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The Impact of Alternate Furrow Irrigation on Water Productivity and Yield of Potato at Small Scale Irrigation, Ejere District, West Shoa, Ethiopia

Adisu Tadese Eba, Teshome Seyoum

Department of Irrigation Enginering, Haramaya University, Haramaya, Ethiopia

Email address:
addisswem@gmail.com (A. T. Eba)

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Abstract: As a result of water resource shortage and the need for food self-sufficiency in Ethiopia, it has become essential to improve the productivity. In this study, an attempt was made to evaluate the impact of alternate furrow irrigation technique on yield and water productivity. Alternate furrow irrigation versus every furrow, fixed furrow and farmer practice (open-ended and unstructured furrow) were evaluated at full crop water requirement. The experimental design used was randomized complete block design with four treatment replicated five times. Results obtained revealed that average water application efficiency of alternate furrow irrigation was 67% which was high as compared to other irrigation methods at all irrigation events. Average application efficiencies of ever furrow irrigation, fixed furrow irrigation and farmer practice were 52%, 61% and 34.4% respectively. The average distribution uniformity of alternate furrow irrigation and every furrow irrigation methods were 89.3% and 85.3% respectively, which showed no significant difference between the two methods. However, average distribution uniformity of fixed furrow irrigation was 75.4%, which showed significant difference between alternate furrow and fixed furrow irrigation methods. Alternate furrow irrigation method produced total tuber yield of 33198 kg/ha which showed insignificant difference as compared with that obtained under every furrow irrigation (33369 kg/ha). Total tuber yield harvested from fixed furrow irrigation and farmer practice were 30177 kg/ha and 30098 kg/ha respectively, which showed insignificant difference between the two methods. High marketable yield of 32667.8 kg/ha was recorded from alternate furrow irrigation. Water productivity of 11.2 kg/m^3, 10.7 kg/m^3, 6.1 kg/m^3 and 4.1 kg/m^3 were produced under alternate furrow, fixed furrow, and every furrow and farmer practice respectively. It was found that alternate furrow irrigation method saved 50% of water as compared with every furrow and 68.4% as compared with farmer practice. Therefore, it is recommended alternate furrow irrigation method with appropriate irrigation interval is suitable irrigation method; for humid climate where soil is dominated by clay soil and water is liming factor for potato crop production.

Keywords: Alternate Furrow, Water Productivity, Tuber Yield

1. Introduction

In almost all regions of the world, water supply is the main constraint to crop production due to water demand for rapid industrialization and high population growth. Water is increasingly recognized as a major component in economic development and poverty reduction. According to the study done on future water availability for global food production, holding the current rates of agricultural water use efficiency constant, an estimated additional amount of 5700 km^3 of fresh water will be required annually to meet the estimated food demand in 2050 [1]. Agriculture is the largest freshwater user on the planet, consuming more than two thirds of total withdrawals [2].

Surface irrigation is the most common executed irrigation system in Ethiopia as well as Western Oromia. This wide spread implementation might be due to its low capital cost, no special technical experience regarding operation and maintenance and no specific equipment are required as a result of long practical background among local farmers regarding the implementation of this irrigation system. Furrow irrigation is most widely used among the surface irrigation methods. In this system water is applied by means of small channels or furrows, which follow a uniform longitudinal slope. Furrow irrigation has low application efficiency because of its high water loss due to surface runoff, evaporation from water in the furrow, evaporation from the soil surface and percolation below root zone. Alternate furrow irrigation (AFI) is a system of irrigating only one side of the plant, i.e., half of the root system, is irrigated at first irrigation event, while the other side receives water on the next irrigation.

Production of potato (*Solanum tuberosum L.*) takes a very important place in the world agriculture, with a production potential of about 381 million tons harvested and 19.3 million hectare planted area [3]. In Ethiopia, potato is grown in four major areas: the central, the eastern, the northwestern and the southern. In the central area, potato production includes the highland areas surrounding the capital, i.e. Addis Abeba, within a 100–150 km radius. In this area potato growing zones are West Shewa and North Shewa. About 10% of the potato farmers are located in this area [4]. Early studies have shown that water is the most important limiting factor for potato production and it is possible to increase production level by well-scheduled irrigation programs throughout the growing season [5].

Almost all of the irrigation schemes of west Shoa zone, the western part of Ethiopia, are small scale and traditional. Farmers seem to have awareness about the benefits of irrigation and proven ability to organize themselves to manage small scale irrigation systems. However, it lacks scientific management; they either over or under irrigate their fields. 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 [6]. 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. Improved irrigation scheduling and water application methods are among the means of cutting losses and increasing efficiency.

The farmers of Ejere wereda West Shoa Zone are using surface irrigation system in which water is applied to the field without determining amount water required for the crop they are growing on that field and using indigenous knowledge for irrigation schedule. In this method water is applied to the field in excess amount and huge amount of water is lost in the form of surface runoff. On the other hand many farmers are left without irrigation water to produce crops during dry season due to shortage of irrigation water resulted from mismanagement of irrigation water by other farmers [6]. Potato crop one of the major crops farmers are producing under irrigation for home consumption and market in western Ethiopia particularly western Shoa. However, water resource is becoming scarce and limiting crop production during dry season in this area, whereas the number of farmers involved in crop production under irrigation is increasing from time to time. Nevertheless, no study was conducted in this area to improve water productivity and water use efficiency of potato under surface irrigation system. Alternating furrow irrigation practice is one of the possible irrigation water management techniques that may help farmers to apply limited amount of water to their crops in time and amount vital for optimum crop water productivity.

In order to allocate the scarce water resources among competing users, identifying irrigation method which maximizes crop water productivity using available water is an obligatory work. The competition for freshwater often implies that, water for irrigation is not always available in the required quantity. Therefore, farmers often have to manage irrigation under moderate or severe water shortage. This experiment is, therefore proposed and executed with the hypothesis that irrigating alternate furrows, i.e., partial wetting of the root system alternatively could save water thereby increasing water productivity (WP) without causing a substantial drop in the yield of potato crop.

As a general objective; this research was planned and implemented to study the impact of alternate furrow irrigation (AFI) on potato yield and water productivity so as to get additional land and sustainable crop and water productivity. Therefore, this study specifically aims at (i) to evaluate the effects of different water application methods on yield and water productivity on farmers' field. (ii) To quantify the amount of water saved under each water application methods.

2. Materials and Methods

2.1. General Description of the Study Area

This experiment was carried Giche small scale irrigation of Ejere Wereda during 2016/17 dry season. The site is located in the western part of Ethiopia at about 10°01'N latitude and 37°9'E longitudes and a distance of 55 km away from Addis Ababa at an altitude of 2400 m above sea level (Figure 1). It has a humid climate with annual mean minimum, mean maximum and average temperatures were 6, 22 and 14°C respectively in 1985-2016. The area receives an annual rain fall of 1200 mm with maximum precipitation in the month of June to August (Holeta Agricultural Research Center meteorological data Record). The soil of the area is characteristically well drained, light to dark brown in color, and very shallow to shallow in depth, clay loam to clay in texture and continuously cultivated (HARC soil laboratory record).

