

Deficit Irrigation Strategies for Sustainable Potato Production in Water-Limited Regions of Dedo District, Ethiopia

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ABSTRACT

Water scarcity constrains potato production where irrigation water is limited and field application efficiency is low. This study evaluated conventional furrow irrigation, alternate furrow irrigation, and fixed furrow irrigation at 60%, 80%, and 100% of crop evapotranspiration for potato production in Dedo District, southwestern Ethiopia. A factorial experiment was conducted using a randomized complete block design with three replications. The assessment considered tuber yield, water use, water productivity, yield response, water savings, additional irrigable area, and economic indicators. The source results show that conventional furrow irrigation at 100% of crop evapotranspiration produced the highest absolute production, but used substantially more water. Alternate furrow irrigation at 80% and 100% of crop evapotranspiration provided higher water productivity with relatively small yield penalties and favorable system-level economic indicators. The findings indicate that irrigation method and irrigation level should be evaluated together when allocating scarce water among potato-producing areas.

Keywords: Potato; Deficit Irrigation; Conventional Furrow Irrigation; Alternate Furrow Irrigation; Fixed Furrow Irrigation; Evapotranspiration; Crop Water Productivity; Yield Response Factor; Water Saving; Additional Irrigable Area; Marginal Rate of Return.

1.0. Introduction

Due to population expansion, climate variability, and conflicting demands from the urban and industrial sectors, agriculture in sub-Saharan Africa is facing growing water restrictions. Deficit irrigation techniques, which maximize water use while preserving agricultural output, are becoming more and more popular as workable and sustainable solutions in this regard. Due to its high nutritional and economic importance and water sensitivity, the potato (*Solanum tuberosum* L.) offers both potential and problems for research on deficit irrigation, especially in water-limited areas like Ethiopia's Dedo District (FAO, 2021).

Applying water below full crop water requirements (ET_c) is known as deficit irrigation, and it permits crops to endure minor water stress during non-critical growth phases. This approach can minimize crop loss and significantly cut water use if properly controlled (Doorenbos & Kassam, 1979). Accurate crop water requirements, irrigation schedule, and effective water application techniques are essential for deficit irrigation to be successful. Numerous studies have demonstrated that potatoes can withstand mild water shortages, particularly when planted under appropriate irrigation conditions and with careful management (Feres & Soriano, 2007; Kang et al., 2004).

Due to its affordability and ease of use, furrow irrigation is still the most popular technique among Ethiopia's smallholder farmers. Nevertheless, conventional furrow systems, such as Conventional Furrow Irrigation (CFI), frequently have problems with consistent water distribution, which results in surface runoff, deep percolation, and low water productivity (Bekele & Tilahun, 2007). Water-saving variations such as Fixed Furrow Irrigation (FFI) and Alternate Furrow Irrigation (AFI) have been created to get around these restrictions. Partial root-zone drying (PRD), which is induced by irrigating alternate furrows while letting the other side dry, improves water uptake efficiency and strengthens root signaling (Kijne et al., 2003). Contrarily, FFI keeps fixed furrows consistently wet

and might work well in situations involving labor or scheduling constraints, albeit frequently at the expense of uniform moisture distribution (Sezen et al., 2011).

AFI's agronomic and economic performance under deficit irrigation in Ethiopia's mid-altitude agro-ecologies is still poorly understood, despite prior research showing that it can increase water productivity and decrease water use by up to 30–50% (Zhang et al., 2000; Pulido-Calvo et al., 2015). Additionally, local irrigation planning frameworks have not adequately incorporated economic metrics like Net Gain from Additional Area (NGAA), Cost Benefit Ratio (CBR), and Marginal Rate of Return (MRR).

Understanding the trade-offs between water savings, yield performance, and economic return is crucial in water-limited areas like the Dedo District, where rainfall is bimodal and irrigation is necessary for off-season crops. In addition to maintaining yields, smallholder farmers need irrigation techniques that enable increased irrigated area and better water-use efficiency. By measuring how water can be redistributed to maximize output at the system level, the Additional Irrigated Area (AIRGA) and Yield Gain from Additional Irrigated Area (YGAIAGA) concepts improve decision-making even more (Pereira et al., 2020).

