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Research Article

Optimizing Garlic Yield Through Furrow Irrigation Systems and Deficit Irrigation in Central Ethiopia, Tiyo District

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Abstract

Water scarcity presents a significant challenge to sustainable agriculture, especially in semi-arid regions like Ethiopia, where limited water availability intensifies dependence on efficient irrigation methods. This study assessed the impact of three furrow irrigation systems—Conventional Furrow Irrigation (CFI), Alternate Furrow Irrigation (AFI), and Fixed Furrow Irrigation (FFI)—combined with four levels of deficit irrigation (100%, 85%, 70%, and 55% of crop evapotranspiration, ETc) on garlic yield and water use efficiency (WUE) in Tiyo District, Central Ethiopia. A factorial randomized complete block design (RCBD) was employed with 12 treatment combinations and three replications. Results revealed that CFI at 85%ETc achieved the highest garlic yield among deficit treatments (82.68 q/ha), while AFI at 100%ETc provided a comparable yield with significantly reduced water use. The maximum irrigation water use efficiency (IWUE) of 31.52 kg/mm was observed under AFI70%ETc, followed closely by AFI100%ETc at 28.64 kg/mm. Crop water use efficiency (CWUE) was highest under CFI100%ETc at 26.35 kg/mm. Despite FFI being less effective due to uneven water distribution, AFI demonstrated consistent superiority in maintaining stable yields and maximizing WUE, especially under limited water conditions. The study concludes that AFI coupled with moderate deficit irrigation (100% or 85%ETc) offers a promising approach for improving garlic productivity and sustainable water management. These findings provide valuable insights for policymakers, researchers, and farmers seeking adaptive strategies to enhance crop performance in water-scarce environments.

Keywords

Garlic (Allium Sativum.), Furrow Irrigation Systems, Deficit Irrigation, Water Use Efficiency, Irrigation Water Use Efficiency (IWUE), Sustainable Water Resource Management, Ethiopia

1. Introduction

Agriculture is very crucial to Ethiopia's economy contributing around 40% to the national GDP and providing employment to, approximately, 80% of the population [4, 5] Despite convincing contributions, the agricultural sector is faced with various challenges including erratic rainfall, low productivity, and ineffective water management practices. These challenges speak to an apparent demand for proper management of water considering the rising population together with climate change-induced changes in rainfall patterns.

In Ethiopia, 97.8% of irrigation systems are surface type, particular with furrow irrigation that suffers from the losses of water and low productivity [11, 12]. Conventional Furrow Irrigation or CFI is widely applied due to its simplicity and

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low cost; however, it suffers from inefficiency particularly due to over-irrigation, uneven distribution of water, evaporation, and runoff. Such inefficiency can severely affect crop growth and productivity, especially with garlic being a water sensitive crop.

Garlic (Allium sativum L.) is an important crop in Ethiopia for its culinary and medicinal purposes taking a wider cultivation in areas such as Tiyo district. Garlic, on the other hand, has a shallow root system, which makes it sensitive to alternating soil moisture conditions [10]. Such inadequate irrigation causes the lack of proper bulb formation, crop yields and low WUE. Irrigation management practice is, therefore, useful in terms of enhancing yield while conserving water use.

Alternative irrigation strategies include Alternate Furrow Irrigation (AFI) and Fixed Furrow Irrigation (FFI) proposed to overcome CFI shortcomings. The AFI system is characterized by irrigation of alternate furrows, allowing every second furrow to dry out before the next irrigation. Water is saved, while the moisture content is kept sufficient for other furrows [2]. As for FFI, water application is done throughout the scenario with specific furrows only watermelon being a sensitive crop.

Deficit irrigation (DI)'s emphasis increased mainly as a result of the study on the way to use water. Less than the total crop requirement of evapo-transpiration (ETc) for irrigation is applied, whereby crops withstand mild water stresses while retaining 85%-90% yield. Some researchers have shown that DI can increase irrigation water use efficiency (IWUE) while reducing water consumption, providing an invaluable resource for the areas where water is limited [6, 7].