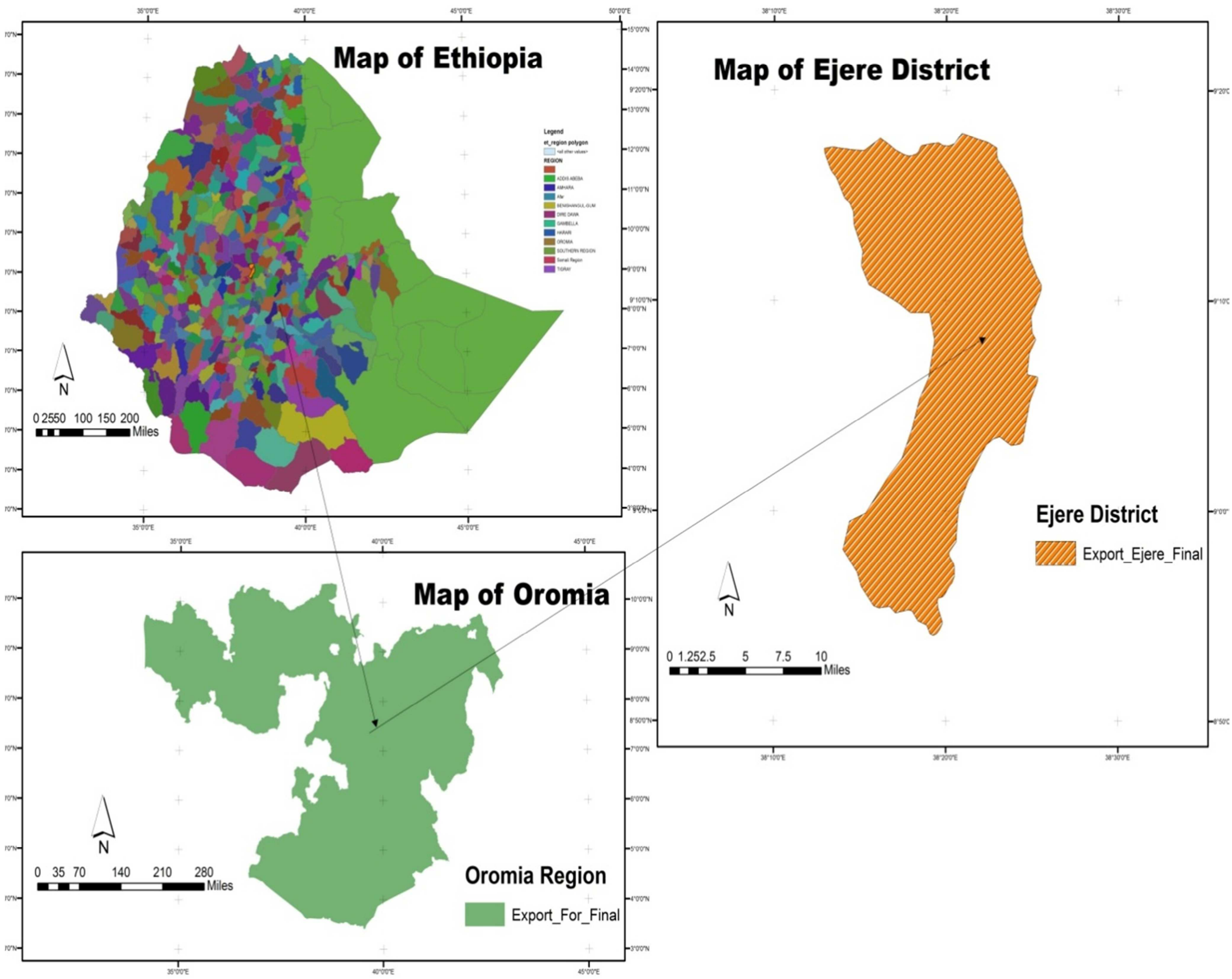

Figure 1. *Location map of the study area.*

Table 1. *Mean monthly Climate data at Ejere district (1985-2016).*

Month	Rainfall (mm)	Min Temp °C	Max Temp °C	Relative humidity (%)	Wind speed km/day	Sunshine Hours
January	50.9	3.4	23.4	51	130	8.0
February	49.9	5.0	23.9	50	147	7.6
March	51.4	6.7	24.4	51	147	7.1
April	56.1	7.9	23.9	56	138	7.0
May	55.5	6.8	24.4	56	130	6.3
June	66.1	7.7	22.4	66	95	5.1
July	77.6	9.1	20.0	78	104	3.4
August	80.2	9.1	19.6	80	95	8.1
September	73.8	7.8	20.3	74	104	5.0
October	57.0	4.9	21.9	57	156	7.6
November	51.9	2.3	22.4	52	147	8.7
December	51.0	1.9	22.8	51	147	8.6
Average	60.1	6	22.5	60.2	128.3	6.9

2.2. Treatments and Experimental Design

The experiment included three irrigation methods: alternate (AFI), every furrow (EFI) and fixed furrow irrigation (FFI) irrigation methods all were block-ended furrow and farmer practice (making furrow with opened). Every furrow irrigation (EFI) in which water was applied to every furrow, fixed furrow irrigation (FFI) in which water was applied as fixed every-other furrow throughout the growth season, alternate furrow irrigation (AFI) which is similar to fixed furrow irrigation (FFI), but water was applied to the furrow which was dry in the previous irrigation cycle. Farmer's practice (FP) (Farmer made every furrow irrigation with open-ended furrows) and irrigated with farmer irrigation interval. Farmers are used fixed irrigation interval system. every furrow irrigation method is in which every furrow has been irrigated throughout growing season with determined irrigation interval. In alternate furrow irrigation (AFI) odd furrows (1, 3, 5 and 7) received water at first irrigation event and even furrows received water at next irrigation (2, 4, 6 and 8) throughout growing season with determined irrigation interval. In fixed furrow irrigation (FFI) water was applied to odd furrows (1, 3, 5, and 7) throughout the growth season with determined irrigation interval and farmer practice which is similar to every furrow irrigation (EFI) but furrows were made by farmer, not tide at the end and was irrigated with farmers irrigation interval.

These treatments were assigned in Randomized Complete Block Design (RCBD) with five replications. The size of each experimental plot was 6 m x 10 m. The experimental field was 27m by 54m and occupied a total area of 1458m^2. A spacing of 75 cm between rows (furrows) and 30 cm between plants was used based on recommendation taken from recently done research result [7] and [8]. Each experimental plot consists of eight furrows and seven ridges with furrow length of 10 m each. A spacing of 1 m was used between blocks and plots within a block respectively. The net area covered by the experiment was 1200 m^2 from the total experimental area of 1458 m^2.

Table 2. *List of treatments.*

Treatment No	Treatment name
1	Every Furrow Irrigation (EFI) block- ended
2	Alternate furrow irrigation (AFI) block- ended
3	Fixed furrow irrigation (FFI) block- ended
4	Farmer practice (FP) with open-ended furrows

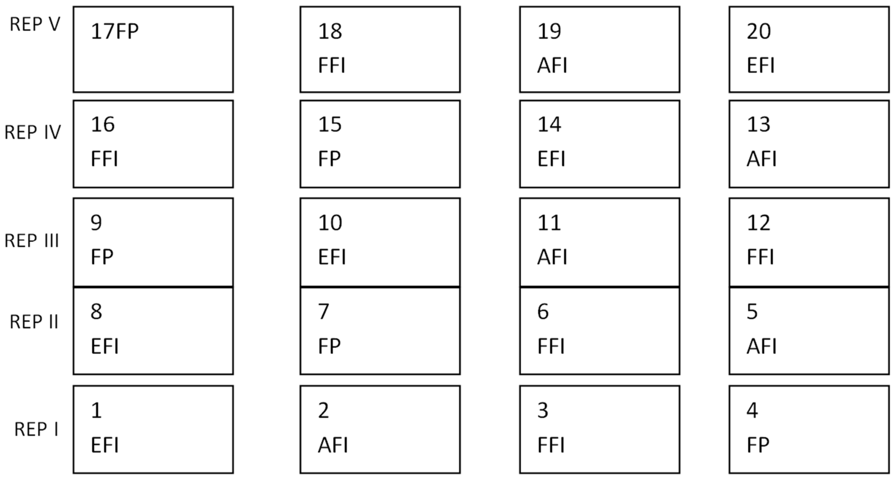

Figure 2. *Randomization of treatments with five replications.*

2.3. Crop Characterization

The test crop used in this study was potato (*Solanum tuberosum* L.) crop. Gudane improved variety was used as test crop having growing period of 120 days. Potato tubers were planted by hand in plot sizes of 6 m by 10 m. Hence, there were a total of 8 rows within a plot and 33 potato tubers within a single row. The spacing of 1m between plots within a block and 1m between blocks were used. The spacing used between within a single row and between rows within a single plot were collected from Holeta Agricultural Research Center, Horticultural crop research team and other references (eg. 2; 12). In addition, plant parameters such as rooting depth and stages of growth were taken from Holeta Agricultural Research Center, Horticultural crop research team. The other crop characteristics such as maximum rooting depth, crop coefficient and maximum allowed depletion level and yield response factor were taken from Food and Agriculture Organization (3). According to FAO Irrigation and Drainage paper maximum root depth of 60cm, crop coefficient of 1.15, allowed depletion level value of 0.70 and total yield response factor of 1.10 were used in determination of crop water requirement. The maximum potato yield from farmers experience in the area is up to 30 t/hectares.

2.4. Desing of Furrows

The most important factors for furrow irrigation are furrow distance, length and slope, and ridge uniformity. Furrow design is an iterative process that should consider the shape of the furrow, the spacing between furrows and furrow length with other factors such as the stream size to be applied and its application time, the soil type and the slope. In potato, the distance between irrigation furrows varies from 60 to 90 cm depending on soil texture. In sandy soil, water leaks away rapid and does not reach far; distance between rows should be smaller than in clay soils. In coarse sandy soils the distance between the furrows should preferably be around 60-65 cm, and in heavier clay soils around 70-80 cm [9]. The spacing between furrows depends on the water movement in the soil type of soil texture and agronomic requirements. In addition, spacing of furrow depends on the type of equipment used in the construction of furrows [10]. Since the textural class of the soil on the study area is clay, spacing of 0.75 m ridges of furrow had been used based on soil texture and agronomic recommendations.

Maximum furrow length depends on slope of the furrows, soil type and depth of water in the furrow. Water should not exceed half ridge height to avoid excess moisture in tuber region. Furrow slope should be not exceeding 0.5% to control erosion. Beyond this there is a major risk of soil erosion following a breach in the furrow system. Soil type also affects furrow length. In sandy soils water infiltrates rapidly, whereas in clay water infiltrates slowly. In sandy soil furrows should be short, so that water can reach the downstream end without excessive percolation losses. In clay soils, furrow can be long as a result of low infiltration rate that results low percolation loss at upper part of the furrow. Maximum furrow length on clay soil of slope less than 0.5% can be extending up to 300 m. Based on the above information 10 m furrow length was used for this study to increase irrigation efficiencies. Heights of ridges vary between 15 cm and 40 cm and the range of spacing commonly used for furrow irrigation is 0.3 to 1.8 m and furrows are generally V-shaped or U-shaped in cross section with depth of 15-30 cm and 25-40 cm wide at the top [9]. The shape of the furrow depends on the soil type and the stream size. Soils with low infiltration rates have usually shallow wide parabolic or U-shaped furrows to reduce water velocity and to obtain a large wetted perimeter to encourage infiltration. U-shaped furrow is widely practiced in the study area because of the nature of the soil found in this area was clay soil with low infiltration rate and it is easy to construct.

