such as Matco, Manguzab, Profit, Ajanta, and others, at varying rates. Fertilizer application, chemical treatments, and weed management were applied uniformly to every experimental plot.

Seven days after seeding, the crop showed 100% germination. For better crop establishment, two common irrigations and a pre-irrigation were conducted at the early germination stage. Before harvesting, more weeding was completed and irrigation water was applied. About 103 days after planting, the crop was ready for harvest. The recommendations provided for the crop in the area were followed for the other crop management techniques.

Based on the daily actual weather data gathered from the Center's weather station, the CROPWAT 8.0 model was used to calculate the daily ETo. Optimum depletion level and root depth were adopted from (Allen *et al* .,1998). Effective rainfall for the season was calculated using the CROPWAT 8.0 model on a daily basis, considering the rainfall reported at MARC Agro meteorological Service. This amount was then subtracted from the net irrigation depth of the next irrigation. A 3-inch Parshall flume was used to measure the amount of irrigation water applied to each experimental plot. All treatments received irrigation on the same days.

3.3 Data Source

The data sources used for this study was listed in Table 3.3.

Table 3-3: Data sources used for the study

No	Data type	Source	Data type collected	Purpose
1	Crop data	FAO 56	Effective root depth and depletion fraction	To determine crop water requirement
2	Soil data	Laboratory Result	FC and PWP	Irrigation scheduling
3	Climate data	Metrological station	Tmax, Tmin, RH, Uand Sunshine hour	Determination of Eto

3.4 Materials used for conducting the experiment

There were different materials that are used from land preparation to data analysis. These materials are listed in Table 3.4

Table 3-4: Materials used for the study

No	Material	Purpose
1	Tractor	To plough and land level
2	Meter	for field Measurement
3	Hoe	For hoeing
4	Parshall flume	Measuring of the discharge
5	Spade	used for irrigation
6	Ruler	For measuring plant height and spike length
7	Knapsack	To spray chemical
8	Stopwatch	For timing
9	Auger and core sampler	Soil sample
10	Oven dry	To dry the soil sample
11	Sensitive balance	To measure the soil sample and yield
12	Sickle	To harvest the wheat crop
13	Stand counter	To count 1000 seed of wheat
14	CROPWAT8.0	To determine ETo, ETc and irrigation scheduling
15	Statistix10	Analysis of data
16	Pressure plate	To determine FC and PWP

3.5 Determination of soil physical properties

3.5.1 Soil texture and bulk density

For textural analysis, disturbed soil samples were collected at three distinct locations along the diagonal of the experimental block, at four different depths: 0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm according to the crop's root depth. The particle size distribution at the MARC soil laboratory was analyzed using the hydrometer method, and the textural class was determined based on the percent of sand, silt, and clay in the USDA textural triangle for each sample.

The soil bulk density was determined from undisturbed soil samples that were collected by using a cylindrical core sampler of size 5 cm in diameter and 5 cm in height at the same location and depth in which the soil collected for textural analysis. The samples were then dried in an oven at 105°C for 24 hours and the bulk density was then calculated using the following equation given by (Hillel, 2004).

$$\rho_b = \frac{W_s}{V_c} \quad (3.1)$$

Where : ρ_b is soil bulk-density (g/ cm³),

W_s is mass of dry soil (g) ,

V_c is volume of soil in the core (cm³).

3.5.2 Soil field capacity (FC) and permanent wilting point (PWP) analysis

In order to determine the moisture content at field capacity (FC) and permanent wilting point (PWP), three locations along the diagonal of the experimental field were used to collect sample of soil at intervals of 0, 15, 30, 45, and 60 cm. A soil sample was saturated and then put into a plastic ring-equipped pressure plate apparatus at MARC laboratory station. After the pressure plate was properly closed, the compressor gauge was set to 1/3 bar for FC and 15 bar for PWP. Once the samples from the pressure plate apparatus were no longer visible, they were

weighed and oven dried for a 24hr at 105 °C. After that, using equation 3.2, TAW was calculated.

$$TAW = (Fc - PWP) * \rho_b * Rd \quad 3.2$$

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

Rd -is root depth (m)

FC -is moisture content at field capacity (%)

PWP -is moisture content at permanent wilting point (%)

ρ_b -is soil bulk density (g/cm³)

But not all the total moisture (water) easily extract by plants. The amount of water that the plants easily extract without suffering and energy from the soil called readily available water (RAW). It is a fraction of TAW which plant can easily extract from the root zone. Mathematically RAW expressed in equation 3.3

$$RAW = TAW * \rho \quad 3.3$$

Where: RAW is the readily available moisture (mm)

ρ is Allowable depletion level (%) 55% for wheat (Allen *et al.*, 1998)

3.6 Determination of crop water requirement

Using daily climatic data maximum temperature (Tmax), minimum temperature (Tmin), relative humidity(RH), Sunshine hour(hrs), and wind speed at 2 m(U₂) gathered from Melkassa Agricultural Research Centre metrological station, then monthly ETo was calculated using the CROPWAT model version 8.0(FAO, 2009) . ETo is computed using the FAO Penman-Monteith formula by the CROPWAT model using equation 3.4

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{900}{T + 273} \right) U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad 3.4$$

Where: ET_o is Reference evapotranspiration (mm/day)

R_n is Net radiation at the crop surface (MJ/M²/day)

G is Soil heat flux density (MJ/M²/day)

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

U₂ is wind speed at 2m height (m/s)

e_s is Saturation vapour pressure (kPa)

e_a is Actual vapour pressure(kPa)

e_s-e_a is saturation vapour pressure deficit(kPa)

Δ is slope vapour pressure curve (kPa/°C)

γ is psychrometric constant (kPa/°C)

Each day evapotranspiration of the crop was determined by multiplying the daily crop coefficient (K_c) of the crop by the daily reference evapotranspiration (E_{To}).

$$ET_c = K_c * E_{To} \quad 3.5$$

Where: E_{Tc} is crop evapotranspiration (mm/day),

K_c is crop coefficient, is a function of crop type and growth stage (dimensionless)

E_{To} is reference evapotranspiration (mm/day)

The K_c value for wheat taken from (Ketema *et al.*, 2019) showed in Table 3.5 through the growth stage. Based on the K_c values of the crop and length of each growth stages, daily crop coefficient was interpolated for development and late season. Because the K_c value at the development stage and late was not constant due to the water needed by the crop was increased from initial to development and incase of late stage the water need of crop decrease and K_c from mid to late. (Appendix figure1) Length of growth stages of wheat was 23, 25, 30 and 25 days for initial, development, midseason and late season, respectively ((Ketema *et al.*, 2019) (Table 3.5).

A successive irrigation depth was applied on that particular day based on RAW for the root depth. Until the cumulative deduction from the applied net irrigation depth approached zero, the crop evapotranspiration for the control treatment (100% ETC) was deducted daily from the

net irrigation depth. The next step involved applying irrigation after the control treatment's cumulative ETC approach to net irrigation depth was implemented.

Wheat effective root depth was taken at germination and interpolated daily for the period between the first day of the starting stage and the last day of the development stage. 0.6m was considered to be the constant effective root depth throughout the mid- and late-season (Appendix figure2).

