

Research Article

Comparative Analysis of Furrow Irrigation Systems for Garlic Cultivation in Central Ethiopia, Tiyo District

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Abstract

This study presents a comparative evaluation of three furrow irrigation systems—Conventional Furrow Irrigation (CFI), Alternate Furrow Irrigation (AFI), and Fixed Furrow Irrigation (FFI)—for garlic (*Allium sativum* L.) cultivation in the Tiyo District of Central Ethiopia. The objective was to assess their impact on garlic growth, yield, water use efficiency (WUE), and economic viability under water-limited conditions. A field experiment was conducted using a randomized complete block design (RCBD) with three replications. Each system was tested under four irrigation levels based on crop evapotranspiration (ET_c): 100%, 85%, 70%, and 55%. The results revealed that while CFI produced the highest yield (9.86 q/ha), AFI achieved a comparable yield (8.27 q/ha) with only 50% of the water used in CFI (246.3 mm vs. 492.5 mm), resulting in superior WUE values—58.77 kg/mm for crop water use efficiency (CWUE) and 44.07 kg/mm for irrigation water use efficiency (IWUE). FFI, on the other hand, underperformed across most parameters due to uneven water distribution. Economically, AFI recorded the highest benefit-cost ratio (BCR = 1.79) and demonstrated the potential to save 28,567 m³/ha of water, which could be used to expand irrigation to an additional 15.12 hectares. The findings highlight AFI as a water-saving and economically viable alternative for garlic production in semi-arid regions. The study recommends the adoption of AFI as a sustainable irrigation strategy to enhance water productivity, reduce operational costs, and support agricultural resilience in water-scarce areas.

Keywords

Irrigation Efficiency, Water-Limited Environments, Garlic Bulb Yield, Ethiopia, Furrow Irrigation

1. Introduction

1.1. Furrow Irrigation Systems

Furrow irrigation is the most common method of surface irrigation applied in Ethiopia, mainly for such crops as garlic, maize, and wheat. The application is done on shallow trenches or furrows between crop rows, which allows the water to infiltrate the soil and reach the root zone of the plant. The method is favored by farmers because of its simplicity, low cost, and minimum technical requirement. However, the effi-

ciency of furrow irrigation is highly dependent on the system used, which dictates water distribution, application efficiency, and overall productivity [9].

Garlic is a high-value horticultural crop in Ethiopia, and it requires precise irrigation management because of its shallow root system and sensitivity to water stress. For garlic to achieve optimum bulb size, weight, and yield, effective water management is necessary. The semi-arid conditions of Tiyo District pose drought risks [14], necessitating efficient irriga-

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Received: 20 March 2025; **Accepted:** 7 April 2025; **Published:** 28 April 2025



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tion. In this context, understanding the performance of different furrow irrigation systems is crucial for improving water use efficiency and ensuring sustainable garlic production in water-scarce regions.

The three most commonly used furrow irrigation systems in Ethiopia include: In CFI, during every irrigation event, water is applied to each and every furrow. The uniform distribution of water may be very favorable for those crops which have a high-water requirement. However, CFI tends to over-apply water with inefficiencies including: Waste of Water: Over-irrigation can allow the water to percolate down into the soil out of the root zone or even to runoff from the field and become lost. Evaporation Losses: The evaporation loss due to the water surface being exposed in every furrow is increased, thereby decreasing water available to plants. Low Efficiency: On-field application efficiency of CFI rarely exceeds 60%, as confirmed by studies on the infiltration characteristics of sandy and loamy soils [1].

1.2. Research Gap and Objectives

Despite these disadvantages, CFI is still in extensive use in Ethiopia simply for its simplicity and ease of practice, particularly among smallholder farmers without access to more sophisticated irrigation methods [9]. In AFI, alternating furrows are supplied with water during a given irrigation, with the rest of the furrows remaining dry. During the next irrigation cycle, the previously dry furrows receive water. This system has gained attention for its potential to improve WUE by reducing furrows irrigated per event. AFI minimizes water application into the root zone and reduces deep percolation and runoff losses associated with the overirrigation of soil [2]. Encourage root development: The alternation of wet and dry soil profiles under AFI encourages root growth to greater depths for plants to access moisture supply from a greater depth during drought periods. Reduce Evaporation: The much smaller wetted surface area considerably reduces evaporation losses compared to CFI.

