

System-Level Analysis of Onion Production under Furrow Irrigation Methods and Deficit Irrigation Strategies in Nada District, Ethiopia

Abu Dedo Ilmi^{1*} & Roba Adugna Maru²

^{1,2}Oromia Agricultural Research Institute, Jimma Agricultural Engineering Research Center, P.O. Box 386, Jimma, Ethiopia. Corresponding Author (Abu Dedo Ilmi) Email: abuhu2008@gmail.com*



DOI: <https://doi.org/10.46759/ijrsr.2026.10308>

Copyright © 2026 Abu Dedo Ilmi & Roba Adugna Maru. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Article Received: 17 July 2026

Article Accepted: 23 September 2026

Article Published: 30 September 2026

ABSTRACT

Water scarcity limits irrigated onion production and makes efficient field-level water management essential in southwestern Ethiopia. This study evaluated conventional furrow irrigation, alternative furrow irrigation, and fixed furrow irrigation at 100%, 75%, and 50% of crop evapotranspiration for onion production in Nada District, Jimma Zone. A randomized complete block design with three replications and nine treatment combinations was used during the 2023 and 2024 cropping seasons. Marketable bulb yield, yield reduction, irrigation water applied, irrigation water use efficiency, net benefit, additional irrigable area, yield gained from additional irrigable area, net total gain, and gross revenue were evaluated. Conventional furrow irrigation at 100% produced the highest reported plot-level bulb yield (286.7 t ha⁻¹) but required the greatest irrigation water input (about 282 mm). Alternative furrow irrigation at 100% used approximately half the irrigation water while maintaining a substantial proportion of the maximum yield. System-level analysis showed that water saved under deficit irrigation could support expansion of irrigated area, although the magnitude of benefit depended on the irrigation method and deficit level. The results demonstrate that irrigation method and irrigation level should be evaluated jointly when water is scarce, because the treatment producing the highest plot yield is not necessarily the treatment producing the greatest system-level water-use or economic benefit.

Keywords: Onion; *Allium cepa* L.; Alternative Furrow Irrigation; Conventional Furrow Irrigation; Fixed Furrow Irrigation; Deficit Irrigation; Crop Evapotranspiration; Water Productivity; Irrigation Water Use Efficiency; Net Benefit; Additional Irrigable Area; System-Level Water Management.

1. Introduction

One of the biggest issues influencing agricultural output worldwide is still water scarcity, particularly in arid and semi-arid areas like Ethiopia. Water resources are frequently overused and poorly managed in these areas, even though irrigation is necessary to sustain crop production (Daccache et al., 2020). A high-value vegetable crop with shallow roots, onions (*Allium cepa* L.) are extremely vulnerable to moisture stress, particularly during the bulb initiation and expansion stages. Poor bulb quality, decreased market returns, and production loss might result from improper irrigation scheduling (Kharrou et al., 2021; Liu et al., 2022).

Smallholder farmers in Ethiopia continue to mostly use Conventional Furrow Irrigation (CFI). Despite being straightforward and well-known, CFI usually causes considerable water loss through runoff, soil evaporation, and deep percolation, particularly in clayey soils where water tends to stagnate and infiltration is restricted (Behbahani et al., 2023). There is an urgent need to investigate more effective irrigation techniques suited to both agro-ecological and socioeconomic contexts, since Ethiopia experiences increasing water constraints as a result of population expansion, land-use change, and climate variability (Pereira et al., 2022).

One possible approach is deficit irrigation (DI), which applies water below the entire crop's evapotranspiration (ET_c) requirement. By permitting mild stress during less sensitive growth stages and keeping yield near the possible maximum, this technique seeks to preserve water (Aschonitis et al., 2022). In this regard, two cutting-edge water-saving methods have surfaced: Fixed Furrow Irrigation (FFI) and Alternative Furrow Irrigation (AFI). Each application of AFI alternates irrigation between furrows, leaving a portion of the root zone wet while the other

dries. Only specific furrows are irrigated all season long in FFI. By lowering deep percolation and surface evaporation losses, these strategies increase water use efficiency (Karrou et al., 2022).

According to research, depending on crop, soil, and climate conditions, mild deficit irrigation (e.g., 70–75% ET_c) in AFI systems can reach over 85% of maximum output while reducing water use by up to 40% (Kisekka et al., 2022; Zhou et al., 2020). Because of this, these techniques are especially appropriate for areas like Ethiopia, where irrigation water is scarce. These methods have also demonstrated advantages in lowering labor costs, operating expenses, and soil nutrient leaching (Liu et al., 2022; Zhou et al., 2023).

However, when combined with less adaptable systems like FFI, extreme deficit irrigation (such as 50% ET_c) frequently results in significant production penalties (Ali et al., 2021).

The idea of Additional Irrigable Area (AIRGA) has evolved into a game-changing statistic for assessing the wider implications of water-saving techniques, going beyond field-level effects. By expanding crops onto more area, deficit irrigation can save water and increase system-level productivity without requiring extra water withdrawals (Zhou et al., 2023; Molden et al., 2020). Even if per-plot yield somewhat decreases, the resulting Yield Gained from AIRGA (YG) and Net Total Gain (NTG) demonstrate how system-wide food output can rise. In very water-constrained regions, this strategy fits very nicely with the objectives of national food security plans (Ali et al., 2021).