Table 3-5: Parameters used for estimation of crop water requirement of wheat

Parameters	Growth stage				
	Initial	Development	Mid	Late	Total
Days after sowing (Dys)	23	25	30	25	103
Crop coefficient (Kc)	0.54		1.15	0.67	
Depletion factor(P)	0.55	0.55	0.55	0.55	0.55

3.6.1 Determination of the net irrigation requirement of the crop

The net irrigation water demand is the amount of water needed by irrigation to meet crop evapotranspiration and water requirements that cannot be fulfilled by precipitation or water stored in the soil profile (I_n). Calculating the net irrigation water require included considering the capability of the soil to hold water from the critical depletion level to the field capacity at the effective root depth(Frenken,2002). The net irrigation was calculated by readily available water minus effective rainfall. If there is no effective rainfall net irrigation equal to RAW.

$$I_n = (Fc - PWP) * \rho * \rho_d * Rd - Pe \quad 3.6$$

Where: I_n -net irrigation water requirement (mm),

Pe-Effective rainfall (mm)

Fc-Mass base moisture content at field capacity (%)

PWP- Mass moisture content at Permanent Wilting Point (%)

ρ - Allowable soil moisture depletion level for wheat (%)

ρ_d –soil bulk density (g/cm³)

Rd- Root depth (m)

3.6.2 Determination of effective rainfall

The amount of rainfall that plants can use effectively to germinate or continue to its growing is referred to as effective rainfall in terms of agricultural production. In other words, some rain is lost to runoff and deep percolation, so that not all of the rainfall reaches on the crops. The Water Service of the FAO established an empirical formula based on studies performed for several arid and sub-humid climates to determine dependable rainfall, the combined effect of dependable rainfall (80% opportunity of exceedance), and estimated losses due to deep percolation and runoff. (FAO, 2009). Determination of effective rainfall was computed based on equation 3.7 and 3.8 of 'dependable rainfall' (FAO/AGLW formula) using daily rainfall data. Daily effective rainfall calculated based on equation below.

$$P_{eff} = 0.6 * P - 10 \quad \text{For precipitation} \leq 70\text{mm} \quad 3.7$$

$$P_{eff} = 0.8 * P - 24 \quad \text{For precipitation} \geq 70\text{mm} \quad 3.8$$

Where: p is monthly dependable rainfall (mm) and

Pe is monthly effective rainfall (mm)

The effective rainfall for the season was calculated using the CROPWAT 8.0 model on a daily basis, taking into account the rainfall recorded at MARC Agro-Meteorological Service. This amount is subtracted from the net irrigation depth of the next irrigation.

3.6.3 Determination of field application efficiency and growth irrigation depth

The ratio of water received at the field intake to water directly stored in the crop root zone is known as the field irrigation application efficiency (Ea). It is affected by the crop root zone's capacity for storage, the rates at which water is supplied, and the rate at which the soil infiltrates. The major water lost in furrow irrigation occurs due to runoff at the tail end and deep percolation at the head end. With proper planning, building, and management, furrow irrigation can achieve 70% field application efficiency. From 50 to 70% is the usual range. 60% is a more common percentage (FAO, 2002). The total amount of water applied by irrigation, including

losses, is referred to as the gross irrigation requirement; alternatively, it can be expressed as the net irrigation demand plus application and other losses. Mathematically it can be expressed in equation 3.9

$$I_g = \frac{I_n}{E_a} \quad 3.9$$

Where: I_g is Gross irrigation (mm)

I_n is Net irrigation depth (mm)

E_a is Field application efficiency (%)

At last, based on the treatments proportion, calculated gross irrigation depth was applied to every experimental plot. Plot area and the depth of the gross irrigation require were used to calculate the volume of water applied for each treatment.

3.6.4 Measurnment of water application

A 3-inch Parshall flume constructed of metal sheet was used to measure the irrigation water applied to each experimental plot. It was installed along a secondary canal 10 m away from the closest plot. The leveling of converging section was examined in every direction. Since the base of the diverging portion of the Parshall Flume slopes slightly upward, leveling the diverging section was only checked across the waterway. In order to prevent submergence flow, the entrance section was positioned 4 cm above the canal bed. To reduce downstream scouring, stone riprap was placed on the downstream side of the canal bed. To find the flow rate of the free flow condition, only one measurement was needed. This is the water height indicated by the Parshall Flume gauge, which is written on the 2/3 of the entry section of the parshall flume wall.

Finally, based on the treatments proportion, calculated gross irrigation depth was given to each experimental plot. The plot area and depth of the gross irrigation demand were used to calculate the volume of water applied for each treatment. The amount of water applied in relation to the discharge-head relation of a 3-inch Parshall flume was used to compute the amount of time needed to irrigate each treatment (Appendix Table2). The discharge level may vary depending on the field conditions; hence the time needed was estimated between 5 and 15 cm head levels

of the parshall flume. It was determined how long it would take to get each furrow filled to the appropriate water depth. It was calculated based on equation 3.10 given by (Michael, 2008). The time taken was recorded by stopwatch.

$$t = \frac{A * I_g}{60Q} \quad 3.10$$

Where: I_g -gross depth of water applied (mm)

t -application time (sec)

A -plot Area (m^2)

Q -flow rate (l/s) at the parshall flume (Appendix table 2)

To apply calculated water the canal was wet until the head become constant at peak head discharge to reduce variation of water divert to plots far from and near to the Parshall flume.

3.7 Data collection

During the experimental study agronomic, growth and yield component datas were collected. Such as agronomic parameters include (sowing date, spacing, fertilizer application time, weeding and pesticide application, date of planting, emergence), growth, yield and yield components (plant height, spike length, number of seed per spike, dry biomass, 1000 seed weight and harvesting index) and water productivity data were collected. These parameters were determined in the following ways:

3.7.1 Growth parameters

Plant height (cm): - This was taken from a sample of five randomly selected wheat plants and measured from the ground level to the top-most leaf using a wood ruler before harvest. The mean from the five plants was then taken as the mean plant height.

Spike length (cm): - Five spikes were taken from each plot at random, their length was measured using ruler before harvest and the average was calculated.

Number of seed per spike (No.): -These was taken from a sample of five randomly selected spike and count the number of seed in each spike and take the average number of seed.

3.7.2 Yield and yield components

In order to assess the effect of treatments on crop yield, the grain yield was collected from central ridges only for the sake of avoiding boarder effects. The grain yield was different based on the furrow spacing. Weight of fresh fruits harvested from the central rows was recorded; the data recorded were estimated in terms of yield per hectare.

1000 seed weight (g): - one thousand seeds were taken randomly from grain yield of the plot and it was measured with stand counter.

Aboveground biomass (kg/ha): - Total aboveground biomass data were collected by weighing the total harvested material, consisting both grain yield and straw yield, from each plot.

Total grain yield (kg/ha): -Grain yield per plot (g/plot) was measured using sensitive balance and converted to hectare basis.

Straw yield (kg/ha): - Straw yield was calculated by subtracting the grain yield from aboveground biomass yield per hectare of each plot.

Harvest index (HI) (%): - is the ratio of grain yield per hectare to total aboveground biomass per hectare. It was determined based on equation 3.11: -

$$HI(\%) = \frac{Grain\ yield(\frac{kg}{ha})}{Above\ ground\ biomass(\frac{kg}{ha})} * 100 \quad 3.11$$

3.8 Water Productivity

Water productivity was determined based on the ratio of economical yield of wheat (grain yield per hectare) to the net irrigation depth and effective rainfall used from germination to harvest expressed as kg of grain yield per m³ of water. It was calculated based on the following formula for water use efficiency(Chandrasekaran et al, 2010).

$$Wp = \frac{Grain\ yield}{Twu} \quad 3.13$$

Where: WP - Water productivity (kg/m³)

Ya - Actual yield (kg/ha)

Twu – Total water used (m^3/ha)

3.9 Economic water productivity

Economic water productivity analysis was computed by considering the general relationship between the crop water use and crop yield per hectare of land at the different irrigation application method using the partial budget analysis. Net income (NI) in Birr/ha, generated from wheat crop, was computed by subtracting the total cost (TC) in Birr/ha from the total return (TR) in Birr/ha obtained from wheat sale as

$$\text{NI} = \text{TR} - \text{TC} \quad (3.14)$$

TC is the sum of FC and VC. Fixed costs (FC) are those that do not vary between irrigation treatments, i.e. wheat seeds, fertilizer, pesticides, land rent and farm implements. Variable costs, on the other hand, are those that do vary between irrigation treatments, i.e. irrigation water and labor. The cost of labor for the furrow irrigation method was different. It depends the time to irrigate the plots base on the treatment.