AFI is thus more appropriate for the regions where water is at a deficit, since it helps farmers continue crop growth with less use of water. Research in semi-arid parts of Ethiopia showed that AFI can realize up to 30% water saving compared to CFI with very minimal yield reductions [2]. Success with AFI requires careful scheduling so as not to deny plants the required moisture at any critical growth stage.

Fixed Furrow Irrigation, or FFI, is the method whereby, during the entire growing season, water is applied to the same set of furrows while the rest of the furrows remain dry. Some key benefits that come along with FFI are as follows: Water Conservation: Overall, FFI uses less water by putting the water in specific furrows and could be an alternative for water-scarce regions as well [1]. Simplified Management: Focusing on specific furrows simplifies water distribution, requiring less labor and time for farmers. However, FFI has a number of challenges, including: Uneven Water Distribution:

Constant irrigation in specific furrows can lead to uneven moisture distribution across the field and may result in water stress for some plants. Salinization of Soil: If in arid regions, dry furrows are not irrigated, salt can be concentrated in the root zone to levels that may be detrimental to plant growth [9].

FFI is less used than CFI and AFI, but it is also an important alternative in conditions where saving water is more important than uniform distribution of moisture. Furrow irrigation systems have been one of the widely studied irrigation systems for efficiency and suitability in semi-arid and arid regions like Ethiopia. Research indicates that irrigation methods significantly affect water productivity and crop yield [9]. [2] found that adopting AFI in Ethiopia improved water use efficiency by 25–30% compared to traditional methods like CFI. Similarly, [1] indicated that fixed furrow systems have a potential for water saving at some cost in uniformity of moisture. This study aims to compare the performance of CFI, AFI and FFI for garlic, with a view to identifying which irrigation system provides the best combination of garlic growth, yield, Cost-benefit analysis and water use efficiency.

2. Materials and Methods

2.1. Experimental Site

The study was conducted in Tiyo District, located in Central Ethiopia. The district is classified as a semi-arid region, with agriculture being the primary livelihood activity for the majority of the population. The area receives an average annual rainfall of approximately 820 mm, with rainfall concentrated mainly between June and September. However, this amount is insufficient to meet the full water needs of crops, particularly during the dry seasons.

Soil Characteristics: The soils in Tiyo District are predominantly clay loam, which has moderate water-holding capacity and is suitable for garlic cultivation. Soil pH ranges from 6.5 to 7.0, indicating a neutral soil environment conducive to garlic growth.

Climatic Conditions: The mean annual temperature ranges between 7.7 °C in December and 25 °C in March, with low relative humidity during the dry season, contributing to higher evapotranspiration rates. The semi-arid climate, coupled with seasonal rainfall variability, necessitates efficient irrigation practices to sustain agricultural productivity [4].

2.2. Experimental Design

The study followed a Randomized Complete Block Design (RCBD) with three replications to minimize variability in soil and environmental conditions. This design is suitable for agricultural experiments as it ensures accurate comparison of treatments while controlling for external factors such as soil fertility gradients and climatic variations.

Treatments: The treatments consisted of three furrow irrigation systems and four irrigation levels, resulting in a total of

12 treatment combinations:

Furrow Irrigation Systems: Conventional Furrow Irrigation (CFI), Alternate Furrow Irrigation (AFI), and Fixed Furrow Irrigation (FFI).

Irrigation Levels: 100% ETc: Full irrigation to meet the crop's evapotranspiration requirement, 85% ETc: Moderate deficit irrigation, reducing water application by 15%, 70% ETc: Severe deficit irrigation, reducing water application by 30%, 55% ETc: Extreme deficit irrigation, reducing water application by 45%. Each treatment combination was randomly assigned to plots within each block to ensure unbiased evaluation of their effects on garlic growth, yield, and water use efficiency (WUE).