2.5. Determination of Crop Water Requirement and Irrigation Schedule

There are three methods for matching irrigation with crop water requirements. The first method is that measure how much of water is contained in soil. The second is by monitoring some attributes of plant that are related to water deficiency; such as canopy temperature, xylem water potential and visible wilting. The third method that calculate amount of water the atmosphere can extract from a well watered crop by using model. CROPWAT version 8.0 was used for this study to determine reference evapotranspiration, crop water requirements and irrigation schedule by utilizing metrological data as an input. For estimation of water irrigation requirements, climatic, crop and soil data have been utilized as an input. This calculation has been done by using FAO Penman- Monteith method [11]. The reference evapotranspiration ETo was calculated by FAO Penman-Monteith method, using decision support software – CROPWAT 8.0 developed by FAO. In this experiment, the reference evapotranspiration (ETo) and crop water requirement (ETc) was estimated from long years climatic data collected from Metrological station of Holeta Agricultural Research Center (Table 3).

Table 3. *Climatic data Used for ET_o calculation (1985-2015).*

Month	Min Temp °C	Max Temp °C	Humidity %	Wind speed km/day	Sunshine Hours
January	3.4	23.4	51	130	8.0
February	5.0	23.9	50	147	7.6
March	6.7	24.4	51	147	7.1
April	7.9	23.9	56	138	7.0
May	6.8	24.4	56	130	6.3
June	7.7	22.4	66	95	5.1
July	9.1	20.0	78	104	3.4
August	9.1	19.6	80	95	8.1
September	7.8	20.3	74	104	5.0
October	4.9	21.9	57	156	7.6
November	2.3	22.4	52	147	8.7
December	1.9	22.8	51	147	8.6
Average	6.0	22.4	60	128.3	6.9

Climatic data displayed on the above table were collected from Holeta Agricultural Research Center starting from 1985 to 2015 for thirty one years.

Irrigation scheduling involves determining both the timing of irrigation and quantity of water to apply. Several methods are available for estimating crop water use. Methods for scheduling irrigation can be classified as observational (personal experience, plant and soil condition), determining soil moisture and calculating evapotranspiration losses. In this study irrigation interval in days and depth of application which is expressed in millimeter has been calculated by using CROPWAT version 8.0. Depth of water application was determined by the model and gave gross water required at experimental field by multiplying with each plot area.

2.6. Water Conveyance and Measurement

The irrigation water source was located in the nearby water channel which is a natural channel convey water from the origin to the farmers field. The earthen channel which was made of soil material by natural phenomenon was used to convey water from distant water source to around the experimental field. And then, the water had been pumped through the pipe connected to the pump which conveyed water to the earthen canal prepared between pipe and experimental field. Water movement in conveyance system requires pressure because of the difference in elevation between water surface in the channel and the field.

Pipe was used to supply water from channel to the experimental field by pressure created pump located near the channel. The water had been applied carefully to every experimental unit through Parshall Flume by measuring depth of water flowing in the flume to ensure application at desired level of water for each treatment and to avoid over flow of water. The flow through Parshall Flume can be either under free flow or under submerged flow conditions. In this case, flow through parshall Flume was occurring under free flow condition. Before using, flumes were calibrated as per guidelines and relevant equation was used under free flow condition [12]. Depth of water flowing in the Parshall Flume was measured using gage located at the throat section of the Parshall Flume and related with discharge given by Parshall Flume flow table. At pre-plant irrigation water was applied to every furrow in each plot, two days before planting with minimum water. The purpose of this irrigation was to bring the upper 30 cm soil depth to field capacity and create good soil to encourage a full and even plant stand. After land was prepared potatoes are planted on the ridge of furrow with open-ended

Figure 3. *Indicated Alterante and Every furrow irrigation from left to right respectively.*

2.7. Determination of Water Productivity

Water productivity was determined by dividing tuber yield by total applied irrigation water and is expressed as follows [13]:

$$WP\left(\frac{kg}{m^3}\right) = \frac{Yield\left(\frac{kg}{ha}\right)}{total\ water\ received\left(\frac{m^3}{ha}\right)} \quad (1)$$

where WP water productivity (kg/m^3), Yield (kg/ha) and total water received (m^3/ha) from planting to harvest and water applied before planting is not included in the total.

2.8. Estimation of Irrigation Performance Indicators

Surface irrigation systems were designed and operated to satisfy the irrigation water requirements of each field. The performance of the system is determined by the efficiency of water conveyed to the field from the channel and distributed within the experimental plot. Irrigation performance mainly determined by using conjunctively various parameters because one is not capable to describe whether the irrigation is satisfied the plant water requirements or not. In this case, two parameters were used to estimate irrigation performance: application efficiency and distribution uniformity.

2.8.1. Field Application Efficiency (AE)

Field application efficiency is the ratio of water directly available to the crop to water received at the field inlet. Application efficiency was calculated based on, water application efficiency (AE) as the ratio between the volume of water held in the root zone of the soil profile after the irrigation and the total volume of water applied during the irrigation process [14].

$$AE(\%) = \frac{D_{sz}}{D_a} * 100 \quad (2)$$

Where D_{sz} depth of water stored in root zone (mm), D_a total depth of water applied to the plot (mm).

Pre and post irrigation soil moisture analysis method was employed for calculating water stored in the crop root zone. The soil samples for moisture content before and after irrigation were taken at three randomly selected points in each plot. The samples were collected at three depths i.e. 0-20, 20-40 and 40-60 cm. The potato crop has maximum root depth of 60 cm; therefore, soil samples were collected down to 60 cm depth. Moisture content of samples was measured on dry weight basis. The depth of water stored in the root zone was calculated by equation given in the procedure adopted by [15].

$$D_s(mm) = M.C * Sp.G * R_Z \quad (3)$$

where: Ds depth of water stored in root zone (mm), M. C moisture content of soil (%), Sp. G specific gravity of soil, Rz depth of root zone of crop (cm).

2.8.2. Distribution Uniformity (DU)

Distribution Uniformity is the measure of how uniformly the water is applied. Poor uniformity causes excessive deep percolation, where water percolates below the root zone and is lost to crop use. An irrigation uniformity of 100% would mean that every point within the irrigated area received the same amount of water as every other point. Typically, distribution uniformity (DU) is based on the post-irrigation measurement of water depth that infiltrates to the soil because it can be more easily measured and better represents the water available to the crop.

The Christiansen Uniformity Coefficient is given as:

$$CU = \left(1 - \frac{\sum|X_i - X|}{nX}\right) 100 \quad (4)$$

where CU is Christiansen uniformity coefficient %, X_i the recorded depth of water stored in root zone (mm) at i^{th} point (from gravimetric moisture determination).

It is the moisture content after oven dry of each of the soil samples from a plot. Soil samples prior to the commencement of the irrigation and two days after irrigation at three points from a plot. N is number of points where samples were taken. X is the mean water depth (mm) of water stored in root zone and is determined by:

$$X = \frac{\sum_{xk=0}^{n} X_i}{N} \quad (5)$$

Distribution uniformity at low quarter (or simply distribution uniformity) (DU_{lq}) is defined as the average water applied in 25% of the area received the least amount of water, regardless of location, divided by the average water applied over the total area.

$$DU_{lq} = 100 * \frac{LQ}{M} \quad (6)$$

where DU_{lq} distribution uniformity at low quarter (or simply distribution uniformity, DU), LQ average low-quarter depth infiltrated (mm) M average depth infiltrated (mm). The moisture content of the soil is taken from each plot at 2m, 5m and 8m starting from the upper end to the lower end for calculations of irrigation uniformity. Soil samples were taken before and after each irrigation events i.e. one day before irrigation and two days after irrigation.

2.9. Data Collection

Data collection was performed before the implementation of the experiment, during the implementation of the experiment and after the implementation of the experiment. Data collected before implementation of the experiment and after harvest were climatic data, soil data and yield and yield component data.

2.9.1. Climatic Data

Long term climatic data was used for estimation of crop water requirement to get actual estimation of reference evapotranspiration ETo and crop evapotranspiration (ET_c). Thirty years climatic data of (maximum and minimum temperature, humidity, wind speed and sunshine hour) on monthly base had been collected from Holeta Meteorological Station of Holeta Agricultural Research Center. The daily minimum (T_{min}) and maximum air temperature (T_{max}) are, respectively the minimum and maximum air temperature observed during the 24-hour and converted to months for thirty years.

