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The role of Deficit Irrigation in Enhancing Water Use Efficiency in garlic (*Allium sativum*) Production, Central Ethiopia's Tiyo District

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ABSTRACT

Water scarcity poses a growing threat to agricultural productivity in arid and semi-arid regions like Central Ethiopia. This study evaluated the role of deficit irrigation (DI) and furrow irrigation systems in enhancing water use efficiency (WUE) and maintaining garlic (Allium sativum L.) yield under limited water conditions. A field experiment was conducted in the Tiyo District, comparing four irrigation levels (100%, 85%, 70%, and 55% of crop evapotranspiration, ETc) across three furrow irrigation systems: conventional (CFI), alternate (AFI), and fixed (FFI). The study followed a randomized complete block design with 12 treatments replicated three times. Results revealed that the highest yield (9862.4 kg/ha) was achieved under CFI100%ETc, while the highest irrigation water use efficiency (28.64 kg/mm) was recorded under AFI100%ETc. Moderate deficit irrigation (85% and 70% ETc) under AFI significantly improved both crop water productivity and water savings without a statistically significant yield loss. These findings demonstrate that AFI combined with moderate DI can optimize water use and sustain garlic production in water-scarce areas. The study provides evidence-based recommendations for improving irrigation practices to enhance agricultural productivity and resilience in regions experiencing water stress.

Keywords: Deficit Irrigation; Water Use Efficiency; Alternate Furrow Irrigation; Fixed Furrow Irrigation; Conventional Furrow Irrigation; Irrigation Scheduling; Crop Water Productivity; Garlic (*Allium sativum* L.); Water Conservation; Tiyo District; Central Ethiopia; Sustainable Agriculture.

1. Introduction

Water scarcity is a major problem for agriculture, especially in arid and semi-arid areas. There are not many water resources here, and competition for them is growing. In this instance, freshwater resources are under pressure due to population expansion, climate change, and growing industrial and urban needs, necessitating creative approaches to water management (FAO, 2021). Since agriculture uses around 70% of the world's freshwater resources, it is crucial to use water efficiently (Molden et al., 2010). A practical method to maximize water use and improve water production is deficit irrigation (DI), in which crops receive water below their full evapotranspiration (ETc) requirements (Fereres & Soriano, 2007).

Because of its shallow root system, the economically significant crop garlic (*Allium sativum* L.) is extremely vulnerable to water stress. To get the best yields and quality, the crop needs precise irrigation management, especially throughout its crucial growth stages (Kebede et al., 2018). In garlic production, effective irrigation is essential since water stress during bulb formation can drastically diminish bulb size and marketability. As a subsistence crop and a source of revenue from both domestic and international markets, garlic is essential to smallholder farmers' lives in Ethiopia (CSA, 2020).

In areas with limited water resources, like Ethiopia's Tiyo District, traditional irrigation techniques frequently lose a lot of water due to evaporation, runoff, and deep percolation. Ayele et al. (2020) believe that improved irrigation techniques, such as AFI and FFI, are viable choices for increasing WUE by lowering needless losses. When DI is integrated with those systems, further water-use optimization ensures sustainable production even in the majority of water-scarce scenarios.

One of the biggest problems Ethiopian agriculture faces is water scarcity. The nation's agriculture sector, which employs over 80% of the workforce and accounts for over 40% of the GDP, is mostly rain-fed and susceptible to unpredictable and unequal rainfall distribution (FAO, 2019). Irrigation is crucial for stabilizing agricultural production and enhancing food security in response to these issues. However, the use of surface irrigation, particularly furrow irrigation, has been linked to low water use efficiency due to inadequate management techniques, resulting in water waste and environmental issues such as salinization and waterlogging (MoA, 2021).