3.10 Statistical Analysis

The data was analyzed by using Statistix10 and mean separation was made using Least Significant Difference (LSD) method. To quantify the relation among irrigation method, furrow spacing, water productivity, and yield and yield components, correlation and regression analyses were carried out.

4 RESULTS AND DISCUSSIONS

4.1 Physical and chemical Properties of the soil

The physical and chemical properties of the soil on experimental site were analyzed at MARC laboratory and summarized in (Table 4.1 and 4.2).

Table 4-1: soil physical property of the experimental site

Soil physical property	Soil depth(cm)				Average
	0-15	15-30	30-45	45-60	
Particle size distribution					
Clay (%)	26.5	24	29	26.5	26.5
Silt (%)	45	42.5	35	37.5	40
Sand (%)	28.5	33.5	36	36	33.5
Textural class	Loam	Loam	Clay loam	Loam	Loam
Bulk density(g/cm3)	1.05	1.15	1.19	1.16	1.26
Fc mass base (%)	33.8	36.5	39.3	37.7	36.82
PWP mass base (%)	20.8	21.1	23.5	22.9	22.08
TAW volume base(mm/m)	20.7	26.6	28.2	28	25.8

Note: -Fc=Field capacity, PWP=permanent wilting point, TAW= Total Available Water

The chemical properties of the soil in the experimental site were showed in the table below.

Table 4-2: Analysis of chemical properties of the experimental site

Soil chemical properties	Soil depth(cm)				
	0-15	15-30	30-45	45-60	Average
pH	6.74	7.07	7.08	7.12	7
EC(dS/m)	0.215	0.229	0.305	0.299	0.26
Total organic matter (%)	4.29	3.9	3.04	1.95	3.3
OC (%)	2.49	2.26	1.76	1.13	1.91
TN (%)	0.21	0.195	0.152	0.097	0.16

Note: -OC=Organic Carbon, EC=Electrical conductivity of the soil, TN=Total Nitrogen

4.2 Crop Water Requirement

The total net irrigation water applied to the wheat crop was 423.1 mm for the conventional furrow irrigation method. The minimum amount of water for wheat was 211.5 mm for both alternate and fixed furrow irrigation method. Irrigation in all treatments was managed by replacing the water lost due to crop evapotranspiration (ET_c) by assuming 60% application efficiency. All treatments were irrigated on the same day. Seasonal crop water requirement of wheat determined based on the seasonal water application depth from sowing to harvesting and vary based on the moisture level of treatments. Common irrigation depth of 54.5 mm was applied for all treatments from sowing for well establishment of the wheat before treatment start. During the experiment there were rainfall and the total effective rainfall recorded was 174 mm that subtract from crop water requirement during the next irrigation treatment application (Appendix Table 1). For conventional furrow irrigation 100% ET_c was applied while for alternative and fixed furrow irrigation half of conventional furrow irrigation i.e. 50% of the conventional water was applied. For the seasonal crop water requirement of wheat with non-stress condition was 423.2 mm the result is in line with (Meskelu *et al.*, 2017).Gross irrigation was computed using application efficiency of 60% for furrow irrigation method. The seasonal CWR of wheat was showed in Table 4.3.

Table 4-3: CWR of wheat

Treatments	Seasonal CWR(mm)	Irrigation Requirement(mm)	Gross irrigation depth(mm)
CFI With 40 cm	423.1	249.1	705.2
AFI with 40 cm	211.5	124.55	352.6
FFI with 40 cm	211.5	124.5	352.6
CFI With 50 cm	423.1	249.1	705.2
AFI with 50 cm	211.5	124.5	352.6
FFI with 50 cm	211.5	124.5	352.6
CFI With 60 cm	423.1	249.1	705.2
AFI with 60 cm	211.5	124.5	352.6
FFI with 60 cm	211.5	124.5	352.6

4.3 Effects of furrow irrigation method and spacing on growth components

4.3.1 Plant height

The analysis of variance showed that Plant height significantly ($p < 0.05$) influenced due to furrow irrigation methods and furrow spacing (Appendix Table 3). Maximum plant height (74.5 cm) was observed for conventional furrow irrigation method which was statistically superior to both fixed and alternate furrow methods, whereas the minimum plant height (63.5 cm) was observed at fixed furrow irrigation method. And this was statistically not significant from that of an alternate furrow irrigation water application method that attained 69.5 cm. No significance difference observed among treatments in plant height of CFI and AFI. At conventional furrow irrigation method the highest plants height was recorded which was higher than the plant height recorded at FFI method by 14.77 %.(Table 4.4) .In case of furrow irrigation method the highest plant height recorded. This is due to plant height is directly proportional to the soil moisture content in the soil root zone. In CFI the moisture content in the soil root zone were highest because of full irrigation water application than AFI and FFI. This coincides with the study of Meskelu *et al.*, (2018), Mulugeta and Kannan (2015) who reported conventional furrow irrigation method leads to the higher yield components and plant height followed by alternate and fixed furrow, respectively.

In case of furrow spacing the analysis of variance revealed that the maximum plant height (73.28 cm) was recorded under 50 cm furrow spacing which is not statistically different from 60 cm furrow spacing. While the minimum plant height of (63.63 cm) was observed from 40 cm furrow spacing which is statistically inferior to both 50 cm and 60 cm furrow spacing and 50 cm furrow spacing improved plant height by 13.17% and 3.61% than 40 cm and 60 cm furrow spacing respectively (Table 4.4). No significance difference observed between 50 and 60 cm furrow spacing. But 50 cm furrow spacing leads to conservation of the available soil moisture through reducing evaporation because of the spacing is narrow than that of 60 cm furrow spacing and the water is evenly distribute to the plant means the plant get the applied water equally and reduce the evaporation loss. For 60 cm furrow spacing is wider than 50 cm which water does not adequately reach to the crop roots and reduces water uptake by the crop and it leads even water distribution and soil moisture stress which affect plant growth. And also it increase evaporation loss because of the spacing is wide then the applied water cannot reach to the plant and it takes time. Due to this the evaporation loss is increased. It may lead moisture stress which affects the plant growth. For 40 cm furrow spacing the spacing is narrower that of 50 cm. In this case resource competition like nutrient, fertilizer and sunlight were high and also soil compaction is very high due to low movement of air and water in the soil which affect the growth of plant height. These could improve growth condition of wheat that leads to increasing plant height. This reveals that the increase in these parameters had positive direct effect on yield and yield component enhancement.

4.3.2 Spike length(SL)

The result of analysis of variance showed that the spike length of wheat was significantly ($p < 0.05$) influenced by the different furrow irrigation methods and furrow spacing's (Appendix Table 3). The longest spike length was observed from CFI method (7.94 cm) and the shortest spike length was recorded from FFI (6.1 cm). The SL in CFI was higher than FFI by 23.55%. But the SL which was recorded in AFI was statistically similar with both CFI and FFI. No significant difference observed among treatments CFI and FFI. But FFI was significantly difference from CFI and FFI (Table 4.4). In case of CFI method the longest spike length were recorded. This is because high moisture content in the root zone due to high amount of irrigation water application than AFI and FFI which is preferable to plant growth like plant height, spike

length and number of seed per spike .Contrary in AFI and FFI the spike length were shorter than CFI. This is due to less soil moisture content in the soil root zone and partial root zone dryness because the irrigation water applied is reduced by half that of CFI. The reductions of soil moisture minimize root elongation and expansion. Which minimize nutrient and water uptake and reduce photosynthesis which is highly related with growth parameters (plant height, spike length).This parameter is directly related with yield component like TSW, GY and AGBM. This coincides with the study of Meskelu *et al.*, (2018), Mulugeta and Kannan, (2015) Jemal, (2018) who reported conventional furrow irrigation method leads to the highest yield components such as plant height and cob length followed by an alternate and fixed furrow, respectively.