This study assesses the combined effects of different furrow irrigation systems (CFI, AFI, FFI) with five levels of deficit irrigation (100%ETc, 85%ETc, 70%ETc, and 55%ETc) on garlic yields and water use efficiency in Tiyo District, Central Ethiopia. By it, the aim is to produce practicable recommendations for improving sustainability in water management and garlic production that can be applicable in other regions with similar water constraints.

Agriculture in Ethiopia is characterized by rain-fed systems, putting it at great risk for fluctuation in the amount of rainfall received. One reason for low efficiencies in water use is that there is little or no proper irrigation infrastructure, and dependence on surface irrigation is high, actually leading to water wastage and also low crop yields. Garlic is very sensitive to water stress when economically, most notably during the bulb formation stage. And the inefficiency of the irrigation systems, particularly with conventional surface furrow irrigation being used, negates this potential for the increased productivity of garlic in the region.

The question of planting crops without abandoning irrigation is of optimum use of water with regards to garlic yield. It is unfortunate that while furrow irrigation alternatives such as AFI and FFI are aimed at reducing water use, almost no research has been made on their combined effects with deficit irrigation strategies on garlic production in Ethiopia. Hence, the study shall assess the interactive effects of different furrow irrigation systems and DI levels on garlic yields and water use efficiency and thus develop recommendations on sustainable water management to such water-constrained watersheds.

2. Materials and Methods

2.1. Description of the Study Area

The Experiment was conducted at kulumsa Agricultural Research Center, which is 170 km far from Addis Ababa. Geographically, the center is situated between 8° 0" to 8o 2" N latitude and 39° 7" to 39° 10" E longitude at an altitude ranging from 1980 to 2230 masl (Figure 1) at east Arsi Zone Tiyo woreda.

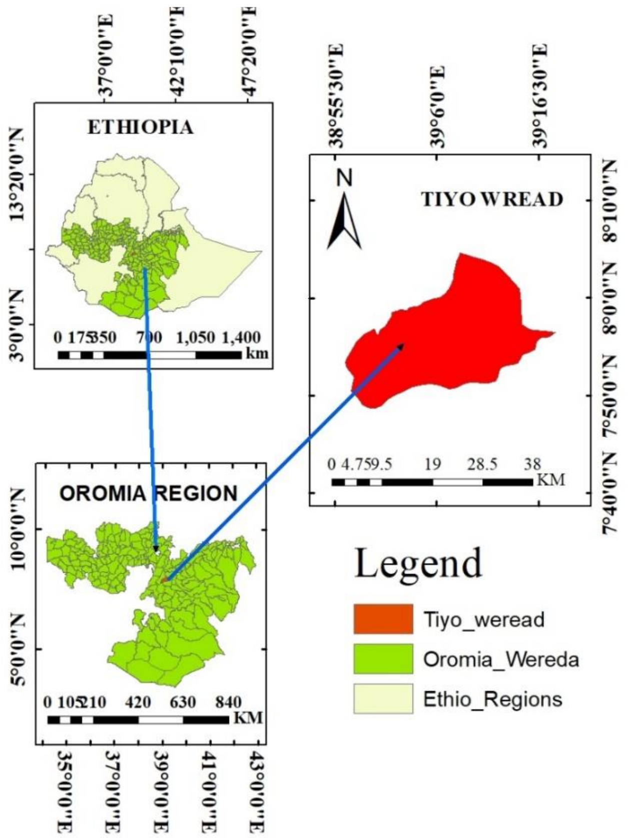

Figure 1. Location of the study site.

2.2. Treatments and Experimental Design

There are two factors in this experiment: furrow irrigation systems and levels of application of irrigation. Within the furrow irrigation systems were: a) Alternative Furrow Irrigation (AFI); b) Fixed Furrow Irrigation (FFI); and c) Conventional Furrow Irrigation (CFI). Within the irrigation levels were: 100%ETc; 85%ETc; 70%ETc; and 55%ETc. The combinations of these two factors are shown in Table 2, and the treatment combinations gave rise to a total of 12 treatments, as shown in Table 2. The experiment was laid in a factorial randomized complete block design (RCBD) with three replications (Table 1).