One of Ethiopia's high-value crops that is extremely vulnerable to water stress is garlic. This can lead to a significant yield drop if improperly handled. According to Kebede et al. (2018), farmers typically use the classic furrow irrigation method, which results in excessive water use and waste. It has been suggested that AFI and FFI enhance furrow irrigation techniques. By alternating water application between furrows or limiting irrigation to a single furrow for the duration of the season, respectively, these techniques conserve water (Ayele et al. (2020)).

Deficit irrigation is another potential strategy that increases irrigation water use efficiency without causing a substantial yield loss by enabling crops to withstand mild water stress. DI is a useful tactic in water-scarce areas since studies have demonstrated that it can significantly increase WUE and lower water consumption (Geerts & Raes, 2009). The combined impacts of DI and enhanced furrow irrigation systems on Ethiopian garlic yield and WUE, however, are not well supported by empirical data.

By evaluating the performance of CFI, AFI, and FFI at four distinct DI levels—100% ETc, 85% ETc, 70% ETc, and 55% ETc—this study will close this gap. The findings will provide useful recommendations for optimizing irrigation to boost garlic output in areas with limited water resources, improving water management and boosting agricultural productivity.

1.1. Objective of the study

To evaluate the effects of different deficit irrigation (DI) levels and furrow irrigation systems on garlic (*Allium sativum* L.) yield and water use efficiency (WUE) under field conditions in the Tiyo District of Central Ethiopia.

1) To determine the impact of various DI levels (100%, 85%, 70%, and 55% ETc) on garlic yield.

2) To assess the performance of three furrow irrigation systems—conventional furrow irrigation (CFI), alternate furrow irrigation (AFI), and fixed furrow irrigation (FFI)—about crop yield and WUE.

3) To identify the most efficient combination of irrigation method and water level that optimizes water productivity without significantly reducing garlic yield.

4) To provide practical recommendations for sustainable water management in garlic production under semi-arid conditions

░ 2. Materials and Methods

2.1. Study Area

The study region was in Central Ethiopia, namely in the Tiyo District. The region has a semi-arid climate with an average of 820 mm of rainfall per year, the most of which occurs from July to September. Temperatures in the district range from 7.7°C in December to 25°C in March, and the rainfall pattern is unimodal. The region's topography ranges from 1,980 to 2,230 meters above sea level, and it is primarily flat to moderately undulating. It is advised to grow garlic on clay loam soils with a good water-holding capacity and moderate fertility (MoA, 2021).

Surface water bodies and seasonal streams provide the study area's irrigation water. Most farmers use furrow irrigation, which is quite inexpensive, although often has low water use efficiency (WUE) because of poor management (Ayele et al., 2020).

