

Response of garlic (*Allium sativum* L.) yield and yield components to various irrigation management strategies at central highland of Ethiopia

Biruk Getaneh Ayele, Shemelies Asseffa Tuji, Abraham Woldemichael Tuhar, Ayele Desalegn Woldemariam

Angaben zur Veröffentlichung / Publication details:

Ayele, Biruk Getaneh, Shemelies Asseffa Tuji, Abraham Woldemichael Tuhar, and Ayele Desalegn Woldemariam. 2025. "Response of garlic (*Allium sativum* L.) yield and yield components to various irrigation management strategies at central highland of Ethiopia." *Discover Agriculture* 3 (1): 142. <https://doi.org/10.1007/s44279-025-00332-2>.

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Response of garlic (*Allium sativum* L.) yield and yield components to various irrigation management strategies at central highland of Ethiopia

Biruk Getaneh Ayele^{1,2*}, Shemelies Asseffa Tuji², Abraham Woldemichael Tuhar² and Ayele Desalegn Woldemariam^{1,2}

*Correspondence:

Biruk Getaneh Ayele
birukgetaneh13@gmail.com
¹Amhara Regional Agricultural
Research Institute, Debre Birhan
Agricultural Research Center,
P.O.Box 112, Debre Birhan, Ethiopia
²Institute of Technology,
Department of Water Resource and
Irrigation Engineering, Hawassa
University, P.O.Box 05, Hawassa,
Ethiopia

Abstract

Garlic is a high value, water sensitive crop that requires precise irrigation management to optimize yield and quality. This study evaluates the effect of deficit irrigation levels (55%, 70%, 85%) and full irrigation (100% ETc) and three furrow irrigation techniques (conventional (CFI), alternative (AFI), fixed (FFI)) on garlic yield and yield components at highlands of Debre Birhan. The experiment was designed with Randomized Complete Block Design (RCBD) in three replications. Irrigation regimes were determined based on combined weather and soil based irrigation scheduling. Result showed that garlic yield and yield components were significantly affected at ($P < 0.001$) by the combined effect of deficit irrigation and furrow techniques. The maximum bulb yield of 8.2 t ha^{-1} (with only 7.8% yield reduction) was found by application of 85% ETc under CFI. However, application of 85% ETc by AFI gave 7.2 t ha^{-1} (19% yield loss) with using half water amount, highlight optimal water use strategies. The application of deficit irrigation (55% ETc) significantly reduced bulb yield of 37.5% compared to the full ETc. The highest plant height (68 cm), leaf length (40 cm), bulb diameter (49 mm), leaf area (198 cm^2) was observed by application of 100% ETc under CFI. Strong positive correlations were observed between yield and yield components. The finding reveals that 85% ETc regulated deficit irrigation under AFI optimizes water use without compromising yield, establishing an efficient irrigation strategy for sustainable garlic production in water-limited regions.

Highlight

- 85% ETc under CFI achieved 8.2 t/ha yield with 7.8% loss from 100% ETc, proving optimal for water saving without significant yield loss.
- 85% ETc under AFI saved 50% water but incurred 19% yield loss, offering a trade-off for water-scarce scenarios.
- Severe deficit (55% ETc) drastically reduced yield (37.5% loss), highlighting garlic's sensitivity to extreme water stress.

Keywords Deficit irrigation, Highland areas, Furrow irrigation, Garlic, Yield



1 Introduction

Garlic (*Allium sativum* L.) is the most widely cultivated *Allium* vegetables in the world [1]. It is also one of the most known highland vegetable in Ethiopia. However, the mean yield of garlic is 8 to 9 t ha⁻¹, which is low from world's average [2]. Maximizing garlic yield requires both optimal irrigation water application [3] and effective integrated soil fertility management [4]. The fast growing population growth has placed high pressure on the global food systems. Irrigated agriculture plays a crucial role in meeting this demand by boosting crop yields and ensuring food security [5]. However, the availability, quantity, and quality of existing fresh water limit the crop productivity and water use efficiency (WUE).

Deficit irrigation (DI) is a planned water management strategy where water is applied below the crop's full requirement to enhance water productivity. It save water, monitoring the soil or plant water status as an irrigation scheduling approach is even more critical for minimizing the risk of yield reduction [6]. All irrigation systems should be designed to ensure uniform water application over the field. In Ethiopia, about 98% of irrigation is practiced using surface irrigation, with furrow irrigation being the most common method [7]. Furrow irrigation had an advantage over others; basin and boarder methods. The use of Alternative Furrow Irrigation (AFI) wetted out only part of the surface, thus reducing evaporation and deep percolation losses [8]. The use of AFI enhanced water use efficiency without negatively affecting yield [9]. As per [8], WUE were found to be higher in AFI than CFI & FFI. AFI enhances WUE by applying less water but maintaining similar or even higher yields due to the improved water retention, root behavior, and plant physiology. Fixed Furrow Irrigation (FFI) technique is a trade-off between lower yield and higher WUE. Thus, the improvement of WUE in irrigated agriculture is crucial [10].

The right furrow technique should be practiced to save water, time, energy, and produce higher productivity. Similarly [11] reported that Garlic is a water-sensitive crop that requires small, frequent amounts of irrigation. As noted by [12] the amount of water saved by AFI and DI could irrigate extra land and produce more yields, further on assures the sustainability of the environments and the overall ecosystem. Irrigation scheduling is important to apply the right amount of water at the right time [13]. For garlic, optimum moisture is needed for better growth, bulb yield and quality [14]. It provides a means of reducing water consumption while minimizing adverse effects on yield [15]. Garlic yield in the highlands of Debre Birhan has been reported to range between 10.4 and 13.1 t ha⁻¹, with key yield components such as plant height (63–74 cm), bulb diameter (35–44 mm), leaf length (49–56 cm), and number of leaves per plant (11.6–12.7) showing considerable variation under different clove sizes and irrigation conditions [16].

While the effects of deficit irrigation (DI) and furrow irrigation techniques have been studied in other crops, their combined impact on garlic productivity in the highlands of Debre Birhan remains unexplored. This region presents unique agro-ecological challenges, including clay loam soils, a variable climate, seasonal water scarcity, and growing pressure on water resources due to expanding irrigated land. Therefore, localized research is necessary to evaluate how DI and furrow irrigation methods influence garlic yield and its components under these specific conditions. The novelty of this study lies in determining crop evapotranspiration (ETc) using both soil moisture measurements and

weather data. Furthermore, it assesses the integrated effect of deficit irrigation levels and three furrow irrigation techniques on garlic yield. The research hypothesis suggests that there is a significant difference in garlic yield and yield components due to the interaction between irrigation levels and furrow irrigation methods. Therefore, the study aims to evaluate the effects of different deficit irrigation levels and furrow irrigation techniques on garlic yield and yield components at Debre Birhan.