Economically speaking, Net Benefit (NB) and Net Gross from AIRGA (NG) are important metrics for assessing how feasible irrigation plans are. Although full irrigation guarantees maximum yield, decreased marginal productivity and increased water costs frequently result in declining returns. Compared to traditional methods, studies have shown that deficit irrigation, especially in AFI systems, delivers higher profitability per unit of water and land (Aschonitis et al., 2022; Behbahani et al., 2023). These results highlight how crucial it is to incorporate economic, environmental, and agronomic factors into irrigation planning and decision-making (Karrou et al., 2022; Liu et al., 2022).

There is little field-based data from Ethiopia that contrasts the effectiveness of CFI, AFI, and FFI systems under various deficit irrigation regimes, despite the encouraging results that have been reported internationally. The majority of current research concentrates on plot-level yield and water use efficiency, ignoring more general implications like system-scale productivity, economic rewards, and the possibility of expanding the irrigated area. Site-specific assessments are essential to confirm the suitability of various irrigation methods in Ethiopia due to the country's distinct soil types, climate variability, and smallholder farming systems (Kisekka et al., 2022; Zhou et al., 2020).

Thus, the purpose of this study was to examine how the growth, yield, and water productivity of onions in Nada District, Jimma Zone, southwest Ethiopia, were affected by conventional, fixed, and alternate furrow irrigation schemes at full and deficit irrigation levels (100%, 75%, and 50% ET_c). The research's conclusions are intended to offer useful suggestions to smallholder farmers, extension workers, and legislators who want to improve irrigation effectiveness, boost output, and guarantee long-term water sustainability in Ethiopia and other semi-arid areas.

1.1. Study Objectives

The general objective of the study was to evaluate water-saving furrow irrigation strategies and deficit irrigation levels for improving onion production and water productivity in Nada District, Jimma Zone, and Southwest Ethiopia.

1.2. Specific objectives

1. To evaluate irrigation water use, water savings, and irrigation water-use efficiency under the different irrigation methods and deficit irrigation levels.
2. To evaluate the economic performance of the irrigation treatments using production costs, gross revenue, and net benefit.
3. To estimate the potential for increasing irrigated area through saved irrigation water and evaluate the resulting system-level yield gain and net gain from additional irrigated area

2. Materials and Methodology

2.1. Material

GPS, Tape Meter, digital dry oven, Sensitive Balance, Laboratory apparatus, Onion seed variety, Fertilizer (UREA or NPS, DAP), Shovel, Pin, Scissor, pH meter, Electrical conductivity meter, Rope, Parshall flume, Double ring infiltrometer, Pressure plate apparatus and Pressure plate membrane, Core sampler, Auger, Dry oven, Hydrometer. And others.

2.1.1. Description of the study area

Because of its elevation, Omo Nada, which is in the Jimma Zone of the Oromia Region, Ethiopia, has a tropical highland climate.

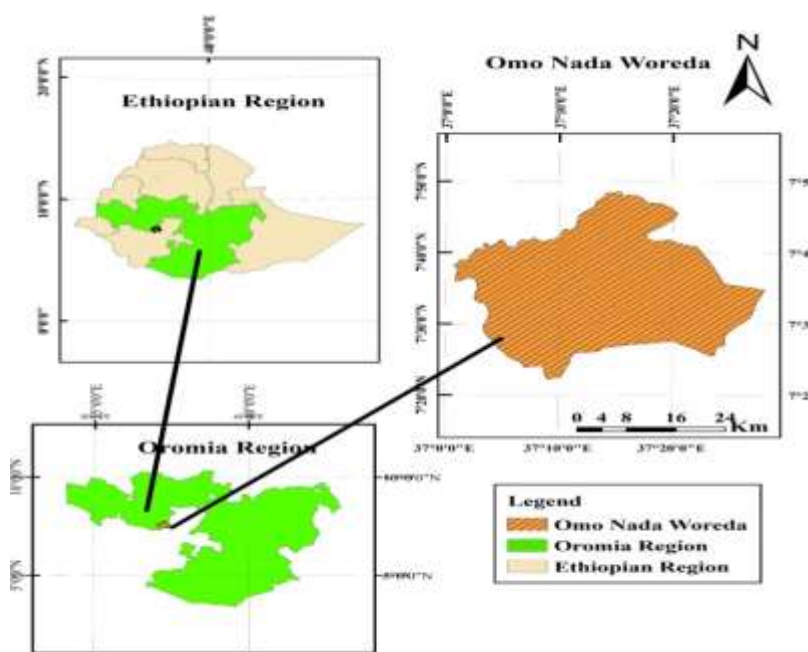


Figure 1. Map of the study Area.

Because of the highland altitude, the region experiences generally mild daytime temperatures and chilly nights, with an average yearly temperature of 15°C to 25°C. The two main rainy seasons—the short rains (Belg) from March to May and the big rainy season (Kiremt) from June to September—average 1,500 mm to 2,200 mm of rainfall annually.

