American Journal of Water Science and Engineering
2024, Vol. 10, No. 4, pp. 108-117
https://doi.org/10.11648/j.ajwse.20241004.13

Research Article

Effect of Deficit Irrigation at Different Growth Stages on the Yield and Water Productivity of Tomato at Adami Tulu Agricultural Research Center

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Abstract

Improving irrigation water management and increasing water productivity are critical to address future water scarcity in arid and semi-arid areas. A promising strategy is to maximize water productivity by exposing crops to a certain level of water stress. The experiment was conducted on-site at the Adami Tulu Agricultural Research Center to study the effect of deficit irrigation at different growth stages on agronomic parameters as well as yield and yield components as well as water productivity of tomato plants. Treatments consisted of a factorial combination of full and three-deficit irrigation with four plant growth stages. The results showed that the interaction effect between deficit irrigation and different plant growth stages significantly affected plant height, fruit height, fruit diameter, fruit yield and water productivity. The highest plant height (75.23 cm), fruit length (84.56 mm), fruit diameter (77.10 mm), marketable fruit yield (48.64 t/ha) and total fruit yield (50.09 t/ha) were obtained under continuous full irrigation achieves levels. While the lowest plant height (54.43 cm), fruit length (55.92 mm), fruit diameter (50.04 mm), marketable yield (22.51 tons/ha) and total yield (28.14 tons/ha) at 60% Etc achieved in the middle were stage treatment. The highest water productivity of 7.85 kg/ha was achieved with the application of 80% ETc in the late season, while the lowest (4.61 kg/ha) was achieved with 60% ETc in the middle treatment phase. Therefore, the results of this study suggest that applying 80% ETc deficit irrigation in the late season stage is the best solution for water conservation without affecting tomato yield while improving water productivity under water-stressed conditions.

Keywords

Crop Growth Stage, Deficit Irrigation, Fruit Yield, Tomato, Water Productivity

1. Introduction

About 70% of the Earth's surface is covered by water [1], but only about 2.5% is freshwater. The world's freshwater resources are expected to become even more stressed in many regions, with over 40 percent of the world's population predicted to live in river basins suffering from severe water shortages by 2050. As pressure on water resources increases, this creates tensions between users and industries and excessive pressure on the environment [2].

Irrigated agriculture is the main consumer of available fresh water worldwide and its consumption is estimated at 70% of existing fresh water supplies. There is a general perception that water use in agriculture is often wasteful and highly in-

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Received: 27 September 2024; **Accepted:** 30 October 2024; **Published:** 26 November 2024

efficient [3]. Although irrigated agriculture accounts for only 17% of the world's cultivated area, it provides 40 to 45% of the world's food and fiber supplies [4]. Consequently, the freshwater resources available to agriculture need to be re-rationalized to meet the development needs of other sectors.

Due to the temporal and spatial imbalance in the distribution of precipitation, it becomes almost impossible to ensure a sustainable and reliable food supply. This often led to critical water shortages, resulting in crop failures. To combat these natural phenomena, it is necessary to switch to efficient irrigated agriculture.

Deficit irrigation is an optimization strategy that allows a certain amount of water stress during a specific growing phase or throughout the season without significant yield loss. Stage-based deficit irrigation is reduced deficit irrigation (RDI) applied at different stages of plant development, using water at the critical growth stages to achieve full evapotranspiration (ETc) of the plant and less at the non-critical growth stages Water is used. The principle of this approach is that the response of plants to RDI-induced water stress varies depending on the growth stage and that reducing irrigation of plants at non-critical stages may not have a significant negative impact on plant productivity, although it may reduce normal plant growth. To effectively apply this approach, one needs to predetermine the critical growth stages for a particular crop species and variety and evaluate the relative sensitivity of crops to water stress at different stages of their life cycle [5].

2. Materials and Methods

2.1. Description of Experimental Area

The experiment was conducted on-site at the Adami Tulu Agricultural Research Center for two consecutive years (2021 and 2022). It is located at 7°51' 40"N and 38°42' 47"E at an altitude of about 1651 meters above sea level. It is located 167 km from Addis Ababa in the southeast of the country on the asphalt road to Hawassa. The average minimum and maximum monthly temperature is between 14.3℃ and 27.7℃, respectively, and the average annual rainfall is 762 mm. And the soil is sandy loam. It is a potential area for the production of horticultural crops with greater diversity.