2 Materials and methods

2.1 Description of the study area

The experiment was carried out at Debre Birhan Agricultural Research Center (DBARC), which is located between 10°001'00" to 10°017'10" N and 39°045'00" to 39°058'20" E and Altitude of 2780 to 2827 m (Fig. 1). The mean precipitation and temperature are 985.0 mm and 14.7 °C respectively. The area is categorized as highland agro ecological zone and characterized by cool and arid environment. Agriculture is the main socio-economic activity of the communities. The main source of water for irrigation is from rivers, dams, and ponds. The irrigation system that the farmers follow is rotational system. The major crops irrigated in the area are wheat, barely, faba bean, garlic, carrot, potato, and cabbage. Based on the long climatic data (1991–2020) from DBARC's meteorological station, the monthly evapotranspiration (ET_o) and rainfall of the area have been shown in Fig. 2.

2.2 Experimental design and setup

The test crop was local garlic variety with plant spacing and row spacing of 10 cm and 60 cm (166,666 plants ha⁻¹) respectively. The seed was planted by using direct sowing methods. The design of the experiment was Randomized Complete Block Design

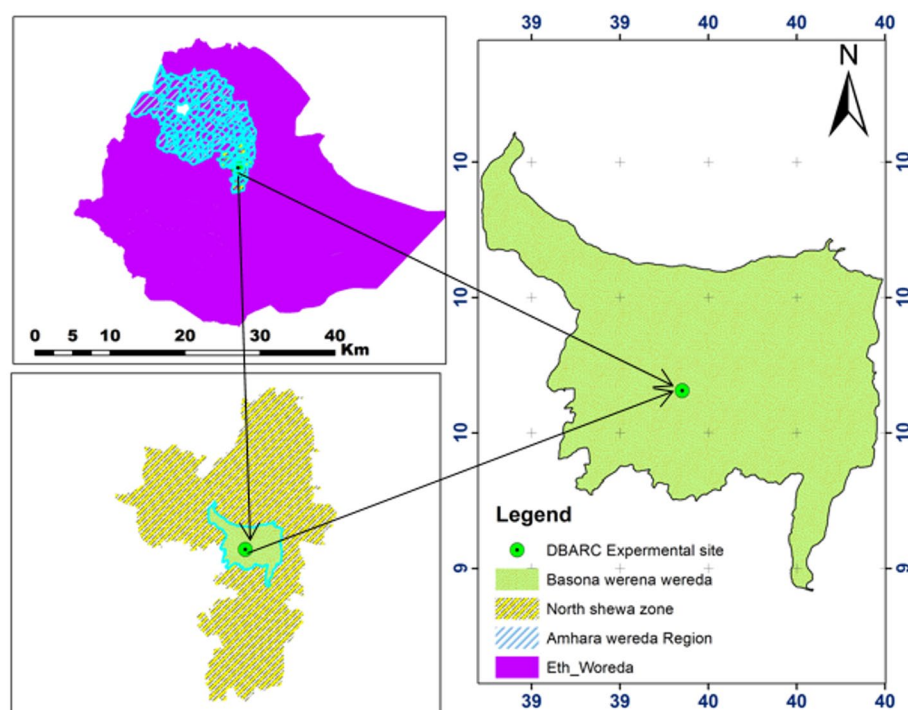


Fig. 1 Geographical location of the study areas

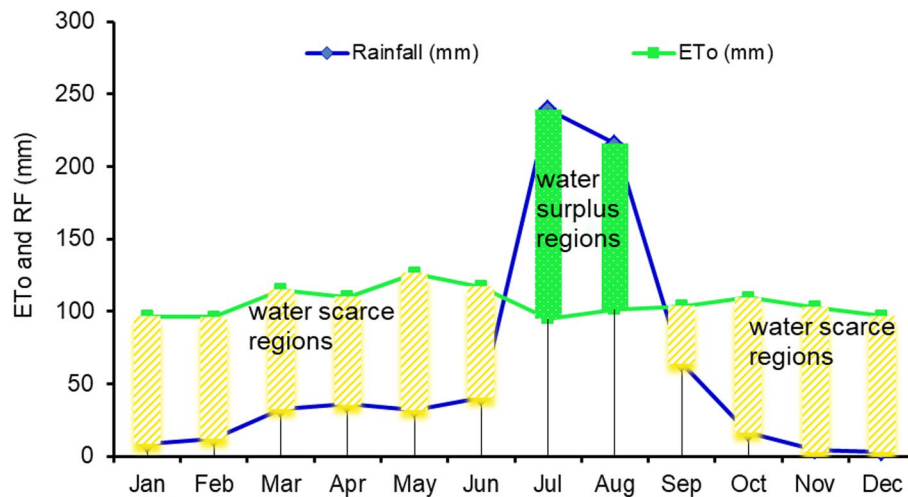


Fig. 2 Mean monthly rainfall and reference evapotranspiration

(RCBD) with two factors; irrigation levels with (55, 70, 85, and 100% ETo) and furrow irrigation techniques (FFI, CFI, and AFI). The spacing between rows and plants were 30 cm and 10 cm respectively. The amount of fertilizer applied were $92 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ and $105 \text{ kg ha}^{-1} \text{ N}$ [16]. Irrigation was scheduled based on garlic growth stages; establishment, vegetative, bulb initiation, bulb development, and maturation. Stage-specific depletion factors, representing the fraction of available soil water allowed depleting before irrigation was applied. Lower depletion factors during sensitive stages ensured optimal moisture, enhancing yield and water use efficiency. The effective rooting depth of garlic ranges from 0.25 to 0.5 cm. According to FAO 56, the depletion fraction for garlic is 0.30 [17]. There was one season cultivation cycle in irrigation and the total growing periods of garlic ranges from 150 to 165 days.

2.3 Soil conditions

In order to analyze the physiochemical properties of the soil, eight samples were collected in diagonal fashion. The soil texture is clay loam to clay with composition of 35.8% sand, 16%, silt and 49.0% clay respectively. The bulk density is 1.14 g/cm^3 . The soil water content at field capacity and permanent wilting point is 34.67% and 24.32% respectively. The total available water (TAW) is 117.5 mm/m. The pH and EC of the soil is 6.1 and 0.17 dS/m. The final steady state infiltration rate of the soil is 0.5 cm/hr and the infiltration rate is 0.84 cm/hr (slow infiltration rate).