The purpose of this study is to assess the economic, hydrological, and agronomic impacts of CFI, AFI, and FFI on potato output in the Dedo District at different ET_c levels (60, 80, and 100%). This study provides evidence-based suggestions to support the implementation of deficit irrigation as a technique for resilient and sustainable potato production under water-scarce situations by examining variables like Yield Response Factor (YRF), Water Saved (WS), Cost Benefit Ratio (CBR), and MRR.

1.1. General Objective

To analyze the economic and strategic impacts of deficit irrigation under different furrow irrigation techniques to enhance sustainability and water productivity in potato cultivation.

1.2. Specific Objectives

1. To evaluate the yield response factor (YRF) of potato to different levels of deficit irrigation across irrigation methods.
2. To quantify water savings, additional irrigable area (AIRGA), and yield gain from expanded coverage under deficit irrigation.
3. To conduct a cost-benefit analysis and calculate the marginal rate of return (MRR) for each irrigation strategy.
4. To recommend sustainable deficit irrigation practices that optimize yield, profitability, and water use in water-scarce conditions

2.0. Materials and Methods

2.1. Study Area Description

The study was conducted in Waro Kolobo Kebele of Dedo District, located in the Jimma Zone of Oromia Regional State, southwestern Ethiopia. The district lies between 7°29' and 7°45'N ' N latitude and 36°40' to 37°00'E

longitude with altitudes ranging from 1,800 to 2,300 meters above sea level. The average annual rainfall ranges from 1,200 mm to 2,000 mm, with a bimodal distribution.