Plot Layout

Plot Dimensions: Each plot measured 3 m × 5m, with garlic planted in double rows within each furrow.

Spacing: Between Plants: 10 merteen Rows: 45 cm, Between Plots: 1 m buffer to prevent water interference., Between Blocks: 2 m separation to allow for proper management.

2.3. Data Collection and Analysis

Irrigation Application and Scheduling: Irrigation was applied using a Parshall Flume to measure and control water flow into each plot accurately. The irrigation schedule was determined based on the crop's water requirements, calculated using the CROPWAT model [5] and with adjustments for water conservation based on modern scheduling strategies [10]. This model considers climatic data, soil characteristics, and crop factors to estimate the crop's evapotranspiration (ETc).

Net Irrigation Requirement (NIR): The NIR was calculated using the formula:

$$NIR = ETc - Pe \quad (1)$$

Where:

ETc = Crop evapotranspiration (mm/day)

Pe = Effective rainfall (mm)

Crop evapotranspiration (ETc) was calculated following FAO guidelines [13].

Gross Irrigation Requirement (GIR): The GIR was derived considering the application efficiency of the irrigation system:

$$GIR = NIR/Ea \quad (2)$$

Where:

Ea = Application efficiency (%)

Irrigation water application: The irrigation interval, (I) was determined for the control treatment (100%ETc) and computed following Eq. (3).

$$I = \frac{NIR}{ETc} \quad (3)$$

Where, I is irrigation interval (Days); NIR is net irrigation requirement (mm), ETc is the mean daily crop water requirement (mm/day)

Parshall flume was used to apply the desired depth of irrigation water to each experimental plot. The time require to irrigate a particular plot/treatment will be obtained following Eq. (4).

$$T = \frac{AD}{6q} \quad (4)$$

Where, T is the time required to irrigate a plot (minutes), A is plotting area (m²), D is the depth of irrigation to be applied for a plot (cm) and q is the flow discharge at a particular head through a Parshall flume (l/s).

2.4. Agronomic Practices

Planting: Garlic cloves were planted manually at a depth of 5 cm, ensuring uniform planting depth and spacing to achieve consistent germination and growth.

Fertilization: Urea (46% N): Applied at a rate of 150 kg/ha, Di-Ammonium Phosphate (DAP, 18-46-0): Applied at a rate of 200 kg/ha, Fertilizers were applied in two splits: half during planting and the other half 30 days after planting., Weeding and Pest Control: Manual weeding was performed biweekly, and pest management was conducted using recommended insecticides to ensure crop health.

Data Collection: Growth Parameters, Plant Height (cm): Measured from the base to the tip of the longest leaf, Leaf Length (cm): Measured for five randomly selected plants per plot. Yield Components, Bulb Size (cm): The average diameter of garlic bulbs harvested from each plot. Measurements were taken using a Vernier caliper for precision., Bulb Weight (g): The weight of individual garlic bulbs was measured using a digital scale, ensuring accurate assessment of bulb size and development, Marketable Bulb Yield (MBY, q/ha): The total yield of garlic bulbs that met marketable size and quality standards, expressed in quintals per hectare. This includes bulbs that are free from defects and meet size requirements for commercial purposes, Unmarketable Bulb Yield (UMBY, q/ha): The total yield of garlic bulbs that did not meet marketable standards due to size, damage, or deformities. This yield was measured to evaluate overall crop performance and the proportion of usable produce.

2.5. Water Use Efficiency (WUE)

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. Hence, CWUE and IWUE as expressed in the following Eq. and were used to obtain the respective values for garlic.