2.4 Irrigation regimes of garlic

FAO Penman Monteith equation was employed to determine ETo in CROPWAT software version 8.0 (Eq. 1). The Kc values were fixed as 0.7 (initial), 1.05 (mid) and 0.7 (late) [17]. Effective rainfall was estimated using the USDA Soil Conservation Service (SCS) method in CROPWAT software. The amount of water used for irrigation is the difference of ETo and effective rainfall. Irrigation scheduling was determined by measuring the actual soil moisture in the experimental field by the gravimetric method. The readily available moisture (RAM) was calculated by multiplying the total available moisture (TAM) with management allowable deficit (MAD). This depth of water extracted effectively by the crop and was considered as 100% ETo. The other treatments were received

based on the percentage of 100% ET_c. At the time when moisture falls below the pre-defined Management Allowable Depletion (MAD) level, irrigation was applied. The frequency of collecting soil sampling was on three days interval.

$$ET_o = \frac{(0.408 * \Delta * (R_n - G)) + \gamma * \left(\frac{900}{(T+273)} \right) * \mu_2 * (e_s - e_a)}{\Delta + \gamma (1 + 0.34\mu_2)} \quad (1)$$

2.5 Deficit irrigation levels

The effect of soil moisture stress on crop evapotranspiration (ET_c) was determined by multiplying the crop coefficient (K_c) by the soil moisture stress coefficient (K_s) (Eq. 4). MAD is the maximum percentage of total available soil water (TAW) that is allowed to be depleted from the root zone before irrigation is required to avoid crop water stress (Eq. 2). The soil moisture stress coefficient (K_s) is used to adjust crop evapotranspiration (ET_c) for water stress (Eq. 3). When the level of soil moisture depletion remains within the Readily Available Moisture (RAM), K_s = 1, meaning no stress. If depletion exceeds RAM (as in deficit irrigation scenarios), K_s < 1, reflecting a reduction in ET_c due to water stress [18]. The value of K_s is determined by the (Eq. 3).

$$MAD = \frac{RAW}{TAW} \quad (2)$$

$$K_s = \frac{TAM - MAD}{TAM - RAM} \quad (3)$$

$$ET_c = K_s * K_c * ET_o \quad (4)$$

For each treatment, irrigation was applied according to the moisture stress in order to fill the depleted amount of water. The treatments were irrigated based on moisture deficit to refill back the soil to field soil back to field capacity. The net irrigation need is used to fill the lost soil moisture in crop root depth back to field capacity. The application efficiency for furrow techniques was 0.70 as for clay loam soil and the water is directly fed in to furrows. The details overview for determination of irrigation was conducted based on the both soil based and evapotranspiration method on excel sheet. The scheduling strategy uses the fraction of available water (FAW) and soil water storage (SWS) to track how much water is lost due to evapotranspiration. Irrigation was scheduled based on soil moisture depletion (D), which was monitored against a predefined threshold corresponding to the MAD. The soil moisture content was assumed to be at field capacity. The amount of water applied for each treatment was shown in Table 1.

2.6 Furrow irrigation techniques

Three furrow techniques; AFI (alternative furrow irrigation), FFI (fixed furrow irrigation), and CFI (Conventional furrow irrigation) techniques were used to apply the amount of water. With CFI, all of the furrows are irrigated during each irrigation event, which results in uniform soil moisture and high water use. While FFI uses less water, it may result in an unequal distribution of moisture. The irrigated furrows are rotated between events using AFI, which maximizes water-use efficiency and promotes deeper root growth. In this experiment, temporary storage (tanker) was used as a source of water supply. Calibrated hose was used to apply water to each furrow techniques. Water

Table 1 The amount of water applied in each level

Treatment	Common irrigation (mm)	Applied water for treatments (mm)	Total irrigation applied (mm/season)
55%ETc @ AFI	59.4	151.8	211.2
70% ETc @ AFI	59.4	194.7	254.1
85% ETc @ AFI	59.4	237.5	297.0
100%ETc @ AFI	59.4	281.6	341.0
55%ETc@ FFI	59.4	151.8	211.2
70%ETc @ FFI	59.4	194.7	254.1
85%ETc @ FFI	59.4	237.5	297.0
100%ETc @ FFI	59.4	281.6	341.0
55%ETc @ CFI	59.4	272.6	332.0
70%ETc @ CFI	59.4	358.3	417.7
85%ETc @ CFI	59.4	444.0	503.5
100%ETc @ CFI	59.4	532.2	591.6

was applied to the plots from a storage tank using a hosepipe. For each irrigation event, the amount of water applied was controlled by measuring the discharge rate of the hose and the duration of application for each treatment. The flow discharge and irrigation time were recorded to determine the volume of water delivered. Pre irrigation and common irrigations were conducted for well establishment. The amount of water applied was determined by multiplying the gross amount by plot area.

2.7 Data measurement and collection

The yield components such as plant height, leaf length, leaf number per plant, leaf area, leaf area index, bulb diameter, and number of cloves per bulb and yield were collected. The frequency for data measurement was 10 days interval.

Plant height (cm) was measured at physiological maturity by a measuring scale for randomly selected ten plants and mean was calculated at various days after sowing (DAS).

Leaf number per plant The mean number of leaves produced by ten sampled plants and was calculated by dividing the total number of leaves counted from the sampled plants to the number of sampled plants to get mean leaf number per plant at different DAS.

Leaf length (cm) The length of three leaves per plant (from upper, middle and bottom) from the ten selected plants were measured at maturity by a ruler and the average leaf length was taken. The frequency for data measurement was 10 days interval.

Leaf area (cm²) Ten garlic plants were randomly sampled for leaf area measurement. From each sampled plant, three leaves were taken from one side of the plant canopy. Leaf area was determined using the destructive method by tracing each leaf on a square-grid sheet. The total leaf area was estimated by counting the number of fully covered squares, $\frac{3}{4}$ covered squares, and half-covered squares. The sum of these square counts was used to calculate the area of one leaf (19).

Leaf area index (LAI) is the one-sided green leaf area per unit ground surface area. It was determined by the following formula (Eq. 5). As the crop develops and shades more and more of the ground, evaporation becomes more restricted and transpiration gradually becomes the major process. It can be determined by the (Eq. 6) [19].

$$LAI = \frac{\text{leaf area per plant (cm}^2\text{)}}{\text{ground area per plant (cm}^2\text{)}} \quad (6)$$

Bulb diameter (cm) The diameter of randomly selected ten bulbs was measured with caliper and averaged out them to know the mean bulb diameter.

Bulb Yields Marketable bulb were separated based on subjective basis from the middle two rows and weighed with a sensitive balance.

2.8 Statistical data analysis

The response of garlic yield components to DI and furrow irrigation techniques at different DAS were analyzed to show the treatment effect. A general linear model was used to determine the variation of yield components and yields of garlic crops as they are affected by irrigation management strategies in R-4.3.1 software [20]. The data were subjected to ANOVA to evaluate the statistical effects of treatments on all yield components and yield components at the 0.05 significance level. Wherever the treatment effect was significant, multiple all-pair wise comparisons test was calculated using fisher's LSD method. Correlation analysis was done to assess the strength and direction of relationships among agronomic parameters. The correlation coefficient indicated the degree of association, with significance tested using standard statistical methods [21].

