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ABSTRACT: Crop production is largely limited by water availability in arid and semi-arid regions of Ethiopia. Changing climate conditions and declining water resources demand appropriate approaches to improve crop yield and water use efficiency through a reduced and more reliable water supply. A field experiment was conducted to evaluate the effect of limited irrigation water use on bread wheat production and water use efficiency under the semi-arid climate conditions of Awash basin of Ethiopia. Five irrigation levels, that is, full irrigation (100% ETc/control), 85% ETc, 70% ETc, 55% ETc, and 40% ETc, were evaluated using a randomized complete block design (RCBD) with four replicates. Statistical analysis has shown a significant effect of irrigation levels on wheat grain yield, water use efficiency, economic profit, wheat grain quality, and aboveground biomass. The highest grain yield (5,085 kg ha^{-1}) was obtained from 100% ETc irrigation application (i.e. 417.2 mm of water), and the lowest grain yield was obtained from 40% ETc (i.e. 223.7 mm of water) application. A deficit level of 85% ETc resulted in a yield that was comparable to that of full irrigation. Compared to other treatments, the 70% ETc application produced the highest water use efficiency (1.42 kg m^{-3}). Using the saved water obtained from 70% ETc deficit irrigation application, 23.4% more wheat could be produced on 1.38 ha of land, resulting in the highest profit (US$2,563.9) and higher MRR (137%). The yield response factor and crop-water production function indicated that maintaining irrigation at optimal levels can prevent potential yield reductions. Consequently, a 70% ETc deficit irrigation application was found to be optimal for increasing wheat grain yield, water use efficiency, and economic benefits from irrigated wheat production. These results suggest that deficit irrigation for wheat under semi-arid climatic conditions is a viable irrigation management option for enhancing water use efficiency.

KEYWORDS: Bread wheat, deficit irrigation, evapotranspiration of crop, semi-arid, water use efficiency

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Introduction

One of the biggest issues facing the world today is the scarcity of freshwater resources, particularly for irrigated agriculture, which is the main consumer of freshwater (Ingrao et al., 2023; Jägermeyr, 2020; World Water Assessment Programme [WWAP], 2015a). In the Awash basin of Ethiopia, which is mainly characterized by arid and semi-arid climatic zones, water is the most limiting constraint and has prime importance for the supply of food (Adeba et al., 2015). The main aspects, like changing climate conditions, rapid population growth, and unmanaged usage of available water resources, lead to distressing conditions in Ethiopia and the globe in general (Adeba et al., 2015; Etissa et al., 2014; Liu et al., 2022; Taye et al., 2018; United Nations International Children's Emergency Fund, 2022). With the increase in water shortage and the need to increase grain production to meet global food demand, how to manage the limited water to obtain the most benefit per unit of water is a great and important issue (International Commission for Irrigation and Drainage, 2022).

Although irrigation of vegetable crops and commercial crops like cotton, fruits, and bananas has a long history in Ethiopia, the production of cereal crops like wheat under irrigation is limited. Wheat (*Triticum aestivum L.*), the target crop in this study, is one of the most significant food crops in the world (Tadesse et al., 2017). The crop constitutes approximately 17% of Ethiopia's overall grain production, positioning it as the third most significant cereal crop in the country, following tef and maize (Central Statistical Agency, 2021). This study underscores the critical need for enhancing agricultural production through sustainable and cost-effective energy solutions for irrigation in Ethiopia. With a focused dedication from the Ethiopian government, significant strides have been made, including expanding cultivation in irrigable lowlands and increasing productivity in rain-dependent agricultural ecosystems (Tadesse et al., 2022). Evidence suggests a notable increase in crop production and expanded cultivation area (Tefera, 2020). However, this expansion into arid and semi-arid lowlands has strained water resources, leading to heightened competition and disputes among water users, particularly in regions like the Awash Basin where water resources are already limited (Etissa et al., 2014). Therefore, the study emphasizes the imperative of improving agricultural water utilization and rationalizing water resource management, particularly in arid and semi-arid areas, to sustainably support agricultural growth and mitigate conflicts (Forouzani & Karami, 2011; Li & Qian, 2018).

In semi-arid regions, maintaining wheat production hinges on implementing irrigation methods that conserve water and

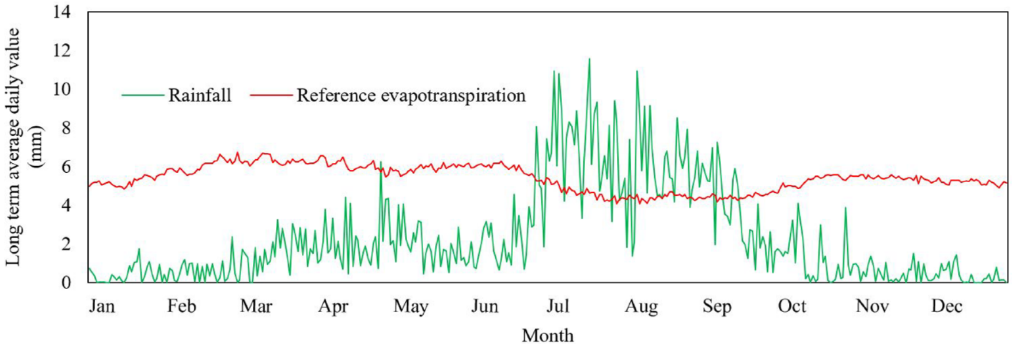

Figure 1. Seasonal water balance of the study area (1992–2022).