The longest spike length was observed at 50 cm spacing (8.05 cm) and this is statistically different with that of 60 cm furrow spacing (7.22 cm). The maximum SL due 50 cm furrow spacing was 22.74% higher than that 40 cm furrow spacing. Significance difference observed between 50 cm and 40 cm spacing (Table 4.4). Furrow spacing affects growth components. When the furrow was narrow (50 cm) than 60 cm furrow spacing and it reduced infiltration and saved water loss by evaporation. But in 40 cm furrow spacing the furrows were more approach than 50 cm spacing and water logging occur because the waited area was small and less aeration process due to high soil moisture content which affect plant growth. In the wider furrow control of weed is difficult and there was nutrient and water completion which reduces plant growth and directly related with yield.

4.3.3 Number of seed per spike (NSPS)

Analysis of variance across the treatment showed that NSPS significantly ($p < 0.05$) affected by furrow irrigation method and furrow spacing (Appendix table 5). Under CFI the maximum NSPS were recorded (42.5) which was statistically superior to AFI and FFI. The minimum NSPS (34) were observed at FFI method this was statistically inferior to both conventional and alternative furrow irrigation methods. Irrigation water application in conventional furrow method leads to an improvement of NSPS by 20 %.over fixed furrow Irrigation water application methods. Significant difference was observed among treatments in CFI, AFI and FFI. Significance difference between each treatment was observed (Table 4.4). NSPS was

affected by furrow irrigation method. Higher irrigation water depth application under CFI method leads to higher moisture content of the soil which creates favorable growth condition for wheat. On the other hand, moisture stress due to reduced irrigation under alternate and fixed furrow leads to affect growth parameters. Mulugeta and Kannan.(2015); Meskelu *et al.*, (2018) and Jemal.(2018) who showed that different furrow irrigation method significantly affected growth parameters.

The study also revealed that maximum NSPS were observed at 50 cm furrow spacing(42.4) and this was statistically superior to both 60 cm furrow spacing and 40 cm furrow spacing. The minimum NSPS (37.4) were obtained from 40 cm furrow spacing which is statistically inferior from 50 cm and 60 cm furrow spacing. NSPS improved in 50 cm furrow spacing by 11.79% than 40 cm furrow spacing. Significance difference occurred between 50 cm and 40 cm spacing (Table 4.4).In case of furrow spacing lateral movement of water and nutrient depends on furrow spacing. In 40 cm furrow spacing plant population were highest than both 50cm and 60cm furrow spacing. Due to this high later movement occurred which affect growth parameter. But in 60 cm the furrow spacing was wider, so the lateral movement of water and nutrient was low which affect plant growth and yield. So that in case of 50 cm spacing there was optimum lateral movement of nutrient and water which improve plant growth and yield.

Table 4-4: Effect of furrow irrigation method and spacing on growth component of wheat

Treatment		PH(cm)	SL(cm)	NSPS
Irrigation method	CFI	74.5 ^a	7.94 ^a	42.54 ^a
	AFI	69.5 ^a	7.55 ^a	41.26 ^b
	FFI	63.5 ^b	6.06 ^b	34 ^c
	LSD _{0.05}	2.297	0.712	0.97
Furrow spacing	50	73.28 ^a	8.05 ^a	42.44 ^a
	60	70.63 ^{ab}	7.29 ^b	37.94 ^{ab}
	40	63.63 ^b	6.22 ^c	37.4 ^b
	LSD _{0.05}	3.523	0.243	1.45
	CV (%)	3.89	2.58	2.82

*Means followed by different letters in a column differ significantly and those followed by the same letter are not significantly different at $p < 0.05$ level of significance. PH = plant height, SL = Spike length and NSPS = Number of seed per spike

4.4 Interaction Effect of Furrow Irrigation Method and Spacing on Growth Component of Wheat

The interaction effect of furrow irrigation method with spacing on plant height, spike length and NSPS were not significant (Appendix Table 3, 4 and 5), Even if no significant effect observed among treatments. No significant difference was observed among treatments in plant height, spike length and NSPS of wheat from CFI with 50cm, CFI with 40 cm and CFI with 60 cm. In addition, no significant effect was found in the plant height, spike length and NSPS of wheat treatments 60 cm with AFI and 60 cm with FFI. Similarly, there is no statically significant difference between CFI and AFI 50 cm spacing (Table 4.5). This coincides with the study of Meskelu *et al.*, (2018), Mulugeta and Kannan. (2015) and Jemal (2018) and who reported conventional furrow irrigation method leads to the highest growth components such as plant height and spike length followed by an alternate and fixed furrow, respectively.

Table 4-5: Interaction effect of furrow irrigation method and spacing on growth component

Treatments	PH(cm)	SL(cm)	NSPS(No)
CFI with 40 cm	70.17 ^{NS}	6.57 ^{NS}	40 ^{NS}
AFI with 40 cm	63.23 ^{NS}	7.17 ^{NS}	38.9 ^{NS}
FFI with 40 cm	57.5 ^{NS}	4.93 ^{NS}	33.33 ^{NS}
CFI with 50 cm	79.23 ^{NS}	8.30 ^{NS}	46 ^{NS}
AFI with 50 cm	72.57 ^{NS}	8.77 ^{NS}	44.67 ^{NS}
FFI with 50 cm	68.03 ^{NS}	7.10 ^{NS}	36.67 ^{NS}
CFI with 60 cm	74.17 ^{NS}	7.80 ^{NS}	41.63 ^{NS}
AFI with 60 cm	72.73 ^{NS}	7.90 ^{NS}	40.2 ^{NS}
FFI with 60 cm	65 ^{NS}	6.17 ^{NS}	32 ^{NS}
CV	3.23	9.65	2.4
LSD (0.05)	3.978	1.035	1.979

Where: LSD is List Significant difference at 5% level, CV is Coefficient of Variation. Means followed in the column followed by the same letters are not significantly different at 5% level of significance.

4.5 Effect Furrow Irrigation Methods and Spacing on Yield and Yield Components of Wheat

4.5.1 Above ground biomass(AGBM)

The analysis of variance showed that above ground biomass significantly ($p < 0.05$) influenced due to furrow irrigation methods and furrow spacing (Appendix Table 6). The maximum above ground biomass (10176 Kg/ha) was observed from CFI method, which was statistically superior to both alternate and fixed furrow irrigation method. While the minimum above ground biomass (9188 Kg/ha) was recorded from fixed furrow irrigation method. Conventional furrow irrigation method leads improvement of yield by 9.71% than fixed furrow irrigation. There was no significant difference observed under CFI and AFI. But there was significance difference between FFI from AFI and FFI (Table 4.6). Conventional furrow irrigation method leads to make a favorable condition for wheat photosynthesis and physiological process due to highest soil moisture content in the root zone because of full irrigation water depth application to the field. Different studies showed that aboveground biomass and grain yield of wheat improved by adequate moisture in the root zone. As far as water is one of the main components of photosynthesis for plants to produce their food, supplying adequate water could leads to increase both aboveground biomass and grain yield. Makino, (2011) reported that 90% of plant biomass is obtained from photosynthesis product, in which water is the main component. In alternate and fixed furrow irrigation method the depth of irrigation water is reduce which leads increment of moisture stress. The reduction of moisture stress affects the ability of plant photosynthesis and assimilation of CO₂ for food production. Guo *et al.*, (2013) reported that moisture stress in plants reduces photosynthesis capacity by reducing chlorophyll content and damage of the reaction center of the photosystem. Hence, the lower irrigation depth in case of fixed and alternate furrow method leads to create partial root zone drying and reduce the amount of water needed by the plant for photosynthesis and uptake and transportation nutrient from the soil for production of food. Similar report was reported by Mulugeta and Kannan (2015) and Jemal,(2018) on maize in which highest aboveground biomass and grain yield obtained under conventional furrow irrigation with irrigation water application of 100% of crop water requirement than the alternate and fixed furrow irrigation method.