2.9.2. Soil Data

The soil samples were collected from experimental site to determine bulk density, soil moisture, field capacity, permanent wilting point, soil texture, pH, OC, OM, CEC, total nitrogen, available phosphorus and exchangeable potassium in laboratory. To determine the bulk density, undisturbed soil samples were taken by core sampler of known volume ($100cm^3$) that was driven into the soil of up to desired depth. Since bulk density varies considerably spatially, the samples were taken at two different soil depths (0-30cm and 30-60cm) of the soil profile and from three locations across the experimental plot. The samples were dried in an oven to determine the dry weight fraction. Then the bulk density was calculated as the ratio of dry weight of the soil to known cylindrical core sampler volume [16].

$$\rho_b = \frac{M_s}{V_t} \quad (7)$$

where ρ_b is bulk density gcm^{-3}, M_s mass of solid (gm) and V_t total volume cm^3.

Gravimetric method was used to determine the initial moisture content and moisture content before and after irrigation events.

Soil samples were collected from each plot at depths of 0-20cm, 20-40cm and 40-60cm of the soil profile. These samples were collected from each plot along the furrow length at 2m, 5m and 8m to get representative soil moisture content of the plot. After weighing the soil sample, it was placed in an oven at 105°C until the constant weight was obtained. After drying, the soil sample was weighed again.

The gravimetric method was used to determine the soil moisture content and calculated as a dry weighed fraction [17].

$$\emptyset m = \frac{Mw - Ms}{Ms} \quad (8)$$

where Øm is soil moisture, Mw is weight of wet soil sample (g) and Ms is weight of dry sample soil (g).

Soil texture of the field was determined in the laboratory using hydrometer method and soil pH was determined from saturation pest extract using pH meter. Double-Ring infiltrometer of 30cm diameter and 60cm diameter was used to measure the infiltration capacity of experimental soil at field level. The infiltration rate is the velocity or speed at which water enters into the soil and expressed as depth (mm) of the water layer that can enter in to the soil in one hour had been calculated from ring infiltromter data.

The water content at field capacity was determined in the laboratory by using a pressure plate apparatus applying -1/3 bar to a saturated soil sample. When water is no longer leaving the soil sample, the soil moisture was taken as field capacity. Permanent wilting point was also determined using pressure membrane apparatus by applying -15 bars to a saturated soil. All soil data were analyzed in soil laboratory of Holeta and Bako Agricultural Research Center. Soil samples were also analyzed for soil chemical properties such as available phosphorus (P), organic matter (OM) and organic Carbon (OC), exchangeable potassium (K), total Nitrogen and Cation exchange capacity (CEC) in soil laboratory of Holeta Agricultural Research Center. Cation exchange capacity (CEC) was determined after saturation of samples with 1M ammonium acetate solution by using the modified Kjeldhal method as described by [18].

Total nitrogen was determined by treating the sample with a mixture of concentrated sulfuric acid and digestion catalysis following the modified Kjeldhal method [18]. Available phosphorus was determined using sodium bicarbonate as extraction solution according to the Olsen method.

2.9.3. Yield and Yield Components

Yield data were recorded on plot basis and extrapolated to hectare basis. All parameters were determined and calculated from the middle 6 rows. That is, the gross size of 6 m x 10 m (60 m^2) and the net (harvestable) plot area was 4.5 m x 10 m (45 m^2). Marketable tuber yield and unmarketable were differentiated based on the fact that marketable tuber yield was tuber yield which was not affected by disease, not deformed and damaged tubers during harvesting. The number of tubers per plant was recorded from 10 plants randomly selected and averaged to get number of tuber per plant at harvest. Maturity of the potato crop was observed when 50% of the plant haulms (vines) showed yellowed or in each plot they show senescence. Diseased, misshaped, damaged tubers during harvest were recorded as unmarketable tuber yield from the middle rows. Total tuber yield ($Kgha^{-1}$) was recorded as the sum of marketable tuber yield and unmarketable tuber yield and calculated as kg per hectare.

2.9.4. Benefit-Cost Ratio (BCR) and Net Return (NR)

The total cost mainly includes labor cost, input cost and fuel costs. Labor cost included costs for land preparation, weeding and watering and estimated based on the study area. Input costs included costs for purchasing of seed and fertilizer. The indigenous irrigation farmers in the study area do not pay for water for their farms. Therefore, they only bear the costs of labor for land preparation, weeding and watering (estimated the man-day labor cost of 70 Ethiopian Birr) as well as the price of seed, fertilizer and fuel to run a pump to withdraw water from the channel. Therefore, labor cost, input cost and fuel costs of the three irrigation method and farmer practice were estimated at plot level based on the observed costs and converted to hectare.

In the study area majority of the farmers are using pumps to convey water from the river channels to their farm land. Based on this fact fuel cost was estimated at plot level and converted to hectare. Gross revenue had been calculated by multiplying total yield in kg ha^{-1} and potato market price per kilogram. The farm-gate price for potato tubers in this study was 3 Ethiopian Birr per kilogram (local price). Net return (NR) and benefit-cost ratio (BCR) due to irrigation were calculated as follows:

$$NR = GR - TC \tag{9}$$

$$BCR = NR/\text{Total costs} \tag{10}$$

where NR Net return (ETB), GR Gross revenue (ETB), TC Total costs (ETB) and BCR Benefit-Cost ratio.

2.10. Statistical Analyses

Analysis was performed on yield, water productivity, and application efficiency and distribution uniformity using SAS statistical software. The data of the experiment was analyzed in randomized complete block design (RCBD), and the mean difference was estimated using the least significant difference (LSD) comparison.

3. Results and Discussion

3.1. Soil Parameters and Soil Water Relation

The results of textural analysis using Hydrometer method of the soil from the experimental site showed that the composition of clay, silt and sand percentage were 52, 21 and 27, respectively. Thus as per the USDA texture triangle classification, the soil was classified as clay loam soil. The field capacity and permanent wilting point of the soil were determined to be 42 and 29 percent, respectively. The infiltration rate determined from Ring infltrometer data was 10 mm/hr. The volumetric soil moisture content remained at field capacity was about 42% for this soil. The volumetric soil moisture content at the wilting point had been dropped to 29%. The above information showed that the soil was categorized under clay soil with good water holding capacity with low infiltration rate

The analyzed data for soil PH before planting showed the soil was slightly acidic for all treatments (table 4). This showed the acidity range of the soil had no impact on plant growth, nutrient and water availability. Potassium (K) is an essential nutrient for plant growth and is classified as a macronutrient due to large quantities of K being taken up by plants during their life cycle. From the soil data analyzed before planting for exchangeable potassium that held on the exchange sites on clay particles (exchangeable K) for all treatment showed that potassium was readily available for plant growth (table 4).

Bulk density reflects the soils ability to function for structural support, water and solute movement, and soil aeration. The bulk density recorded from collected soil sample before planting for all treatments was in the range that not restricts root growth (table 4). Soil sample analyzed for available phosphorus showed that P content of the soil was with the range of available for plant growth for all treatments. Analyzed soil data before planting showed that enough organic matter content was found in soil for all treatments (table 4). The cation exchangeable capacity (CEC) of soils varies according the clay %, the type of clay, soil pH and amount of organic matter. Based on this information CEC of the experimental soil was showed that soils dominated by clays with variable surface charge are typically strongly weathered (table 4). Nitrate-nitrogen (NO3-N) measures the amount of available nitrogen in the soil that can be absorbed immediately by plants. From the analyzed soil data collected before planting total nitrogen availability of the soil was within the range of available for plant growth (table 4).

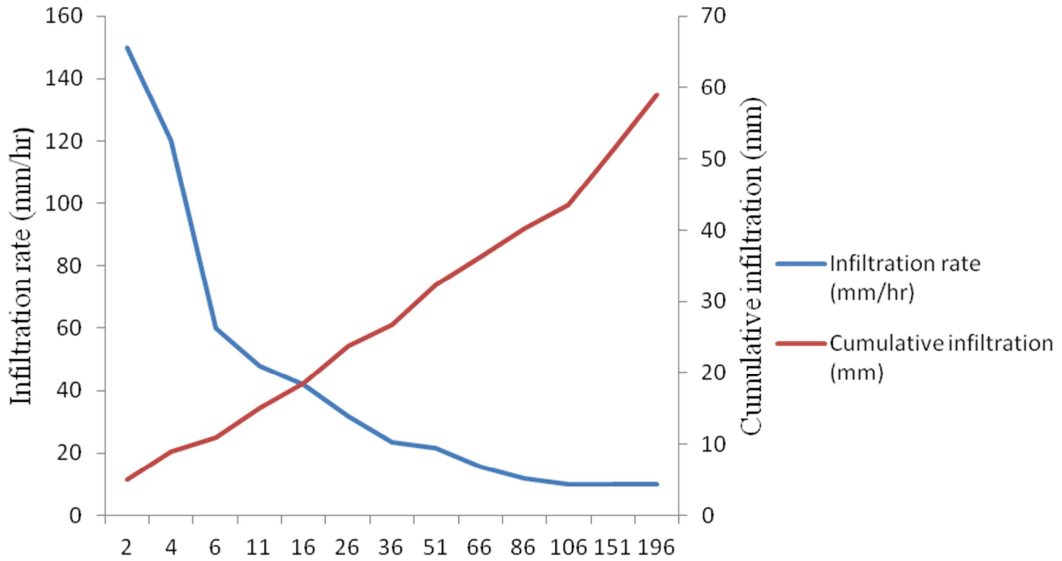

Figure 4. *Infiltration rate (mmhr^{-1} and Cumulative Infiltration (mm) curves.*