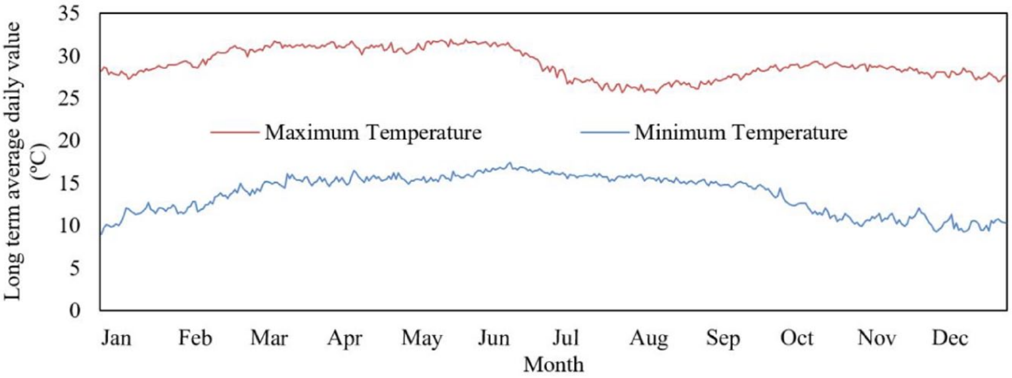

Figure 2. Seasonal variation of temperature in the study area (1992–2022).

enhance water use efficiency (Du et al., 2010). Deficit irrigation, a water-saving technique in agriculture, involves supplying crops with less water than their full requirements (Du et al., 2015). Research indicates that this technique is effective in improving water use efficiency and reducing water wastage, particularly in cereal crops such as wheat (Asmamaw et al., 2023; Du et al., 2010).

Deficit irrigation involves applying water below the crop's full requirements, inducing mild stress (Food and Agricultural Organization [FAO], 2011; WWAP, 2015b). While some production reduction is anticipated, the saved water can be used to irrigate additional land or for other beneficial purposes, potentially outweighing the yield loss (FAO, 2011). Deficit irrigation can also enable plants to more efficiently use water (Laita et al., 2024). Moreover, it aims to leverage biochemical changes within plant systems triggered by water stress conditions (Golzardi et al., 2017).

Some studies have reported that wheat can withstand a water shortage with minimal yield loss (Asmamaw et al., 2023; Du et al., 2010; Memon et al., 2021). However, more research is needed on improved and disease-resistant varieties, such as Kingbird, a stem rust-resistant wheat variety developed for lowland areas in Ethiopia (McCandless, 2015; Nigus et al., 2022).

In this study, a field experiment was conducted to evaluate the effects of varied depths of deficit irrigation on yield, grain quality, water use efficiency, and the financial advantage of the Kingbird wheat variety under water-limited condition.

Materials and Methods

Description of the study area

The field experiment was conducted at the experimental farm of Melkassa Agricultural Research Center (MARC; latitude 8°24′N, longitude 39°21′E, and altitude of 1550 m) in Ethiopia for two consecutive years in the cropping season (December–March) of 2021/2022 and 2022/2023.

The area is characterized by a semi-arid climate. The weather station data from the center was used to examine seasonal variation of climatic variables and reference evapotranspiration. The seasonal fluctuation in rainfall, reference evapotranspiration, and temperature data from records spanning 31 years (1992–2022) is shown in Figures 1 and 2, respectively. The short rainy season occurs in the area from March to April followed by the main rainy season from June to September with some dry spells in May. The seasonal pattern of evapotranspiration along with rainfall shown in Figure 1 signifies the occurrence of large evapotranspiration deficit in the area throughout the year, except for the period from late June to early September. The higher air temperatures and reference evapotranspiration (ETo, mm) occur from March to May, whilst the lower air temperatures and reference evapotranspiration (ETo, mm) occur in January and December and July and August, respectively. The average relative humidity and wind speed observed in the area were 53.66 ± 12.83% and 2.64 ± 0.82 m s^{-1}, respectively.

Table 1. Soil Characteristics in the Experimental Site.

SOIL DEPTH (CM)	TEXTURE	FC% (W/W)	WP% (W/W)	AWC (MM/15 CM)	BD (G CM^{-3})	EC (DS M^{-1})	PH
0–15	Clay loam	34.44	23.57	18.10	1.11	1.49	6.53
15–30	Clay loam	36.78	23.51	22.29	1.12	1.55	6.47
30–45	Clay loam	35.97	21.89	23.65	1.12	1.70	6.45
45–60	Clay loam	34.19	20.77	22.95	1.14	1.78	6.45

Based on the MARC soil laboratory analysis report, the soil of the experimental farm was clay loam and categorized as Andosol (Getnet et al., 2022). The percentage soil water content at field capacity was between 34.19% and 36.78%, and the permanent wilting point was between 20.77% and 23.57% on a weight basis. The bulk density was between 1.11 and 1.14 g cm^{-3}, and electrical conductivity (EC) was between 1.47 and 1.78 dS m^{-1}. The average soil pH of the experimental site as determined during the study was. Some physical and chemical properties of the study area are listed in Table 1.