Their plots and replications were separated by a buffer zone of 2m for canals carrying no irrigation water and 2.5 m for supply canals carrying irrigation water supply primarily to eliminate the influence from lateral movement of water and 1m between plots.

Table 1. Treatment combinations.

Irrigation Level	Furrow Irrigation System		
	AFI	FFI	CFI
100%Etc	T1	T5	T9
85%Etc	T2	T6	T10
70%Etc	T3	T7	T11
55%Etc	T4	T8	T12

Table 2. Experimental treatments.

Treat ment	Designation	Description
T1	AFI100%ETc	Alternative furrow irrigation with 100%ETc
T2	AFI85%ETc	Alternative furrow irrigation with 85%ETc
T3	ALI70%ETc	Alternative furrow irrigation with 70%ETc
T4	ALF55%ETc	Alternative furrow irrigation with 55%ETc
T5	FFI100%ETc	Fixed furrow irrigation with 100%ETc
T6	FFI85%ETc	Fixed furrow irrigation with 85%ETc
T7	FFI70%ETc	Fixed furrow irrigation with 70%ETc
T8	FFI55%ETc	Fixed furrow irrigation with 55%ETc
T9	CFI100%ETc	Convectional furrow irrigation with 100%ETc
T10	CFI85%ETc	Conventional irrigation with 85%ETc
T11	CFI70%ETc	Conventional irrigation with 70%ETc
T12	CFI55%ETc	Conventional irrigation with 55%ETc

2.3. Agronomic Data Collection

Relevant agronomic data were recorded during the experiment period. Five randomly selected plants from the central three rows per plot excluding the border rows and border plants were taken as a sample. Plant height (cm), Leaf number, Leaf length (cm), Bulb height (cm), Bulb diameter (cm Marketable bulb yield, Unmarketable bulb yield (UMC), Total bulb yield (kg ha^{-1}), and Days to maturity.

2.4. Water Use Efficiency

Water use efficiency could be determined based on the ratio of yield of marketable yield to the crop depth of water and irrigation depth of water used from germination to harvest, according to the following formula.

$$\text{IWUE} = \frac{Y}{IWR} \text{ and } \text{CWUE} = \frac{Y}{CWR}$$

2.5. Statistical Analysis

The collected data were statistically analyzed appropriately for RCBD. When the data have shown statistical differences among treatments, mean separation was done using the least significant difference (LSD). The R statistical software was used for the analysis of variance. Correlation analysis was performed to obtain the correlation coefficients among the collected data.

3. Results and Discussion

3.1. Soil Sample Analysis

The results of soil sample analyses on soil physical and chemical properties are given in Table 3 and Table 4.

3.1.1. Soil Physical Characteristics

According to the laboratory study, the experimental plot's particle size distribution ranged between 32% and 69% for the clay content, 17% and 20% for the sand content, and 34% and 44% for the silt content (Table 3.). As a result, it is discovered that the soil textural classes are clay for soil depths of 20 to 40 cm and silty clay loam for soil depths of 0 to 20 cm and 40 to 60 cm. The experimental site's bulk density varied somewhat and got higher as depth climbed. With a mean bulk density of 1.19 gm/cm^3, the bulk density ranged from 1.13 to 1.26 gm/cm^3. With a mean value of 187.4 mm/m, the TAW fluctuated within a narrow range of 185.7 to 188.7 mm/m.