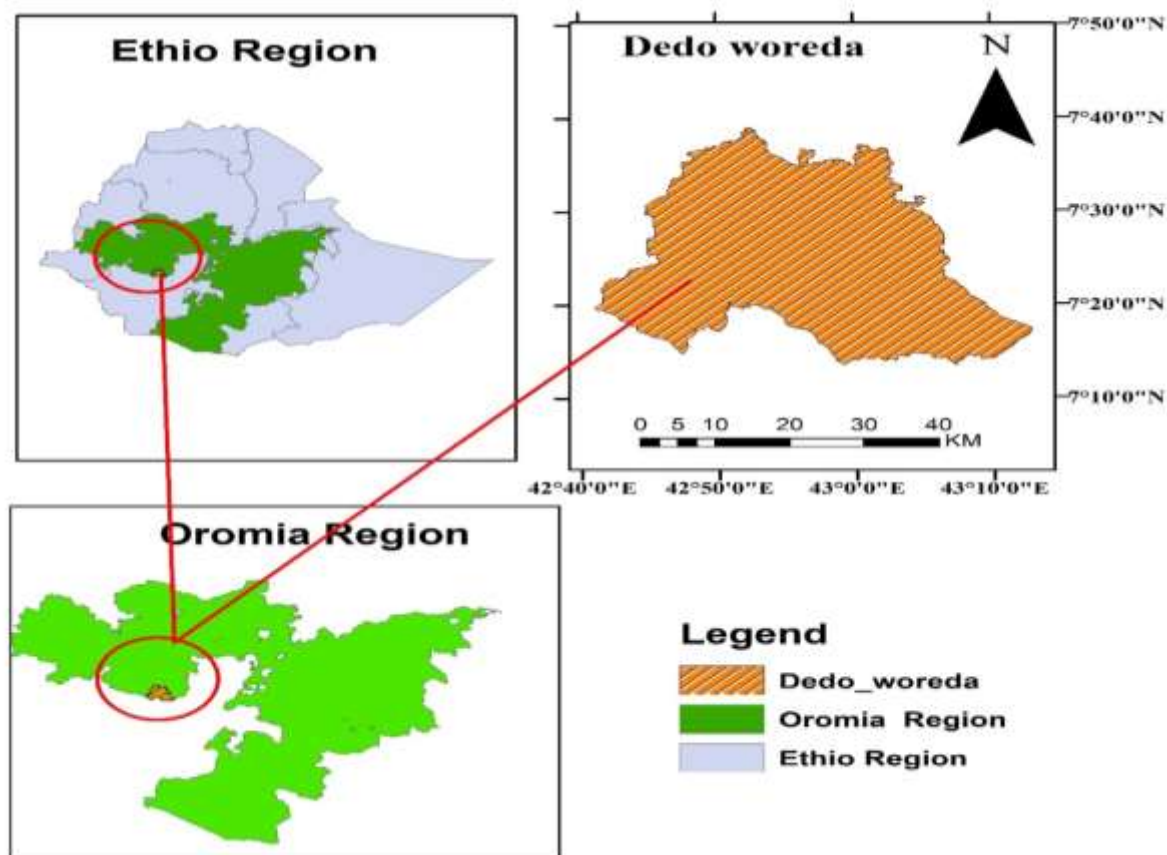


Figure 1. Study area.

2.2. Experimental Design and Treatments

A factorial combination of three furrow irrigation methods (AFI, FFI, and CFI) and three irrigation levels (60%, 80%, and 100% ETc) was laid out in a randomized complete block design (RCBD) with three replications. The total number of treatment combinations was nine.

2.3. Agronomic Practices

The improved potato variety "Gudene" was selected for its adaptability and performance. Seed tubers were planted at a spacing of 75 cm between rows and 30 cm between plants. Standard agronomic practices such as land preparation, fertilization, and pest control were uniformly applied across all treatments.

Determination of crop water requirement

The CROPWAT program was used to calculate the crop water requirements of onions for the different growth phases based on the replenishment of soil water depletion. The CROPWAT software was fed monthly climate data from the study area meteorological station, soil physical characteristics of the irrigation scheme, including texture, field capacity, permanent wilting point, and available water capacity, as well as the soils' infiltration capacity. The crop type, data on growth stages, the times to maturity, the effective rooting depth, and the number of days till maturity are other inputs needed by the model.

The reference evapotranspiration (ETo) and onion crop coefficient (Kc), as provided by Allen et al. (1998), are 0.5 for the initial stage, $0.5 < Kc < 1.15$ for the crop developmental stage, 1.15 for the mid-season stage, and 0.6 for the late-season stage. This is necessary to calculate the amount of water needed (CWR) to make up for the amount of water lost through evapotranspiration (ETc). CROPWAT software was used to calculate the crop water need (ETc) based on crop coefficient (Kc) and ETo during the growth season.

$$ETc = ETo * Kc \quad (1)$$

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

$$aIRn = ETc - Pe \quad (2)$$

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

$Pe = 0.6 * P - 10/3$ for P month ≤ 70 mm or

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

Where, Pe (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:

$$IRg = IRn / Ea \quad (4)$$

where, IRg gross irrigation requirement (mm), Ea irrigation efficiency

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

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

Where, T = Application time (min), A = Area to be irrigate (m^2), IRg = 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 ($gm\ cm^{-3}$), ρ_w = Density of water ($gm\ cm^{-3}$) 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:

$$BD = Ms / Vs \quad (7)$$

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.

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.

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

Where CWP is crop water productivity (kg/m^3), Y crop yield (kg/ha), and ET is the seasonal crop water consumption by evapotranspiration (m^3/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 the marketable potato crop 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).

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

2.4.3. Yield Gained from AIRGA (YG)

Yield Gained from AIRGA estimates the additional onion production that would result if the AIRGA were cultivated using the same treatment method. It is calculated by multiplying the AIRGA by the yield per hectare under that treatment:

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

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 represents the net balance between the yield lost in the main plot due to reduced irrigation and the yield gained from the additional irrigated area. It allows an integrated understanding of whether water-saving practices lead to an overall increase or decrease in production.

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

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. Growth 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 potatoes 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 tubes 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 Growth 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 an 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.

3.0. Results and Discussion

3.1. Physical and chemical properties of soil on the experimental

The soil at the experimental station exhibited a predominantly clay texture throughout the soil profile (0–20 cm, 20–40 cm, and 40–60 cm), with average particle size distributions of 20.9% sand, 56.1% clay, and 23.0% silt (Table 1). The average field capacity (FC) and permanent wilting point (PWP) were 35.6% and 23.9%, respectively. The total available water (TAW) averaged 135 mm, with a bulk density (BD) of 1.16 g/cm³ (Table 1).