Experimental treatments and design

An experimental trial consisting of five irrigation levels was conducted for two successive cropping seasons (2021/2022–2022/2023). The irrigation levels were applications of 100% ETc, 85% ETc, 70% ETc, 55% ETc, and 40% ETc, where ETc represents crop evapotranspiration estimated using the soil water balance method. The experiment was laid out in a randomized complete block design (RCBD) with four replications. A total of twenty experimental plots, each measuring 3.6 m in width and 5 m in length, were used in the experiment.

Crop management

Bread wheat, a kingbird variety, was planted for two consecutive years with haricot bean-wheat cropping sequences during both the 2021/2022 and 2022/2023 cropping seasons. The Kingbird is the resistant variety to the Ug99 and TKTTF stem rust strains and is recommended to be planted in the lower elevation agro-ecologies from 1,200 to 2,000 m above sea level (McCandless, 2015). After the land was well prepared and ridges were made with 60 cm ridge spacing, sowing was done by drilling manually in a row with a seeding rate of 125 kg ha^{-1} in early December of each year. The seed was sown in a double row (spaced 20 cm) on both sides of the ridges. Weed management was done manually and regularly. The crop was harvested on March 16, 2022, for the first-year experiment and on March 28, 2023, for the second-year experiments.

Soil fertilization

All treatments received the recommended doses of Urea (46% N) and NPS (19% N, 38% P_2O_5, and 7% S) as fertilizer sources. At planting, a full dose of NPS (125 kg ha^{-1}) and 25% of the Urea (25 kg ha^{-1}) were applied as a basal dressing. The remaining Urea (75 kg ha^{-1}) was top-dressed at tillering stage (Tilahun & Tamado, 2019).

Soil moisture monitoring

Soil moisture was monitored using a calibrated neutron probe (CPN 503DR) and the gravimetric method. Measurement were done before and after irrigation evens at depths of 0 to 15, 15 to 30, 30 to 45, and 45 to 60 cm for the control treatment. The gravimetric technique was applied to the top 15 cm, while the neutron probe was used for depths between 15 and 60 cm.

Crop water requirement

The soil water balance method of irrigation scheduling was employed to estimate the required amount and timing of irrigation for the crop. The simplified Kang et al. (2002) water balance equation was utilized to calculate the evapotranspiration of the crop (ETc) during the wheat growing season, represented as:

$$ETc = IW + P \pm \Delta S \tag{1}$$

where ETc is the actual crop evapotranspiration, IW is the applied irrigation water, P is the precipitation and ΔS is the change in soil water storage between two consecutive irrigation events measured before irrigation using neutron probe and gravimeter. All measurements are expressed in millimeters of water depth.

Run-off was not accounted for in the water balance equation due to all plot furrows were blind-ended and encircled by wider bunds, with irrigation water application carefully controlled to prevent overflow (Andales et al., 2015). Since the irrigation water was intended solely to replenish depleted soil moisture for the control treatment and to a lesser extent for deficit levels, deep percolation was considered negligible (Asmamaw et al., 2023). Moreover, capillary rise was not considered, as the groundwater table is below 16 m at the study site (Metaferia Consulting Engineers, 2019).

Irrigation management

Irrigation was triggered whenever the total available soil moisture content in the effective root zone of the control treatment was depleted by 50% ($\rho = .50$; Allen et al., 1998). The other plots received irrigation water in accordance with their ETc proportion, that is, 85%, 70%, 55%, and 40% of the amount applied for the control treatments.

At each irrigation event, water was diverted into the experimental field from a field canal at a constant rate. The measured amount of water was allowed to enter each plot and each furrow for a given time. A 3″ throat width calibrated standard Parshall flume installed at the inlet of the experimental field was used to measure the water flow. The time duration required to apply the desired depth of water per irrigation was determined as:

$$t = \left(\frac{DA}{Q}\right) \tag{2}$$

where, t is the time (in s) required to apply the desired depth of water, D is the irrigation depth (mm) applied at the irrigation event, A is the area of the plot to be irrigated (m^2), and Q is the discharge (l s^{-1}) measured using Parshall flume, based on the water level in the flume throat.

Crop data collection

The wheat crop harvested from the middle rows was used to determine grain yield and aboveground biomass. The harvested crop was then manually threshed with wooden sticks, and the cleaned grain was weighed to determine the yield. The grain moisture level was recorded using a grain moisture meter to adjust the measured grain weight to the standard moisture level of 13.5% for wheat (Reese & Carlson, 2018). The plant aboveground biomass was dried in an oven set at 65°C (International Maize and Wheat Improvement Center, 2013).

For the wheat grain quality test, one thousand seeds were counted from threshed grains using a Preuffer Contador seed counter and weighed to estimate thousand kernel weight (TKW). TKW is highly affected by water deficits and helps in assessing the impact of deficit irrigation on final yield. To assess the quality of the wheat, the protein and starch content of the grain were also examined in the food science lab at Kulumsa Agricultural Research Center.