3 Results

3.1 Effect of deficit irrigation and furrow techniques on garlic yield and yield components

The result of the combined effect of deficit irrigation levels and furrow techniques on garlic yield and yield components is presented in Table 2. It revealed that plant height, number of leaf per plant, leaf length, leaf area, leaf area index, bulb diameter and bulb yield were significantly influenced ($p < 0.001$) by water deficit levels and furrow techniques. The maximum values of all parameters were obtained by the application of 100% ETc under conventional furrow irrigation (CFI), while the minimum values were obtained with the application of 55% ETc under fixed furrow irrigation (FFI) (Table 2). As the amount of irrigation levels increased the response of garlic yield and yield

Table 2 ANOVA table for yield and yield components of Garlic crop

Treatments	ph (cm)	LL (cm)	No.L/P	LA (cm ²)	LAI (cm ² /cm ²)	D (mm)	Y (t ha ⁻¹)
55%ETc @ AFI	52def	32def	7.2de	117de	0.39ef	38 cd	5.4 fg
70% ETc @ AFI	55cde	34de	7.2de	129dce	0.43def	43bcd	6.4e
85% ETc @ AFI	56bcd	36bcd	8.4ab	141 cd	0.47de	45ab	7.3d
100%ETc @ AFI	59abc	39ab	9.2a	154bc	0.51 cd	48ab	8.1bc
55%ETc@ FFI	48f	29.7f	6.8e	104e	0.35f	38d	4.5 h
70%ETc @ FFI	51ef	30.4ef	7.4cde	118de	0.39ef	41bcd	5.1 g
85%ETc @ FFI	55cde	32.7def	8.3abc	126cde	0.42def	44abc	5.9ef
100%ETc @ FFI	55ce	32.3def	8.6ab	138dc	0.46de	45abc	6.4e
55%ETc @ CFI	57abc	34.4cde	7.8bcd	144 cd	0.48de	42bcd	6.5e
70%ETc @ CFI	59abc	38.2abc	8.8a	182ab	0.61bc	45abc	7.6 cd
85%ETc @ CFI	61ab	40.9a	8.6ab	197a	0.66ab	47ab	8.4b
100%ETc @ CFI	62a	42.2a	9.2a	209a	0.74a	50a	9.1a
mean	55.6	35.2	8.3	146.6	0.49	43.6	6.72
LSD _{0.05}	4.86**	4.04**	0.9**	29.22**	0.1**	6.72*	0.30**
CV (%)	5.18	6.82	6.8	11.8	11.45	9.14	5.34

Ph (plant height), LL (leaf length), No.L/P (number of leaves per plant), LA (leaf area), LAI (leaf area index), and D (bulb diameter); Y (yield) **, *, ns showed highly significant difference ($p < 0.001$), significance difference at $p < 0.05$ and no significant difference respectively

components also were increases. Treatments irrigated with CFI show the highest garlic performance and yield under all irrigation levels compared to AFI and FFI. Treatments irrigated with AFI well performed and resulted in higher yield and yield components when compared with FFI. Maximum yield of garlic (9.1 t ha^{-1}) and the minimum yield of garlic (4.5 t ha^{-1}) were obtained with irrigating 100% ETc under CFI and 55% ETc under FFI respectively. According to different studies conducted at different places, garlic yield obtained by using various water management strategies, ranging from 7.5 to 21.3 t ha^{-1} [22]. The optimal garlic yield was obtained with the application of 85% ETc under AFI. This finding is in close agreement [26], who found a bulb yield of garlic as 9.9 t ha^{-1} with 100% ETc water application.

Figure 3 illustrates the relationship between applied water and garlic yield. The regression model suggests yield of garlic increases as irrigation water level increased from 55% ETc to 100%ETc (Fig. 3). As the regression result shows, 80% increase in yield of garlic was observed due to the increase of irrigation water application. This shows that water is the limiting factor for garlic yield, but other factors are also yield limiting. The range of seasonal water amount in this study ranges from 211 to 592 mm. Another study conducted with various water management showed, a total seasonal water application for garlic ranges from 249 mm to 546 mm [22]. The optimum garlic yield was obtained by the application of $3880 \text{ m}^3/\text{ha}$ of water.

3.2 Effect of deficit irrigation levels under furrow techniques on growth performance of Garlic at various days after sowing

3.2.1 Plant height (ph)

The increase in the ph of garlic was attributed to the higher amounts of water applied under the three furrow irrigation techniques across all sampling days after sowing (DAS) (Fig. 4). The maximum Ph of 68 cm was observed in treatments received 100% ETc under CFI and the minimum Ph of 51.3 cm was recorded with 50% ETc under FFI at 150 DAS. However, garlic Ph showed a decreasing rate at 125 DAS, at ripening stage. Ph increased from 65 DAS to 125 DAS, maximum at 125 DAS, followed by small decline at 150 DAS