2.2. Experimental Treatments and Design

The treatments of the experiment consisted of factorial combinations of deficit irrigation applications (full irrigation, 20% deficit, 30% deficit, and 40% deficit of crop evapotranspiration) and four crop development stages (initial, developmental, middle stage, and late season). These growth stages are selected taking into account the most relevant phonological stages in terms of their response to irrigation based on the recommendations of various researchers. The experiment was arranged in a Randomized Complete Block Design (RCBD) and repeated three times.

The experimental field plot was created by dividing the field into 3 blocks and 39 plots, with each experimental plot measuring 4 m x 4 m. Buffer zones with distances of 1 m or 1.5 m were provided between the plots or blocks.

The test field was prepared by plowing with a tractor-driven implement and then harrowing, leveling and hilling by hand. Tomatoes (variety Galilama) were sown on seedling trays in the greenhouse and transplanted after four weeks into the experimental plots with planting and row spacings of 50 cm and 100 cm, respectively. To ensure that the system provides common irrigation for all treatments before starting differential irrigation. All agricultural practices except variable factor were standard recommended practices for the area. Weeding and inter-row cultivation were carried out by hand hoes when necessary. NPS fertilizer was applied during transplanting at a rate (200 kg/ha) in all treatments, and N fertilizer was applied at a rate of 150 kg/ha split (half during transplanting and half after 6 weeks). The control of diseases and pests was carried out in accordance with the recommendation of the agronomist of the research center.

2.3. Determination of Crop Water Requirement

Plant water requirements (ETc) were calculated from climate data by integrating the influence of plant characteristics directly into the evapotranspiration of the reference plants. The FAO Penman-Monteith method was used to determine reference culture evapotranspiration (ETo). The Penman-Monteith equation is given by the equation:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Where: ETo = Reference evapotranspiration (mm/day), R_n = Net radiation at the crop surface (MJ/m_2 per day), G = Soil heat flux density (MJ/m^2 per day), T = Mean daily air temperature at 2 m height (℃), U_2 = Wind speed at 2 m height (m/sec), e_s = Saturation vapor pressure (kPa), e_a = Actual vapor pressure (kPa), e_s - e_a = Saturation vapor pressure deficit (kPa), Δ = Slope of saturation vapor pressure curve at temperature T (kPa/°C), γ = Psychrometric constant (kPa/°C).

Experimentally determined ratios of ETc and ETo, called harvest coefficients (Kc), are used to relate ETc to ETo, as given by the equation:

$$ETc = ETo \times Kc$$

Where: ETc = crop evapotranspiration (mm/day), ETo = reference crop evapotranspiration (mm/day) and Kc = crop coefficient

Irrigation Requirement (IR) can be estimated using the expression:

$$\text{IR} = \text{CWR} - \text{Effective rainfall}$$

Where: IR in mm, CWR in mm, and effective rainfall which is part of the rainfall that entered into the soil and made available for crop production in mm.

Effective rainfall was estimated using the method given in CROPWAT software using reliable rainfall (FAO formula).

$$P_{eff} = 0.6 \times P - 10 \; for \; month \leq 70 \; mm$$

$$P_{eff} = 0.8 \times P - 24 \; for \; month > 70mm$$

Where: P is rainfall in mm and P_{eff} is effective rainfall in mm

The irrigation plan was created using Cropwat 8.0 software. In the model, one of the calculation methods for optimal irrigation scheduling without yield loss is irrigation occurring at 100% readily available soil moisture depletion to replenish the soil to its field capacity. The RAW was calculated from the expression:

$$RAW = \rho \times TAW$$

Where: RAW in mm, p is in fraction for allowable soil moisture depletion for no stress, and TAW is total available water in mm.

Total available soil water (TAW) was calculated from soil moisture content at field capacity (FC) and permanent wilting point (PWP) using the following expression:

$$TAW = \frac{FC - PWP}{100} \times (pb \times Dz)$$

Where: FC and PWP in % on a weight basis, Pb is the bulk density of the soil in gm/cm^3, and Dz is the maximum effective root zone depth in mm.