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

Soil Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Texture	FC (%)	PWP (%)	TAW (mm)	BD (g/cm ³)	OC (%)	OM (%)	EC (dS/m)	pH
0–20	18.7	59.2	22.1	Clay	35.6	21.6	140	1.08	1.98	3.42	6.50	7.05
20–40	26.0	49.8	24.2	Clay	35.2	21.7	137	1.17	1.18	2.03	6.95	7.09
40–60	18.1	57.2	24.7	Clay	34.9	22.3	127	1.23	1.16	2.00	7.00	7.11
Average	20.9	56.1	23.0	Clay	35.6	23.9	135	1.16	1.44	2.48	6.82	7.08

3.2. Crop Water Requirement and Irrigation Water Requirement for Potato (2023/24)

In the 2023/24 cropping season, the **Irrigation Water Requirement (IWR)** for conventional furrow irrigation (CFI) was 210.94 mm for 100% ET_c, 168.69 mm for 80% ET_c, and 126.54 mm for 60% ET_c. For alternative and fixed furrow irrigation methods (AFI/FFI), the IWR values were 105.5 mm for 100% ET_c, 84.35 mm for 80% ET_c, and 63.27 mm for 60% ET_c.

Correspondingly, the **Crop Water Requirement (CWR)** under CFI was 359.49 mm at 100% ET_c, 287.59 mm at 80% ET_c, and 215.69 mm at 60% ET_c. For AFI/FFI, the CWR amounted to 179.75 mm at 100% ET_c, 143.80 mm at 80% ET_c, and 107.85 mm at 60% ET_c.

3.3. Crop Water Requirement and Irrigation Water Requirement for Potato (2024/25)

For the 2024/25 season, the **IWR** under conventional furrow irrigation (CFI) was reduced to 168.99 mm for 100% ET_c, 135.19 mm for 80% ET_c, and 101.39 mm for 60% ET_c. Meanwhile, the AFI and FFI methods required 84.50 mm, 67.60 mm, and 50.70 mm of irrigation water for 100%, 80%, and 60% ET_c levels, respectively.

The **CWR** in this season for CFI was 201.42 mm at 100% ET_c, 161.14 mm at 80% ET_c, and 120.85 mm at 60% ET_c. Under AFI and FFI, CWR was 100.71 mm, 80.57 mm, and 60.43 mm for the respective ET_c treatments.

Table 2. Depth Water Application on the Treatments (mm) year 2024.

TRT	CFI100 *ETC	CFI80 *ETC	CFI60 *ETC	AFI/FFI100 *ETC	AFI/FFI800 *ETC	AFILFFI60 *ETC
26-Dec-23	19.52	15.59	11.71	9.76	7.795	5.855
4-Jan-24	19.52	15.59	11.71	9.76	7.795	5.855
14-Jan-24	25.98	20.78	15.59	12.99	10.39	7.795
1-Feb-24	25.98	20.79	15.59	12.99	10.395	7.795
14-Feb-24	39.98	31.98	23.98	19.99	15.99	11.99
6-Mar-24	39.98	31.98	23.98	19.99	15.99	11.99
16-Mar-24	39.98	31.98	23.98	19.99	15.99	11.99

Table 3. Depth Water Application on the Treatments (mm) year 2025.

TRT	CFI100 *ETC	CFI80 *ETC	CFI60 *ETC	AFI/FFI100 *ETC	AFI/FFI800 *ETC	AFILFFI60 *ETC
31-Dec-24	19.52	15.62	11.71	9.76	7.81	5.86
14-Jan-25	19.53	15.62	11.72	9.76	7.81	5.86
25-Jan-25	25.91	20.73	15.55	12.96	10.36	7.77
10-Feb-25	25.91	20.73	15.55	12.96	10.36	7.77
22-Feb-25	39.06	31.25	23.44	19.53	15.62	11.72
7-Mar-25	39.06	31.25	23.44	19.53	15.62	11.72

3.4. Yield Response Factor (YRF) or K_y

The sensitivity of potato output to decreased water availability in alternative furrow systems was shown in the yield response factor (YRF), which peaked under AFI at 60% ETc. The YRF model, which has been widely used for irrigation planning since its development by Doorenbos and Kassam (1979), quantified the link between yield decline and water shortfall. Reference YRF values for several crops, including potatoes, were provided by FAO in 2021. These values showed high sensitivity during tuber development. Fereres et al. (2011) emphasized that to avoid yield penalties, high YRF values under AFI necessitate cautious irrigation timing. Similar reactions were noted by Kang et al. (2004) in potatoes, where irrigation time and technique were highly connected with production reduction under deficit conditions.