Table 3. *Soil physical properties of the experimental area.*

Soil depth (cm)	Soil moisture content		Bulk density (gm/cm^3)	TAW (mm/m)	Particle size distribution (%)			Textural class
	FC (%v)	PWP (%v)			Clay	Sand	Silt	
0 - 20	50.83	32.26	1.13	185.7	36.9	19.6	43.5	Silty clay loam
20 - 40	52.21	33.44	1.18	187.7	68.7	17.6	13.7	Clay
40 - 60	51.85	32.98	1.26	188.7	32.4	19.6	48.0	Silty clay loam
Mean	51.63	32.89	1.19	187.4	46.0	18.9	35.1	Clay

3.1.2. Soil Chemical and Water Quality Analysis

The pH of the soil in the experimental field was found to be almost neutral and to range very narrowly between 7.0 and 7.1. An essential metric for determining the acidity or alkalinity of soil is its pH, which expresses the concentration of hydrogen ions in the soil. A pH range of 6.0 to 8.0 is ideal for garlic growth [8]. Through a 60 cm soil profile, the soil exhibited a CEC of around 12.1 me/100gm of soil, indicating a poor fertility state. and a garlic threshold value of 1.2 dS/m, which is below the typical ECe of 0.27 dS/m [21]. The average values of the soil's OM and OC contents were 1.82% and 1.04%, respectively.

The laboratory results of the irrigation water quality indicate that the pH value was 7.5 and the ECw value was 0.69 dS m^{-1} (Table 4). According to [22], irrigation water is classified in terms of pH as low (below 7), slight to moderate (7-8), and severe (above 8). Based on this classification, the characteristic of the irrigation water in the study area was found slight to moderate (Table 4).

Bauder reported that irrigation water quality in terms of salinity hazard has four categories: ≤ 0.75 dS m^{-1} none; 0.76 - 1.5 dS m^{-1} some; 1.51 - 3.0 dS m^{-1} moderate and ≥3.0 dS m^{-1} severe [3]. Based on the above categories the irrigation water quality of the study area was classified as none.

Table 4. *The soil and water chemical analysis.*

Soil depth (cm)	pH	ECe (dS/m)	OC (%)	OM (%)	CEC (me/100gm)
0 - 20	7.1	0.28	1.2	2.1	14.6
20 - 40	7.1	0.25	1.1	1.89	11.8
40 - 60	7.0	0.29	0.9	1.6	9.8
Average	7.1	0.27	1.1	1.82	12.1
Irrigation water	7.5	0.69			

3.2. Garlic Water and Irrigation Water Requirements

The daily ETo was generated using CROPWAT 8.0 for windows using the Kc values as derived below (Allen et al., 1998), based on the daily weather data acquired from the Kulumsa meteorological station throughout the growth season from February 23 to July 15, 2022. It was discovered that the seasonal crop water needs were 374.35 mm and the irrigation water requirements were 298.5 mm, respectively.

Table 5. displays the net and gross depths of water required for the treatments under full irrigation. Table 5. displays the gross depth of irrigation applied for each treatment during the growth season. The gross irrigation need applied under each treatment ranged from 135.45 to 497.52 mm per season, based on a 60% irrigation application efficiency. Under was the least amount of gross irrigation water applied. irrigation water was delivered. And hence, the least water used to produce the garlic yield from AFI and FFI treatments was 135.45 mm.

Table 5. *Crop water and irrigation water requirements for the control treatment.*

Date	ETc (mm)	RF (mm)	Effective rainfall (mm)	NIR (mm)	GIR (mm)
26-Feb		3.9	2		
8-Mar	26.24			31.1	51.8
18-Mar		49	29.1		
19-Mar		4.7	2.5		
20-Mar		18	10.5		
23-Mar		9.8	5.6		
6-Apr	84.34			40.54	67.57
12-Apr		4.5	2.37		
13-Apr		25.3	14.85		
15-Apr		3.5	1.77		
16-Apr		2.3	1.05		
17-Apr		0.3	0		
23-Apr		3.9	2.01		
24-Apr		3.3	1.65		
25-Apr		4.5	2.37		
26-Apr		0.2	0		
30-Apr	82.33			44.78	74.6
5-May	43.56			44.78	74.6
13-May	44.62			44.78	74.6
22-May	44.82			44.78	74.6
3-Jun	48.43			47.78	79.6
Total	374.35	133.2	75.77	298.5	497.5