In case of furrow spacing the maximum aboveground biomass (10477 Kg/ha) was observed at 50 cm furrow spacing. The minimum (9131 Kg/ha) aboveground biomass obtained at 40 cm furrow spacing was statistically inferior to both treatments. The highest aboveground biomass of wheat at 50 cm furrow spacing lead to an improvement of 12.85% and 7.3% over 40 cm furrow spacing and 60 cm furrow spacing respectively. Significance difference between 50 cm and 40 cm furrow spacing was observed (Table 4.6). The furrow spacing significantly affect above ground biomass. In case of 50 cm furrow spacing the horizontal water movement was better than 60cm furrow spacing. The plant also used as surface mulch and conserve of soil in the root zone. And also 50 cm furrow spacing had more harvested row than 60 cm furrow spacing in equal area. Because when the furrow spacing is wide the number of row is increase. In 50 cm furrow spacing the plant population was higher than 60 cm. There was less nutrient competition than 40 cm furrow spacing because in 40 cm spacing the population was highest and resource competition was high and affect yield. In case of wider space (60 cm) moisture stress high because of uneven distribution of water.it causes moisture stress in plants reduces plant photosynthesis which affects the grain yield of wheat.

4.5.2 Grain yield production(GY)

The analysis of variance showed that grain yield of wheat significantly ($p < 0.05$) affected by furrow irrigation method and furrow spacing (Appendix Table 7). The maximum GY observed from conventional furrow irrigation (4683.1 Kg/ha) and the minimum GY was recorded from FFI (3740 Kg/ha). The highest grain yield of wheat obtained at conventional furrow irrigation method lead to an improvement of 20.14% than the fixed furrow method. CFI water application method showed least yield reduction than FFI water application method and the greatest yield reduction occurred at FFI. The reduction of irrigation water from the conventional furrow to fixed furrow water application leads to reduction of grain yield by 20.14 % (Table 4.6). The data showed that grain yield was directly related with the amount of irrigation water applied to the field. The higher amount of irrigation water application leads larger amount of grain yield production and less amount of irrigation water application leads to less amount of grain yield production per hectare. The reduction of grain yield is that of the soil dries, the rate of water absorption by roots falls, short of transpiration rate by the plant, thus creating an internal water deficit, which affects photosynthesis and reduce food production (Farooq *et al.*,2009).

According to Pradha *et al.*, (2013) though crops such as wheat grain yield increase with amount of irrigation water increase. The straw yield decreased in the case of alternate and fixed furrow might be due to a reduction in photosynthesis in which chlorophyll is important. This may be due to the higher photosynthesis rate performed due to large biomass production, which most part of the biomass is straw. According to Shamsi(2010), the effect of moisture stress reduces chlorophyll content, which leads to minimizing biomass production. Similarly Jemal, (2018) stated straw yield is affected by furrow irrigation method.

In case of furrow spacing the maximum grain yield was recorded at 50 cm furrow spacing (4630.3 Kg/ha) and it was statistically different with 40 cm furrow spacing. The minimum grain yield (3837.4 Kg/ha) obtained 40cm furrow spacing. Yield reduction from 40 cm to 50 cm furrow spacing was 17.2%. The yield reduction was related with grow component of wheat (Table 4.6).

4.5.3 Straw yield (SY)

The analysis of variance showed that straw yield of wheat significantly ($p < 0.05$) affected by furrow irrigation method and furrow spacing. (Appendix Table 9). CFI method leads the highest grain yield (5146 Kg/ha). And the minimum straw yield recorded at FFI (3984.7 Kg/ha) has no significant difference with an AFI water application method. There was significance difference between FFI with CFI and FFI (Table 4.6). Straw was directly proportional with moisture content with in the soil root zone. There was no significance difference between AFI and CFI. But there was significance difference between FFI with AFI and CFI.

In furrow spacing the straw yield (5166.7 Kg/ha) recorded at 50 cm and the minimum straw yield (3984.7 Kg/ha) observed at 40 cm furrow spacing. In case of furrow spacing the highest straw yield was recorded under 50 cm furrow spacing (Table 4.6). This is because straw yield was related with both AGBM and GY. CFI is significantly different from FFI.

4.5.4 Thousand seed weight(TSW)

The analysis of variance revealed that TSW was significantly ($p < 0.05$) influenced by the furrow irrigation and spacing (Appendix Table 8). CFI method leads the maximum (33.55 g) TSW and FFI leads the minimum (25.77 g) TSW. The TSW which observed at the CFI method was statistically similar with TSW which observed at AFI method. The maximum TSW recorded at

CFI system which was 23.19 % higher than FFI. Significance difference between FFI with CFI and AFI was observed (Table 4.6). The TSW was directly related with the amount of irrigation water which applied to the field. CFI system occurred the maximum soil moisture in the root zone compared to AFI and FFI. This is because high irrigation water applied at CFI system. Soil moisture was directly related with the biological process of plant (transpiration, photosynthesis) which affects the plant growth and related with TSW.

The highest TSW observed under furrow spacing was (32.34 g) at 50 cm furrow spacing which was statistically superior to 40cm furrow spacing (28.1 g). In case of 50 cm furrow spacing there was TSW increment than 60 cm furrow spacing by 5.85 %. Significance difference observed between 50 cm and 40 cm furrow spacing (Table 4.6). In case of furrow spacing the wider furrow spacing affect the lateral movement of resources (water, fertilizer) which related with TSW. The narrower (40 cm) furrow spacing leads high resource competition because of number of plant population which is directly related with yield component. In case of 50 cm furrow spacing the lateral movement of water and fertilizer was better than 40cm and 60 cm. There was less evaporation loss and low resource competition and management practice (weeding, irrigation water application and spray of chemicals) was better than 40 cm and 60 cm spacing.

Grain yield and TSW closely related with the amount of irrigation depth which is applied in the crop field. This study related with Mansouri et al., (2010) who revealed that TSW and grain yield were greater when the applied irrigation water was high. Meskelu *et al.*, (2018) also stated that irrigation water application depth directly related with TSW.

Table 4-6: Effect of Furrow Irrigation method and spacing on yield components of wheat

Treatment		AGBM(Kg/ha)	GY(Kg/ha)	SY(Kg/ha)	TSW(gm)
Irrigation method	CFI	10176 ^a	4683.1 ^a	5146 ^a	33.55 ^a
	AFI	9956 ^a	4486.6 ^a	4818.6 ^a	31.68 ^a
	FFI	9188 ^b	3740 ^b	3984.7 ^b	25.77 ^b
	LSD0.05	490.74	553.25	552.68	2.3401
Furrow spacing	50	10477 ^a	4630.3 ^a	5166.7 ^a	32.34 ^a
	60	9712 ^{ab}	4441.9 ^{ab}	4894.4 ^a	30.55 ^{ab}
	40	9131 ^b	3837.4 ^b	388.2 ^b	28.1 ^b
	LSD0.05	888.82	607.24	995.81	2.884
	CV (%)	6.95	10.78	16.36	7.26

*Means followed by different letters in a column differ significantly and those followed by the same letter are not significantly different at $p < 0.05$ level of significance. AGBM = above ground biomass per hectare, GY = grain yield per hectare, SY = straw yield per hectare and TSW = thousand seed weight

4.6 Interaction Effect of Furrow Irrigation Method and Spacing on Yield and yield Components

The interaction effect of furrow irrigation method with spacing on yield and yield components were not significant (Appendix Table 6, 7.8 and 9), even if no significant effect observed among treatments. No significant difference was observed among treatments in grain yield, above ground biomass, straw yield and thousand seed weight of wheat from CFI with 50 cm, CFI with 40 cm and CFI with 60 cm. In addition, no significant effect was found in the above ground biomass, grain yield, straw yield and thousand seed weight of wheat treatments 60 cm with AFI and 60 cm with FFI. Similarly, there is no statically significant difference between CFI and AFI 50 cm spacing (Table 4.7). Meskelu et al., (2018), Mulugeta and Kannan. (2015) and Jemal,(2018) revealed that conventional furrow irrigation method leads to the higher yield components and plant height followed by alternate and fixed furrow, respectively.