3.5. Water Saved (WS)

Lastly, compared to the CFI100%ETc treatment, the water saved (WS) under AFI and FFI at 60% ETc was significant, surpassing 40%. Deficit irrigation techniques can save a lot of water, especially when paired with partial root-zone drying, as Kirda (2002) showed. One of the best methods for conserving water in root and tuber crops is alternate furrow irrigation, as shown by Sezen et al. (2011). Zhang et al. (2000) also found that, with the right management, AFI might maintain yield while reducing water input by as much as 50%. In light of global water shortage and climate change, FAO (2021) continues to advocate for water-efficient technologies, such as managed deficit irrigation and AFI, as crucial practices.

3.6. Additional Irrigated Area (AIRGA)

A greater area might be irrigated with the same amount of water since $AFI \times 60\% ET_c$ conserves water. Redistributing conserved water to increase coverage without raising overall water abstraction is a key component of the AIRGA concept.

This approach was endorsed by Pereira et al. (2020), particularly in areas with limited water resources where growing irrigated acreage through increased efficiency is more practical than increasing water supplies. According to calculations by Fereres and Soriano (2007), managed deficit irrigation can raise AIRGA by as much as 50% in certain systems. According to Kijne et al. (2003), AIRGA is a crucial indicator for assessing irrigation treatments at the system level. Additionally, Mekonnen and Alemayehu (2023) showed that AFI at 60% ET_c permitted irrigated potato fields to expand by up to 30%.

3.7. Yield Gain from Additional Irrigated Area (YG AIRGA)

When taking into account the additional area watered, the overall production increased even though the yield per unit was lower for $AFI \times 60\% ET_c$ than for $CFI \times 100\% ET_c$. Consequently, YG is computed by incorporating the area expansion factor in addition to per-plot yield.

FAO (2022) emphasizes that yield gain should take into account both production per unit land and production per unit water. Bekele and Tilahun (2021) assert that YG must be viewed through the prism of total production from redistributed water when there is limited access to water. According to Kang et al. (2019), partial root-zone drying techniques can improve harvest index and promote carbohydrate translocation, which indirectly supports YG in deficiency systems.

3.8. Yield Reduction (YR), Yield Gain from Additional Irrigated Area (YG(AAIRG)), and Net Gain Analysis

In the face of finite water resources, effective irrigation water management necessitates both maximizing the use of conserved water to increase overall production and preserving acceptable crop yields. Two important metrics in this context—Yield Reduction (YR) and Yield Gain from Additional Irrigated Area (YG(AAIRG))—offer vital information about the potential and trade-offs associated with deficit irrigation techniques. The Yield Response Factor (YRF), Cost-Benefit Ratio (CBR), Water Saved (WS), Additional Irrigable Area (AIRGA), and Net Gain from Additional Area (NGAA) for each treatment are shown in Table 6 along with these measures.

3.8.1. Yield Reduction (YR)

The decrease in yield in comparison to the full irrigation treatment (CFI at 100% ET_c), which acts as the baseline, is known as yield reduction (YR). Table 6 illustrates that YR varies among irrigation techniques and rises with the degree of deficit irrigation. Under CFI at 80% ET_c , the YR was at its lowest (126.78 kg/ha), while under FFI at 60% ET_c , it was at its highest (491.56 kg/ha). This outcome emphasizes how sensitive yield is to water stress, especially when using the furrow irrigation technique. The alternating furrow irrigation (AFI) technique was particularly resilient to deficiency irrigation situations, with moderate production decreases (129.00 to 170.78 kg/ha across water levels).