Soil bulk density (Pb), also called dry bulk density, was calculated as the weight of dry soil (Ms) divided by the total soil volume (Vs).

$$BD = \frac{Ms}{Vs}$$

Where: Ms is the weight of oven-dry soil, and Vs is the volume of the same soil in cm^3.

Taking into account the daily CWR and RAW, the watering interval was calculated using the expression:

$$Interval = \frac{RAW}{CWR}$$

Where: RAW in mm and CWR in mm/day

The gross irrigation requirement IRg for a given event was calculated using the expression:

$$IRg = \frac{Interval \times CWR}{Ea}$$

Where: IRg is mm, interval in days, CWR in mm/day and Ea is the irrigation water application efficiency in fraction.

2.4. Data Collection and Analysis

The data sources for this research were both primary and secondary data. Daily climate data such as precipitation, maximum and minimum temperature, relative humidity, sunshine hours, and wind speed were collected and used to determine reference evapotranspiration (ETo) and effective precipitation through CROPWAT 8.0 software.

Representative soil samples were collected to examine some soil properties (field capacity and permanent wilting point, bulk density, organic matter, texture, electrical conductivity (ECe), and PH) of the study area. Samples were taken at a depth interval of 30 cm within the effective root zone. This helped determine the total available water content of the soil.

Soil bulk density was determined by collecting undisturbed soil samples from an effective root zone at 15 cm intervals using a core sampler. The soil samples were oven-dried at a temperature of 105 ℃ for 24 hours. Then the bulk density (ρb) was determined as follows [6]:

$$\rho b = \frac{M_s}{V_b}$$

Where: ρ_b = Soil bulk density (g/cm^3), M_s = the mass of soil after oven-dry (g), and V_b = bulk volume of soil (cm^3).

2.5. Agronomic Data

The height of five plants was randomly assigned and measured from the ground to the tip of the longest mature leaf 75 days after transplanting. Yield parameter data such as fruit height, fruit diameter and fruit weight were also recorded from the same plants and an average value was given. To assess the effect of treatments on water productivity, fruit yield in the middle rows of each plot was collected and weighed. The harvested yield was divided into marketable and non-marketable categories depending on the size and degree of damage. Number of unmarketable fruits per hectare: Fruits with cracks, rot, damage from insects, diseases and birds, as well as sunburn and particularly small fruits were collected from five marked plants and considered unmarketable.

Water productivity (WP) was determined by dividing the total crop yield by the net amount of irrigation water applied to the crops, as given by the following equation [7]:

$$WP = \frac{Y}{ETc}$$

Where: WP is water productivity (Kg/m^3), Y is total fruit yield per unit area (Kg/ha), ETc is crop evapotranspiration (mm).

2.6. Water Saving

The amount of water saved by the treatments compared to the control was calculated as follows:

$$W_s = \frac{W_c - W_t}{W_c} \times 100$$

Where:

W_s is water saving (%), W_c is total water used in control treatment (m^3/ha) and W_t is total water used in treatment (m^3/ha)

Yield response factor (K_y)

The relationship between evapotranspiration deficit [1 – (ETa/ETc)] and yield depression [1 – (Ya/Ym)] is always linear. The slope of this linear relationship is called the yield response factor or crop response factor (Ky). It is defined as the decrease in yield per unit decrease in ET. This relationship is expressed by the equation:

$$\left[1 - \left(\frac{y_a}{y_m}\right)\right] = K_y \left[1 - \left(\frac{ET_a}{ET_m}\right)\right]$$

Where: Y_m (ton/ha) and Y_a (ton/ha) are the maximum (from a fully irrigated treatment) and actual yields, respectively. The ET_m (mm/ha) and ET_a (mm/ha) are the maximum/fully irrigated treatment and actual evapotranspiration, respectively, while K_y is the yield response factor.

2.7. Economic Analysis

The economic analysis was carried out to assess the benefits arising from the deficit application at different stages. To determine economic feasibility, a benefit-cost analysis was carried out. The costs of tomato production include the costs of field preparation, the costs of seeds, sowing, fertilizers, weed control, crop protection measures, irrigation water, and harvesting. Production revenue was estimated based on average market prices (15 Birr/kg) prevailing at the time of harvest. The price level for irrigation water of 1 Birr/238 m3 practiced in the Awash River Basin was taken into account [8]. All costs and benefits were calculated on a hectare basis in Ethiopian birr (birr/ha). Then, the total production cost, benefit-cost ratio, and irrigable area by using the saved water, the net return from the saved water, and the net return from tomato cultivation over 1 ha were estimated.