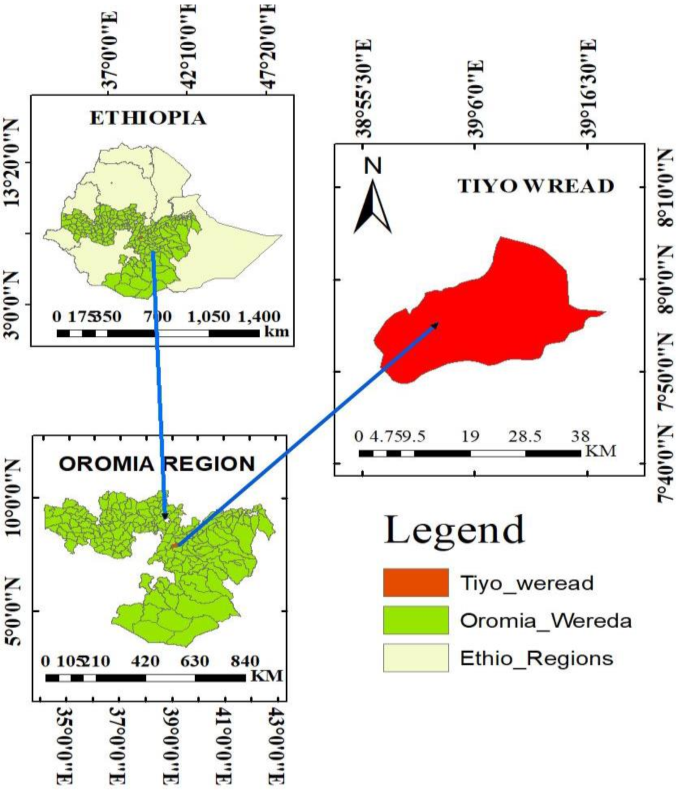

Figure 1. Study area map

2.2. Experimental Design

The experiment was laid out as a factorial experiment in a Randomized Complete Block Design (RCBD) with three replications to minimize variability in soil and environmental conditions. The factors under investigation were:

Furrow Irrigation Systems: Conventional Furrow Irrigation (CFI): Every furrow is irrigated during each irrigation event. Alternate Furrow Irrigation (AFI): Water is applied to alternating furrows, allowing one side to remain dry during each irrigation cycle. Fixed Furrow Irrigation (FFI): Water is consistently applied to specific furrows throughout the growing season.

Deficit Irrigation Levels: 100% ETc: Full irrigation based on crop water requirements; 85% ETc: Moderate deficit irrigation, applying 85% of the crop water requirement; 70% ETc: Severe deficit irrigation, applying 70% of the crop water requirement; and 55% ETc: Extreme deficit irrigation, applying 55% of the crop water requirement.

The treatment combinations resulted in 12 distinct treatments (3 irrigation systems × 4 irrigation levels), as shown in Table 1.

Table 1. Treatment, irrigation, and deficit level

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

2.3. Agronomic Practices

The experimental plots were prepared by plowing and leveling. Garlic cloves were planted in double rows within each furrow, with a spacing of 10 cm between plants and 45 cm between rows. Fertilizer application was uniform across all plots, using 150 kg/ha of urea and 200 kg/ha of DAP, based on local recommendations (Kebede et al., 2018).

2.4. Irrigation Scheduling and Application

Irrigation water was applied based on the crop's water requirements, calculated using the CROPWAT model (FAO, 2019). The net irrigation requirement (NIR) was determined using Equation 1:

$$NIR = ETc - Pe \qquad \ldots(1)$$

Where:

ETc = Crop evapotranspiration (mm/day).

Pe = Effective rainfall (mm).

The gross irrigation requirement (GIR) was calculated considering a field application efficiency of 60% using Equation 2:

$$GIR = NIR/Ea \qquad \ldots(2)$$

Where:

Ea = Application efficiency (%).

A Parshall flume was used to measure and control the flow rate of irrigation water into each plot, ensuring accurate water application (Allen et al., 1998).

2.5. Data Collection

Data collection focused on soil moisture, crop growth parameters, yield, and water use efficiency (WUE):

Soil Moisture Monitoring: Soil moisture was monitored before and after each irrigation event using gravimetric methods. Samples were taken at depths of 0-20 cm, 20-40 cm, and 40-60 cm from each plot.

Crop Growth Parameters: Five plants per plot were randomly selected for measurements, including plant height, leaf number, and bulb diameter.

Yield: Garlic bulbs were harvested, weighed, and categorized into marketable and unmarketable yields. Total yield per hectare was calculated based on the net plot area.

Water Use Efficiency (WUE):

WUE was calculated using Equation 3:

$IWUE = Yield\ (kg/ha)\ /IWR\ (mm)$ And $CWUE = yield/ETc(mm)$ …(3)

3. Results and Discussion

3.1. Yield Response Factor to Deficit Irrigation

Garlic yield was significantly different among the various deficit irrigation (DI) levels and furrow irrigation systems, indicating the sensitivity of this crop to available water. From the deficit irrigation, the highest yield (82.68 q/ha) was obtained under CFI85%ETc. This indicates that a certain level of reduction in the supply of water (15% below full irrigation) did not result in any yield loss. This could be attributed to better utilization of the available water and lower losses by deep percolation (Fereres & Soriano, 2007).