Table 4. *Soil parameters of experimental plots before planting.*

Treatment	PH	Available p ppm	Organic Carbon (%OC)	Organic Matter (%OM)	Total Nitrogen (%N)	Execahngable (K) K (cmol (+)/Kg soil	CEC	Bulk density
Every furrow irrigation	6.37	7.4	1.45	2.53	0.12	0.76	26.5	1.35
Alternate furrow irrigation	6.49	7	1.54	2.78	0.13	0.76	26.3	1.36
Fixed furrow irrigation	6.60	7.6	1.7	2.88	0.14	0.85	21.4	1.36
Farmer practice	6.46	7.2	1.78	2.7	0.13	0.74	24.5	1.35

Soil data analyzed for PH from soil sample collected after planting showed that slight reduction of soil PH for all treatments (table 5). However, no change was observed on the PH range as compared to that obtained before planting. This showed the applied treatments had no impact on soil PH. After planting Exchangeable Potassium (K) content of all experimental plots was increased relatively compared to that obtained before planting (table 5). This implied that some amount of K was become at exchangeable site after planting due to the implementation of the experiment. Analyzed result for bulk density form soil sample collected after planting for all treatments showed that bulk density value decreased after planting (table 5).

This reflected that bulk density of the experimental soil was decreased due to the disturbance of soil while plowing and other agronomic practice. Phosphorus content of the experimental soil was increased after planting as a result of addition of inorganic fertilizers (table 5). Analyzed soil data after planting also showed that organic matter content and cation exchange capacity (CEC) of the experimental soil were increased (table 5). This may be related to the increment of the microbial activity that in turn increases the organic matter content and CEC of the soil. The analyzed soil data collected after planting showed that nitrogen content of the experimental soil was increased du e to addition of inorganic fertilizer at planting and after planting (table 5).

Table 5. *Soil parameters of experimental plots after planting.*

Treatment	PH	Available P (Ppm)	Organic Carbon (%OC)	Organic Matter (%OM)	Total Nitrogen (%N)	Execahngable (K) K (cmol (+)/Kg soil	CEC	Bulk density
Every furrow	6.28	11.4	2.23	3.21	0.17	0.88	28.90	1.30
Alternate furrow	6.39	13.20	2.17	3.81	0.18	0.88	28.73	1.31
Fixed furrow	6.50	12.80	2.20	3.65	0.18	0.92	23.4	1.31
Farmer practice	6.36	11.8	2.55	4.10	0.22	0.83	27.4	1.30

3.2. Amount of Water Applied Under Each Treatment

As per the output of the model, the optimum seasonal irrigation requirement was found to be 584.3 mm (5843m^3/ha) for every furrow irrigation method (table 6). For the alternate furrow irrigation (AFI) and fixed furrow irrigation (FFI), 292.2mm (2922m^3/ha) of water was needed throughout the growing season of potato crop (table 6). Application of irrigation water according to CROPWAT model was started after twelve days i.e. after the crop is fully geminated. Before germination all experimental plots were irrigated with the same amount of water. Totally eight irrigation events were considered in the experimental site for determination of application efficiency, distribution uniformity, water productivity and water use efficiency excluding irrigation events prior to planting and before germination (table 6).

Table 6. *Details of irrigation during the growing season in the potato grown experiment.*

Treatment	Number of irrigation (number)	Depth of Water Applied (W_d (mm)
Every furrow irrigation (EFI)	8	584.3
Alternate furrow irrigation (AFI)	8	292.2
Fixed furrow irrigation (FFI)	8	292.2
Farmer practice (FP)	12	925.6

The alternate furrow and fixed furrow irrigation treatment consumed less water as compared with every furrow irrigation method (table 6).

The treatment considered as farmer practice was irrigated by farmer himself with twelve number irrigation events (table 6). The amount of water consumed by treatment implemented by farmer (Farmer practice) was calculated from depth of water flowing in the parshall flume located at the entrance of the plot and the time of irrigation. The seasonal amount of water consumed by the alternate furrow irrigation and every furrow irrigation were amounted to 292.2mm (2922m^3 m^3 ha^{-1}), and 584.3 mm (5843m^3 ha^{-1}) respectively. According to the study done on development of irrigation best management practices for potato for maximum yields, the crop water requirement (CWR) of potato for a 120 to 150 day crop growth is 500 to 700 mm depending on climate [19]. Amount of water applied for every furrow irrigation treatment was agreed with the range of water requirement stated previously.

Based on the fact that alternate furrow and fixed furrow irrigation reduces number of furrow under irrigation and the amount of water applied to these treatments was reduced by half as compared with every furrow irrigation method. Alternate furrow irrigation technique has been fundamentally based on alternatively wetting and drying opposite parts of the ridge of furrows under which the plant root system is thought to be located. Amount of water applied under alternate furrow irrigation was also agrees with conclusion says alternate furrow irrigation is commonly applied as part of a deficit irrigation program because it does not require the application of more than 50–70% of the water used in a fully irrigated furrow (every furrow irrigation method) [20]. On the other hand, alternate furrow irrigation technique recorded lower values of total evapotranspiration as compared with every furrow irrigation technique. This may be due to less evaporation from the dry furrow that was reflected on decreasing total evapotranspiration [21]. Table 6 indicates that alternate furrow and fixed furrow irrigation techniques saved 50% of irrigation water as compared with every furrow irrigation technique and 68.4% as compared with farmer practice, whereas every furrow irrigation method saved 37% of irrigation water as compared with farmer practice.

The lowest depth of water applied (W_d) under alternate furrow irrigation method as compared to every furrow irrigation is as a result of great reduction of wetted surface in alternate furrow irrigation; almost half of the soil surface is wetted in alternate furrow irrigation. This result supports the outcome obtained by the study that conclude alternate furrow irrigation method which can supply water in a way greatly reduces the amount of wetted surface, which leads to less evapotranspiration and less deep percolation [22].

3.3. Field Application Efficiency (AE)

The results shown in table 7 are the average values of water application efficiency calculated separately for each irrigation events. A total of eight irrigation events were considered during observations. Irrigation application efficiencies under every furrow irrigation method where found between 50 to 55% with average of 52% for all irrigation events, whereas values under alternate furrow irrigation method were found between 64 to 68% with average of 67 % for all irrigation events. The result depicted there is significant ($p < 0.05$) difference between every furrow and alternate furrow irrigation. Table 7 also shows the result of water application efficiency under alternate furrow irrigation method was higher by 15% as compared to every furrow irrigation method under clay loam soil. The wetted perimeter of alternate furrow irrigation is less as compared to every furrow irrigation method. Hence, alternate furrow irrigation method saves a considerable volume of irrigation water.

The results of this study are in close agreement with the conclusion that furrow irrigation methods have wider range of 60-90% [23]. On overall basis, the values of water application efficiency of every furrow irrigation method are within acceptable ranges as described by the study [24]. As shown in table 7 application efficiencies under fixed furrow irrigation method where found between 59% to 63% with average of 61% for all irrigation events, whereas under alternate furrow irrigation method the average value is 67 %. The result shows that there is no significant ($p < 0.05$) difference between alternate furrow and fixed furrow irrigation methods. From the obtained results, one can clearly see that water application efficiency of alternate furrow irrigation method was higher than fixed furrow irrigation by 7% only. The results of this study are in close agreement with the conclusion that the mean value of application efficiency of alternate furrow irrigation is higher than that of fixed-every furrow in which the drier furrow remains dry throughout the growing season, due to low lateral and more downward water flow is expected in fixed furrow method [25].

As indicated in table 7 application efficiencies under farmer practice where found between 31 to 41% with average of 34% for all irrigation events, whereas the average values of 52, 67 and 61% where observed under every furrow, alternate furrow and fixed furrow irrigation respectively. According to the results of table 7, there was high significance ($p < 0.05$) difference between framer practice and other methods.

The result indicated that farmer practice resulted low application efficiency of 34.4% that is lower by 17.6% as compared to that obtained under every furrow irrigation method. In addition, results obtained under farmer practice shows low application efficiency that is lower by 32.6% as compared to alternate furrow irrigation. This shows that there was high significance difference between farmer practice and alternate furrow irrigation method. Table 7 also showes alternate furrow irrigation (AFI) is the most effective tools to minimize water application by half as compared with full furrow irrigation and increase irrigation water application efficiency. This result supports the outcome obtained by the study that conclude that alternate furrow irrigation method is a way to save irrigation water and improve irrigation efficiency [22].