Water use efficiency

Water use efficiency (WUE) is a widely used parameter to describe irrigation effectiveness in terms of crop yield. The WUE was determined using the relationship described in Howell (2001), which is the ratio of the grain yields attained for each treatment to the corresponding seasonal amount of water consumed by the crop.

$$WUE = \left(\frac{Y}{ETa}\right) \tag{3}$$

where, WUE represents water use efficiency (kg m^{-3}); Y denotes grain yield (kg ha^{-1}); ETa denotes actual crop evapotranspiration (m^3 ha^{-1}).

Crop–water production function

The relationship between wheat grain yield and the corresponding water used by the crop was determined by non-linear regression analysis. In this model approach, the irrigation levels were taken into consideration for projecting the wheat yield. Wheat yield was taken as a dependent variable and plotted against irrigation level as an independent variable to derive a mathematical crop-water production function (Varzi, 2016).

Crop yield response factor

The yield response factor (K_y), which connects a drop in relative yield to an evapotranspiration deficit was used to express the relationship between wheat yield and water used by the crop (Foster & Brozović, 2018). The basic functional relationship between evapotranspiration and crop yield is given by equation (4), which expresses relative crop yield (i.e. the ratio of actual yield to estimated maximum crop yield, Ya/Ym) as a function of relative seasonal crop evapotranspiration rate (ETa/ETm) and K_y, which defines crop yield response factor (Doorenbos & Kassam, 1979).

$$\left\{1 - \frac{Ya}{Ym}\right\} = Ky\left\{1 - \frac{ETa}{ETm}\right\} \tag{4}$$

Cost benefit analysis

The purpose of the economic component of the study was to evaluate and compare the economic returns of producing wheat using different levels of deficit irrigation. Such evaluation is necessary to give farmers and farm managers useful recommendations (Asmamaw et al., 2023) regarding the economics of water saving through efficient irrigation water management. During the wheat growing seasons, production inputs (seed, fertilizer, machine, labor, land, and water) and their costs, along with the market value of wheat grain produced were recorded (Table 2). The cost of the energy used to pump the water was also recorded and utilized in the analysis as the cost of the irrigation water. Input costs, revenue, and gross profit were calculated per hectare. The additional land that could be irrigated using the saved water due to deficit irrigation, besides the extra costs associated with cultivating additional land (fertilizer, seed, labor, and other charges) were then considered. The three economic performance indicators used were: (i) gross benefit; (ii) marginal or incremental net benefits; and (iii) marginal rate of return (MRR). All financial figures were converted into United States dollars (US$) using the prevailing exchange rate of 54 Ethiopian birr (ETB) as of April 11, 2023.

Statistical analyses

The collected data were subjected to an analysis of variance (ANOVA) appropriate to RCBD and analyzed using R software, version 4.3.1. Whenever the treatment effects were found to be significant, Tukey's honest significant difference (HSD) test was performed to assess any significant difference among treatment means at a level of .05. The relationships between yield and water used, yield reduction and water deficit, and biomass and plant height were analyzed using a regression model.

Results and Discussion

Weather conditions during the crop growing period

The wheat-growing season from December to March was a dry period. Summary of weather data, namely: minimum and maximum air temperature (°C), relative humidity (%), wind speed ($\mathrm{m\,s^{-1}}$, recorded at a height of 2 m), sunshine hours ($\mathrm{h\,day^{-1}}$), and solar radiation prevailing during the experimental periods are shown in Table 3. During the crop seasons, the daily minimum and maximum temperatures ranged between 4°C and 19°C, and 21.5°C and 35°C, respectively.

Relative humidity ranged from 36% to 61% during the 2021/2022 growing season and from 56% to 88% during the 2022/2023 growing season. The reference evapotranspiration (ETo) during the experimentation was estimated using the CropWat model employing the Penman-Monteith equation. The ETo obtained in the first cropping season was found to be greater than that of the second season due to relatively high evaporative demand (low relative humidity and high radiation) (Table 3).

Table 2. Average Values Used for the Cost Benefit Analysis.

ITEM	VALUES (US$)
Seed (US$ $\mathrm{kg^{-1}}$)	1.30
Fertilizer (US$ $\mathrm{ha^{-1}}$)	111.11
Labor cost (US$ $\mathrm{ha^{-1}}$)	333.33
Water cost (US$ $10^{-3}\,\mathrm{m^{-3}}$)	7.04
Pesticides (US$ $\mathrm{ha^{-1}}$)	125.00
Machine cost for land preparation (US$ $\mathrm{ha^{-1}}$)	185.19
Machine cost for harvesting (US$/100 kg)	3.70
Cost of land (US$ $\mathrm{ha^{-1}}$)	592.59
Wheat grain price (US$ $\mathrm{kg^{-1}}$)	0.83

Seasonal water used

The depth of irrigation water used and the seasonal water requirement of the treatments are given in Table 4. In the first experimental year (2021/2022), a total of 395 mm of irrigation water was used for full irrigation treatment (100% ETc) with 14 irrigation events. The amount of irrigation water used for other treatments varied between 173 and 341 mm depending on the level of water deficit imposed. The overall irrigation water used for each deficit treatment was proportionate to the deficit level, apart from the two common irrigations given to the plant establishment (25 mm). In the second experimental year (2022/2023), the irrigation amount in the full irrigation treatment was 305 mm with 11 irrigation events. For the other treatments, the irrigation amount varied from 140 to 265 mm. The total irrigation given to establish the plant before starting the treatment was 30 mm. The effective amount of precipitation was 29.4 and 105 mm in the seasons 2021/2022 and 2022/2023, respectively.