Crop Water Use Efficiency (CWUE):

$$CWUE = \text{Bulb Yield (kg/ha)} / ETc \text{ (mm)} \quad (5)$$

Irrigation Water Use Efficiency (IWUE):

$$IWUE = \text{Bulb Yield (kg/ha)} / \text{Irrigation Water Applied (mm)} \quad (6)$$

Cost-Benefit and Net Return Analysis: The benefit-cost ratio (BCR) in ETB measures the increase in net return (NR) which was generated by total cost expenditure (TC) and compared following Eq. (7).

$$BCR = \frac{NR}{TC} \quad (7)$$

The amount of water saved (WS) per hectare of land will be attained by subtracting from CFI (100% ETc) application level which was used as a control from the treatments. The net return for the additional area (NRA) for harvested marketable yield was calculated as the difference between the sum of the cost of labor for a combination of irrigation Systems and application levels, the cost of water that was saved from application levels, and the revenue lost due to yield decreases resulting from this factor protocol was obtained following Eq. (8).

$$NRA = (G * LS + C * WS) - P * YL \quad (8)$$

3. Results and Discussion

3.1. Growth and Yield Performance

3.1.1. Growth Performance

Table 1. Growth Performance of Garlic Under Different Furrow Irrigation Systems (Plant Height and Leaf Length).

Furrow Type (FT)	Plant Height (PH)	Leaf Length (LL)
CFI	47.48a	42.5a
AFI	43.53b	37.71b
FFI	43.15b	37.37b
LSD (5%)	1.4972	0.0128
CV (%)	3.35	9.27

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

Plant Height and Leaf Length (PH, LL): The growth performance varied significantly among the three furrow irrigation systems: Conventional Furrow Irrigation - CFI, Alternate Furrow Irrigation - AFI, and Fixed Furrow Irrigation -

FFI. The garlic irrigated under AFI performed best, as shown by Table 1, where it had the highest average PH (43.53 cm) and LL (37.71 cm). However, when absolute values are considered, the CFI treatments have the highest PH (47.48 cm) and LL (42.5 cm), followed by AFI and FFI, with values of 43.15 cm for PH and 37.37 cm for LL, respectively.

According to the LSD values, the differences between treatments were significant ($P < 0.05$). The low CV for PH (3.35%) and the moderate CV for LL (9.27%) suggested that the plant height measurement was highly reliable, whereas the leaf length data was moderately reliable.

Statistically, CFI treatments had a significant difference though AFI had comparable values that had lower variability than FFI which were effective in enhancing better growth. The higher level of growth under CFI has been due to the continued presence of water, thereby satisfying continued nutrient uptake and assimilation. However, its practicability is doubted considering the high-water usage emanating from it. [1, 6]. AFI improves the penetration of roots through alternate wet and dry furrows, which allows efficient moisture and nutrient utilization. It is supported by literature where alternate irrigation systems improved aeration in the root zone and reduced waterlogging conditions [2, 3]. The low performance recorded under FFI reflects poor water distribution, as sometimes dry zones are created around the root zone, hence limited growth [9].

3.1.2. Yield Performance

Bulb Size (BD, cm): The highest bulb diameters were recorded under CFI conditions, 46.05 cm, followed by AFI, 45.27 cm, and FFI, 42.92 cm. The higher bulb size in CFI could be attributed to the non-fluctuating soil moisture during the critical bulb formation stage. However, AFI gave almost identical results with much water saving and hence can be considered more viable.

Bulb Weight (BW, g): CFI showed the highest bulb weight (36.32 g), followed by AFI with 35.21 g. FFI, due to its poor water distribution, had smaller and lighter bulbs, weighing 33.68 g. These results are in agreement with works by [2, 6] and [16] which highlighted that consistent moisture is important for the development of the bulb.

Bulb Yield (BY, q/ha): The highest total bulb yield was recorded under CFI (9.86 q/ha), followed by AFI (8.27 q/ha) and FFI (7.17 q/ha). While CFI maximized yield, AFI achieved considerable yields with reduced water input, highlighting its potential as a water-efficient alternative. Reduced yields under FFI align with findings on water-stressed garlic in similar climates [11, 16].

Table 2. Yield Components of Garlic Under Different Furrow Irrigation Systems (Bulb Diameter, Bulb Weight, and Bulb Yield).