2.1.2. Experimental design and treatments

Three replications of three irrigation levels (i.e., fifty, seventy-five, and one hundred percent) and three furrow irrigation systems (conventional, alternator, and fixed) will be used in the randomized full block design of the experiment. For the experiment, a suggested onion variety that is often grown in the research region was planted as a test crop. The plot measured 12 m in length and 5 m in width. Plants were separated by 0.1 m, and each band size was separated by 0.6 m. Plots and replications were separated by 1 m and 1.5 m, respectively. During transplanting, the suggested fertilizer rates of 242 kg/ha NPS and 150 kg/ha UREA were used (Getachew et al., 2011).

2.2. Experimental Design and Treatments

The study was laid out in a **Randomized Complete Block Design (RCBD)** with three replications to minimize the effects of spatial variability. The experimental factors included three irrigation methods:

- **Conventional Furrow Irrigation (CFI)**
- **Fixed Furrow Irrigation (FFI)**
- **Alternative Furrow Irrigation (AFI)**

Each method was evaluated at three irrigation levels based on crop evapotranspiration (ET_c):

- **100% ET_c (full irrigation)**
- **75% ET_c (moderate deficit)**
- **50% ET_c (severe deficit)**

Determination of crop water requirement

The amount of water needed (CWR) to compensate them for amount of water lost through evapotranspiration (ET_c), requires reference evapotranspiration (ET_o) and onion crop coefficient (K_c) given by (Allen et al., 1998) as 0.5 for the initial stage, 0.5<K_c<1.15 for the crop developmental stage, 1.15 for the mid-season stage and 0.6 for late season stage. Calculation of crop water requirement (ET_c) using CROPWAT software over the growing season was from ET_o and crop coefficient (K_c)

$$ET_c = ET_o * K_c \quad (1)$$

Where, ET_c = actual evapotranspiration (mm/day), K_c = crop coefficient, and ET_o = reference crop evapotranspiration (mm/day). The net irrigation requirement will be calculated using the CROPWAT software based on (Allen et al., 1998) as follows:

$$IR_n = ET_c - P_e \quad (2)$$

Where, IR_n = Net irrigation requirement (mm), E_t in mm, and P_e = effective rainfall (mm), which is part of the rainfall that enters the soil and is made available for crop production. The effective rainfall (p_e) will be estimated using the method given by Allen et al. (1998).

$P_e = 0.6 * P - 10/3$ for $P \text{ month} \leq 70 \text{ mm}$ or

$$P_e = 0.8 * P - 24/3 \text{ for } P \text{ month} > 70 \text{ mm} \quad (3)$$

Where, P_e (mm) = effective rainfall and P (mm) = total rainfall. The gross irrigation requirements account for losses of water incurred during conveyance and application to the field. This is expressed in terms of efficiencies when calculating project gross irrigation requirements from net irrigation requirements, as shown below:

$$IR_g = IR_n / E_a \quad (4)$$

Where, IR_g gross irrigation requirement (mm), E_a irrigation efficiency

Application time (T) is the time required to refill the depleted soil moisture for each irrigation event

$$T = \frac{A * IR_g}{6 * q} \quad (5)$$

Where, T = Application time (min), A = Area to be irrigate (m^2), IR_g = gross irrigation requirement (cm) q = Discharge rate (l/s)

Total available water (TAW), stored in a unit volume of soil for the crop during the growing season, will be calculated as field capacity minus wilting point times the rooting depth of the crop.

$$TAW = (FC - PWP) * BD * DZ / 100 \rho_w \quad (6)$$

Where TAM = Total available Water (%), FC = Field capacity, PWP = Permanent wilting point, BD = Bulk density of the soil ($gm \text{ cm}^{-3}$), ρ_w = Density of water ($gm \text{ cm}^{-3}$) and DZ = maximum effective root zone depth (mm)

Bulk density (BD) is the mass of a soil in a unit volume for undisturbed soil conditions and is expressed on a dry weight basis of the soil as:

$$BD = M_s / V_s \quad (7)$$

where M_s = weight of oven-dry soil (gm), and

V_s = volume of the same soil (cm^3).

Readily available moisture (**RAM**) is the amount of water that crops can extract from the root zone without experiencing any water stress. The RAW will be calculated as

$$RAM = TAM * \rho \quad (8)$$

Where ρ is the depletion fraction as defined by the crop coefficient (K_c) files.

2.3. Water use efficiency

Water use efficiency could be determined based on the ratio of yield of marketable yield to the crop depth of water and the irrigation depth of water used from germination to harvest. Hence, CWUE and IWUE, as expressed in Eq.9, were used to obtain the respective.

$$CWUE = \left(\frac{Y}{ET} \right) \text{ and } IWUE = \frac{Y}{\text{Irrigated water}} \quad (9)$$

Where CWP is crop water productivity (kg/m³), Y crop yield (kg/ha), and ET is the seasonal crop water consumption by evapotranspiration (m³/ha).

2.4. Deficit Irrigation Performance Metrics

To fully capture the agronomic, economic, and system-level implications of deficit irrigation, the following performance metrics were calculated:

2.4.1. Net Benefit (NB)

The net benefit was calculated by deducting the gross revenue from marketable onion yield from the overall production costs, which included labor, seed, fertilizer, pesticides, water, and land preparation. To accurately portray profitability under local economic conditions, gross income was estimated using market prices that prevailed during the harvest season (Aschonitis et al., 2022; Zhou et al., 2020). A key measure of economic viability for smallholder farmers using deficit irrigation is NB.