Table 7. *Application efficiency of all irrigation events.*

Treatment	AE first irrigation %	AE second irrigation %	AE third irrigation %	AE fourth irrigation %	AE fifth irrigation %	AE Sixth irrigation %	AE seventh irrigation %	AE eighth irrigation %	Overall mean
EFI	$53^{a}\pm3$	$51^{b}\pm3$	$50^{b}\pm3$	$55^{c}\pm1$	$51^{a}\pm3$	$54^{b}\pm3$	$51^{b}\pm2.4$	$51^{b}\pm3$	52^{b}
AFI	$67^{a}\pm3$	$68^{a}\pm3$	$68^{a}\pm3$	$67^{a}\pm1$	$68^{a}\pm3$	$64^{a}\pm3$	$68^{a}\pm2.4$	$67^{a}\pm3$	67^{a}
FFI	$61^{a}\pm3$	$63^{a}\pm3$	$62^{a}\pm3$	$61^{a}\pm1$	$59^{a}\pm3$	$60^{a}\pm3$	$62^{a}\pm2.4$	$60^{a}\pm3$	61^{a}
FP	$34^{b}\pm3$	$32^{c}\pm3$	$38^{c}\pm3$	$32^{d}\pm1$	$31^{b}\pm3$	$33^{c}\pm3$	$34^{c}\pm2.4$	$41^{c}\pm3$	34.4^{c}
LSD (0.05)	16.5	14.7	11.2	10.2	14.3	9.3	15.8	14.8	13.4
CV	15.4	11.7	17.2	12.2	16.3	18.4	15.7	17.2	15.5

Means the treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

3.4. Distribution Uniformity

The tools used to evaluate distribution uniformity of irrigation methods were the Christiansen Uniformity Coefficient and distribution uniformity at low quarter (or simply distribution uniformity, DU) as given in the table 8 and 9. The results shown in the table 8 are the average values of coefficient of uniformity (CU) calculated separately for each irrigation events. As indicated in this table the highest coefficient of uniformity (CU) was recorded under every furrow irrigation method which is not significantly ($p < 0.05$) different from that recorded under alternate furrow irrigation. However, significant ($p < 0.05$) difference is observed between alternate furrow and fixed furrow irrigation methods. This may be due to low lateral movement of water in fixed furrow irrigation as compared to alternate furrow irrigation.

Low coefficient of uniformity was recorded under farmer practice which shows high significance ($p < 0.05$) difference as compared with other methods.

Table 8. *Coefficient of uniformity (CU).*

Treatments	CU for the first irrigation	CU for the second irrigation	CU for the third irrigation	CU for the fourth Irrigation	CU for the fifth Irrigation	CU for sixth irrigation	CU for seventh irrigation	CU for Eight irrigation	Overall mean
EFI	$87^{a}\pm3$	$87^{a}\pm3$	$89^{a}\pm2$	$88^{a}\pm3$	$87^{a}\pm2$	$89^{a}\pm1$	$86^{a}\pm3$	$88^{a}\pm2$	87.6
AFI	$89^{a}\pm3$	$92^{a}\pm3$	$91^{a}\pm2$	$90^{a}\pm3$	$90^{a}\pm2$	$92^{a}\pm1$	$88^{a}\pm3$	$92^{a}\pm2$	90.5
FFI	$80^{b}\pm3$	$78^{b}\pm3$	$84^{b}\pm2$	$80^{b}\pm3$	$81^{b}\pm2$	$80^{b}\pm1$	$79^{b}\pm3$	$84^{b}\pm2$	80.8
FP	$76^{c}\pm3$	$70^{c}\pm3$	$74^{c}\pm2$	$74^{c}\pm3$	$75^{c}\pm2$	$73^{c}\pm1$	$70^{c}\pm3$	$73^{c}\pm2$	73.1
LSD (0.05)	4.7	6.4	3.2	5.4	3.6	4.3	6.2	3.2	
CV	17.5		17	15.6	12.6	31.2	10.5	15.4	

Means treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

The output of statistical analysis revealed that there was no significant ($p < 0.05$) difference between every furrow irrigation and alternate furrow irrigation in terms of water distribution uniformity (DU) as indicated in table 9, whereas significant difference is observed between alternate furrow and fixed furrow irrigation methods. The average value of distribution uniformity obtained under fixed furrow irrigation for all irrigation events was 75.4%, which is lowered 13.9% as compared with alternate furrow irrigation (table 9).

This supports the outcome obtained by the study that concludes that the soil water in the irrigated side of alternate furrow irrigation is depleted more effectively than corresponding side in fixed furrow [26]. The root system can partially compensate for the increasing limited water availability on the non-irrigated side of alternate furrow irrigation due to an increase in root hydraulic conductivity which increases distribution uniformity of irrigation water under alternate furrow irrigation sytem. This also agrees with the outcome obtained by the study that concludes that larger hydraulic gradient in the soil-root interface was observed under alternate furrow irrigation than under fixed furrow irrigation [27].

As indicated in the table 9, there was high significance ($p < 0.05$) difference between farmer practice and other irrigation methods. Low distribution uniformity (DU) is recorded under farmer practice as compared with other irrigation methods. This is based on the fact that, in farmer practice water is applied by farmer without determination of crop water requirement and using fixed irrigation schedule system which reduces the irrigation efficiency and distribution uniformity.

Table 9. *Distribution uniformity (DU).*

Treatments	DU for the first irrigation	DU for the second irrigation	DU for the third irrigation	DU for the fourth Irrigation	DU for the fifth Irrigation	DU for sixth irrigation	DU for seventh irrigation	DU for Eight irrigation	Overall mean
EFI	85^{a}±3	85^{a}±2	86^{a}±3	84^{a}±2	87^{a}±3	86^{a}±2	85^{a}±3	84^{a}±2	85.3
AFI	86^{a}±3	92^{a}±2	93^{a}±3	87^{a}±2	90^{a}±3	93^{a}±2	86^{a}±3	87^{a}±2	89.3
FFI	74^{b}±3	75^{b}±2	76^{b}±3	75^{b}±2	74^{b}±3	75^{b}±2	78^{b}±3	76^{b}±2	75.4
FP	64^{c}±3	63^{c}±2	64^{c}±3	64^{c}±2	65^{c}±3	64^{c}±2	56^{c}±3	59^{c}±2	62.4
LSD (0.05)	6.4	8.5	9.3	8.2	7.6	9.4	5.6	6.2	
CV	15.5	14.7	16.5	15.6	13.6	12.3	10.8	15.4	

Means treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

3.5. Yield and Yield Components

3.5.1. Number Tubers per Plant

Table 10 shows that average number of tuber per plant i.e. total number of tubers. Irrigation methods significantly influenced total number of tubers (marketable and unmarketable tubers) collected from each plot (table 10). The highest number of tubers (16) was produced under every furrow irrigation method, whereas the lowest number of tubers (6) was produced under famer practice (table 10).

As shown in the table 10 no significant ($p < 0.05$) different was observed between every furrow and alternate furrow irrigation methods in terms of number of tubers, whereas significant difference was observed between alternate furrow and fixed furrow irrigation methods.

The highest number of tubers (16 per plant) was harvested from every furrow irrigation method which showed insignificant difference compared to that obtained from alternate furrow irrigation (14 per plant) (table 10). This implies that, under alternate furrow irrigation method more number of tubers was harvested as compared with that obtained under fixed furrow irrigation method (19 per plant) due to uniform water distribution in alternate furrow irrigation than fixed furrow irrigation which in turn increased the tuber yield harvested from alternate furrow irrigation.

Table 10. *Effect of irrigation methods on number of tubers per plant.*

Treatment	Water applied (mm)	Average tuber number per plant
Every furrow irrigation	584.3	16^{a}±1.1
Alternate furrow irrigation	292.2	14^{a}±1.1
Fixed furrow irrigation	292.2	9^{b}±1.1
Farmer practice	925.6	6^{c}±1.1
LSD		3.4
CV		17.2

Means of treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

3.5.2. Potato Tuber Yields

To determine the impact of irrigation methods on yield, tuber yield was differentiated as total yield, marketable yield and unmarketable yield. This is because; the whole purpose of doing the experiment was to assess how much water could be saved by alternate irrigation method with minimum or no yield reduction as compared with other methods (every furrow irrigation, fixed furrow irrigation and farmer practice). With the intention of comparing the yield performance each irrigation methods, tuber yield from six central rows for all treatments was collected, weighed and yield per hectare was extrapolated. The yield collected from each treatment was further differentiated to total yield, marketable yield and unmarketable yields.

Table 11 shows average tuber yield in terms of total tuber yield, marketable and unmarketable yield collected from each irrigation methods including farmer practice. As indicated in the table 11 the difference observed between every furrow and alternate furrow irrigation methods in terms of total tuber yield was statically insignificant at 5% significant level.

This shows that, the total tuber yield was nearly the same in both (EFI and AFI) irrigation methods; whereas total depth of water applied under every furrow irrigation was almost double as compared with that of applied under alternate furrow irrigation. Minor yield reduction (171 kg/ha) was observed under alternate furrow irrigation as compared with every furrow irrigation which is less than 1% (table 11). This implies that, applying alternate furrow irrigation will not produce significant yield reduction as compared with every furrow irrigation method in terms of total tuber yield. Therefore, by implementing alternative furrow irrigation technique, almost the same tuber yield was obtained comparing with the every furrow irrigation method. This result agreed with outcome obtained by the study that concludes alternate furrow irrigation (AFI) or partial root-zone drying (PDI) can increase water productivity with no or minor yield loss [28]. The result also agreed with the outcome obtained the study that reported that alternate furrow irrigation or partial root-zone drying (PDI) saved irrigation water compared to every furrow irrigation while maintaining similar yield with every furrow irrigation [29].