2.8. Statistical Analysis

The collected data were analyzed using the SAS 9.2 software package. Whenever the treatment effect was determined to be significant, treatment means were compared using least significant difference (LSD).

3. Results and Discussions

3.1. Soil Physico-Chemical Analysis

The selected physicochemical soil properties of the test site in two soil depth intervals are shown in Table 1. The determination of the percentage particle size revealed that the soil texture of the study area is sandy loam. The average bulk density of the soil in the study area was 1.272 g/cm^3. The mean soil PH, EC, and OC values in the study area were 7.8, 0.145 ds/m, and 1.04%, respectively. The moisture content at field capacity, permanent wilting point, and total available water were 12.98%, 6.78%, and 78.80 mm/m, respectively.

Table 1. *Selected physicochemical properties of the soil.*

Soil properties	Soil depth (cm)		Mean
	0-30	30-60	
Sand (%)	71	76	73.5
Silt (%)	15	11	13
Clay (%)	14	13	13.5
Textural class	Sandy loam	Sandy loam	Sandy loam
Bulk density (gcm-3)	1.271	1.272	1.272
PH-water (1:2.5)	7.9	7.7	7.8
ECe (ds/m)	0.166	0.123	0.145
OC (%)	1.25	0.82	1.04
FC (%)	14.1	11.85	12.98
PWP (%)	8.71	4.85	6.78
TAW (mm/m)	20.57	26.71	78.80

3.2. Crop Water Requirement

The net and gross depth of irrigation water applied in the different treatments during the experimental period and the relative water savings due to deficit application at different growth stages are shown in Table 2. The variations in net and gross irrigation requirements that occurred between treatments were due to deficit application at different growth stages. The net irrigation depths applied varied between 394.18 mm for the 60% ETc mid-stage treatment and 460.18 mm for the full irrigation depth application.

Table 2. *Crop and irrigation water requirement.*

Treatments	CWRn (mm)	CWRg (mm)	Pefn (mm)	IWRg (mm)	Rws		
					mm	(m^3/ha)	(%)
Control	460.18	657.40	11.4	646.00	0.0	0.0	0.0
80%ETc@I	444.61	635.16	11.4	623.76	22.2	222.4	3.4
80%ETC@D	437.21	624.58	11.4	613.18	32.8	328.2	5.1
80%ETC@M	427.18	610.26	11.4	598.86	47.1	471.4	7.3
80%ETC@L	439.68	628.12	11.4	616.72	29.3	292.8	4.5
70%ETC@L	429.44	613.48	11.4	602.08	43.9	439.2	6.8
70%ETC@D	425.72	608.17	11.4	596.77	49.2	492.3	7.6
70%ETC@I	436.83	624.04	11.4	612.64	33.4	333.6	5.2
70%ETC@M	410.68	586.69	11.4	575.29	70.7	707.1	10.9
60%ETC@I	429.04	612.92	11.4	601.52	44.5	444.8	6.9
60%ETC@D	414.23	591.76	11.4	580.36	65.6	656.4	10.2
60%ETC@M	394.18	563.12	11.4	551.72	94.3	942.8	14.6
60%ETC@L	419.19	598.84	11.4	587.44	58.6	585.6	9.1

CWRn=net water requirement, CWRg=gross water requirement, IWRg=gross irrigation water requirement, P_{ef}=effective rainfall and Rws=relative water saved I - Initial

Effects of deficit irrigation at different growth stages on agronomic parameters of Tomato

The effects of deficit irrigation at different growth stages on tomato agronomic parameters such as plant height, number of branches per plant, and number of clusters per plant are shown in Table 3.