Table 6. *Depth of irrigation water application (mm).*

Date	AFI/FFI 100%ETc	AFI/FFI 85%ETc	AFI/FFI 70%ETc	AFI/FFI 55%ETc	CFI 100%ETc	CFI 85%ETc	CFI 70%ETc	CFI 55%ETc
8-March	25.90	22.01	18.13	14.24	51.80	44.03	36.26	28.49
6-April	33.79	28.72	23.65	18.58	67.57	57.44	47.30	37.17
30-April	37.32	31.72	26.12	20.52	74.63	63.44	52.24	41.05
5-May	37.32	31.72	26.12	20.52	74.63	63.44	52.24	41.05
13-May	37.32	31.72	26.12	20.52	74.63	63.44	52.24	41.05
22-May	37.32	31.72	26.12	20.52	74.63	63.44	52.24	41.05
3-June	37.32	31.72	26.12	20.52	79.63	63.44	52.24	41.05
Total	246.27	209.33	172.39	135.45	497.52	418.65	344.77	270.89

3.3. Growth Parameters: Plant Height, and Leaf Length

Plant Height

It was revealed by the analysis of variance that a very significant difference (P<0.05) exists among the different irrigation systems and irrigation levels applied on plant heights (Table 7). The maximum plant height of 50.53 cm was obtained from CFI with 100%ETc application, and it showed no significant difference with CFI85%ETc and CFI70%ETc applications. Among the deficit irrigation regimes, the application of 85%ETc provided the tallest plant among the deficit irrigations, and it shows no significant difference against CFI70%ETc, AFI100%ETc, and FFI100%ETc applications conjunctively.

Garlic plants irrigated under Alternate Furrow Irrigation (AFI) obtained a significantly greater plant height than that of those irrigated through Conventional Furrow Irrigation (CFI) and Fixed Furrow Irrigation (FFI). The improved plant height under AFI is likely due to its ability to maintain the requisite soil moisture and reduce waterlogging, thus acting favorably towards root and shoot development [2].

Leaf Length

Application of furrow irrigation systems and deficit irrigation levels had significant (P<0.05) effects on garlic leaf length. A negative trend in leaf length was observed with decreasing irrigation levels. CFI55%ETc produced the longest leaf at 44.27cm and was not statistically different from CFI100%ETc, CFI85%ETc, and FFI85%ETc treatments (Table 7). The lowest leaf length of 36.73cm was observed with the deficit irrigation level of 70%ETc under FFI, and it was statistically similar to FFI55%ETc, FFI100%ETc, and with all other deficit irrigation treatments under AFI and CFI70%ETc treatments.

The leaf length followed a similar trend, AFI treatments having longer leaf lengths than CFI and FFI. Alternating dry and wet furrows under AFI might have improved root activity and nutrient uptake, thus leading to better vegetative growth [9, 10].

FFI consistently produced a lower plant height and leaf length compared to CFI which produced medium ones-the reason being uniform water application pressure. Reduced water supply in the FFI treatments probably led to stress, which limited photosynthesis and vegetative growth.

3.4. Yield Parameters: Bulb Yield, Bulb Diameter, and Weight Bulb

Bulb yield,

The analysis of variance revealed that the total bulb yield of garlic was significantly affected (p<0.05) by the furrow irrigation systems and irrigation levels (Table 7). The control treatment produced the highest yield of 98.62 qt/ha, which was significantly higher than any other treatment. Among the deficit irrigation applications, CFI85%ETc yielded the highest total bulb yield of 82.68 qt/ha but did not differ significantly from the CFI70%ETc and AFI100%ETc applications. The lowest bulb yield was recorded at 42.75 qt/ha [6, 7].

Nevertheless, AFI100%ETc achieved nearly equivalent yields while using less water, emphasizing that it has a possibility for improving water use efficiency without significant yield loss [1, 2] On the other hand, FFI55%ETc had the lowest yield owing to inadequate and uneven water distribution.