The AFI100%ETc and AFI85%ETc treatments also attained high yields with less water applied. The ability of Alternate Furrow Irrigation (AFI) to sustain high yields while saving water can be attributed to how the alternating phases of wetting and drying induce deeper roots, thereby increasing water extraction efficiency from a specified soil profile (Geerts & Raes, 2009). On the other hand, the lowest yields were obtained under the FFI55%ETc treatment, indicating the limitation of FFI when combined with severe water stress.

Table 2. Garlic yields a response factor to water

Treatment	Eta (mm ha^{-1})	ETm (mm ha^{-1})	Ya (kg ha^{-1})	Ym (kg ha^{-1})	Ya/Ym	ETa/ETm	Ky
CF100%ETc	374.3	374.3	9862.4	9862.4	1	1	-
CFI85%ETc	318.2	374.3	8268.1	9862.4	0.8	0.9	1.1
CFI70%ETc	262.0	374.3	7647.3	9862.4	0.8	0.7	0.7
CFI55%ETc	205.9	374.3	5530.9	9862.4	0.6	0.6	1.0
AFI100%ETc	187.2	374.3	7125.2	9862.4	0.7	0.5	0.6
AFI85%ETc	159.1	374.3	5686.1	9862.4	0.6	0.4	0.7
AFI70%ETc	131.0	374.3	5488.5	9862.4	0.6	0.4	0.7
AFI55%ETc	93.6	374.3	4289.2	9862.4	0.4	0.3	0.8

FFI100%ETc	187.2	374.3	5516.8	9862.4	0.6	0.5	0.9
FFI85%ETc	159.1	374.3	4797.2	9862.4	0.5	0.4	0.9
FFI70%ETc	131.0	374.3	4557.3	9862.4	0.5	0.4	0.8
FFI55%ETc	93.6	374.3	4275.1	9862.4	0.4	0.3	0.8

NB: ETa = actual ETc, ETm = measured, Ya = actual yield, Ym = measured, and Ky = response factor.

3.2. Water Use Efficiency and Irrigation Levels

3.2.1. Irrigation Water Use Efficiency (IWUE)

The highest IWUE (28.64 kg/mm) was under the treatment of AFI100%ETc. This will justify that AFI optimizes water use by application of water to alternating furrows, which reduces loss through evaporation and runoff (Ayele et al., 2020). Reduced water application under AFI treatments increases IWUE without sacrificing yield; hence, it would be an ideal strategy in water-scarce regions.

3.2.2. Crop Water Use Efficiency (CWUE)

CWUE improved in all DI treatments, with the highest values recorded in AFI and FFI systems. This is evidence that DI enhances the ability of the crop to convert water into biomass and economic yield. For instance, applications of 85% ETc and 70% ETc under AFI resulted in a higher CWUE, indicating better use of available water resources (Molden et al., 2010).

Results: Moderate levels of DI, namely 85% ETc and 70% ETc, were found to be effective in improving both IWUE and CWUE in the trade-off between water conservation and crop productivity.

3.3. Relative Yield Reduction and Water Saving

At the DI levels of 85% ETc and 70% ETc, relative yield reduction was almost negligible compared to the fully irrigated treatment (100% ETc). The yield reductions under these moderate deficit levels were statistically nonsignificant, indicating that the garlic could tolerate some water stress without much reduction in yield (Kebede et al., 2018).

The significant water savings achieved under these treatments highlight the potential of DI to optimize water use in regions where water is a limiting factor. For instance, applying 85% ETc saved 15% of water, which could be allocated to irrigating additional land or stored for future use. These findings align with previous studies suggesting that DI can enhance water productivity in water-scarce regions (Geerts & Raes, 2009)

Table 3. Irrigation level on garlic water use efficiency

Treatment	Bulb yield (Kg/ha)	CWR (mm)	IWR (mm)	CWUE (Kg/mm)	IWUE (Kg/mm)
CF100%ETc	9862.4a	374.35	497.52	26.35a	19.82c
CFI85%ETc	8268.1b	374.35	418.65	22.09b	19.55c
CFI70%ETc	7647.3b	374.35	344.77	20.43b	21.96bc
CFI55%ETc	5530.9d	374.35	270.89	14.76d	20.21c