Furrow Type (FT)	Bulb Diameter (BD, cm)	Bulb Weight (BW, g)	Bulb Yield (BY, q/ha)
CFI	46.05a	36.32a	9.86a
AFI	45.27a	35.21a	8.27b
FFI	42.92b	33.68b	7.17c
LSD (5%)	2.31	1.49	0.045
CV (%)	5.17	4.26	2.5

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

LSD values validated that among the treatments, differences were highly significant for all the parameters taken into consideration ($P < 0.05$). Very low values of CV range from 2.5 to 5.17%, showing high precision and reliability in yield measurements. Bulb diameter and bulb weight variations between CFI and AFI are insignificantly different, indicating AFI may act as a substitute to CFI on yield components.

Higher yield of bulb obtained under CFI refers to the maintaining of adequate moisture during critical stages of bulb formation. Its high-water requirements, however, limit it in most regions that experience limited availability of this valuable resource. [3, 9] observed this. On the contrary, AFI gave close to comparable yields with significantly reduced water inputs, highlighting suitability for regions with scarce water. [2, 6, 16] and reported that alternate irrigation is effective in maintaining bulb size and weight. Poor performance of

FFI is due to the dry zones in the field that impede the uniform development of bulbs [1].

3.2. Water Use Efficiency

IWUE: AFI had the highest IWUE, 28.64 kg/mm, followed by CFI, 50.81 kg/mm, and FFI, 33.69 kg/mm. Alternating irrigation in AFI reduces evaporation and runoff, hence improving water use efficiency at high yields. This is in agreement with the findings of [1, 3, 11].

CWUE: The CWUE was the highest for AFI (58.77 kg/mm), followed by CFI (67.79 kg/mm) and FFI (44.92 kg/mm). A better water use efficiency under AFI could be due to the fact that it tends to develop a better root structure that captures better moisture levels [2, 6, 16, 7].

Table 3. Water Use Efficiency Metrics of Garlic Under Different Furrow Irrigation Systems (CWUE and IWUE).

Furrow Type (FT)	Crop Water Use Efficiency (CWUE, kg/mm)	Irrigation Water Use Efficiency (IWUE, kg/mm)
CFI	50.81a	67.79a
AFI	44.07b	58.77b
FFI	33.69c	44.92c
LSD (5%)	7.6	5.72
CV (%)	13.31	13.35

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

Significant differences ($P < 0.05$) existed among treatments for both CWUE and IWUE. The moderate CV values of 13.31% for CWUE and 13.35% for IWUE are considered acceptable variability.

AFI was more efficient in water use than CFI and FFI, showing that with AFI, similar yields can be obtained with significantly lower water use. This finding agrees with previous studies by [2, 3, 15, 16] that emphasized the role of

alternate irrigation in enhancing water productivity. Although CFI gave higher absolute yields, high-water consumption reduces its suitability for sustainable agriculture in a water-limited setting as noted by [9, 16]. The efficiency was the lowest in FFI because of uneven distribution of water, which reduced the potential for water-to-biomass conversion and yield.

3.3. Cost-Benefit and Net Return Analysis

The cost-benefit analysis (Table 4) showed that the highest net return, 178,423 ETB, resulted from the control treatment of CFI100%ETc. In the deficit irrigation treatments, the highest net return, 160,002 ETB, was observed in AFI, whereas the lowest, 89,604 ETB, was obtained from FFI. The net income is affected by water application and furrow irrigation systems.

AFI and FFI conserved 28,567.57 m³ha⁻¹ of water, which could irrigate an additional area of 15.12 ha. This water-saving approach improved cultivated area and labor use efficiency with a minimal loss in yield. AFI has also continued to show higher NR and BCR than FFI and CFI at the same level of water application. This is in agreement with [8], who noted that AFI optimizes yield and economic returns in water-scarce regions.

Table 4. Cost-benefit analysis.