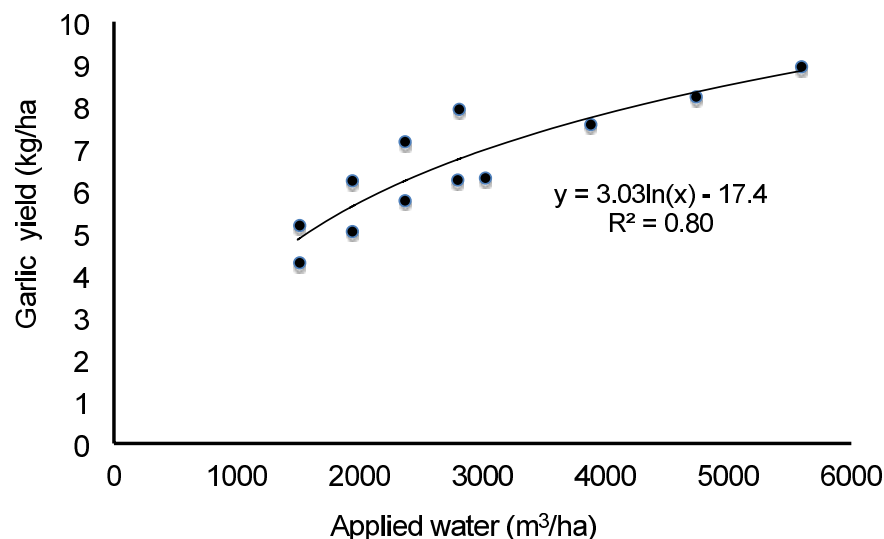


Fig. 3 The response of garlic bulb to applied irrigation water

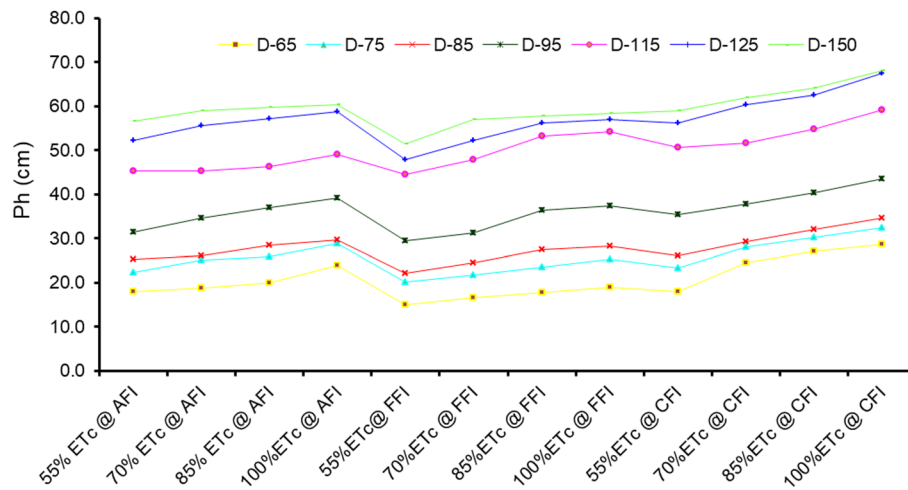


Fig. 4 The effect of deficit irrigation and furrow techniques on plant height of garlic at various DAS

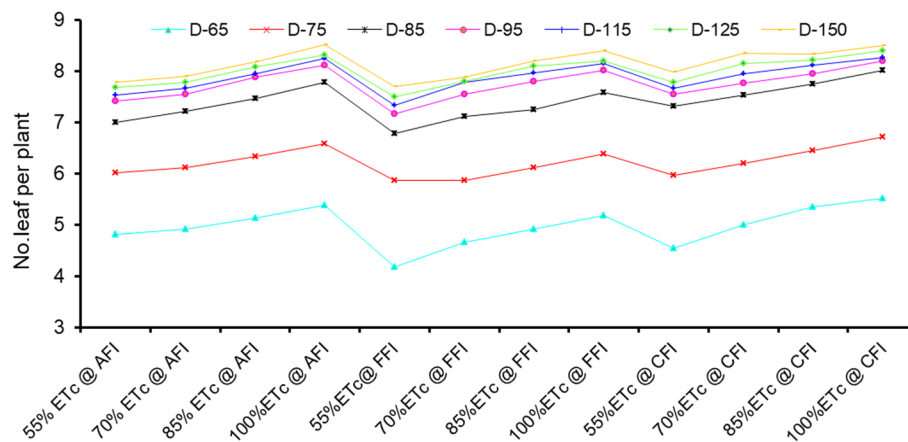


Fig. 5 The effect of deficit irrigation and furrow techniques on leaf number per plant of garlic at various DAS

due to ripening. The fastest growth of Ph was observed from 85 DAS to 115 DAS, indicating a rapid vegetative stage. The application of 85% ETc showed intermediate Ph, suggesting moderate DI may be valuable with low yield penalty. From furrow techniques perspectives, AFI well performed in comparable to CFI at all DI levels, indicating best water use efficiency. In contrast, FFI underperformed due to low water distribution in the root zone. This finding aligns with the results reported by [22], who observed that plant height increased linearly with higher levels of applied irrigation water.

3.2.2 Number of leaf per plant

Figure 5 presents the response of number of leaf per plant to different irrigation levels and furrow techniques. The number of leaf per plant of garlic increased from 65 DAS (4) to 150 DAS (9), indicating continuous vegetative growth. The increase in number of leaf per plant is exponential until 95 DAS, then after there was no much difference (115 DAS, 125 DAS, and 150 DAS). Similar to plant height, the number of leaves per plant increase with higher water application. For instance, 100% ETc resulted in highest leaf count and 55% ETc resulted to smallest number of leaves. The optimal water application of 85% ETc maintained reasonable leaf number. AFI showed optimal leaf numbers with all irrigation

levels, potential as water saving strategy. CFI resulted in maximum leaf number; but less efficient under water restrictions.

3.2.3 Leaf length (LL)

The response of garlic leaf length to DI and furrow techniques at different DAS is shown at Fig. 6. The maximum leaf length was obtained under the application of 100% ETc for all furrow techniques. The minimum LL was recorded in the application of 55% ETc. However, leaf length obtained by 100% ETc and 85% ETc are similar, and the same is true for 70% ETc and 55%. With regards to furrow techniques, CFI well performs in improving LL than AFI and FFI. The application of water by AFI resulted in optimal leaf length of garlic, which will result in better yield. AFI improve LL with the same amount of water application.

3.2.4 Leaf area

Leaf area of garlic is significantly affected by amount of water application and furrow irrigation techniques (Fig. 7). It is increasing progressively from 65 DAS to 150 DAS. The fast LA development occurred between 95 DAS and 125 DAS, indicating the active vegetative growth phase. The maximum leaf area of garlic was observed by the application of 100% ETc under all the three furrow techniques. Water application by AFI resulted in Optimal LAI incomparable with CFI, and higher than FFI with the same amount of water applied. The decrease in irrigation level from 100% ETC to 55% ETC showed a decrease of leaf area and leaf area index. The application of 85% ETc maintained 70 to 85% of the LA values obtained from the application of 100% ETc. However, the leaf area index for different irrigation levels found as in the range of 1.3 to 1.64 cm²/cm² [25]. Thus, the application of 85% ETc under AFI resulted in optimal LA and LAI, possible to provide better water productivity of garlic.