Table 3. *Effects of deficit irrigation on tomato agronomic parameters.*

Treatments	Plant height (cm)	Number of branches per plant (NBP)	Number of cluster per plant (NCP)
Control	75.23^{a}	4.77^{a}	17.03^{a}
80%ETC@I	69.35^{bc}	4.27^{bc}	15.35^{bc}
80%ETC@D	67.65^{cd}	4.10^{cd}	14.92^{bcd}
80%ETC@M	66.30^{de}	4.07^{cd}	14.48^{cde}
80%ETC@L	70.50^{b}	4.43^{b}	15.92^{ab}
70%ETC@L	64.11^{ef}	3.90^{de}	13.83^{de}
70%ETC@D	63.93^{ef}	3.80^{ef}	13.53^{ef}
70%ETC@I	63.76^{f}	3.80^{ef}	13.57^{ef}
70%ETC@M	61.13^{g}	3.63^{fg}	13.38^{gh}
60%ETC@I	58.05^{h}	3.47^{gh}	11.83^{gh}
60%ETC@D	54.91^{i}	3.37^{h}	11.42^{hi}
60%ETC@M	54.43^{i}	3.03^{i}	10.38^{i}
60%ETC@L	60.43^{gh}	3.67^{efg}	12.62^{fg}

Treatments	Plant height (cm)	Number of branches per plant (NBP)	Number of cluster per plant (NCP)
LCD	2.45	0.26	1.15
CV	2.29	3.92	5.01

The highest plant height of 75.23 cm was measured in the application of full irrigation in all phases and was significantly different from all other treatments, while the smallest plant height of 54.43 cm was measured in the 60% ETc treatment in the middle phase statistically not significantly different from 60% ETc at the development stage. The better performance of this growth parameter under full irrigation at all stages could be due to the optimal water-air balance of the soil around the plant root zone and the easy availability of soil nutrients. This result is confirmed [9], who reported that the highest plant height was recorded by the control treatment and the lowest by deficits in vegetative, flowering, and fruit development.

The highest number of branches per plant was recorded in full irrigation applications at all stages and was significantly different from all other treatments. While the lowest number of branches per plant was recorded in mid-season treatment with 60% ETc. This result is consistent with [10] who reported that inadequate irrigation affects the number of tomato branches. As studied by [11], the number of branches per plant of a tomato crop varies between three and nine.

The highest number of clusters per plant was recorded under full irrigation at all treatment stages and was significantly different from all treatments except 80% ETc in late-season treatments [9]. While the lowest number of clusters per plant was observed in the midseason treatment with 60% ETc, it was not significantly different from the developmental stage treatment with 60% ETc.

Effects of deficit irrigation at different growth stages on Tomato yield and yield attributes

The effects of deficit irrigation at different growth stages on tomato yield and yield components such as number of fruits per cluster, number of fruits per plant, fruit diameter, fruit length, marketable yield, non-marketable yield, total yield, and water productivity were presented in Table 4.

Table 4. *Effects of deficit irrigation at different growth stages on yield, yield characteristics and water productivity.*

Treatments	Number of fruit per cluster (NFC)	Number of fruit per plant (NFP)	Fruit diameter (mm)	Fruit length (mm)	Marketable Yield (t/ha)	Unmarketable Yield (t/ha)	Total Yield (t/ha)	Water productivity (Kg/m^3)
Control	5.23^{a}	77.63^{a}	77.10^{a}	84.56^{a}	48.64^{a}	1.46^{f}	50.09^{a}	7.62^{ab}
80%ETC@I	4.56^{bc}	68.17^{bc}	65.50^{bc}	74.53^{bc}	41.98^{bc}	2.94^{de}	44.92^{ab}	7.07^{abc}
80%ETC@D	4.39^{cd}	64.59^{cd}	62.25^{cd}	72.13^{bc}	39.17^{cd}	2.74^{e}	41.91^{bc}	6.71^{cd}
80%ETC@M	4.35^{cd}	63.37^{d}	61.79^{cd}	69.78^{bcde}	38.42^{cde}	2.69^{e}	41.11^{bcd}	6.74^{bcd}
80%ETC@L	4.79^{b}	71.28^{b}	70.51^{ab}	75.37^{b}	46.07^{ab}	3.23^{de}	49.29^{a}	7.85^{a}
70%ETC@L	4.15^{de}	58.72^{e}	58.72^{cde}	65.58^{def}	35.23^{def}	3.52^{d}	38.75^{cde}	6.17^{ed}
70%ETC@D	4.16^{de}	55.96^{ef}	58.47^{de}	66.69^{cdef}	32.72^{fg}	3.27^{de}	35.99^{def}	5.76^{ef}
70%ETC@I	4.15^{de}	56.73^{ef}	58.64^{cde}	65.50^{def}	33.48^{efg}	3.35^{d}	36.83^{cdef}	5.79^{ef}
70%ETC@M	4.00^{ef}	52.94^{fg}	58.14^{def}	63.55^{efg}	29.81^{gh}	2.98^{de}	32.79^{fg}	5.37^{efg}
60%ETC@I	3.74^{fg}	49.68^{gh}	50.92^{g}	55.92^{g}	26.78^{hi}	6.69^{b}	33.47^{efg}	5.27^{fg}
60%ETC@D	3.56^{gh}	47.70^{h}	51.41^{fg}	56.67^{g}	24.18^{i}	6.04^{c}	30.22^{g}	4.84^{g}
60%ETC@M	3.29^{h}	40.78^{i}	50.04^{g}	56.78^{g}	22.51^{i}	5.63^{c}	28.14^{g}	4.61^{g}
60%ETC@L	3.99^{ef}	53.99^{fg}	54.23^{efg}	61.03^{fg}	30.81^{fgh}	7.70^{a}	38.51^{cde}	6.13^{def}
LCD	0.27	4.55	6.94	8.54	5.08	0.59	5.59	0.89
CV	3.89	4.63	6.89	7.62	8.75	8.89	8.63	8.63