3.8.2. Yield Gain from Additional Irrigated Area (YG(AAIRG))

The ability to irrigate more land with the water saved from deficit irrigation gives rise to the idea of yield gain from extra irrigated area (YG(AAIRG)). The amount of water saved with each treatment is used to compute this additional irrigated area, and the yield per unit area attained under that treatment is used to estimate the equivalent yield increase. AFI typically outperforms the other approaches, with YG(AAIRG) values ranging from 129.70 kg (CFI at 80% ETc) to 322.91 kg (AFI at 100% ETc). This implies that initial yield losses can be offset by a significant increase in irrigable land, which can be supported by the water savings under AFI.

3.8.3. Net Gain from Additional Area (NGAA)

The difference between YG (AAIRG) and YR is known as the net gain from additional area (NGAA), and it offers a comprehensive evaluation of the agronomic and economic advantages of every irrigation technique. A positive NGAA confirms the strategy's effectiveness by showing that the yield from the extra area exceeds the yield lost as a result of deficit watering. AFI at 100% ETc produced the largest net gain (193.91 kg), followed by CFI at 80% ETc (2.92 kg) and AFI at 80% and 60% ETc (83.27 and 72.92 kg, respectively), according to the results (Table 6). On the other hand, all FFI treatments displayed significant negative NGAA values, suggesting that the yield from more irrigated land did not balance out production losses.

According to this analysis, alternating furrow irrigation (AFI) offers a strategic advantage by enabling significant water savings with tolerable yield penalties, especially at full or moderate deficit levels. Redirecting the saved water to increase the irrigated area can increase yields and have a positive net effect on overall production. However, in situations where water is scarce, fixed furrow irrigation (FFI) has continuously demonstrated high production losses that outweigh any advantages of expanded area, making it ineffective.

3.8.4. Implications for Irrigation Planning and Water Policy

According to the results, AFI can be a very successful deficit irrigation technique to increase water productivity when there is a shortage of available water. By using YR and YG (AAIRG) as complementary indicators, irrigation techniques can be evaluated more comprehensively, taking into account the wider impact on system output as a whole in addition to yield results per hectare. These findings demonstrate how crucial it is to take yield stability and growth potential into account when developing irrigation techniques for sustainable agriculture.

Table 4. Effect of Furrow Irrigation Method and Deficit Irrigation Level on Potato Yield, Yield Reduction, Irrigation Water Use, Water Savings, Production Cost, and Gross Revenue.

TRT	YR	YRF (K)	WS (mm)	AIRGA (ha)	YG(AAIRG) Kun	NGAA
CFI*100*ETc	0.00	0	0	0.0	0.00	0.00
CFI*80*ETC	126.78	1.05	54.92	0.2	129.70	2.92
CFI*60*ETc	142.56	1.36	109.80	0.4	252.96	110.40
AFI*100*ETc	129.00	1.67	137.22	0.5	322.91	193.91
AFI*80*ETC	152.45	2.01	164.69	0.7	235.71	83.27
AFI*60*ETc	170.78	2.60	192.13	0.9	243.70	72.92

FFI*100*ETc	391.78	0.99	137.22	0.5	191.53	-200.24
FFI*80*ETC	422.33	1.14	164.69	0.7	146.79	-275.55
FFI*60*ETc	491.56	1.22	192.13	0.9	135.00	-316.56

3.9. Economic Analysis

3.9.1. Cost-Benefit Ratio (CBR) and Marginal Rate of Return (MRR)

The irrigation treatments' economic evaluation showed notable variations in the approaches' profitability and the degree of deficit. Because of its remarkable yield of 774.89 kun/ha, CFI $\times$ 100% ETc generated the highest gross and net returns (ETB 464,934/ha and ETB 344,934/ha, respectively) with a CBR of 3.87. Its MRR of 2871.5%, which demonstrated that full irrigation under typical furrows delivers maximum profit when water and capital are not limiting factors, justified the investment despite increased operating expenses (ETB 120,000/ha).

On the other hand, AFI $\times$ 100% ETc and CFI $\times$ 80% ETc produced yields that were much lower than CFI100, but they were still profitable, with CBRs of 2.58 to 2.59 and net returns of about ETB 23,886/ha. In line with Pulido-Calvo et al. (2015), who pointed out the cost-saving benefits of alternate furrows, these treatments demonstrate the economic effectiveness of AFI, particularly in situations with a moderate deficit. Similarly, by lowering labor and water inputs without significantly lowering yield, Hsiao et al. (2007) proposed that deficit irrigation may be profitable.