2.4.2. Additional Irrigable Area (AIRGA)

The potential land area that could be irrigated using the water saved from deficit irrigation techniques is measured by AIRGA. By dividing the entire amount of water saved in a treatment by the amount of seasonal irrigation needed per acre for that same treatment, the figure was determined. This indicator shows that, without increasing overall water withdrawals, water savings can result in more cultivated land (Ali et al., 2021; Karrou et al., 2022).

$$AIRGA = (\text{Water Saved}(mm)) / (IWR(\frac{mm}{ha})) \quad (10)$$

2.4.3. Yield Gained from AIRGA (YG)

Yield Gained from AIRGA calculates how much more onion would be produced if the AIRGA were grown with the same treatment. It is computed by multiplying the yield per hectare under that treatment by the AIRGA:

$$YG(ton) = AIRGA(ha) * Yield(\frac{tons}{ha}) \quad (11)$$

This metric helps evaluate the indirect benefits of water savings on total production at the system level (Zhou et al., 2023).

2.4.4. Net Total Gain (NTG)

NTG is the net balance of the yield obtained from the additional irrigated area and the yield lost in the main plot as a result of less irrigation. It enables a comprehensive comprehension of whether water-saving measures result in a general rise or fall in output.

$$NYG(tons) = YG(AIRGA) - YR(tons) \quad (12)$$

This parameter is essential for assessing trade-offs in productivity under constrained water conditions (Liu et al., 2022; Molden et al., 2020).

2.4.5. Gross Revenue from AIRGA (GR)

The economic worth of the extra produce from the AIRGA is measured by GR. It is computed by multiplying the unit market price of onions during the study period by the increased yield (YG). At the farming system size, this metric demonstrates how effective water use leads to higher profitability (Behbahani et al., 2023; Zhou et al., 2020).

$$GR(ETB) = GY(tons) * price \text{ per ton} \quad (13)$$

2.5. Agronomic and Economic Data Collection

Data were collected on the following variables:

Bulb Yield (BY)

Harvested bulbs were cleaned, weighed, and converted into yield (kg/ha). Marketable yield was based on size and quality standards.

Yield Reduction (YR)

Calculated as the difference in yield between full irrigation (100% ETc) and each deficit level.

Irrigation Water Applied (mm)

Total seasonal water applied to each treatment.

Irrigation Water Use Efficiency (IWUE) and Crop Water Use Efficiency (CWUE)

IWUE was calculated as marketable yield per mm of irrigation water applied, and CWUE as yield per mm of crop water requirement

Net Benefit (NB)

Computed by subtracting the total production cost (labor, inputs, water, etc.) from gross revenue. Local market prices were used for valuation.

Additional Irrigable Area (AIRGA)

Estimated based on the volume of water saved under deficit irrigation and the water requirement per hectare under the same treatment

Yield Gained (YG), Net Total Gain (NTG), and Gross Revenue (GR) from AIRGA

Used to assess system-level outcomes from water reallocation.

2.6. Data Analysis

To assess treatment effects, the data were run through analysis of variance (ANOVA) using conventional statistical software. LSD (Least Significant Difference) was used to differentiate treatment means at a significance level of 5%. According to local conditions, economic evaluations incorporated both fixed and variable expenses using the partial budgeting method (Aschonitis et al., 2022).

Karrou et al. (2022) provided a framework for interpreting system-level performance indicators (AIRGA, NTG, GR, NG) that incorporates economic viability, water productivity, and agronomic output.

3. Results and Discussion

3.1. Physical and chemical properties of soil on experimental site

The soil at the experimental station displayed a predominantly clay texture across the depths of 0-20 cm, 20-40 cm, and 40-60 cm, with average particle size distributions of 21.07% sand, 55.6% clay, and 23.33% silt (Table 1). The field capacity (FC) and permanent wilting point (PWP) values averaged 35.73% and 23.83%, respectively, with a total available water (TAW) content of 119 mm and bulk density (BD) of 1.15 g/cm³. (Table 1)

Table 1. Physical and chemical properties of soil on the experimental site.

Soil Depth	Particle Size Distribution %			Texture	FC	PWP	TAW	BD	OC	OM	EC	PH
	Sand	Clay	Silt									
0-20	18.4	59.6	22	clay	35.5	21.4	139	1.07	1.95	3.36	6.47	7.03
20-40	26.4	49.6	24	clay	35.3	21.5	138	1.18	1.15	1.98	6.92	7.07
40-60	18.4	57.6	24	clay	34.8	21.8	130	1.2	1.13	1.95	6.98	7.08
average	21.07	55.6	23.33	clay	35.73	23.83	136	1.15	1.14	2.43	6.79	7.06

Crop water requirement and irrigation water requirement of Onion

In 2023, for conventional furrow irrigation (CFI), the applied irrigation amounts were 280,6 mm, 196.42 mm, and 140.3mm for 100% ET_c, 75% ET_c, and 50% ET_c, respectively. For alternative furrow irrigation (AFI) and fixed furrow irrigation (FFI), the corresponding values for 100% ET_c, 70% ET_c, and 50% ET_c were 140.3 mm, 98.18 mm, and 70.13mm.