Bulb Diameter

The bulb size was measured to assess the quality of garlic. Variance analysis has shown that the furrow irrigation system and the irrigation levels significantly (P < 0.05) influenced bulb diameter (Table 7). Maximum bulb diameter recorded was 48.73 mm, which came from CFI 100% ETc application, and was not significantly different from CFI at 85% ETc and 70% ETc; AFI at 100% ETc, 85% ETc, and 70% ETc; and FFI at 100% ETc applications. However, the smallest bulb diameter of 40.67 mm was recorded from FFI and shows no differences with FFI at 85% ETc and 55% ETc; AFI at 55% ETc and 70% ETc; and CFI at 55% ETc and 70% ETc applications.

This agrees with the recommendations given by Bayu Enchalew et al. (2016) and by Yemane Mebrahtu et al. (2018) stating the larger plant photosynthetic areas such as plant height and leaf number due to elevated irrigation levels led to increased assimilate partitioning to the bulbs, hence an increase in bulb diameter. The findings are also consistent with that of Kannan Narayanan and Mulugeta Mohammed Seid, (2015) who stated that the highest water application plots were producing harvests with the highest percentage of larger bulbs while those with limited water supply produced smaller bulbs. Further, Gebeyehu Tegenu et al. (2019) asserted that bulb diameter increased with the amount of water applied in irrigation. In the same manner, this indicates that transpiration and rates of photosynthesis and growth were stalled by water stress, since the stressed plants produced bulbs of smaller sizes. A study conducted by [20] also confirmed the bulb diameter to have a growing tendency with increasing levels of irrigation application.

Bulb weight

Bulb weight from treatments with furrow irrigation systems and irrigation levels was not significantly affected (Table 4) according to the analysis of variance. The highest bulb weight (43.13gm) was recorded from the application of CFI100%ETc (Table 7). Bulb weights from CFI85%ETc, and CFI70ETc, AFI100%ETc, and AFI85%ETc, and FFI100%Etc were better than or around equal to the average bulb weights of the treatments. The lowest average bulb weight of 30.2mm was recorded from the application of FFI55%etc, while the bulb weight obtained from the application of AFI55%Ec was found to be within a narrow range, the minimum weight recorded in the application of FFI55%etc.

In the same way, [19] observed significant increase in average bulb weight at 120%ETc irrigation levels. Average bulb weight responded to irrigation water increment. This increment in bulb weight was probably caused by taller plants represented by a significant increase in the number of leaves for the better synthesis and transportation of assimilates sourced into the sinks [10, 23].

Further indicated by the large bulb weights and diameters of the former treatments that maintained adequate soil moisture during critical growth increments, including bulb initiation and development, those phases are especially at risk from water stress [9, 10].

Table 7. Effect of furrow irrigation system and irrigation level on garlic plant growth and yield parameter.

Treatments	LL (cm)	Plant height (cm)	BD (mm)	WB (gm)	BY (Kg/ha)
CF100%ETc	43.20[ab]	50.53[a]	48.731[a]	43.1	9862.4[a]
CFI85%ETc	42.13[abc]	48.47[ab]	46.13[abcd]	41.3	8268.1[b]
CFI70%ETc	39.73[bcd]	48.07[ab]	44.20[abcde]	40.8	7647.3[b]
CFI55%ETc	44.27[a]	44.07[cdef]	43.33[bcde]	36.0	5530.9[d]
AFI100%ETc	38.60[cd]	46.53[bcd]	47.93[ab]	40.1	7125.2[bc]
AFI85%ETc	38.87[cd]	43.07[ef]	46.00[abcd]	39.9	5686.1[cd]
AFI70%ETc	37.20[d]	42.27[ef]	44.33[abcde]	32.7	5488.5[d]
AFI55%ETc	36.33[d]	41.27[ef]	42.73[cde]	31.1	4289.2[d]
FFI100%ETc	39.67[bcd]	47.20[bc]	47.40[abc]	39.9	5516.8[d]
FFI85%ETc	41.93[abc]	44.53[cde]	42.67[cde]	34.9	4797.2[d]
FFI70%ETc	36.73[d]	43.33[def]	40.67[e]	33.4	4557.3[d]
FFI55%ETc	39.67[bcd]	40.80[f]	42.00[de]	30.2	4275.1[d]
Mean	39.86	45.01	44.68	36.9	6087.01
CV	6.34	4.32	6.61	18.04	14.59
LSD (0.05)	4.28	3.29	5.00	NS	1504.1

NB: Figures carrying the same letters are not significantly different from each other

3.5. Water Use Efficiency

Efficient use of water is a critical consideration in regions with limited water resources. This study evaluated water use efficiency (WUE) through Crop Water Use Efficiency (CWUE) and Irrigation Water Use Efficiency (IWUE) metrics.