Statistical analysis showed that the application of phased deficit irrigation significantly affects the number of fruits per cluster, the number of fruits per plant, fruit width, fruit length, yield and water productivity.

The highest number of fruits per cluster was recorded under full irrigation at all treatment stages and was significantly different from all treatments. While the lowest number of fruits per cluster was recorded in the 60% ETc treatment at the mid-stage, it was significantly different from all treatments except the 60% ETc at the development stage. This may be due to the application of deficit irrigation during development and mid-stage, particularly at 60% ETc, which reduces the number of flowers per plant and this leads to a reduction in the number of fruits per cluster.

The highest number of fruits per plant was recorded under full irrigation at all treatment stages and was significantly different from all treatments. While the smallest fruits per plant were recorded at the middle stage in the 60% ETc treatment, they were statistically significantly different from all treatments. It is observed that the number of fruits in the developmental and middle stages is strongly influenced by water stress. This is due to flower abort. This result is similar to [12] who find that applying deficit irrigation during the flowering and fruit development phase reduces the number of reproductive organs, resulting in a reduction in fruit number per plant.

The highest fruit diameter was recorded under full irrigation at all treatment stages. While the smallest fruit diameter was found in the 60% ETc treatment in the middle stage, it was not statistically significantly different from 60% ETc in the late season, 60% ETc in the early season, and 60% ETc in the developing season. Reducing the irrigation level from 100% ETc to 60% ETc increased the unmarketable yield to some extent.

The highest fruit length was recorded under full irrigation at all treatment stages and was significantly different from all treatments. While the smallest fruit length was found in the early-stage 60% ETc treatment, it was not significantly different from late-stage 60% ETc, mid-stage 60% ETc, and mid-stage 60% ETc and mid-stage treatments.

The highest marketable yield was recorded at full irrigation in all treatment stages and was significantly different from all but 80% ETc in late-season treatments, while the lowest was observed at 60% ETc in the middle treatment stage and was not statistically significantly different from 60% ETc in early stage and 60% ETc in development stage treatments. 80% ETc likely did not affect yield in the late season compared to the fully irrigated treatment ($p \leq 0.05$). This result is consistent with [13] who reported that a DI of 100 to 75% ETc did not affect fruit weight during the vegetative phase or fruiting phase; whereas the DI significantly reduced fruit weight during the reproductive phase or throughout the season.

This result showed that the application of deficit irrigation in the middle and development phases, i.e. in the flowering and fruit development phase, leading to a potential reduction in yield. This may be because insufficient application during these phases leads to the flowers breaking off, resulting in a loss of yield. This result was consistent with [9, 14], which stated that the application of deficit irrigation in the flowering and development stages resulted in yield reduction.

The highest non-marketable yield was recorded at 60% ETc in the late season treatment and was significantly different from all treatments, while the smallest was observed at full irrigation in all treatment stages and was statistically significantly different from other treatments ($p \leq 0, 05$).