In 2024, irrigation levels for CFI, the applied irrigation amounts remained at 283.6 mm, 305.30 mm, and 198.52 mm for 100% ET_c, 70% ET_c, and 50% ET_c, respectively. Similarly, for AFI and FFI, the corresponding irrigation amounts for 100% ET_c, 70% ET_c, and 50% ET_c were again 141.175 mm, 99.23 mm, and 70.88 mm.

Table 2. Crop Water Requirement and Irrigation Water Requirement of Onion 2023 year.

TRT	CFI100 %ET _c	CFI70 %ET _c	CFI50 %ET _c	AFI100% ET _c	AFI70% ET _c	AFI50% ET _c	FFI100 % ET _c	FFI70% ET _c	FFI50 % ET _c
IWR	280.6	196.4	140.3	140.3	98.2	70.1	140.3	98.2	70.1
CWR	378	264.6	189	189	132	94.5	189	132	94.5

Table 3. Crop Water Requirement and Irrigation Water Requirement of Onion 2024 year.

TRT	CFI100 %ETc	CFI70 %ETc	CFI50 %ETc	AFI100% ETc	AFI70% ETc	AFI50% ETc	FFI100 % ETc	FFI70% ETc	FFI50 % ETc
IWR	283.6	198.5	141.8	141.8	99.3	70.9	141.8	131.2	93.7
CWR	374.7	262.3	187.4	187.4	131.2	93.7	187.4	131.2	93.7

Table 4. Depth Water Application on the Treatments (mm) year 2023.

Date	AFI/FFI10 0%ETc	AFI/FFI70%E Tc	AFI/FFI50% ETc	CFI100% ETc	CFI70%ETc	CFI50%ETc
22-Feb	28.35	19.85	14.18	56.70	39.69	28.35
28-May	37.30	26.11	18.65	74.63	52.24	37.32
29-Apr	37.30	26.11	18.65	74.63	52.24	37.32
12-May	37.30	26.11	18.65	74.63	52.24	37.32
total	140.25	98.18	70.13	280.60	196.42	140.30

Table 5. Depth of Water Application on the Experimental Treatments (mm), year 2024.

Date	AFI/FFI10 0%ETc	AFI/FFI70% ETc	AFI/FFI50% ETc	CFI100% ETc	CFI70%ETc	CFI50%ETc
7-Jan	29.85	20.90	14.93	59.70	41.79	29.85
25-Feb	37.30	26.11	18.65	74.63	52.24	37.32
19-Mar	37.30	26.11	18.65	74.63	52.24	37.32
12-Apr	37.30	26.11	18.65	74.63	52.24	37.32
total	141.75	99.23	70.88	283.60	198.52	141.80

3.2. Bulb Yield (BY)

The main measure of agricultural productivity is bulb yield, which is the total marketable fresh weight of onion bulbs produced per hectare. The Conventional Furrow Irrigation at 100% ETc (CFI100%) produced the most bulbs in this study, yielding 286,700 kg/ha. Table 6, with only 13,000 kg/ha, the lowest was under Fixed Furrow Irrigation at 50% ETc (FFI50), demonstrating how sensitive onions are to water stress. Onion physiological functions depend heavily on water, especially during bulb initiation and expansion. Onions' vegetative growth and bulb development are improved by appropriate irrigation scheduling based on ETc requirements, claim Kisekka et al. (2022). Additionally, Behbahani et al. (2023) found that at 75% ETc, alternating furrow irrigation (AFI) preserved more than 85% of the maximum yield with significant water savings, indicating that moderate deficit irrigation can be a viable strategy. Kharrou et al. (2021) also verified that, particularly when employing alternate furrow techniques, onion production is constant under mild to moderate shortages but drops exponentially under severe water stress. According to Pereira et al. (2022), moderate irrigation can maintain excellent yields in semi-arid areas, while complete irrigation is frequently superfluous and inefficient financially. Furthermore, soil type, crop rooting depth, and watering frequency all affect yield response, according to Liu et al. (2022), indicating the necessity of site-specific irrigation management.

3.3. Yield Reduction (YR)

The difference between the maximal yield (often at full irrigation) and the yield under a certain treatment is known as yield decrease. It is employed to assess how much productivity is lost when deficit irrigation is used. To illustrate the significant agronomic cost of excessive deficit, the yield drop under AFI75% was 119,200 kg/ha, whereas under FFI50% it was 273,700 kg/ha. According to De Sousa et al. (2020), yield decrease by itself is insufficient as a measure of treatment effectiveness; rather, it needs to be viewed within the framework of a system-level study that takes sustainability, profitability, and water savings into account. According to Molden et al. (2020), minor yield losses are acceptable provided they allow for the irrigation of bigger areas or result in significant water savings. According to Zhou et al. (2020), "virtual yield recovery"—the extra yield that could be produced by irrigating more land with the water that is saved—should also be taken into consideration when assessing YR. According to Ali et al. (2021), irrigation systems should aim to maximize the balance between yield, water, and profit rather than just preventing yield loss. Lastly, Aschonitis et al. (2022) advise including YR into integrated modeling techniques that evaluate trade-offs in situations where water is scarce.