Of all the deficiency therapies, AFI $\times$ 60% ETc had the highest MRR (780.4%), closely followed by AFI $\times$ 80% ETc (MRR = 119.6%). They reinforce FAO's (2021) appeal for cost-effective, water-saving irrigation solutions by demonstrating the economic advantage of AFI under moderate deficit, especially when water scarcity and cost limitations are highlighted.

Conversely, the lowest net returns and CBRs (1.70–1.92) were obtained with FFI treatments (Fixed Furrow Irrigation), indicating both agronomic and economic inefficiency. This suggests that even at full ETc, FFI is less appropriate for water conservation.

Overall, these findings underscore that AFI $\times$ 60–80% ETc offers a cost-efficient and water-conserving strategy, while CFI $\times$ 100% ETc, though resource-intensive, remains the most profitable when yield maximization is the goal.

Table 5. Partial Budget Analysis and Marginal Rate of Return (MRR).

Treatment	TY (kun/ha)	Gross Income (ETB/ha)	Cost (ETB/ha)	Net Return (ETB/ha)	CBR	MRR (%)
FFI $\times$ 60% ETc	283.3g	170,000	100,000	7,000	1.7	–
FFI $\times$ 80% ETc	352.5f	211,500	110,000	10,150	1.92	315
FFI $\times$ 100% ETc	383.1e	229,860	120,000	10,986	1.92	83.6
AFI $\times$ 60% ETc	604.1d	362,460	100,000	22,746	2.68	780.4
AFI $\times$ 80% ETc	622.4c	373,440	110,000	23,344	2.67	119.6
CFI $\times$ 60% ETc	632.3c	379,380	145,000	23,438	2.62	18.8

AFI × 100% ET _c	645.8b	387,480	120,000	23,748	2.58	6.2
CFI × 80% ET _c	648.1b	388,860	150,000	23,886	2.59	2.2
CFI × 100% ET _c	774.89a	464,9340	300,000	344,934	3.87	2871.5

4.0. Conclusion and Recommendation

The results of this study show that in water-limited situations, deficit irrigation, when combined with effective furrow irrigation systems, can significantly increase water productivity while preserving commercially viable potato yields. Despite having the best absolute yield, CFI at 100% ET_c used a lot more water and cost more in inputs. On the other hand, AFI at 80% and 100% ET_c substantially outperformed other treatments in terms of crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and economic return metrics like MRR and NGAA, while producing only slightly lower outputs.

By lowering inefficient water losses and promoting partial root-zone drying, the application of AFI at deficit levels successfully optimized water allocation and improved the physiological resilience of the plant. FFI was less successful in ensuring yield stability and economic profitability, especially at lower ET_c levels. In addition to maintaining output, the use of water-saving irrigation techniques like AFI opens up possibilities for increasing irrigated acreage while maintaining the same water budget.

4.1. Future Research Recommendations

Promote the adoption of Alternate Furrow Irrigation (AFI) at 80-100% ET_c levels as a sustainable and efficient strategy for smallholder potato producers in water-limited regions.

Provide extension support and training on irrigation scheduling, partial root-zone drying, and moisture monitoring to improve farmer adoption of deficit irrigation practices.

Avoid Fixed Furrow Irrigation (FFI) at severe deficit levels due to poor performance in yield and economic efficiency.

Encourage integrated irrigation planning at the community level using indicators such as Yield Response Factor (YRF), Marginal Rate of Return (MRR), and Additional Irrigable Area (AIRGA) for informed water allocation.

Conduct long-term studies on soil health, tuber quality, and labor efficiency to fully assess the broader sustainability impacts of deficit irrigation systems.

Conduct multi-season and multi-location trials to validate the performance of the irrigation strategies under different soils, climates, varieties, and water-availability conditions.

Declarations

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Consent for publication

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

Authors' Contributions

Abu Dedo Ilmi led study implementation, data analysis, and manuscript preparation; Roba Adugna Maru contributed to field supervision and manuscript review.

Informed Consent

Not Applicable

Availability of Data and Material

The underlying experimental data are available from the corresponding author upon reasonable request, subject to author and institutional approval.

Institutional Review Board Statement

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Not Applicable

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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.

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