AFI100%ETc	7125.2bc	374.35	246.27	19.03bc	28.64a
AFI85%ETc	5686.1cd	374.35	209.33	15.19cd	26.89ab
AFI70%ETc	5488.5d	374.35	172.39	14.66d	31.52a
AFI55%ETc	4289.2d	374.35	135.45	11.46d	31.35a
FFI100%ETc	5516.8d	374.35	246.27	14.74d	22.18bc
FFI85%ETc	4797.2d	374.35	209.33	12.82d	22.69 bc
FFI70%ETc	4557.3d	374.35	172.39	12.17d	26.17ab
FFI55%ETc	4275.1d	374.35	135.45	11.42d	31.25a
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.

3.4. Correlation between WUE and Irrigation Levels

It has been found that CWUE had a strong positive relation with irrigation levels, mainly at 85%ETc and 70%ETc, with great increases of CWUE under the moderate deficit irrigation treatments. The results thus show that moderate water stress may improve the ability of garlic to use water efficiently to produce biomass, resulting in a higher yield per unit of water applied. Alternating between flooding and drought conditions, such as in the case of AFI, helps with better water uptake and growth of roots for improved WUE outcomes (Ayele et al., 2020).

Data analysis in Table 1 indicated that CWUE has a positive and significant correlation with bulb yield (r = 0.67***), plant height (r = 0.67***), and IWR (r = 0.83***). This suggests that efficient irrigation management is the key to optimized crop performance and water use. Otherwise, there was a strongly negative correlation between IWUE and irrigation levels (r = -0.616***), indicating that greater water inputs decreased irrigation efficiency.

Bulb Yield and CWUE: A strong positive correlation between CWUE and bulb yield was recorded (r = 0.67***), underlining that moderate DI levels, 85%ETc and 70%ETc, optimized garlic yield per unit of water consumed.

Growth Parameters and Yield: The results show strong, significant correlations in plant height (r = 0.67***), leaf width (LW) (r = 0.58***), and bulb diameter (BD) (r = 0.36*) with final yield, explaining that growth metrics determine yield.

IWR and IWUE: While IWR showed a strong positive relationship with most growth parameters, IWUE had a strong negative correlation with increasing irrigation levels, indicating diminished efficiency with higher water inputs.

These results emphasize the importance of applying deficit irrigation (DI) at moderate levels to improve resource use efficiency without compromising yield. The findings are consistent with previous studies that propose careful water management through DI and efficient application systems, such as AFI, as a way to sustain crop productivity in water-scarce regions (Geerts & Raes, 2009).

Table 4. Correlation between Growth, Yield, and Yield Components

	Plant height (cm)	NLP (Number)	LL (cm)	LW (cm)	pdstm (cm)	ND (cm)	BD (cm)	BL (cm)	GNo (Number)	WSB (gm)
Plant height (cm)	1***	0.498**	0.474**	0.457**	0.588***	0.46**	0.419*	0.385*	0.426**	0.445**
NLP (Number)		1	0.44**	0.29NS	0.31NS	0.26NS	0.38*	0.52**	0.39*	0.53***
LL (cm)			1***	0.07NS	0.36*	0.36*	0.259NS	0.14NS	0.35*	0.31NS
LW (cm)				1***	0.43**	0.50**	0.42*	0.54***	-0.01	0.50**
pdstm (cm)					1***	0.25NS	0.20NS	0.20NS	0.13NS	0.12NS
ND (cm)						1***	0.36*	0.47**	0.28NS	0.44**
BD (cm)							1***	0.50**	0.27NS	0.57***
BL (cm)								1***	0.18NS	0.48**
GNo (Number)									1***	0.49**
WSB (gm)										1***
WGLO (gm)										
Bulb yield (q/ha)										
Bulb yield (kg/ha)										
CWR (mm)										
IWR (mm)										
CWUE (Kg/mm)										
IWUE (Kg/mm)										