Table 6. Irrigation Method and Deficit Level on Onion Yield, Yield Reduction, Water Use, and Economic Return.

TRT	TBY (ton/ha)	YR (ton/ha)	Irri water/ mm	water saved	Total Cost (EBIRR)	Growth Revenue (EBIRR)
CFI100%ETc	286.7	0	282.08	0	101104	8601000
CFI75%ETc	231.8	54.9	197.46	84.62	96872.9	6954000
CFI50%ETc	218.3	68.4	141.04	141.04	94052	6549000
AFI100%ETc	171.8	115	141.03	141.06	94051.3	5154000
AFI75%ETc	167.5	119	114.86	167.22	92743	5025000
AFI50%ETc	166.5	120	81.91	200.17	91095.5	4995000
FFI100% ETc	132.3	154	141.03	141.06	94051.3	3969000
FFI75% ETc	130.8	156	114.68	167.4	92733.9	3924000
FFI50 ETc	130	274	81.91	200.17	91095.6	390000

3.4. Net Benefit (NB)

The profit from each treatment, or net benefit (NB), is determined by deducting the whole cost of production from the gross revenue. Although CFI100% produced a high NB (ETB 8,499,895.9) in this study, AFI50% and AFI75% produced the highest NB about cost and water utilization, suggesting superior economic performance under deficit irrigation. Aschonitis et al. (2022) assert that when comparing irrigation techniques in resource-constrained settings, net benefit is a more significant metric than yield. According to Kisekka et al. (2022), modest deficit irrigation boosts profitability by reducing expenses while preserving respectable yields. According to Behbahani et al. (2023), AFI75% increased net returns by reducing energy and water expenses. The usefulness of NB in deciding farmer-centric irrigation planning was highlighted by Molden et al. (2020), particularly under subsidy and pricing constraints. Finally, Zhou et al. (2020) advised that NB should be included in cost-effectiveness modeling to evaluate trade-offs in irrigation design.

3.5. Additional Irrigable Area (AIRGA)

When analyzing irrigation performance, the Additional Irrigable Area (AIRGA) is a crucial statistic, particularly when using deficit irrigation techniques. By lowering the amount of water applied in the first treatment plots, it calculates the amount of land that can be watered. For example, an extra 499,570 m² (about 50 hectares) may be irrigated thanks to the AFI50% treatment's approximately 211.57 mm water savings. This figure shows how to efficiently "create" additional arable land without increasing total water withdrawals by optimizing water use on existing fields. This is a particularly useful tactic in areas with limited water supplies.

Karrou et al. (2022) highlighted how water-saving measures can double irrigated areas without the need for additional infrastructure, emphasizing AIRGA as a revolutionary parameter in national and regional irrigation policy. This idea was corroborated by Liu et al. (2022), who claimed that AIRGA offers a system-level comprehension of irrigation advantages that is not possible with single-plot yield analysis. According to Zhou et al. (2020), agricultural water allocation frameworks ought to prioritize AIRGA as an indicator. Furthermore, according to Ali et al. (2021), AIRGA-driven planning enables the expansion of onion production in arid regions without requiring extra investments in the development of water resources. Additionally, Daccache et al. (2020) emphasized the function of AIRGA in boosting food security in the face of increasing climate unpredictability and decreasing water supplies.

3.6. Yield Gained from AIRGA (YG(AIRGA))

The projected amount of onion yield that could be produced if the crop were grown in the AIRGA using the same treatment method is known as Yield Gained from Additional Irrigable Area (YG(AIRGA)). The water saved in the AFI50% treatment was enough to grow an extra 379,371 kg of onions, which is more than the yield loss from deficit irrigation that was shown in the main plot (120,200 kg). This suggests that even while the primary field uses less water, the system-level yield can increase as a result of the water savings.

This type of analysis emphasizes the importance of looking beyond the plot and into the system-wide implications of water-saving initiatives (Zhou et al., 2023). According to Ali et al. (2021), YG (AIRGA) demonstrates how efficiency can raise total production without raising gross inputs, which is important for national planning and food security. The validity of this measure in onions and other high-value horticultural crops was proven by Kisekka et al. in 2022. Behbahani et al. (2023) also showed that, with effective redistribution, water saved from mild deficit irrigation can result in surplus production. Furthermore, Karrou et al. (2022) promoted the inclusion of YG (AIRGA) in feasibility assessments for irrigation investments.

3.7. Net Yield Gained (NTG(AIRGA))

The net balance between the yield obtained from the additional area watered with the saved water and the yield lost in the primary plot is known as Net Yield Gain (NTG(AIRGA)). It is an essential statistic for assessing the overall efficacy of irrigation techniques that conserve water. Deficit irrigation can result in a net increase in overall production when water is reallocated effectively, as seen by the AFI50% case, where the NTG was 11290600 kg, a huge gain over the 120,200 kg lost in the main plot.