Table 4-7: Interaction effect of furrow irrigation method and spacing on yield components

Treatments	AGBM(kg/ha)	GY(kg/ha)	SY(kg/ha)	TSW(kg/ha)
CFI with 40 cm	9256 ^{NS}	4277.70 ^{NS}	4324.1 ^{NS}	29.767 ^{NS}
AFI with 40 cm	9117 ^{NS}	4010.10 ^{NS}	3994.3 ^{NS}	28.667 ^{NS}
FFI with 40 cm	9021 ^{NS}	3224.40 ^{NS}	3346.4 ^{NS}	25.867 ^{NS}
CFI with 50 cm	10976 ^{NS}	5028.80 ^{NS}	5271.1 ^{NS}	36.9 ^{NS}
AFI with 50 cm	10446 ^{NS}	4874.80 ^{NS}	5781 ^{NS}	33.533 ^{NS}
FFI with 50 cm	10008 ^{NS}	3987.20 ^{NS}	4448.1 ^{NS}	26.6 ^{NS}
CFI with 60 cm	10297 ^{NS}	4742.70 ^{NS}	5333 ^{NS}	34 ^{NS}
AFI with 60 cm	10305 ^{NS}	4574.70 ^{NS}	5190.5 ^{NS}	32.833 ^{NS}
FFI with 60 cm	8535 ^{NS}	4008.30 ^{NS}	4159.5 ^{NS}	24.833 ^{NS}
CV	4.89	12.52	11.57	7.51
LSD(0.05)	849.9	958.26	957.27	4.05

Where: LSD is List Significant difference at 5% level, CV is Coefficient of Variation. Means followed in the column followed by the same letters are not significantly different at 5% level of significance.

4.7 Effect of furrow Irrigation Methods and Spacing on WP and HI

4.7.1 Water productivity

The analysis of variance revealed that water productivity highly significant ($P < 0.05$) affected by furrow irrigation method and spacing (Appendix Table 10). From the result AFI showed maximum water productivity than CFI and FFI. The water productivity observed at AFI (2.1 Kg/m³) which was statistically superior to CFI and FFI. The minimum water productivity observed at CFI (1.25 Kg/m³) (Table 4.8). In AFI the irrigation water application was half

(50%ETc) from the CFI or full irrigation (100ETc) results high water productivity than CFI. The lower water productivity was observed at CFI because of there was a water loss through evaporation from the soil surface and deep percolation. Alternate furrow irrigation method also reduced runoff by creating barrier between water and soil surface. Significance difference between FFI with AFI and CFI occurred. The water productivity recorded at AFI system was higher than CFI by 40.46%. The total amount of irrigation water applied at AFI was half of CFI. Due to this there was a little difference on yield but it was no significant. In FFI there was a high yield reduction compared to CFI because of there was a high moisture stress at the non-irrigated furrow which was not permanently irrigated through the growing season.

The maximum water productivity (2.02 kg/m³) observed at 50 cm furrow spacing the minimum water productivity (1.47 kg/m³) was occurred at 40 cm furrow spacing. The highest water productivity obtained at 50 cm furrow spacing higher than 60 cm furrow spacing by 13.26 % (Table 4.8).

The study of Kang *et al.*, (2000) indicated that AFI had better performance for increasing WP relative to alternate furrow irrigation resulted in significant reduction in Maize grain yield..

Enhancement of water productivity may be achieved due to improving crop yield, which is a numerator component, using different agronomic practices. These practices include crop selection, adequate amount of water, fertilizer application, weed management and others. Another way to increase water productivity is to assess the crop with different water application methods in furrow irrigation and furrow spacing which is a denominator component in WP. This method is especially important in water scarce areas.

4.7.2 Harvest index(HI)

The analysis of variance indicated that furrow irrigation methods and furrow spacing significant ($p < 0.05$) influence on harvesting index (Appendix Table 11). The highest (43.59 %) harvesting index was obtained at conventional furrow method and it was statistically superior to both fixed and alternate furrow method. On the other hand, the minimum (35.78%) harvesting index was obtained at fixed furrow a condition which was statistically similar to that of alternate furrow method (Table 4.8). Application of irrigation water from fixed furrow method to conventional furrow methods increased harvest index significantly and the increment was consistent. This

result implies that, grain formation was highly affected by moisture content. This result is in line with Samuel *et al.*, (2019) variation of soil moisture affect harvest index of wheat. Mulugeta and Kannan(2015) stated that that harvesting index depends on furrow irrigation method. There was significance difference between CFI and FFI.

In case of furrow spacing the maximum HI (44.01%) was observed under 50 cm furrow spacing which is significantly different from 40 cm furrow spacing and the minimum harvest index (35.41%) was observed under 40 cm (Table 4.8). Harvest shows the relation between grain yield and above ground biomass.

Table 4-8: Effect of furrow irrigation method and spacing on WP and HI

	Treatment	Wp(Kg/m ³)	HI (%)
Irrigation method	CFI	1.25 ^a	43.59 ^a
	AFI	2.09 ^a	40.72 ^a
	FFI	1.90 ^b	35.78 ^b
	LSD0.05	0.26	2.92
Furrow spacing	50	2.02 ^a	44.01 ^a
	60	1.75 ^{ab}	40.66 ^{ab}
	40	1.47 ^b	35.41 ^b
	LSD0.05	0.34	2.59
	CV (%)	14.77	10.67

Where: LSD is List Significant difference at 5% level, CV is Coefficient of Variation. Means followed in the column followed by the same letters are not significantly different at 5% level of significance.

4.8 Interaction Effect of Furrow Irrigation Method and Spacing on WP and HI

The analysis of variance showed there was no interaction effect between furrow irrigation method and furrow spacing on improving water productivity and harvest index (Appendix Table 9 and 10). No significant difference was observed among treatments in water productivity and harvest index of wheat from CFI with 50 cm, CFI with 40 cm and CFI with 60 cm. In addition, no significant effect was found water productivity and harvest index of wheat treatments 60 cm with AFI and 60 cm with FFI. Similarly, there is no statically significant difference between CFI and AFI 50 cm spacing (Table 4.9).

Table 4-9: Interaction effect of furrow irrigation method and spacing on WP and HI

Treatments	WP(kg/m ³)	HI (%)
CFI with 40 cm	1.06 ^{NS}	40.17 ^{NS}
AFI with 40 cm	1.55 ^{NS}	33.73 ^{NS}
FFI with 40 cm	1.80 ^{NS}	32.33 ^{NS}
CFI with 50 cm	1.57 ^{NS}	45.60 ^{NS}
AFI with 50 cm	2.52 ^{NS}	44.78 ^{NS}
FFI with 50 cm	1.97 ^{NS}	41.67 ^{NS}
CFI with 60 cm	1.12 ^{NS}	45.00 ^{NS}
AFI with 60 cm	2.21 ^{NS}	43.65 ^{NS}
FFI with 60 cm	1.92 ^{NS}	33.33 ^{NS}
CV	14.36	7.1
LSD (0.05)	0.45	5.06

Where: LSD is List Significant difference at 5% level, CV is Coefficient of Variation. Means followed in the column followed by the same letters are not significantly different at 5% level of significance

4.9 Effect of Furrow Irrigation Method and Spacing on Water Saving and Yield Reduction

In order to compare the water saved and yield reduction CFI with 60 cm furrow spacing consider as control treatment. The net water saved from AFI and FFI was 50% compared to CFI. This implies that as water stress levels increase water savings increase. Relative yield reduction was increased with increasing moisture stress levels for wheat (Table 4.10). The result shows CFI with 50 cm had yield increment compared to CFI with 60 cm furrow spacing. AFI with 50 cm show yield increment and water saved in +2.78% and 50% respectively compared with the control treatment (Table 4.10). By using the saved water additional land is irrigated and additional crop may be grow. As compared to CFI with 50 cm spacing shows yield increment than the control treatment (CFI with 60 cm spacing) by +6.03%. This shows that water saved was affected by furrow spacing in addition to furrow irrigation method. As the furrow spaced wide the water stress also increase because of the water stress related to the horizontal movement of water with in the furrow. In case of narrow furrow spacing (40 cm) high moisture

content occurs because of the wetted area was small. Due to the reason of high water saved and low yield increment of the control treatment AFI with 50 cm furrow spacing is the most alternate method of irrigation water management system.