The variation in depth of irrigation and seasonal water requirement values during the two years was due to the difference in weather conditions during the two growing seasons. The lower depth of irrigation observed in the second-year experiment was mainly because of lower air temperatures, higher air humidity, lower solar radiation, and higher effective rainfall (Sun et al., 2010; Tari, 2016).

Grain yield

The two-year research study revealed a significant ($p < .05$) impact of deficit irrigation levels on wheat grain yield during both the 2021/2022 and 2022/2023 growing seasons (Table 5). Increasing irrigation levels from 40% to 100% of ETc consistently increased yield in both years. The average wheat yield ranged from 2.51 to 5.09 $\mathrm{t\,ha^{-1}}$ with the highest yield (5.09 $\mathrm{t\,ha^{-1}}$) obtained under full irrigation (100% ETc) and the lowest yield (2.51 $\mathrm{t\,ha^{-1}}$) observed under 40% ETc.

A clear trend of decreasing wheat yield was observed as water deficit levels increased, with the most significant reductions occurring at the highest deficit levels. Yield reductions at 55% and 40% ETc were markedly higher, at 32% and 51%,

Table 3. Weather Conditions During the Study Period (2021/2022 and 2022/2023).

GROWING SEASON (DECEMBER–MARCH)	T_{MIN}	T_{MAX}	RELATIVE HUMIDITY	WIND SPEED	SUNSHINE HOUR	SOLAR RADIATION	ETO
	°C	°C	%	$\mathrm{M\,S^{-1}}$	H	$\mathrm{MJ\,M^{-2}\,DAY^{-1}}$	MM/DAY
2021/2022	12.07 ± 3.64	29.92 ± 1.81	48.72 ± 5.50	2.39 ± 0.52	9.55 ± 1.47	22.13 ± 2.40	5.37 ± 0.67
2022/2023	10.81 ± 3.49	28.92 ± 2.11	78.48 ± 8.37	2.42 ± 0.73	8.53 ± 2.39	20.95 ± 3.40	4.35 ± 0.54

Table 4. Irrigation Dates and Depth of Irrigation During 2021/2022 and 2022/2023 Growing Season.

DAS	ETO MM	DEPTH OF IRRIGATION IN MM DURING 2021/2022					DAS	ETO MM	DEPTH OF IRRIGATION IN MM DURING 2022/2023				
		100% ETC	85% ETC	70% ETC	55% ETC	40% ETC			100% ETC	85% ETC	70% ETC	55% ETC	40% ETC
1–5	25	15	15	15	15	15	1–5	23	15	15	15	15	15
6–11	30	10	10	10	10	10	6–11	26	15	15	15	15	15
12–16	24	15	13	11	8	6	12–25	55	15	13	10	8	6
17–23	38	15	13	11	8	6	26–33	34	20	17	14	11	8
24–31	40	25	21	18	14	10	34–40	31	25	21	17	14	10
32–38	36	30	26	21	17	12	41–49	41	30	26	21	16	12
39–49	51	30	26	21	17	12	50–57	38	35	30	25	19	14
50–55	31	30	26	21	17	12	58–64	34	40	34	28	22	16
56–60	26	35	30	25	19	14	65–73	39	40	34	28	22	16
61–67	39	40	34	28	22	16	74–82	43	40	34	28	22	16
68–75	46	40	34	28	22	16	83–103	81	30	26	21	16	12
76–83	48	40	34	28	22	16							
84–2	57	40	34	28	22	16							
93–102	67	30	25	21	17	12							
Total (mm)	558	395	341	286	230	173		445	305	265	222	180	140
RF_{eff} (mm)		29.4	29.4	29.4	29.4	29.4			105	105	105	105	105
ETc (mm)		424.4	371.4	312.4	257.4	202.4			410	370	327	285	245

Note. DAS = days after sowing; ETo = reference evapotranspiration; ETc = crop evapotranspiration; RF_{eff} = effective rainfall.

Table 5. Wheat Grain Yield at Different Irrigation Levels During 2021/2022 and 2022/2023.

DI TREATMENTS	GRAIN YIELD (T HA^{-1})		
	2021/2022	2022/2023	POOLED
100% ETc	5.01^{a}	5.16^{a}	5.09^{a}
85% ETc	4.72^{ab}	4.94^{ab}	4.83^{ab}
70% ETc	4.39^{b}	4.71^{b}	4.55^{b}
55% ETc	3.36^{c}	3.59^{c}	3.47^{c}
40% ETc	2.35^{d}	2.67^{d}	2.51^{d}
CV	4.95	3.70	5.87
$HSD_{0.05}$	0.44	0.35	0.35

Note. Figures carrying different letters are significant different at 5% probability.

Table 6. Water Use Efficiency Obtained During 2021/2022 and 2022/2023.