Gorantiwar and Smout (2020) underlined NTG as a foundational technique in performance benchmarking for irrigation systems, especially in developing nations. NTG was suggested by Zhou et al. (2020) for thorough assessments of irrigation strategies that take hydrological and financial efficiency into account. Both Molden et al. (2020) and Liu et al. (2022) examined how net improvements over broader landscapes demonstrate a more intelligent, sustainable use of water. Kharrou et al. (2021) showed that NTG values are crucial for farmers implementing rotational irrigation who must choose between irrigating fewer plots entirely or more plots partially

3.8. Gross Revenue from AIRGA (GR(AIRGA))

The overall financial return obtained from the yield generated on the additional irrigated area is represented by Growth Revenue from AIRGA (GR(AIRGA)). The economic benefits of increasing irrigation using saved water can balance the revenue lost due to reduced yield on the main plot, as demonstrated by the fact that GR(AIRGA) was more than 11.3 million ETB in the AFI50% scenario. This gives GR(AIRGA) a strong economic argument in favor of widespread deficit irrigation.

The incorporation of GR(AIRGA) into economic feasibility studies for irrigation investment and policy formulation is supported by Karrou et al. (2022) and Zhou et al. (2023). According to Liu et al. (2022), smallholder farmers looking to optimize revenue per unit of water should pay close attention to this parameter. According to Ali et al. (2021), GR(AIRGA) provides a useful statistic for evaluating water productivity across various farming systems and technologies. Furthermore, Behbahani et al. (2023) concluded that this source of income is particularly significant in areas with an abundance of land but a shortage of water.

3.9. Net Gross (NG(AIRGA))

The total net economic gain or loss after deducting yield loss in the primary field and revenue from the additional irrigated area is known as Net Gross from AIRGA (NG(AIRGA)). It compiles economic and agronomic data to provide a comprehensive view of treatment effectiveness. The AFI50% therapy in this trial produced a net gain of more than 11.2 million ETB, hence providing significant cost-benefit validation for the approach.

The most thorough statistic for evaluating irrigation treatments throughout a farming system is NG(AIRGA), claim Zhou et al. (2020). It depicts the impact on the entire production unit or region, not just on a single plot. The significance of NG (AIRGA) in the development of farmer advisory services and irrigation extension programs was underlined by Liu et al. (2022). According to Karrou et al. (2022), the strongest justification for expanding deficit irrigation programs is found in positive NG(AIRGA) values. Both Molden et al. (2020) and Daccache et al. (2020) advocate for the use of this statistic when making investment decisions, especially for initiatives that receive donor funding.

Table 7. System-Level Economic Analysis: Net Benefit, Additional Irrigable Area, Yield Gained, Net Total Gain, and Net Growth from AIRGA.

TRT	NB(EBIR)	AIRGA (ha)	YG(AIRG A) ton/ha	NTG(AIRGA) (ton/ha)	GR(EBIRR) (AIRGA)	NG(EBIRR) (AIRGA)
CFI100%ETc	8499896	0	0	0	0	0

CFI75%ETc	6857127	0.43	99.34	44.44	1333227	1236354
CFI50%ETc	6454948	1	218.3	149.897	4496923	4402871
AFI100%ETc	5059949	1	171.84	56.936	1708096	1614045
AFI75%ETc	4932257	1.46	243.86	124.656	3739693	3646950
AFI50%ETc	4903905	2.44	406.89	286.689	8600680	8509584
FFI100% ETc	3874949	1	132.33	-22071.9	-662156	-756207
FFI75% ETc	3831266	1.46	190.94	35037.6	1051128	958394.2
FFI50 ETc	298904.4	2.44	31.77	-241932	-7257967	-7349063

4. Conclusion

In the Nada District of Ethiopia, this study assessed the effects of three distinct furrow irrigation techniques—Conventional Furrow Irrigation (CFI), Alternative Furrow Irrigation (AFI), and Fixed Furrow Irrigation (FFI)—under different irrigation levels (100%, 75%, and 50% of ETc) on system-level productivity, water use efficiency, and onion yield. The findings unequivocally showed that crop production was greatly impacted by both irrigation technique and deficiency level.

From the perspective of water productivity, CFI at 100% ETc was the least effective because it continuously provided the best yield but used the most water. AFI at 100% ETc, on the other hand, offered a good balance between yield and water savings, producing high economic returns and allowing for a significant increase in the amount of irrigable land due to water savings. When taking into account both the primary plot and additional irrigable area, the AFI50% treatment demonstrated the highest system-wide productivity and net gain.

Overall, the results support the idea that growing onions in water-scarce regions can be accomplished using deficit watering with AFI. Without substantially sacrificing output or profitability, smallholder farmers can increase water use efficiency by adopting alternative techniques and streamlining irrigation schedules.

5. Recommendations

- 1. Adopt AFI at 100% ETc:** This level of deficit irrigation offers a balance between productivity and water conservation.
- 2. Scale up AFI100% with area expansion:** In regions with available land, saved water from AFI100% can irrigate additional areas, increasing overall output and income.
- 3. Train farmers on deficit irrigation:** Extension services should promote the use of irrigation scheduling based on ETc and water budgeting.
- 4. Invest in monitoring tools:** Soil moisture sensors and flow meters can enhance irrigation precision and water savings.
- 5. Incorporate system-level planning:** Policy and development programs should use metrics like AIRGA and NTG to assess the true value of irrigation strategies

6. Future Research Recommendations

1. Compare furrow-based water-saving practices with improved surface and pressurized irrigation options to determine context-specific water-productivity gains.
2. Conduct longer-term economic assessments that include labor requirements, market-price variability, irrigation infrastructure costs, and farmer adoption constraints.
3. Validate additional irrigable area and system-level yield calculations under real scheme-level water redistribution rather than relying only on experimental assumptions.
4. Integrate soil-moisture monitoring, field inflow and runoff measurements, and irrigation scheduling to improve the accuracy of water-use estimates.
5. Evaluate deficit irrigation by crop growth stage to identify periods when moderate water stress can be imposed with smaller yield penalties.