3.5.1. Irrigation Water Use Efficiency (IWUE)

In short, the analysis of variance indicated that furrow irrigation systems and irrigation levels of deficit had a significant ($P<0.05$) impact on IWUE as shown in Table 8. The highest IWUE recorded under AFI with 70%ETc irrigation application reaches the maximum of 31.52kg mm-1, which shows no significant difference with AFI100%ETc, AFI85%ETc, AFI55%ETc, FFI70%ETc, or FFI55%ETc. Among these deficits, it comes out that AFI100%ETc gave the best garlic yields of 71.25 qt/ha and saved 50% of the required irrigation water. Thus, for garlic in the Kulumsa climate, the IWUE of 28.64 kg mm-1 is high efficiency.

These findings were reflected in their conclusions by [23] that AFI improved crop water use efficiency for the crop under study. In AFI, some furrows are irrigated and adjacent furrows are not, while the WUE comes up by reduced evaporation from the soil surface, the use of such irrigation systems results in a bonus of having lower yields despite having higher WUE [14]. When there was not sufficient water to fully irrigate, the yields of garlic under AFI were superior to those which were fully cut off.

In general, IWUE was affected by crop yield potential, irrigation method, estimation and measurement of ET, and crop environment. It was reported [11, 23] that irrigation water could be conserved while maintaining yields under limited water conditions as this crop is sensitive to drought stress.

The lowest irrigation water use efficiency of 19.55kg mm-1 was recorded under CFI practice with 85%ETc deficit irrigation application, which did not show a significant difference from the control (100%ETc) irrigation application, CFI70%ETc, CFI55%ETc, FFI100%ETc, or FFI85%ETc applications.

3.5.2. Crop Water Use Efficiency (CWUE)

The variance analysis of variance has indicated that the furrow irrigation systems and deficit irrigation levels had a significant effect on CWUE at P<0.05. The highest CWUE of 26.35kg mm-1 as shown in Table 8. was achieved under CFI with 100%ETc irrigation applications and had a significant difference from all other efficiencies. Among the deficit irrigation, CFI with 85%ETc application gave the highest CWUE of 22.09kg mm-1 and shows no significant differences with CFI70%ETc and AFI100%ETc applications. The water saved from the CFI70%ETc application was only one-third of the CWR and the yield reduction from the AFI85%ETc application was about 6 quintals. In contrast, the water saved under AFI is 50% and the yield reduction from the CFI85%ETc application is over 11 quintals. Hence, considering CWUE of 19.03 kg mm-1it can be observed that with 50% water saved and half of the yield obtained under AFI (71.25 q/ha) could be produced. Similarly, it can be observed that an IWUE of 28.64 kg mm-1 will be considered optimal.

These results are in harmony with the findings of [13, 15] who reported that the lower reduction in the yield of AFI and higher CWUE could be due to the better distribution of its roots on both sides from the ridge, which can increase water and fertilizer uptake by plants. The results showed that alternative drying of the root zone outperformed the fixed drying of the root zone. Results showed that AFI increased CWUE for garlic relative to CFI. This result agreed with [14, 16], who reported that deficit irrigations increased the water use efficiency of crops. Equally, [16-18] showed that crop water use efficiency is higher at lower levels of available soil moisture.