IWUE (Kg/mm)	CWUE (Kg/mm)	IWR (mm)	CWR (mm)	Bulb yield (kg/ha)	Bulb yield (q/ha)	WGLO (gm)
-0.549***	0.67***	0.817***	0.0 NS	0.67***	0.67***	0.163NS
-0.24 NS	0.52**	0.45*	0NS	0.52**	0.52**	0.01NS
-0.45**	0.36*	0.52**	0.0 NS	0.36*	0.36*	0.11NS
-0.14 NS	0.58***	0.58***	0.0 NS	0.58***	0.58***	0.55***
-0.23	0.47 **	0.47**	0.0 NS	0.47**	0.47**	0.1 NS
-0.39*	0.33NS	0.53***	0.0 NS	0.33NS	0.32NS	0.60***
-0.30 NS	0.36*	0.46**	0.0 NS	0.36*	0.36*	0.30NS
-0.11 NS	0.48**	0.44**	0.0 NS	0.48**	0.48**	0.34*
-0.26 NS	0.4 *	0.39*	0.0 NS	0.4*	0.4*	0.08NS
-0.27 NS	0.56***	0.53**	0.0 NS	0.56***	0.56***	0.46**
-0.14 NS	0.28NS	0.32NS	0.0 NS	0.28NS	0.28NS	1***
-0.12 NS	1***	0.83***	0.0 NS	1***	1***	
-0.12 NS	1***	0.83***	0.0 NS	1***		
0 NS	0NS	0 NS	1***			
-0.616***	0.828***	1***				
-0.12 NS	1***					
1***						

4. Summary, Conclusion, and Recommendations

4.1. Summary

This study has the potential for deficit irrigation (DI) and efficient furrow irrigation systems to optimize water use and improve garlic yield in water-scarce regions. Results show that DI at 100% ETc and 85% ETc with Alternate Furrow Irrigation (AFI) maintain garlic productivity while saving water. These results provide vital guidance on sustainable water management practices in agricultural production in the water-limited areas of Ethiopia.

4.2. Conclusion

Deficit irrigation, mainly at AFI100%ETc and AFI85%ETc, is one of the feasible strategies that can be used to increase water use efficiency in garlic production without significant yield loss. Alternate Furrow Irrigation appeared as the most efficient system, achieving the highest IWUE and balancing water saving with yield sustainability. Those results give pragmatic recommendations to farmers and decision-makers for the optimization of water use in water-scarce regions. With its adoption, DI and efficient furrow irrigation systems can help in the practice of better water management for sustainable development and increased agricultural productivity despite the challenges associated with water scarcity.

4.3. Recommendations

For maximum garlic production, using Deficit Irrigation with AFI100% ETc and AFI85% ETc, in water-scarce regions, since AFI is the most effective irrigation system as it improves water use efficiency drastically.

Farmers must be trained to practice efficient irrigation scheduling, water monitoring, and proper crop management to optimize water use and reduce waste.

Promote Policy Support to Water-Efficient Technologies: Policymakers must enforce, or at least promote and provide incentives for, advanced water application techniques, particularly drip and sprinkler irrigations in water-scarce regions. This will help in understanding its practical applications and benefits.

4.4. Future Suggestions

Conduct multi-location trials for different climate zones.

Assess long-term impacts of deficit irrigation on soil health.

Integrate economic analysis with yield response.

Evaluate farmer adoption and feedback across districts.

Investigate the influence of furrow configuration on crop diseases.

Declarations

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Competing Interests Statement

The author has declared that no competing financial, professional, or personal interests exist.

Consent for publication

The author has consented to the publication of this research work.

Authors' contributions

Author’s independent contribution.

Availability of data and materials

Supplementary information is available from the author upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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