DI TREATMENTS	WUE (KG M^{-3})		
	2021/2022	2022/2023	POOLED
100% ETc	1.18^{b}	1.26^{b}	1.22^{bc}
85% ETc	1.27^{ab}	1.33^{ab}	1.31^{ab}
70% ETc	1.39^{a}	1.44^{a}	1.42^{a}
55% ETc	1.29^{ab}	1.26^{b}	1.28^{b}
40% ETc	1.16^{b}	1.09^{c}	1.13^{c}
CV	5.22	3.88	6.14
HSD$_{0.05}$	0.15	0.11	0.11

Note. Figures carrying same letter are not significantly different at 5% probability.

respectively. In contrast, at optimal deficit levels of 85% and 70% ETc grain yield decreased by only about 5.11% and 10.61%, respectively. Given that the yield reduction is relatively lower compared to the amount of water saved, the 85% and 70% ETc deficit levels are considered optimal for expanding irrigation in water-scarce areas. The result is consistent with the findings of previous studies (Asmamaw et al., 2023; Meena et al., 2019; Memon et al., 2021; Tari, 2016), emphasizing the importance of optimal water availability for maximizing wheat yield.

Water use efficiency

Water use efficiency (WUE) was calculated based on water consumption throughout the wheat growing season. Statistical analysis revealed a significant ($p < .05$) effect of all deficit irrigation levels on WUE in both the 2021/2022 and 2022/2023 growing seasons (Table 6). The pooled WUE ranged between 1.13 and 1.42 kg m^{-3}. The highest WUE values were observed with 70% ETc irrigation, followed by 85% and 55% ETc irrigation, indicating optimal water use efficiency in these treatments. Notably, the highest WUE did not coincide with the maximum grain yield.

WUE peaked at 70% ETc but decreased as irrigation amounts were further increased or decreased. This suggests a complex relationship between irrigation level, yield, and WUE. While lower water application limited grain yield, increasing water application led to improvements in both grain yield and WUE. However, the rate of improvement in yield and WUE diminished with further increases in water application. Ultimately, when WUE reached its peak, additional water use resulted in only marginal increases in grain yield, leading to a decline in WUE.

These findings are consistent with previous studies (Meena et al., 2019; Memon et al., 2021), which also reported a significant increase in WUE with reduced water use in wheat. The results of the study highlight the importance of finding an optimal balance between water use and grain yield to maximize WUE in wheat production.

Crop water production function

The relationship between wheat yield and cumulative water use exhibited a curvilinear pattern, as illustrated in Figure 3. A strong quadratic polynomial relationship, with a coefficient of determination (R^2) of .96, provided the best fit to describe this relationship. The resulting regression equation is presented as equation (5). The analysis revealed that beyond a certain threshold, further increases in water use did not significantly affect yield performance. Similar observations of non-significant yield increase beyond a threshold water application have been reported in wheat by Zhang et al. (2023). Bozkurt et al. (2006) also found significant second-order polynomial relationships between grain yield and irrigation water use for hybrid maize.

$$Y = -0.0492ETa^2 + 44.513ETa - 4886.9\ (r^2 = 0.9554) \quad (5)$$

Figure 4 presents the linear relationship between relative yield reduction and relative actual evapotranspiration deficit, illustrating the impact of water deficit on wheat yield. A linear decrease in relative yield was observed with increasing relative ETc deficit, resulting in a K_y value of 0.93 based on the pooled data. This implies that the applied water stress had a moderate impact, leading to a less than proportional reduction in wheat grain yield. Seasonal K_y values ranged from 0.45 to 1.20 for the different deficit irrigation levels. K_y values consistently increased as water deficit increased. The lowest K_y values were observed under mild deficit irrigation (85% and 70% ETc), where the yield reduction was approximately half of the relative ETc deficit. This suggests that the induced water stress was relatively tolerable. This result indicates that in the semi-arid to arid climate of the Awash Basin and in areas with similar climates and management practices, optimal deficit irrigation application may be a viable strategy. This approach could potentially lead

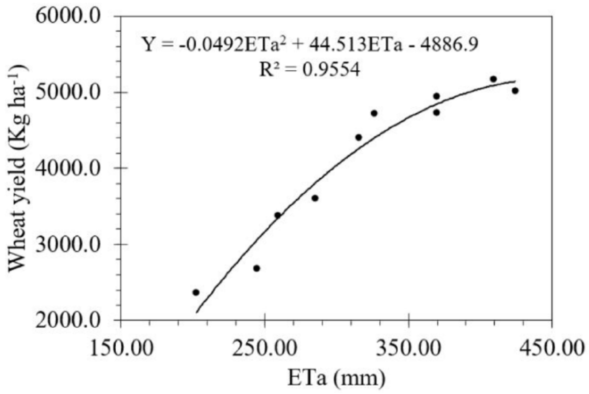

Figure 3. Relationships between wheat grain yield and seasonal water used.

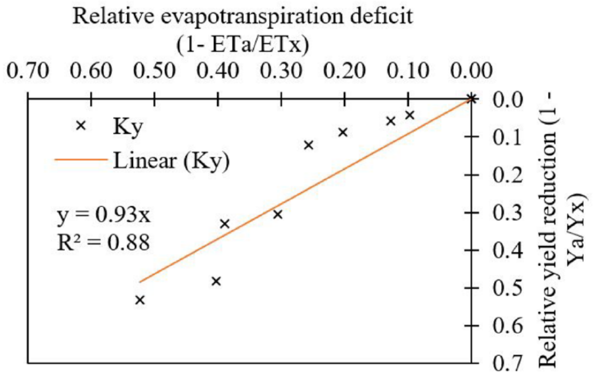

Figure 4. Linear yield response function for wheat subjected to water deficit levels.

to water savings without substantial yield penalties, particularly when K_y values exceed 1.