Table 4-10: The effects of furrow irrigation method and spacing on water saving and yield penalty

Treatments	Gy(Kg/ha)	Water saved (%)	Yield reduction (%)
CFI with 40 cm	4277.7	0	9.8
AFI with 40 cm	4010.1	50	15.45
FFI with 40 cm	3224.4	50	32.01
CFI with 50 cm	5028.8	0	+6.03
AFI with 50 cm	4874.8	50	+2.78
FFI with 50 cm	3987.2	50	15.3
CFI with 60 cm	4742.7	0	0
AFI with 60 cm	4574.7	50	3.54
FFI with 60 cm	4008.3	50	15.49

4.10 Economic Analysis

Economic analysis was done using a partial budgeting and marginal return value under the prevailing market pricing of expenses and returns. According to CIMMYT (1988), the adjusted grain yield was computed from the average grain yield by reducing it by 10%. The total costs considered for the economic study were the cost of labor required for irrigating the experimental assuming that all other expenses incurred were uniform for each treatment. The total return is the cost of returning from the adjusted grain yield output at the market price of wheat during harvesting. The average cost of labor daily was 60.00 ETBirr , while the farm gate price of wheat during the harvesting time was 55.00 ETBirr per kg taken for analysis. All costs and returns were computed in Ethiopian Birr per hectare (ETBirr/ha).

Table 4-11: Economic analysis result using partial budgeting

Treatments	VC ET birr	GY Kg/ha	AY Kg/ha	TI ET birr	NI ET birr	B/C
CFI	17361.1	4683	4214.7	231809	214447	12.4
AFI	8680.6	4486	4037.4	222057	213376	24.6
FFI	8680.6	3740	3366	185130	176449	20.3

Note: VC=Variable Cost, GY= Grain yield, AY=Actual yield, I=Total income, NI=Net income and B/C=benefit cost ratio

The time required for irrigating the experimental plots with the conventional furrow irrigation method was three hours; thus, the time required for irrigating land of one ha was 289.4 hr. During the experimental period, labor cost was 60 ETBirr/ person/ 8hrs thus implementation cost for irrigating a hectare of land with conventional, alternate and fixed furrow irrigation was 17361,8680 and 8680 ET birr/ha/person respectively.

4.11 Correlation of Yield and other Parameters

The correlation coefficient showed that yield and yield components significantly related to each other showed in (Table 4.13).This correlation shows that increment of growth and yield parameters lead the enhancement of grain yield. Grain yield had no significant relation with the water productivity but it was negatively correlated with most of the parameters excluding with grain yield. This means that reduction of irrigation amount result enhancement of water productivity but it reduce yield. Jemal, (2018) also stated that WP inversely relation with yield and yield component except GY.

Table 4-12: Pearson's correlation coefficient(r) of growth and yield component of wheat as influenced by furrow irrigation method

	PH	SL	NSPS	TTSW	AGBM	GY	Sy	WP	HI
PH	1								
SL	0.853	1							
NSPS	0.763	0.827	1						
TSW	0.751	0.677	0.815	1					
AGBM	0.651	0.722	0.769	0.627	1				
GY	0.683	0.697	0.665	0.610	0.492	1			
Sy	0.706	0.720	0.712	0.580	0.691	0.433	1		
WP	-0.193	-0.210	-0.264	-0.226	-0.142	0.088	-0.251	1	
HI	0.784	0.769	0.717	0.621	0.710	0.700	0.614	-0.146	1

*PH=plant height, Sl=spike length, NSPS=Number of seed per spike, TSW=Total thousands seed weight, AGBM=Above ground biomass, GY=Grain yield, Sy=straw yield, WP=water productivity and HI=Harvest index

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this experiment was to determine the optimal furrow irrigation method and furrow spacing through analyzing the effect furrow irrigation methods and furrow spacing on wheat crop yield and water productivity. The results of this research show that in order to improve crop yields, methods of irrigation and furrow spacing has a major impact. The result of the investigation showed that the highest yield was generated when applying the conventional furrow irrigation method while the lowest yield was observed under fixed furrow irrigation. When compared to conventional furrow irrigation, the alternate furrow irrigation conduct helps save approximately 50% of the irrigation water applied. Additionally, it was determined that when the total amount of irrigation water decreased it also decreased the efficiency of water use. When furrow irrigation application method changed from conventional to alternate and fixed the amount of water applied reduced from 100% to 50%. According to the results of the study, wheat yield enhanced as the amounts of irrigation increased from fixed and alternate stress of irrigation water to conventional furrow irrigation full application. This is because water is used more efficiently at the lower water application depth. The result of the study showed that conventional furrow irrigation and 50 cm furrow spacing obtained maximum grain yield than other treatments. But in case of water productivity Alternate furrow irrigation method score the highest water productivity (2.09 Kg/m^3) without significant yield reduction. From this study in water scarce area AFI and 50 cm furrow spacing is the best method for water saving.

5.2 Recommendation

- In water scarce area alternative furrow irrigation (AFI) is recommended to get better yield and water productivity. However in areas having sufficient water resources conventional furrow irrigation (CFI) method can be practiced.
- Smallholder farmers can use 50 cm furrow spacing to increase yield and water productivity by saving their water and land.

- In water scarce area farmers can use alternate furrow irrigation and 50cm furrow spacing to save water and land in order to get better yield and water productivity.
- This experiment was conducted at a one site in one season. Therefore, conducting the same experiment for one or more seasons, and initiating similar experiments with different environmental conditions is recommended for the validity of this finding.

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APPENDECIES

Appendix Table 1 : Effective rain fall recorded through the season

Month	Date	Rainfall (mm)	Effective rainfall (mm)
March	1	2.3	0
	2	5	0
	12	55.5	36.4
	13	7.5	1.2
	14	25.5	12.4
	15	7.4	1.1
	18	27.5	14
	22	14.3	5.2
	23	13.2	4.6
	29	7.5	1.2
April	1	17.5	7.2
	20	63.5	42.8
	26	2.5	0
	27	36.5	21.2
	29	18.3	7.6
	30	14.3	5.2
May	1	27.5	14
	2	2.5	0
	5	10.5	3
	8	7.3	1
	21	5.4	0
	24	2.3	0
	30	7.7	1.3
	31	2.3	0

Appendix Table 2 :Free flow discharge values for different size of Parshall flumes

Head (cm)	Throught width (inches)				
	1	2	3	6	9
	Discharge (l/s)				
2	0.14	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	26.44
15	3.191	6.377	9.358	19.027	29.383

Appendix Table 3 :Analysis of variance of plant height

Source	DF	SS	MS	F	P
Rep	2	26.07	13.036		
Sp	2	447.03	223.513	30.85	0.0037
Error Rep*Sp	4	28.98	7.246		
FRW	2	547.07	273.534	54.7	0
Sp*FRW	4	30.64	7.66	1.53	0.2548
Error Rep*Sp*FRW	12	60.01	5.001		
Total	26	1139.8			

Appendix Table 4 :Analysis of variance of Spike length

Source	DF	SS	MS	F	P
Rep	2	0.0622	0.03111		
Sp	2	15.26	7.63	221.52	0.0001
Error Rep*Sp	4	0.1378	0.03444		
FRW	2	17.6822	8.84111	18.38	0.0002
Sp*FRW	4	0.4511	0.11278	0.23	0.9136
Error Rep*Sp*FRW	12	5.7733	0.48111		
Total	26	39.3667			