3.2.5 Weight of bulb

The weight of the bulb showed a significant changes due to the deficit levels and furrow irrigation techniques. Garlic bulb weight increased progressively with time across all treatments, showing the cumulative effect of irrigation and growth duration. The highest changes in weight of bulb were observed after 125 DAS (Fig. 8). The application of 100%

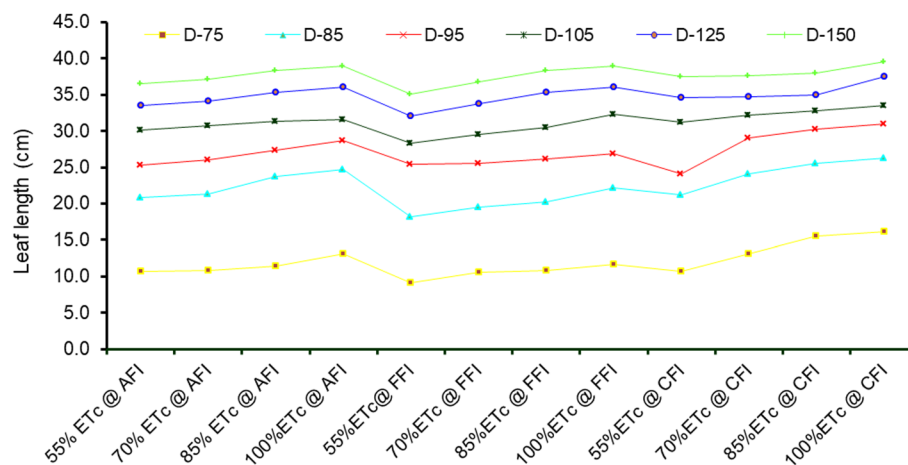


Fig. 6 The effect of deficit irrigation and furrow techniques on leaf length of garlic at various DAS

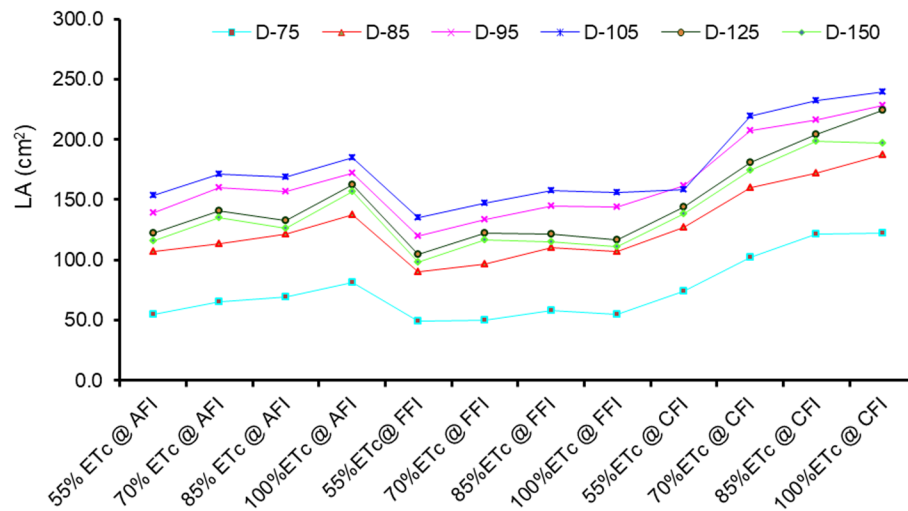


Fig. 7 The effect of deficit irrigation and furrow techniques on leaf area of garlic at various DAS

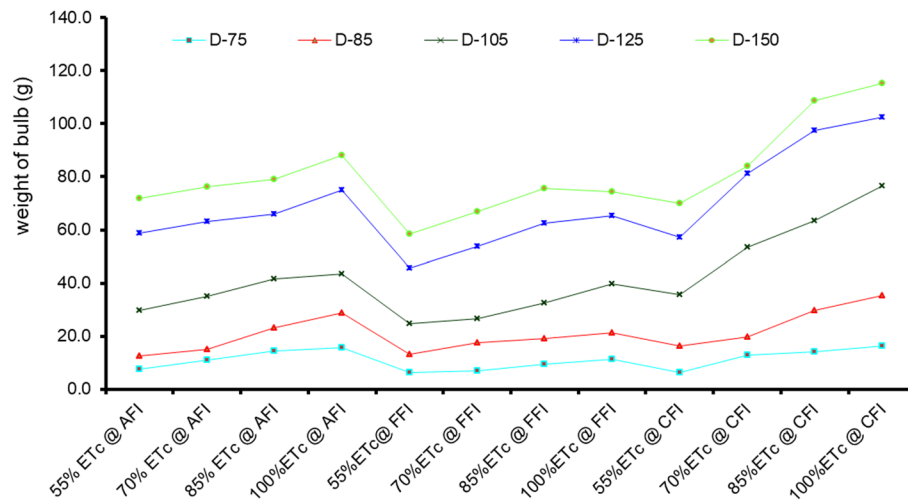


Fig. 8 The effect of deficit irrigation and furrow techniques on weight of bulb of garlic at various DAS

ETc and 85% ETc showed highest weight of bulb under the three furrow techniques. The application of 55% ETc resulted in lowest weight of bulb. However, the application of 85% ETc resulted in moderate bulb yield of garlic. AFI well performed as compared with FFI in producing weight of bulb, but with the same water amount application. This may be attributed to the more favorable soil moisture distribution achieved under the application of full crop water requirement (100% ETc) and 85% ETc, which in turn contributed to improved bulb yield.

3.3 Yield components at physiological maturity

The largest bulb diameter (47 mm) was achieved with the application of 100% ETc, showing no significant difference compared to the treatment that received 85% ETc. In contrast, the smallest bulb diameter (39 mm) was observed under 55% ETc, which was statistically similar to the 70% ETc treatment (Fig. 9). This indicates that a slight reduction in irrigation does not significantly affect bulb diameter, and thus has minimal impact on bulb yield and total biomass. Specifically, reducing irrigation from 100% ETc

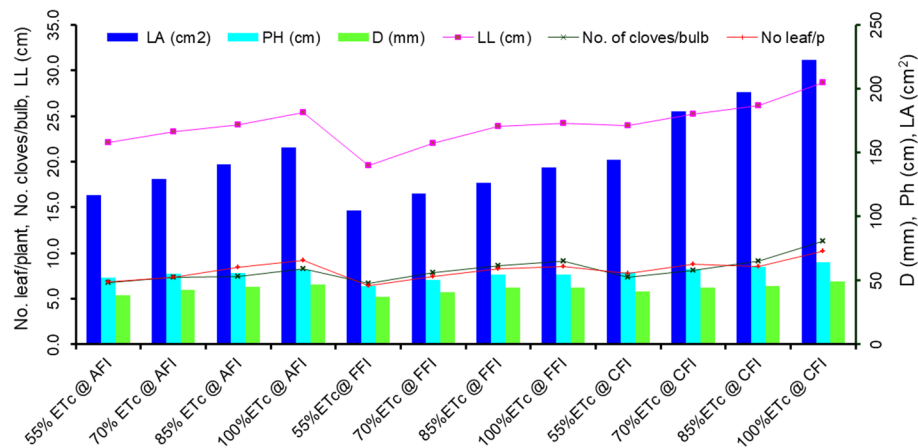


Fig. 9 The effect of deficit irrigation and furrow techniques on yield components of garlic at physiological maturity

to 55% ETc resulted in a 17% decrease in bulb diameter, whereas a reduction to 85% ETc led to only a 4.2% decrease. These findings suggest that moderate reductions in irrigation have little to no adverse effect on bulb diameter and yield. Further research could be conducted to explore the interaction between water and other yield limiting factors (fertilizer, mulches, and disease management).