Above-ground biomass

Mean above-ground biomass was significantly ($p < .05$) affected by the deficit irrigation levels in both growing seasons (2021/2022 and 2022/2023) as shown in Table 7. The highest AgBM was obtained at the control/full irrigation level during 2022/2023, followed by the same treatment in 2021/2022. Compared to full irrigation, the biomass reduction was 8.6% and 15.7% under deficit irrigation applications of 85% and 70% ETc. Lower AgBM was obtained at 40% ETc irrigation application followed by 55% ETc irrigation application. The increased AgBM in the full irrigation treatment may be due to higher plant height, higher tiller number and better growth (Khan et al., 2011; Memon et al., 2021). A study by Thapa et al. (2019) shows that maintaining higher biomass production is necessary for higher yields in a semi-arid environment, as wheat biomass decreased significantly from high to low watering regimes as it matured. This finding is consistent with Han et al. (2010) and Memon et al. (2021), who reported that deficit water application reduced biomass production, but the well-watered situations improved yield. The concept of water use efficiency (WUE) is not solely about crop yield but also about the biomass that has economic benefits, particularly in the context of animal feed. Efficiently converting water into biomass for animal feed is a critical aspect of sustainable agriculture, particularly for the study area. It helps reduce the environmental impact of agriculture, as it minimizes water consumption while meeting the nutritional needs of livestock (Heinke et al., 2020; Kebebe et al., 2015).

Table 7. Wheat Above Ground Biomass as Affected by Deficit Irrigation Levels.

DI TREATMENTS	AGBM (T HA^{-1})		
	2021/2022	2022/2023	POOLED
100% ETc	12.45^{a}	12.65^{a}	12.55^{a}
85% ETc	11.28^{b}	11.65^{ab}	11.46^{b}
70% ETc	10.38^{c}	10.79^{b}	10.60^{b}
55% ETc	8.18^{d}	8.73^{c}	8.48^{c}
40% ETc	6.65^{e}	7.17^{d}	6.90^{d}
CV	2.69	4.83	6.21
HSD$_{0.05}$	0.60	0.11	0.91

Note. Figures carrying different letters with in a column are significantly different at 5% probability.

Wheat grain quality under different irrigation levels

Protein ratio. Protein ratio is an important indicator of wheat grain quality. This study revealed significant ($p \leqslant .05$) differences in protein ratios due to varying levels of water deficit. Across treatments, the protein ratio ranged from 14.10% to 15.84% (Figure 5). Protein ratios increased with increasing levels of water deficit. Generally, lower irrigation levels resulted in higher protein ratios, while higher irrigation levels led to lower protein ratios. Similar findings indicating an inverse relationship between irrigation amount and protein ratio were observed in other studies (Flagella et al., 2010; Tari, 2016). Therefore, monitoring protein content during deficit irrigation practices can provide valuable insights into how irrigation water optimization impacts not only the quantity of the harvest but also its nutritional value.

Starch ratio. Starch plays a critical role in wheat grain production and significantly influences flour processing quality (Regina & Guzmán, 2020). This study found significant differences ($p < .05$) in starch ratios among different irrigation levels across both growing seasons. Higher starch ratios were consistently achieved with full irrigation, 85% ETc, and 70% ETc irrigation levels. Conversely, treatments at the highest deficit levels (40% and 55% ETc) exhibited lower starch ratios (Figure 5). These findings highlight that water stress significantly ($p \leqslant .05$)

reduces starch content in wheat, a finding consistent with previous studies by Flagella et al. (2010) and Lu et al. (2014). Understanding this relationship is crucial for assessing wheat grain composition, and developing strategies to optimize crop management in water-scarce environments. Therefore, carefully managing irrigation levels under deficit irrigation is essential to achieve both optimal yield and high-quality grain.

Thousand-kernel weight

Thousand-kernel weight (TKW), as an indicator of grain quality, was evaluated for the deficit irrigation treatments as indicated in Table 8. The deficit irrigation significantly ($p < .05$) affected TKW. The TKW values were higher under full irrigation followed by 85% and 70% ETc. A significantly lower TKW was obtained at higher deficit irrigations of 55% and 40% ETc. The result indicates that TKW is less sensitive to deficit irrigation as long as the deficit level is not higher than 70% ETc. The lower TKW attained at lower irrigation levels may result from the shriveling of the grains, which affected the weight. This finding is in line with previous research reports (Asmamaw et al., 2023; Meena et al., 2019; Xue et al., 2014).

Economic performance analysis

The economic performance of different irrigation treatments for wheat is presented in Tables 9 and 10, which detail the total production cost, gross return, gross profit, marginal profit, and marginal rate of return (MRR).

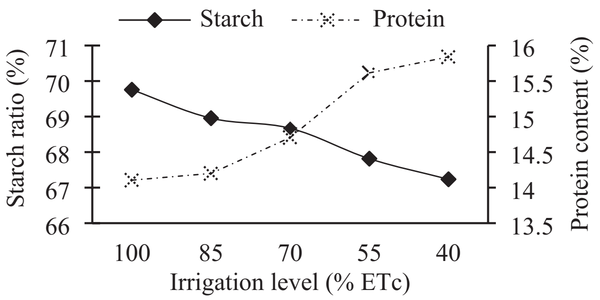

Figure 5. Protein and starch ratio of wheat under different irrigation levels.