The highest total yield was recorded at full irrigation in all treatment stages and was not significantly different from 80% ETc in the late season and 80% ETc in the initial phase of treatment, while the lowest was observed at 60% ETc in the middle treatment phase and was statistically different it is not significantly different from 70% ETc in the middle stage, 60% ETc in the initial stage and 60% ETc in the development stage.

The reason for the better performance of these growth parameters under control treatment was due to the application of full irrigation regime during all growth stages of the crop. This can be attributed to an optimal water-air balance of the soil around the plant root zone and easy availability of soil nutrients.

Although statistically there was no significant difference from full irrigation application in all phases, the highest water productivity was recorded from 80% ETc in the late season treatment due to a non-significant yield difference from the control, while water application appeared to be reduced from 80% ETc in the late season treatment compared to control. Although the lowest value was observed from 60% ETc in the middle treatment stage and was not statistically significantly different from 70% ETc in the middle stage, 60% ETc in the initial stage and 60% ETc in the development stage.

Previous studies have shown that inadequate irrigation reduces tomato fruit yield under drought stress conditions [15]. Other results have also shown that water stress during the vegetative stage had no negative impact on tomato yield [14]; [16, 17] also reported that total and marketable tomato yield decreased in the most stressed treatment with a deficit of 75%. As studied by [15], there were no adverse effects on total fruit and marketable yield when deficit stress was applied during the vegetative phase.

3.3. Yield Response Factor (K_y)

The observed yield response factors (Ky) for tomato production ranged from 1.2 to 6.6. The highest Ky was 6.6 at 60% ETc in the initial stage, followed by 70% ETc in the initial stage. The lowest Ky was 1.2 at an 80% deficit at the end of the season, followed by 2.9 at an 80% deficit at halftime. The observed Ky was comparatively higher under insufficient irrigation water application during the developmental and initial stages. On the other hand, lower values were obtained due to insufficient irrigation with water in the late and middle stages of the tomato. According to [18], Ky values above 1.15 indicate a high sensitivity of the crop to water shortage.

The higher Ky values indicate that the crop would suffer a greater yield loss, and vice versa: the lower the Ky values, the smaller the yield loss due to water stress. The result showed that the application of DI in the development and early stages resulted in significant yield loss compared to the late season and mid-stage with the same deficit application. This shows that deficit levels spread across different growth stages can lead to significantly different declines in earnings. In general, the result indicates that the crop's sensitivity to soil moisture is deficient at certain growth stages.

Table 5*. Yield response factor.*

Treatments	ETa (mm)	Yield (ton/ha)	1-(Ya/Ym)	1-(ETa/ETm)	Ky
Control	657.4	48.64	0.00	0.00	
80%ETC@I	635.16	41.98	0.14	0.03	4.0
80%ETC@D	624.58	39.17	0.19	0.05	3.9
80%ETC@M	610.26	38.42	0.21	0.07	2.9
80%ETC@L	628.12	46.07	0.05	0.04	1.2
70%ETC@L	613.48	35.23	0.28	0.07	4.1
70%ETC@D	608.17	32.72	0.33	0.07	4.4
70%ETC@I	624.04	33.48	0.31	0.05	6.1
70%ETC@M	586.69	29.81	0.39	0.11	3.6
60%ETC@I	612.92	26.78	0.45	0.07	6.6
60%ETC@D	591.76	24.18	0.50	0.10	5.0
60%ETC@M	563.12	22.51	0.54	0.14	3.7
60%ETC@L	598.84	30.81	0.37	0.09	4.1

3.4. Economic Analysis

As shown in Table 6, the highest and lowest total costs of 356,808.25 Birr/ha and 348,046.18 Birr/ha occurred with full irrigation in all phases and 60% ETc in the middle phase of treatments, respectively. The negative sign of the net return recorded under 60% ETc in development and 60% ETc in mid-stage treatments indicates that there is an economic loss in these treatments due to the application of 60% ETc in development and 60% ETc in the middle phase resulted in loss of yield. The highest benefit-cost ratio of 1.8 was achieved with full irrigation at all stages and 80% ETc in late-season treatments. In addition, a net return of Birr 12,576.63 is expected to be achieved from water saved in 80% treatment etc. in the late season. Therefore, 80% ETc could be considered to have an economic advantage over the others in the late season.