4 Discussion

4.1 Effect of deficit irrigation and furrow techniques on yield and yield components of Garlic

The obtained garlic yield in this study was from 4.5 to 9.1 t ha⁻¹. Another study conducted with different water management resulted in a bulb yield range from 3.8 to 53 t ha⁻¹ [25]. The decrease in irrigation level from 100% ETc to 55% ETc reflects a decrease of 37.5% of bulb yield of garlic. However, the decrease in irrigation level from 100% ETc to 85% ETc reflects a nearly small change in bulb diameter (9% decrease). This indicates a small reduction in irrigation levels resulted in little reduction on bulb yield. In general, for major horticultural crops, reducing the amount of water applied typically leads to a decrease in yield. However, the best water use efficiency can be achieved with a 20 to 30% water deficit, resulting in only a modest yield reduction of 4 to 8% [27]. Irrigation of garlic on a weekly basis would have produced the maximum yield [28] [29], reported that plots which received the greatest volumes of water yielded with higher percentages of large-size bulbs whereas water shortages lead to higher percentages of small size bulbs. The maximum total bulb yield (9.1 t ha⁻¹) was recorded under the application of 100% ETc under CFI, followed closely by the 85% ETc under CFI and 85% ETc under AFI. This suggests that higher bulb yield is associated with increased total bulb yield in garlic. The garlic crop demonstrated the ability to tolerate moderate water deficits through optimized regulated deficit irrigation, maintaining its physiological functions. As a result, water limitations at moderate levels did not lead to reductions in growth performance or yield [30].

4.2 Effect of deficit irrigation levels under furrow techniques on growth performance of Garlic at various days after sowing

4.2.1 Plant height

In this study, the obtained Ph ranges from 48 cm to 62 cm. These values align with another study who obtained similar range [23]. Another study, on clove size effect on yield and yield components, found higher values of Ph ranges from 64 to 75 cm [16]. Following all DAS, plant height generally increases as the amount of deficit irrigation levels increase in all three-furrow techniques. However, the higher plant height was observed on 125 DAS and 150 DAS for all treatments. This indicates that plant height increases with the amount of water applied. In contrast, Ph was increased up to 90 DAS, and then it showed a decreasing rate [25]. Furthermore, garlic plants grown under AFI method exhibited greater height compared to those under FFI method, even when the total volume of water applied was the same. This suggests that irrigation method, in addition to water quantity, plays a significant role in influencing plant growth performance. The application of 85% ETc under AFI resulted in good Ph and water conservation, making it an effective water management strategy in water-limited areas. While the application of 100% ETc under CFI remains recommended water management strategies where water is abundant.

4.2.2 Number of leaf per plant

Moreover, under the same amount of water applied, garlic plants in AFI treatment produced more leaves by approximately 1.5 leaves; compared to those in FFI method. Therefore, a slight reduction in ETc levels did not result in a significant change in the number of leaves per plant. This finding is consistent with the results of [23], who reported a leaf number ranging from 7 to 10 per plant. However [16], found a range of leaf number from 11.6 to 12.7. The variation might be due to the variation in climate condition, seed materials, soil types, and other management practices. AFI well optimize the number of leaf of garlic next to CFI. However, the amount of water applied is half of CFI, indicates that its efficiency in water-limited conditions by optimizing soil moisture distribution. This suggests that when adequate moisture is available in the root zone, plants can extract sufficient water to sustain photosynthesis through stomatal opening, thereby supporting the emergence of new leaves. The application of 100% ETc produced higher leaf number followed by 85% and 70% ETc. In areas where water is abundant, the application of 100% ETc under CFI is recommended, whereas 85% ETc under AFI remains the best water management strategy under water limited areas.

4.2.3 Leaf length

The mean leaf length obtained in this study at 150 DAS ranges from 35 cm to 40 cm. However, this result is not aligned with other studies result, who found a mean leaf length of 49 to 56 cm [16]. This might be due to the variation in location, soil fertility, climate, and clove size of seed material. The application of deficit amount of nearly 15–25% would not have significant change on leaf length. This might be due to water stress delays leaf tip emergence and reduces leaf expansion of garlic [24]. An exponential increase in garlic leaf length was observed up to 105 days after sowing (DAS) across all treatments. Beyond this point, further increases were minimal, likely because the plant

shifts its energy toward enhancing bulb quality during the maturity stage. The increase in leaf length is affected by the amount of water applied and furrow irrigation techniques.

4.2.4 Leaf area

The increase in leaf area in 100% of irrigation level may be due to better availability of soil moisture to facilitate nutrient availability and photosynthesis.

Similarly, under water stress conditions in the root zone, the plant expends more energy to extract water, resulting in a lower rate of photosynthesis, reduced leaf expansion, and a smaller leaf area. This ultimately reflects poor garlic performance and leads to reduced bulb yield [24]. The increase in leaf area showed minimal differences after 85 days after sowing (DAS); however, a gradual increase continued up to 150 DAS. LAI development follows predictable temporal patterns, peaking at mid-growth stages at 125 DAS. AFI well performed in improving garlic leaf area in comparable to CFI at higher ETc levels (85–100%). LA values below 150 cm² observed at 55% ETc may indicate inadequate canopy for optimal photosynthesis at 150 DAS. The strong relation between the amount of water applied and LA showed water as the primarily driver of good canopy development and yield of garlic.

4.2.5 Weight of bulb

The lowest aboveground biomass was recorded in plots irrigated with 55% ETc, which was statistically similar to that of 70% ETc. However, a biological difference was observed between the two treatments, suggesting a physiological response not fully captured by statistical significance. This shows a small reduction of irrigation water levels would not have brought significant reduction of above ground biomass. A reduction in irrigation level from 100% ETc to 55% ETc led to a 27.3% decrease in aboveground biomass. In contrast, reducing irrigation from 100% ETc to 85% ETc resulted in only a minor decrease of 4.5%. This suggests that a slight reduction in irrigation has little to no impact on aboveground dry biomass.