Table 8. *Effect of furrow irrigation and irrigation level on garlic water use efficiency.*

Treatment	Bulb yield (Kg/ha)	CWR (mm)	IWR (mm)	CWUE (Kg/mm)	IWUE (Kg/mm)
CF100%ETc	9862.4^{a}	374.35	497.52	26.35^{a}	19.82^{c}
CFI85%ETc	8268.1^{b}	374.35	418.65	22.09^{b}	19.55^{c}
CFI70%ETc	7647.3^{b}	374.35	344.77	20.43^{b}	21.96^{bc}
CFI55%ETc	5530.9^{d}	374.35	270.89	14.76^{d}	20.21^{c}
AFI100%ETc	7125.2^{bc}	374.35	246.27	19.03^{bc}	28.64^{a}
AFI85%ETc	5686.1^{cd}	374.35	209.33	15.19^{cd}	26.89^{ab}
AFI70%ETc	5488.5^{d}	374.35	172.39	14.66^{d}	31.52^{a}
AFI55%ETc	4289.2^{d}	374.35	135.45	11.46^{d}	31.35^{a}
FFI100%ETc	5516.8^{d}	374.35	246.27	14.74^{d}	22.18^{bc}
FFI85%ETc	4797.2^{d}	374.35	209.33	12.82^{d}	22.69^{bc}
FFI70%ETc	4557.3^{d}	374.35	172.39	12.17^{d}	26.17^{ab}
FFI55%ETc	4275.1^{d}	374.35	135.45	11.42^{d}	31.25^{a}
Mean	6087.01	374.35	254.89	16.26	25.19
CV	14.59			14.59	13.87
LSD (P = 0.05)	1504.1	NS	NS	4.018	5.917

NB: Figures carrying the same letters are not significantly different from each other

4. Summary

Efficient water management is critical for garlic production, particularly in semi-arid regions like Ethiopia. This study evaluated the effects of furrow irrigation systems (CFI, AFI, FFI) and deficit irrigation levels (100%ETc, 85%ETc, 70%ETc, and 55%ETc) on garlic growth, yield, and water use efficiency.

Key Findings:

1) *AFI* consistently outperformed other systems in WUE metrics, with the highest IWUE observed at *AFI70%ETc*.
2) *CFI100%ETc* achieved the highest garlic bulb yield, while AFI provided the best balance of yield and water savings.

3) *FFI* showed poor performance due to uneven water application, highlighting its limitations in water-scarce regions.

These findings demonstrate that adopting AFI with moderate deficit irrigation can significantly enhance garlic production while conserving water resources. Such strategies are essential for achieving sustainable agriculture in Ethiopia.

5. Conclusion

This study highlights the potential of improved furrow irrigation systems and deficit irrigation strategies for sustainable garlic production in Ethiopia. The main findings are:

1) *Alternate Furrow Irrigation (AFI)* demonstrated superior performance in water use efficiency (WUE) and yield stability, particularly under 100%ETc and 85%ETc treatments.
2) While *CFI100%ETc* achieved the highest garlic yield, *AFI100%ETc* provided comparable yields with significantly less water usage.
3) *FFI* underperformed in most parameters due to uneven water distribution and inadequate soil moisture in dry furrows.

These results confirm that AFI and moderate deficit irrigation strategies offer practical solutions for improving garlic production in water-scarce regions, ensuring sustainability without significant yield losses.

6. Recommendations

Based on the study findings, the following recommendations are proposed:

1) Adopt Alternate Furrow Irrigation (AFI100%ETc):

AFI systems are highly effective in improving water use efficiency while maintaining stable yields. Farmers in water-scarce regions should prioritize this system to optimize irrigation practices.

2) Invest in Farmer Training:

Training programs should be implemented to educate farmers on the benefits of AFI and deficit irrigation strategies. These programs should also teach proper scheduling and monitoring of irrigation.

3) Expand Research to Other Crops:

Similar studies should be conducted for other water-sensitive crops to generalize the benefits of these systems across various agricultural practices.

Abbreviations

AFI	Alternative Furrow Irrigation
CFI	Conventional Furrow Irrigation
FFI	Fixed Furrow Irrigation
WUE	Water Use Efficiency
IWUC	Irrigation Water Use Efficiency
CWUE	Crop Water Use Efficiency
DI	Deficit Irrigation

Author Contributions

Abu Dedo Ilmi is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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