Table 6*. Economic analysis.*

Treatments	UMY (kg/ha)	AMY (kg/ha)	TC (birr/ha)	TR (birr/ha)	NR (birr/ha)	B/C	IL_{sw} (ha)	NR_{ws} (birr)
Control	48,640	43,776	356,808.25	656,640.00	299,831.75	1.8	0.00	0.00
80%ETC@I	41,980	37,782	352,492.05	566,730.00	214,237.95	1.6	0.04	7,501.50
80%ETC@D	39,170	35,253	351,976.28	528,795.00	176,818.73	1.5	0.05	9,291.35
80%ETC@M	38,420	34,578	351,278.18	518,670.00	167,391.83	1.5	0.08	12,930.31
80%ETC@L	46,070	41,463	352,148.85	621,945.00	269,796.15	1.8	0.05	12,576.63

Treatments	UMY (kg/ha)	AMY (kg/ha)	TC (birr/ha)	TR (birr/ha)	NR (birr/ha)	B/C	IL_{sw} (ha)	NR_{ws} (birr)
70%ETC@L	35,230	31,707	350,532.85	475,605.00	125,072.15	1.4	0.07	8,954.11
70%ETC@D	32,720	29,448	350,360.28	441,720.00	91,359.73	1.3	0.08	7,395.37
70%ETC@I	33,480	30,132	350,876.05	451,980.00	101,103.95	1.3	0.05	5,404.83
70%ETC@M	29,810	26,829	349,662.18	402,435.00	52,772.83	1.2	0.12	6,360.37
60%ETC@I	26,780	24,102	349,260.05	361,530.00	12,269.95	1.0	0.07	890.44
60%ETC@D	24,180	21,762	348,744.28	326,430.00	-22,314.28	0.9	0.11	-2,475.17
60%ETC@M	22,510	20,259	348,046.18	303,885.00	-44,161.18	0.9	0.17	-7,393.66
60%ETC@L	30,810	27,729	348,916.85	415,935.00	67,018.15	1.2	0.10	6,553.64

UMY = Unadjusted marketable yield, AMY = Adjusted marketable yield, Adjustment coefficient was 10%, TC = Total cost, TR = Total return, NR = net return, B/C = benefit-cost ratio, ILsw = irrigable land with saved water, NRsw = net return from saved water, Field price of water and tomato yield was 1 birr/238 m^3 [8] and 15 birr/kg, respectively.

4. Conclusions and Recommendations

The results show that the highest marketable yield was observed with full irrigation water application at all growth stages and the highest yield reduction was observed with 40% loading treatments in the middle and development stages. Applying deficit irrigation at 80% ETc during the late season saves 4.5% of water without significant yield loss by improving water productivity. This saved water irrigates additional land to generate more profit. On the other hand, the use of deficit irrigation during the development and middle stages results in potential yield losses.

The crop yield response factor values indicate that tomatoes are more sensitive to water stress at the initial and developmental stages. Therefore, the results of this study suggest that applying 80% of ETc deficit irrigation in the late season is the best solution for water conservation without affecting tomato yield while improving water productivity under water-stressed conditions.

Abbreviations

CWP	Crop Water Productivity
ECe	Electrical Conductivity
ETc	Crop Evapotranspiration
ETo	Reference Culture Evapotranspiration
FAO	Foods And Agricultural Organization
FC	Field Capacity
IR	Irrigation Requirement
IR_g	Gross Irrigation Requirement
Kc	Crop Coefficient
OC	Organic Carbon
Pb	Soil Bulk Density
PWP	Permanent Wilting Point
RAW	Readily Available Soil Water
RCBD	Randomized Complete Block Design
RDI	Reduced Deficit Irrigation
TAW	Total Available Soil Water
WP	Water Productivity

Acknowledgments

We would like to thank the Oromia Agricultural Research Institute for providing the necessary budget to experiment. In addition, I would like to thank the researchers and technical support of the Irrigation, Drainage, and Water Utilization Engineering Research Team of Adami Tulu Agricultural Research Center.

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Conflicts of Interest

The authors declare no conflicts of interest.

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