4.3 Yield components at physiological maturity

As shown in Fig. 8, garlic growth characteristics typically improved as water levels rose, with the application of 100% ETc with consistently producing the greatest values for the most of the growth attributes. Strong sensitivity to water levels and furrow procedures was demonstrated by the most notable increases in leaf area and length. While there were slight variations in leaves per plant, plant height and bulb diameter. Overall, the increased water application had a good impact on the growth and development of garlic; with 100% ETc under CFI showed the maximum results (9.1 t ha⁻¹) and the application of 55% ETc under FFI resulted in the minimum values (4.5 t ha⁻¹) in all parameters. The yield of garlic depends on several factors, fertility management, seed material quality, varieties, climatic conditions and other biotic and abiotic factors. For instance, the archived garlic yield by using various water management strategies showed a bulb range of 7.5 to 21.45 t ha⁻¹ (22). Another study showed an achieved garlic bulb yield of 34 and 30 t ha⁻¹ with drip and gravity irrigation methods [31]. The obtained result is however very smaller than others studies, which showed a detailed investigation on garlic production is important. All yield components exhibited an increasing trend with increasing irrigation water levels. However, the optimum yield (8.3 t ha⁻¹) was achieved under

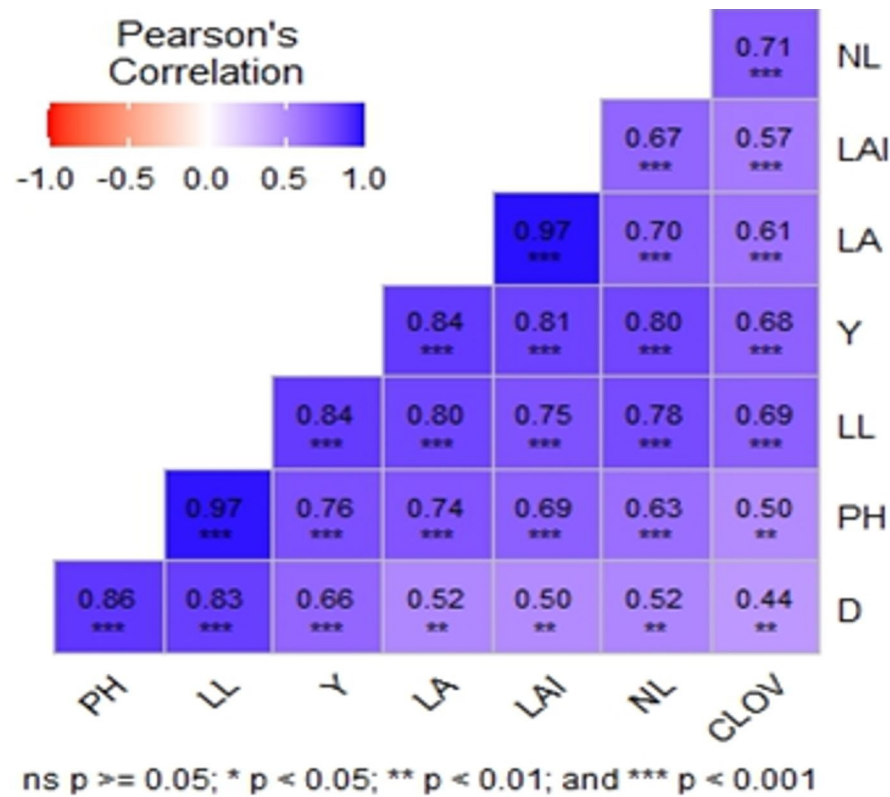


Fig. 10 Pearson's correlation coefficient of yield and yield components of garlic

the application of 85% ETc with AFI. This aligned with another study, they found a garlic yield of 6.8 t ha⁻¹ with the application of 80% ETc [32].

4.4 Correlation analysis

Figure 10 shows a Pearson's correlation matrix that illustrates the connections between a number of garlic yield and growth factors. Asterisks (***) = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, ns = not significant) indicate statistical significance. The color intensity and values show the strength and direction of correlation. Garlic yield was highly positive and significantly linked with plant height ($r = 0.76$), leaf length ($r = 0.84$), LA ($r = 0.84$), LAI ($r = 0.81$), number of leaves per plant ($r = 0.80$), clove number ($r = 0.68$), and bulb diameter ($r = 0.66$), according to the Pearson correlation analysis (Fig. 10). Moreover, all yield components were positively and strongly correlated each other. For instance, plant height was highly correlated with leaf length ($r = 0.97$) and the others in such manner (Fig. 10).

A strong relation between ETc and growth parameters shows water availability as a promising factor for garlic growth and yield. In water-scarce regions, applying regulated deficit irrigation of 85% ETc under AFI is recommended to optimize better garlic growth and yield. The effect of AFI may stem from optimal root zone soil moisture distribution and partial drying effect. Conversely, in areas with abundant water resources, application of 100% ETc under CFI can be practiced to maximize garlic yield and yield components. These irrigation management strategies can be applicable in the study area and other similar agro ecological zones. Future research should be recommended to explore

the interaction effect of water with fertilizer application to refine irrigation water management strategies.

5 Conclusion

This study addressed a crucial research need for water-efficient production in the area by evaluating the combined impacts of furrow irrigation and deficit irrigation (DI) on garlic production in highland of Debre Birhan. The key findings demonstrate that; the highest garlic yield and yield components were obtained with full irrigation (100% ETc) under conventional furrow irrigation (CFI), demonstrating that the best water supply maximizes output. This can be applied in areas where water resource is abundant. However, the application of 85% ETc regulated deficit irrigation under AFI provides optimal yield and yield components with high water saving, considered as an option for water-saving technique for regions with water limited areas. The better performance of AFI method over the CFI and FFI contributed to better crop growth and more efficient water distribution. Strong correlations between garlic yield and yield components; such as plant height, leaf length, leaf area, and bulb diameter, underscore the importance of optimizing irrigation strategies to maximize garlic production.

To maximize water use without compromising yield, farmers should use regulated deficit irrigation at 85% ETc under AFI; drops below 70% ETc should be avoided to prevent significant yield losses. Yield components such as plant height, leaf length and leaf area index can be used as early indicators of crop performance for irrigation. Policy makers should be promoting the importance DI and AFI through training for farmers cultivating garlic. Further research is needed to explore the integrated use irrigation and nutrient management for enhancing garlic productivity.

Acknowledgements

The authors would like to acknowledge Debre Birhan Agricultural Research Center, for providing me this scholarship's and Department of Water Resource and Irrigation Engineering, Institute of Technology, Hawassa University.

Plant guidelines

The authors confirm that the use of plants cultivated in this study complies with relevant institutional, national, and international guidelines and legislation.

Source of seeds in this study

Study Seeds were collected from Debre Birhan Agricultural Research Center.

Author contributions

Biruk Getaneh participates in initiating the proposal; collecting and encoding the data, analysis, and interpretation of the data and writing the full manuscript. Shemelies Asseffa and Abraham Woldemichael participate in advising proposal initiation and implementation, and finally revising the draft of the manuscript. Ayele Desalegn participates in editing and reviewing the manuscript.

Funding

No funding was received for this research.

Data availability

The data supporting this study are available upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 10 April 2025 / Accepted: 21 August 2025

Published online: 29 August 2025

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