As indicated in table 11 total tuber yield was decreased significantly under fixed furrow irrigation compared to every furrow and alternate furrow irrigation techniques. The total tuber yield under fixed furrow irrigation was lowered by 3192kg/ha (9.5%) and 3021 kg/ha (9.1%) as compared with every furrow and alternate furrow irrigation respectively (table 11). The difference in total tuber yield between alternate furrow irrigation and fixed furrow irrigation is due to low moisture availability in fixed furrow irrigation technique as result of only even furrows were received water throughout the growing season. On the other hand, reduction in tubers yield under fixed furrow irrigation may be attributed due to little lateral movement of water and high downward movement of water and drying of un-watered furrows throughout the growing period of the crop. This result supports the outcome obtained by the study that stated yield is decreased significantly in fixed furrow irrigation as compared with alternate furrow and every furrow irrigation techniques [30].

By comparing total tuber yield observed under farmer with every furrow and alternate furrow irrigation, high significant difference was observed at 5% significant level (table 11). The yield reduction obtained under farmers practice were 3271kg/ha (9.8%), 3100kg/ha (9.3%), as compared with every furrow and alternate furrow irrigation techniques respectively (table 11).

This implies that the extra amount of water added under farmer practice shows adverse effect on potato tuber yield. Farmers in the study area commonly uses fixed irrigation scheduling system because of the scarcity of water and high competition to use available water for crop production. However, fixed irrigation scheduling is not appropriate method to meet crop water requirement as per growth stage the crop. This indicates that the amount of water applied under farmer practice is not agreed with crop water requirement needed at each growth stage.

As indicated in table 11 no significant difference was observed between fixed furrow irrigation and farmer practice. The farmers generally lack knowledge on aspects of soil-water-plant relationship and they apply water to the crop regardless of the plant needs. They seem to relate irrigation occurrence to number of days after planting with fixed intervals rather than crop growth stage progress. This result agrees with outcome obtained study that conclude improper irrigation depth and frequency can substantially reduce yields by increasing the proportion of rough, misshapen tubers [31].

Table 11 also shows As the differences observed in marketable tuber yield between every furrow and alternate furrow irrigation methods was not significant at 5% significant level. In addition to this, there was no statistically significant difference in marketable tuber yield between fixed furrow and farmer practice. However, there was statistically significant difference in marketable tuber yield between alternate furrow and fixed furrow irrigation (table 11). The lowest marketable yield was observed under framer practice which shows insignificant difference as compared with fixed furrow irrigation (table 11). The difference observed in marketable tuber yield between fixed furrow and farmer practice was only 1320.9kg/ha that shows insignificant difference between the two methods (table 11).

The difference observed between alternate furrow and fixed furrow irrigation in terms of marketable yield may be related to; under fixed furrow irrigation technique only little amount of water was moved laterally towards the un-watered furrows and large portion of water moves down ward due to watering of furrows that received water at all irrigation events and remain dry un-watered furrow throughout the growing season. This affects the size and quality of potato tubers which agrees with the study result that suggestes given fixed furrow irrigation lowers quality of tubers as a result of limitation of water to only one side of furrow [32].

Table 11 also indicates that, fixed furrow irrigation and farmer practice were resulted low marketable yield of 29587.6kg/ha and 28266.7kg/ha respectively as compared to that obtained under alternate furrow irrigation and every furrow irrigation. Therefore, the study indicated that low marketable yield was recorded at farmer practice this was due to poor water application method that affects the marketability of the tubers. Improper irrigation depth and frequency can substantially reduce yields by increasing the proportion of rough, misshapen tubers that reduce the quality of potato for marketability [31]. In addition, high unmarketable yield (1831.1 kg/ha) was recorded under farmer practice as a result of poor irrigation water management.

Table 11. *Effects of irrigation method on tuber yield.*

Treatment	Total. Yield (kg/ha)	Marketable Yield (kg/ha)	Unmarketable yield (kg/ha)
Every furrow irrigation	33369^{a}±811	31839.2^{a}±516.5	1482.9^{a}±29.7
Alternate furrow irrigation	33198^{a}±811	32667.8^{a}±516.5	534.2^{b}±29.7
Fixed furrow irrigation	30177^{b}±811	29587.6^{b}±516.5	821.3^{b}±29.7
Farmer practice	30098^{b}±811	28266.7^{b}±516.5	1831.1^{a}±29.7
LSD	2499.5	1591.4	497.35
CV	14	12.3	15.7

Means of treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

3.6. Water Productivity (WP), Irrigation Water Saved and Additional Area Gained

3.6.1. Water Productivity (WP)

The amounts of water applied for the potato from planting to harvest over the growing season are given in table 6. Water productivity (WP) based on fresh tuber production was expressed as the ratio of tuber yield at harvest to the water applied is given in the table 12.

The WP values obtained in this study were similar to those reported for potato by others and were affected by irrigation techniques. It is clear that by increasing irrigation water application, a decreasing in crop water productivity could be obtained and vise versa.

As indicated in table 12 there was significant difference at 5% significant level in water productivity (WP) values between irrigation techniques. The highest water productivity value was 11.2 kgm^{-3} obtained from the alternate furrow irrigation treatment followed by 10.7 and 6.1kgm^{-3} obtained from fixed furrow and every furrow irrigation methods respectively whereas, the lowest value of 4.1kgm^{-3} was obtained from farmer practice (table 12).

This finding agreed with result states that an adverse relationship was found between the amounts of water applied and water productivity of the crop [33]. The applied water was used more efficiently in the alternate furrow irrigation treatment in which the lower amount of water applied produces higher water productivity value.

The higher mean value of water productivity obtained under alternate furrow irrigation was related to lower amount of water applied with uniform lateral movement in crop root zone and minor tuber yield reduction obtained under this method. The reason of having more water productivity (WP) and minor yield reduction for alternate furrow irrigation could be related to better distribution of water in root zone in both sides of the ridge that increases water and fertilizer uptakes by plant. This result indicates that alternate furrow irrigation is appropriate to increase water productivity by allow applying less irrigation water for potato production which supports the outcome of the study that says using alternate furrow irrigation or partial root zone drying (PDI) higher water productivity (WP) and even better fruit quality can be produced [34].

Table 12 also shows that the difference observed in water productivity between alternate and fixed furrow irrigations was statistically significant at 5% significant level. The same amount of irrigation water was applied for alternate furrow and fixed furrow irrigation techniques. However, alternative drying of root zone under alternate furrow irrigation method showed higher water productivity than fixed drying of root zone under fixed furrow irrigation method. This is due to uniform water distribution between ridges in alternate furrow than fixed furrow irrigation. Uniform water distribution between ridges in alternate furrow irrigation method enhanced root growth and improved nutrient uptake of crop which increases the yield than fixed furrow irrigation method.

Table 12. *Effects of irrigation methods on water productivity and water use efficiency.*

Treatment	Water productivity (kg/m^3)
Every furrow irrigation	$6.1^{c}\pm0.13$
Alternate furrow irrigation	$11.2^{a}\pm0.13$
Fixed furrow irrigation	$10.7^{b}\pm0.13$
Farmer practice	$4.1^{d}\pm0.13$
LSD	0.41
CV	10.3

Means of treatments denoted by the same letter within a column are not statistically significantly different at 5% level of significance.

The results of this study are in close agreement with the conclusion that alternative furrow irrigation enhanced root growth and increased nutrient uptake of the crop [35]. The difference observed in total water productivity (WP) between farmer practice and other irrigation techniques was statistically highly significant (table 12). The reduction of water productivity in farmer practice was related with more volume of water added in farmer practice without yield advantage. This indicates that extra amount of water is added to farmer practice plot as a result of improper irrigation depth and fixed schedule system.

3.6.2. Irrigation WATER Saved and Additional Area Gained

Table 13 indicated that amount of water saved under each irrigation methods comparing with each other. This table also indicated that additional area can be irrigated by amount of water saved under each irrigation methods. Every furrow irrigation method saved 341.3mm of water applied under farmer practice (table 13). This amount of water can be used to irrigate 0.58ha of additional land using every furrow irrigation method for potato production. Similarly, alternate furrow irrigation and fixed furrow irrigation methods saved 633.4mm of water applied under farmer practice which can be used to irrigate 2.17ha of additional land using alternate furrow or every furrow irrigation method for potato production (table 12). Alternate furrow and fixed furrow irrigation received the same amount of irrigation water, whereas low water productivity was obtained under fixed furrow irrigation compared to alternate furrow irrigation method. This result is in close agreement with the conclusion that alternate furrow irrigation increase water productivity as compared with fixed furrow irrigation techniques by saving irrigation water [29].