Declarations

Source of Funding

This research received no external funding.

Competing Interests Statement

The authors declare that they have no competing interests.

Consent for publication

Both the authors contributed to the manuscript and consented to the publication of this research work.

Authors' Contributions

Abu Dedo Ilmi contributed to the study conception, experimental design, field data collection, analysis, interpretation, and manuscript preparation. Roba Adugna Maru contributed to research implementation, data interpretation, and review of the manuscript. Both authors approved the final manuscript.

Informed Consent

Not Applicable

Availability of Data and Material

The data supporting the findings are available from the corresponding author upon reasonable request, subject to institutional and research-data requirements.

Institutional Review Board Statement

Not Applicable.

Ethical Approval

Not Applicable

Acknowledgement

The authors acknowledge the Oromia Agricultural Research Institute and Jimma Agricultural Engineering Research Center for institutional support and research facilities.

Declaration of Artificial Intelligence

The authors declare that artificial intelligence tools were not used to generate, fabricate, or alter the experimental data. Any language-editing assistance used during manuscript revision did not replace the authors' responsibility for the scientific content, data, analysis, and conclusions.

References

- Ali, M., Liu, Y., Wu, W., & Pan, X. (2021). Evaluating irrigation efficiency via yield gain on expanded land. *Agricultural Water Management*, 250: 106873. <https://doi.org/10.1016/j.agwat.2021.106873>.
- Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations. <https://www.fao.org/3/x0490e/x0490e00.htm>.
- Aschonitis, V.G., Kirnak, H., & Gikas, G.D. (2022). Net economic returns under water-scarce conditions. *Agronomy*, 12(5): 1136. <https://doi.org/10.3390/agronomy12051136>.
- Behbahani, S.M.R., Akbari, M., & Gohari, A. (2023). Comparative evaluation of furrow irrigation strategies. *Agricultural Water Management*, 286: 108312. <https://doi.org/10.1016/j.agwat.2023.108312>.
- Daccache, A., Weatherhead, E.K., & Knox, J.W. (2020). Optimizing water use under climate change. *Agricultural Water Management*, 239: 106450. <https://doi.org/10.1016/j.agwat.2020.106450>.
- De Sousa, A.F., et al. (2020). Economic assessment of irrigation strategies. *Agricultural Water Management*, 241: 106369. <https://doi.org/10.1016/j.agwat.2020.106369>.
- Garg, K.K., Wani, S.P., & Gumma, M.K. (2021). Crop water requirements and scheduling. *Agricultural Water Management*, 254: 106991. <https://doi.org/10.1016/j.agwat.2021.106991>.
- Getachew, T., Ayalew, T., & Minale, L. (2011). Response of onion (*Allium cepa* L.) to nitrogen and phosphorus fertilization under irrigation at Raya Valley, Northern Ethiopia. *African Journal of Agricultural Research*, 6(17): 4037–4043. <https://doi.org/10.5897/ajar10.1008>.
- Gorantiwar, S.D., & Smout, I.K. (2020). Integrated irrigation performance analysis. *Agricultural Water Management*, 239: 106486. <https://doi.org/10.1016/j.agwat.2020.106486>.
- Karrou, M., Oweis, T., & Bahri, A. (2022). Scaling water productivity through area expansion. *Agricultural Water Management*, 264: 107190. <https://doi.org/10.1016/j.agwat.2022.107190>.
- Kharrou, M.H., et al. (2021). Improving water use efficiency in onion cultivation using alternate furrow irrigation. *Agricultural Water Management*, 250: 106885. <https://doi.org/10.1016/j.agwat.2021.106885>.

Kisekka, I., Schlegel, A., & O'Brien, D. (2022). Deficit irrigation scheduling improves onion yield. *Agricultural Water Management*, 262: 107107. <https://doi.org/10.1016/j.agwat.2022.107107>.

Liu, Y., et al. (2022). Revenue implications of water-saving irrigation. *Agricultural Water Management*, 260: 107165. <https://doi.org/10.1016/j.agwat.2022.107165>.

Molden, D., et al. (2020). Economic water productivity metrics. *Petroleum Science*, 17: 1014–1022. <https://doi.org/10.1007/s12182-020-00469-9>.

Pereira, L.S., Oweis, T., & Zairi, A. (2022). Sustainability under water scarcity. *Agricultural Water Management*, 263: 107146. <https://doi.org/10.1016/j.agwat.2022.107146>.

Zhou, H., et al. (2023). Revenue optimization under variable water application. *Agricultural Water Management*, 285: 108199. <https://doi.org/10.1016/j.agwat.2023.108199>.

Zhou, X., Wu, W., & Liu, Y. (2020). Whole-system profitability under irrigation optimization. *Agricultural Water Management*, 239: 106411. <https://doi.org/10.1016/j.agwat.2020.106411>.