Appendix Table 5 :Analysis of variance of NSPS

Source	DF	SS	MS	F	P
Rep	2	1.82	0.91		
Sp	2	137.607	68.803	56.09	0.0012
Error Rep*Sp	4	4.907	1.227		
FRW	2	381.936	190.968	215.38	0
Sp*FRW	4	9.691	2.423	2.73	0.0793
Error Rep*Sp*FRW	12	10.64	0.887		
Total	26	546.6			

Appendix Table: 6 Analysis of variance of above ground biomass

Source	DF	SS	MS	F	P
Rep	2	828950	414475		
Sp	2	8198000	4099000	8.89	0.0337
Error Rep*Sp	4	1844663	461166		
FRW	2	4847879	2423940	10.62	0.0022
Sp*FRW	4	2886739	721685	3.16	0.0543
Error Rep*Sp*FRW	12	2739406	228284		
Total	26	2.14E+07			

Appendix Table: 7 Analysis of variance of grain yield

Source	DF	SS	MS	F	P
Rep	2	3112969	1556484		
Sp	2	3088522	1544261	7.17	0.0475
Error Rep*Sp	4	861037	215259		
FRW	2	4456270	2228135	7.68	0.0071
Sp*FRW	4	127006	31751	0.11	0.9769
Error Rep*Sp*FRW	12	3481782	290149		
Total	26	1.51E+07			

Appendix Table 8: Analysis of variance of TSSW

Source	DF	SS	MS	F	P
Rep	2	65.552	32.776		
Sp	2	83.351	41.675	14.42	0.0148
Error Rep*Sp	4	11.561	2.89		
FRW	2	245.974	122.987	31.03	0
Sp*FRW	4	54.496	13.624	3.44	0.0431
Error Rep*Sp*FRW	12	47.569	3.964		
Total	26	508.502			

Appendix Table 9: Analysis of variance of Straw yield

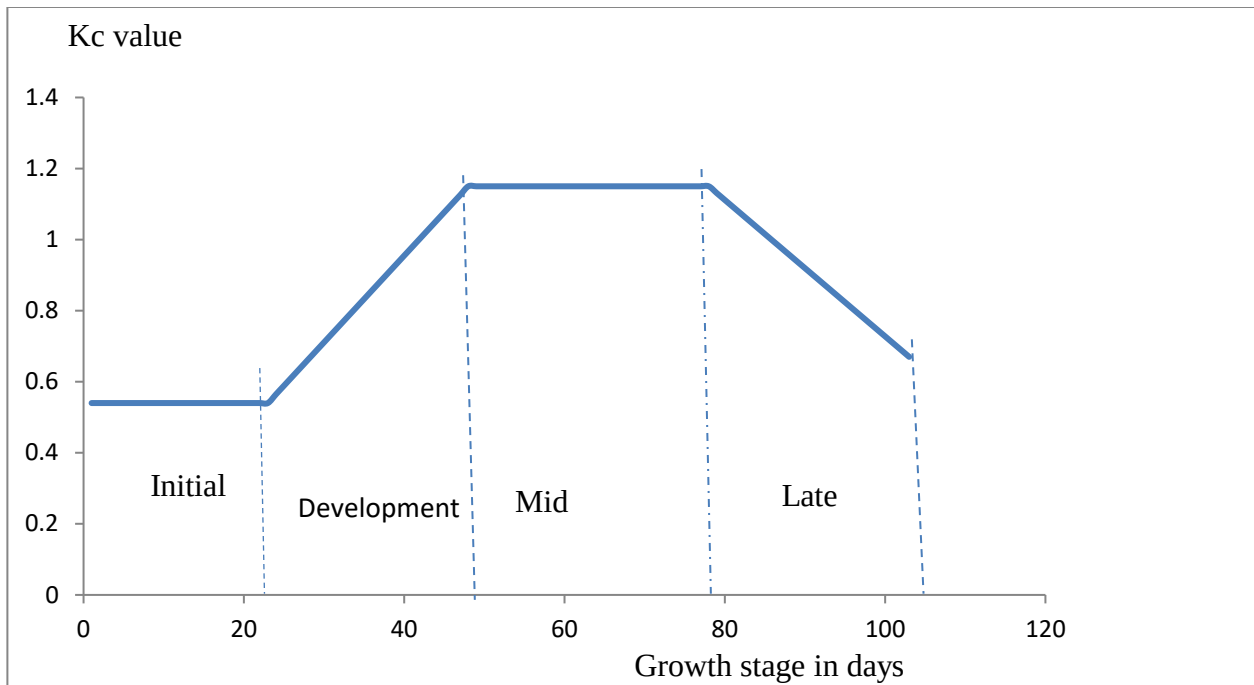
Source	DF	SS	MS	F	P
Rep	2	1332951	666476		
Sp	2	8162751	4081376	7.05	0.0488
Error Rep*Sp	4	2315500	578875		
FRW	2	6454518	3227259	11.15	0.0018
Sp*FRW	4	204369	51092	0.18	0.9462
Error Rep*Sp*FRW	12	3474581	289548		
Total	26	2.19E+07			

Appendix Table 10: Analysis of variance of water productivity

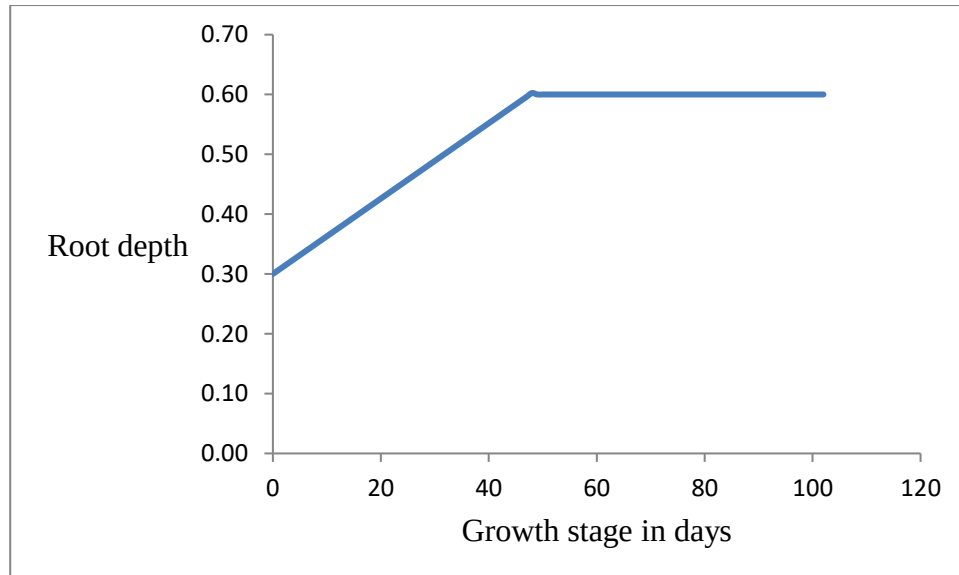
Source	DF	SS	MS	F	P
Rep	2	0.62367	0.31184		
Sp	2	0.53147	0.26574	10.06	0.0275
Error Rep*Sp	4	0.10561	0.0264		
FRW	2	3.42539	1.71269	21.53	0.0001
Sp*FRW	4	0.3103	0.07758	0.98	0.4566
Error Rep*Sp*FRW	12	0.95444	0.07954		
Total	26	5.9509			

Appendix Table 11: Analysis of variance of harvest index

Source	DF	SS	MS	F	P
Rep	2	32.405	16.202		
Sp	2	338.454	169.227	9.29	0.0314
Error Rep*Sp	4	72.903	18.226		
FRW	2	280.975	140.488	17.38	0.0003
Sp*FRW	4	93.944	23.486	2.9	0.068
Error Rep*Sp*FRW	12	97.02	8.085		
Total	26	915.701			



Appendix Figure 1: Crop coefficient of wheat for different growth stage



Appendix Figure 2: Root depth of wheat through the growth stage







Appendix Figure 3: Pictorial presentation of the experimental season