Alternate furrow irrigation and fixed furrow irrigation saved 292.1mm of water applied under every furrow irrigation method which can be used to irrigate 1ha of additional land using alternate furrow or fixed furrow irrigation method for potato production. Moreover, applying alternate furrow irrigation method increased water productivity 45.5% and saved 292.1mm (50%) of water consumed under every furrow irrigation method. This amount of water was sufficient to irrigate one hectare of potato cropped area using alternate furrow irrigation technique that can earn better economic returns as compared to every furrow irrigation method.

Similarly, applying alternate furrow irrigation technique increased water productivity by 63.4% and saved 633.4 mm (68.4%) of water consumed under farmer practice. This amount of water is sufficient to irrigate 2.17ha of potato cropped area using alternate furrow irrigation technique that can earn better economic returns as compared to that of farmer practice. In addition, fixed furrow irrigation saved 633.4mm (68.4%) of water as compared with farmer practice but less in water productivity as compared to alternate furrow irrigation (table 13). Generally, alternate furrow system increased water productivity (WP) with minor or no yield reduction as compared to every furrow irrigation system. This finding agrees with result of the study that conclude alternate furrow irrigation increases water productivity with minor or no yield reduction and save substantial quantity of irrigation water [36].

Table 13. *Irrigation water saved and additional area gained under each treatments.*

Treatment	Irrigation water saved (mm) Comparing three irrigation method with FP	Additional irrigated can be irrigated (ha)	Irrigation water saved (mm) Comparing AFI and FFI methods with EFI method	Additional irrigated can be irrigated (ha)
EFI	341.3	0.58	0	0
AFI	633.4	2.17	292.1	1
FFI	633.4	2.17	292.1	1
FP	0	0	0	0

3.7. Benefit-Cost Ratio (BCR) and Net Return (NR)

Table 14. *Expenses involved in the implementation of irrigation treatments.*

Treatments	Labor cost (ETB)		Input cost (ETB)		Fuel cost (ETB)	Total cost (ETB)
	Land preparation and Weeding	Watering	Fertilizer	seed		
EFI	950	1550	5780	2720	3966	14966
AFI	570	930	5780	2720	1983	11983
FFI	570	930	5780	2720	1983	11983
FP	1520	2480	5780	2720	5950	18450

Table 15. *Revenues gained from the implementation of irrigation treatments.*

Treatments	Marketable tuber yield kgha-1	Unit price (Per Kg)	Total price
EFI	31967.1	3	95901.3
AFI	32682.7	3	98048.1
FFI	29465.6	3	88396.8
FP	28333.3	3	84999.9

Table 16. *Benefit-cost ratio (BCR) and net return (NR) associated with the adopted irrigation treatments.*

Treatments	Applied water m^3ha^{-1}	Fuel cost ETB	Labor cost $ETBha^{-1}$	In put cost $TBha^{-1}$	Total cost ETB	Marketable tuber yield kgha-1	Gross Revenue ETB	Net revenue ETB	Benefit-cost ratio
Ever furrow	5843	3966	2500	8500	14966	31967.1	95901.3	80935.3	5.4
Alternate furrow	2922	1983	1500	8500	11983	32682.7	98048.1	86065.1	7.2
Fixed furrow	2922	1983	1500	8500	11983	29465.6	88396.8	76413.8	6.48
Farmer practice	9256	5950	4000	8500	18450	28333.3	84999.9	66549.9	3.6

Estimation of cost and revenue earned was done based on the expenses involved to produce potato around study area and revenues can be gained from production potato in the study area. Estimated benefit-cost ratio (BCR) and net return (NR) were affected by the irrigation techniques. Maximum benefit-cost ratio (BCR) was 7.2 obtained from alternate furrow irrigation followed by 6.5 from fixed furrow irrigation and 5.4 from every furrow irrigation technique, whereas minimum benefit-cost ratio was 3.6 observed from farmer practice. The total cost mainly includes labor, input and fuel costs. Labor costs (labor cost for land preparation, weeding and watering) were estimated based on the study area. Low labor cost was estimated for alternate furrow and fixed furrow irrigation as a result of cost used to irrigate the two techniques is low as compared with every furrow irrigation and farmer practice.

However, net revenue gained from fixed furrow irrigation was low as a result of low marketable yield collected from this treatment as compared with alternate furrow irrigation. From the results of this study, alternate furrow irrigation was the best method to improve water productivity, water use efficiency and economic return from potato production. The result benefit-cost ratio indicated in table 16 showed that all irrigation methods are feasible. However by comparing alternate furrow irrigation with other methods, farmers can get more benefit from alternate furrow irrigation compared to other irrigation methods.

4. Summary, Conclusions and Recommendations

4.1. Summary

At present situation, the depth of rainfall is low or its distribution is uneven, and highly erratic to meet the daily crop evapotranspiration requirement. Under this condition, the need to use the available water economically and efficiently is unquestionable. Based on the actual crop need, irrigation management has to be improved so that the water supply to the crop can be reduced while still achieving high yield. Alternate furrow irrigation is one of the irrigation management practices that can save irrigation water. This experiment was conducted to study the effect of alternate furrow irrigation system by comparing with others irrigation techeniques on yield, water productivity and water use efficiency of potato (*Solanum tuberosum L.*). This study emphasized on comparison of irrigation methods to identify the irrigation management strategies which could contribute for water saving, increase water productivity and water use efficiency with no or minimum yield reduction in the humid climate of Western Ethiopia particularly West Shoa zone of Oromia region. Results confirmed that irrigation treatments significantly influenced yield, water productivity and water use efficiencies of potato.

In order to compare irrigation methods some parameters such as application efficiency, distribution uniformity, tuber yield and water productivity were measured for all irrigation treatments. Highest value of irrigation performance indicators (coefficient of uniformity and distribution uniformity) were obtained under alternate furrow irrigation. From the investigation the highest total tuber yield was observed under every furrow irrigation method which showed little difference as compared with alternate furrow irrigation. The yield reduction observed under alternate furrow irrigation is less than 1 % as compared with every furrow irrigation method, which has no significant impact on marketable yield of the potato crop. The highest marketable yield (32682.7kgha^{-1}) was obtained from alternate furrow irrigation, whereas the lowest marketable yield (28333.3kgha^{-1}) was obtained from farmer practice.

Comparing the results of the irrigation methods from the point of crop water productivity, it clearly confirmed that, alternate furrow irrigation method had more beneficial use of water followed by fixed furrow irrigation and every furrow irrigation methods respectively. The highest water productivity (WP) value (11.2kg m^{-3}) was obtained under alternate furrow irrigation (AFI), whereas the lowest value (4.1kg m^{-3}) was obtained under famer practice.

Alternate furrow and fixed furrow irrigation methods saved 50% of water applied under of every furrow irrigation method. However; under fixed furrow irrigation method low water productivity was recorded as compared with alternate furrow irrigation method.

This study advocates that alternate furrow irrigation was substantially saved water than every furrow irrigation method without significant yield reduction which is sufficient to irrigate additional area of potato cropped land. Moreover, alternate furrow irrigation method increased the benefit-cost ratio (BCR), net return (NR) in addition to saving water.

4.2. Conclusions

The results demonstrated conclusively that alternate furrow irrigation method is more effective in enhancing water productivity (WP) and water use efficiency (WUE) as compared with other methods. The study results confirmed that with alternate irrigation strategy it is possible to increase water productivity and save significant depth of water for irrigation without significant yield reduction. From this result, one can conclude that applying alternate furrow irrigation method improved water efficiency by saving 50% of water applied under every furrow irrigation method which is sufficient to irrigate one hectare potato cropped land. Similarly, applying alternate furrow irrigation method improved water use efficiency by saving 68.4% of water applied under farmer practice which is sufficient to irrigate two hectare of potato cropped land. These results indicated that alternate furrow irrigation (AFI) is appropriate to increase water productivity (WP) and water use efficiency (WUE) by allowing application of less irrigation water with minor or no yield reduction as compared to every furrow irrigation method.

Therefore applying alternate-furrow irrigation with appropriate irrigation intervals is efficient method in the study area where soil is mainly dominated by clay soil and water become limiting factor in potato production. It can be conclude that using alternate irrigation is a good water management technique to save irrigation water without reducing the yield of potato crop. The preference between alternate furrow irrigation method and other methods depends on the value of water in relation to crop returns. This water application technique is much important for highlands of western Ethiopia like the West Shoa zone of Oromia region and other similar agro-ecology elsewhere in the Ethiopia where limited amount of water is available for irrigation and irrigation water management is very poor.

4.3. Recommendations

Generally this study would like to recommend farmers, water managers, water use associations and decision makers to use water efficiently using alternate furrow irrigation and increase their agricultural production by expand irrigable land with existing amount of water in a given irrigation scheme. Therefore, alternate furrow irrigation method with appropriate irrigation interval is suitable irrigation method; for humid climate where soil is dominated by clay soil and water is liming factor for potato crop production. Similarly, alternate furrow irrigation with appropriate intervals will essentially be the best choice under similar conditions of the study area. Thus, it is recommended that all possible efforts should be made to introduce the technology to the farming community since the use of alternate furrow irrigation method saves reasonable amount of water without affecting the production in humid area using appropriate varieties of potato crop.

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