When considering the same land area (1 ha), the deficit irrigation experiment demonstrated a positive correlation between water applied and income (Table 9). The full irrigation treatment yielded the highest income, while the lowest irrigation level (40% ETc) resulted in the lowest income. The average cost of cultivation and gross income were highest under full irrigation and lowest under 40% ETc irrigation.

However, employing deficit irrigation to save water introduces an opportunity cost associated with water conservation. This cost arises from the potential to allocate the saved water to irrigate additional land, assuming such land is available. Evaluating profitability based on this alternative use of conserved water revealed that deficit irrigation treatments still yielded economic benefits (Table 10). The cost-benefit analysis showed that moderate deficit irrigation treatments (70% ETc followed by 85% ETc) resulted in the highest gross return, gross profit, marginal profit, and MRR. Water deficit treatments at 40% and 55% ETc demonstrated lower benefits compared to the control treatment. Furthermore, the MRR of these treatments (40% and 55% ETc) was less than 100%, rendering them less economically viable for wheat production. Therefore, based on these findings, the most favorable irrigation level for wheat production is 70% ETc, followed by 85% ETc.

Table 8. Thousand Kernel Weight Under Different Deficit Irrigation Levels.

DI TREATMENTS	1,000 KERNELS WEIGHTS (G)		
	2021/2022	2022/2023	POOLED
100% ETc	34.34^{a}	33.73^{a}	34.03^{a}
85% ETc	33.90^{a}	33.30^{ab}	33.60^{a}
70% ETc	33.29^{ab}	33.20^{ab}	33.25^{a}
55% ETc	31.02^{b}	32.03^{bc}	31.52^{b}
40% ETc	30.80^{b}	31.68^{c}	31.24^{b}
CV	3.41	1.92	3.36
HSD$_{0.05}$	2.51	1.43	1.61

Note. Figures carrying different letters with in a column are significantly different at 5% probability.

Table 9. Yield, Return, Total Cost, and Gross Profit Per Hectare of Land.

TREATMENTS	YIELD (KG)	RETURN (US$)	TOTAL COST (US$)	GROSS PROFIT (US$)
100% ETc	5,085	4,237.5	1,722.2	2,515.3
85% ETc	4,830	4,025.0	1,709.5	2,315.5
70% ETc	4,555	3,795.8	1,695.8	2,100.0
55% ETc	3,475	2,895.8	1,652.4	1,243.4
40% ETc	2,510	2,091.7	1,613.2	4,78.4

Table 10. Yield, Return, Total Cost, Gross Profit, Marginal Benefit, and MRR Per Unit of Water Used.

TREATMENTS	YIELD (KG)	RETURN (US$)	TOTAL COST (US$)	GROSS PROFIT (US$)	MARGINAL PROFIT (US$)	MRR (%)
100% ETc	5,085	4,237.5	1,941.3	2,296.2	Control	Control
85% ETc	5,577	4,647.5	2,237.7	2,409.8	113.6	138
70% ETc	6,274	5,228.7	2,664.8	2,563.9	267.7	137
55% ETc	5,928	4,940.1	3,294.3	1,645.8	–650.5	–
40% ETc	5,600	4,666.3	4,300.5	365.8	–1,930.4	–

Conclusion

The widespread cultivation of irrigated wheat in Ethiopia's arid and semi-arid regions has sparked concerns regarding water scarcity. Addressing this issue necessitates urgent action, combining scientific innovation with policy initiatives to enhance water management and ensure the sustainability of wheat production. To address this, a field experiment was conducted to assess the impact of varying irrigation levels on bread wheat production, water use efficiency and economic viability in the Awash basin.

The experiment tested five irrigation levels: 100% ETc (full irrigation), 85% ETc, 70% ETc, 55% ETc, and 40% ETc. The findings reveal that the highest grain yield, 5.09 t/ha, was achieved with full irrigation (100% ETc) using 417.2 mm of water. The lowest yield was observed at 40% ETc, which used only 223.7 mm of water. Notably, the 85% ETc level produced a yield comparable to full irrigation, suggesting some flexibility in water usage without sacrificing yield.

A significant highlight was the 70% ETc irrigation level, which resulted in the highest water use efficiency at 1.42 kg/m^3 water. Moreover, the water saved at this level could enable the cultivation of an additional 23.4% more wheat on 1.38 ha of land, leading to the highest economic profit of US$2,563.9 and a MRR of 137%. Furthermore, important grain quality parameters, including kernel weight and starch content, remained relatively stable even at deficit levels of up to 70% ETc.

These findings underscore the importance of adopting a 70% ETc irrigation threshold in scenarios of moderate water scarcity, as it maximizes yield per unit of water used. The overall advantages of employing the 70% ETc irrigation level, followed closely by 85% ETc, suggest potential strategies for either expanding irrigated areas when land is available or redirecting saved water to other beneficial uses when land is limited. These insights offer a sustainable path for wheat cultivation amidst water resource challenges in the study area.

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Author Contributions

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Declaration of Conflicting Interests

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