Treatment	Irrgat. water (mm)	Labor cost (Birr)	Water cost (Birr)	Operation cost (Birr)	Total cost (Birr ha ⁻¹)	Marketable yield (kg ha ⁻¹)	Gross revenue (Birr)	Net return (birr)	CBR
CFI	492.5	7000	147761	12000	166761	9862	345184.0	178423	1.07
AFI	246.3	3500	73880	12000	89380	7125	249382.0	160002	1.79
FFI	209.3	3500	62798	12000	78298	4797	167902.0	89604	1.14

NB: In this cost-benefit analysis:

- 1) The number of irrigation occasions was seven.
- 2) The water price was assumed 30 birrs for an m3.
- 3) The unit price of Garlic was assumed at 35 birrs for a 1kg.

4. Summary

This study compared three furrow irrigation systems—Conventional Furrow Irrigation (CFI), Alternate Furrow Irrigation (AFI), and Fixed Furrow Irrigation (FFI)—in terms of growth, yield, water use efficiency, and economic performance for garlic cultivation in Tiyo District, Ethiopia. CFI achieved the highest garlic yield (9.86 q/ha), but at the cost of high-water consumption (492.5 mm). AFI, with significantly less water use (246.3 mm), demonstrated a balance between yield (8.27 q/ha) and water conservation, achieving the highest irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE).

The cost-benefit analysis highlighted AFI as the most economically efficient system, yielding a net return of 160,002 ETB ha⁻¹, compared to 178,423 ETB ha⁻¹ under the control treatment (CFI100%ETc) and 89,604 ETB ha⁻¹ under FFI. Water savings from AFI allowed the irrigation of an additional 15.12 hectares, demonstrating its potential to expand cultivated areas and increase productivity in water-limited regions.

5. Conclusion

AFI is a water-efficient and economically viable alternative to traditional irrigation methods, achieving comparable yields to CFI while significantly conserving water and reducing costs. While CFI maximized yields, its high-water require-

ment limits its feasibility in water-scarce environments. FFI performed poorly across most metrics due to uneven water distribution, underscoring its limitations for crops requiring consistent soil moisture. The cost-benefit analysis revealed that AFI provides the best balance between yield, water savings, and economic returns, making it the most sustainable choice for garlic cultivation in semi-arid regions.

6. Recommendations

Promote Alternate Furrow Irrigation (AFI): Farmers should adopt AFI to optimize water use and maximize returns. Training programs can help ensure proper implementation, including irrigation scheduling and monitoring.

Utilize Water Savings for Land Expansion: The water saved through AFI should be used to expand irrigated areas, improving overall productivity and addressing food security challenges in water-limited regions.

Conduct Further Research: Similar studies should be conducted on other high-value crops to validate the effectiveness of AFI and explore its application in diverse agro-climatic conditions. Future adoption of AFI could integrate climate-smart practices [12] and to enhance resilience.

Abbreviations

CFI	Conventional Furrow Irrigation
AFI	Alternate Furrow Irrigation
FFI	Fixed Furrow Irrigation

WUE	Water Use Efficiency
CWUE	Crop Water Use Efficiency
IWUE	Irrigation Water Use Efficiency

Author Contributions

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

Conflicts of Interest

The author declares no conflicts of interest.

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Biography



Abu Dedo Ilmi is an expert in Water Resources and Irrigation Engineering with extensive experience in hydrology, irrigation systems, and sustainable water management. He earned his MSc in Irrigation Engineering and his BSc in Water Resources and Irrigation Engineering from Haramaya University, Ethiopia. With over eight years of experience working with local and international NGOs, he has played a key role in infrastructure development, water resource management, and irrigation system evaluation. His research focuses on hydraulic performance, sustainable irrigation practices, and climate change impact on hydrology. Abu has authored and co-authored several research papers and proceedings in irrigation technology, soil-water conservation, and agricultural water management. He is actively engaged in international collaborations and has contributed to innovative solutions in deficit irrigation, furrow irrigation efficiency, and sustainable farming techniques.

Research Field

Abu Dedo Ilmi: Irrigation system performance, Deficit irrigation management, Water resource management, Hydrology and climate change, Soil-water conservation, Agricultural water efficiency, Furrow irrigation techniques, Hydraulic engineering in agriculture, Sustainable irrigation practices, Crop water use efficiency.