Original Research Article
Effect of Growth Stage-based Water Stress on Yield and Water Use Efficiency of Tomatoes (*Solanum lycopersicon L.*) in Semi-Arid Regions of Tigray, Ethiopia

ABSTRACT

Water availability is a major concern in regions with limited water resources. Implementation~~ing~~ of ~~the~~ best irrigation water management methods can maximize crop yields and irrigation water use efficiency. In order to conserve irrigation water, deficit irrigation measures are prioritized as the main policy. An experiment was carried out in Laelay Koraro district, Tigray, Ethiopia during ~~the off~~ seasons of 2018 and 2019 to study the impact of growth stage-based deficit irrigation on tomato yield, yield characteristics, and water usage efficiency. The experiment used a randomized complete block design (RCBD) with three replications, testing three irrigation levels (100%, 50%, and 25% of crop irrigation requirement) and four FAO-defined tomato growth stages (initial, developmental, mid, and late seasons). Data on agronomic~~y~~ parameters and irrigation water were collected and analyzed statistically. The results revealed that reducing irrigation amount by up to 75% during the development growth stage significantly decreased marketable yield by up to 66.5%. However, the highest water use efficiency (9.2 kg/m^3) was achieved by reducing irrigation amount by 75% during the end-growth stage of tomatoes. Treatments with the lowest water use efficiency (3.5 kg/m^3) were those receiving 75% less irrigation amount than the full requirement during the development growth stage. Reducing irrigation to less than 75% of the full requirement during tomato development stages can greatly impact marketable yield and water use efficiency. Therefore, the tomato crop is highly susceptible to water stress when receiving more than 50% of the full irrigation requirement during its developmental growth stage.

Key words: Growth Stages; Marketable yield; tomato; water use efficiency

1. INTRODUCTION

Sustainable use of water in agriculture is a key issue. Adopting techniques to conserve irrigation water and maintain adequate yields can help renew this ever-limited resource (Nangare et al., 2016, and Kuşçu et al., 2014). In areas with persistent water scarcity and summer drought, maximizing water productivity can be more profitable for farmers than maximizing yield. The latest innovative technology for agricultural water conservation is deficit irrigation (DI). It is a water saving method where plants are exposed to positive levels of water stress during certain growth stages or during the whole growth stage (Pereira, 2017, and Lorite, et al., 2007). The expected yield discounts may be small compared to the benefits of saving water.

The purpose of deficit irrigation is to increase crop water use efficiency (WUE) by reducing the amount of water used (Comas et al., 2017, Kirda, 2002, Igbadun et al., 2008). The deficit irrigation approach involves irrigating the soil with much less water than is needed for transpiration and using an appropriate irrigation schedule, which may generally be derived from subject experiments (Wang, 2017, Uvis and Zhang, 1998, M' Hamed et al., 2015, and Al Barak, 2006). The crop's tolerance to water deficit during the growing season varies according to the phonological stage (Istanbulluoglu et al., 2009). Optimal irrigation schedules are often determined based on water efficiency. Deficit irrigation techniques have the ability to optimize

Commented [Sarwar1]: Too old reference. Replace it with some new ones water efficiency. However, the effect of insufficient irrigation on yield varies among different crops (Costa et al., 2007 and Khapete, 2019). Records of how unique plants cope with mild water stress provide ideas for successful control of irrigation water.

Therefore, the knowledge of plant response to water stress is very important for the knowledge of management change, which is important for irrigation water conservation strategies in water stressed areas. Most of the horticultural production areas are located in hot and dry climates due to favorable climatic conditions. But lack of soil moisture is common in these areas instead. In addition, water-saving irrigation strategies, including deficit-irrigation, may optimize water efficiency in those locations by stabilizing yield and improving crop quality (Costa et al., 2007).

Tomato (*Solanum lycopersicon L*) is one of the widely cultivated vegetable plants in Tigray, Ethiopia. The application of regulated deficit irrigation (DI) techniques to this crop may additionally considerably result in saving irrigation water (Costa et al. 2007). Study's findings confirmed contradictory effects at the adoption of deficit irrigation techniques for tomato plants. Some researchers stated that the application of deficit irrigation for the complete or partial developing season of tomatoes minimizes fruit losses and maintains excessive fruit count (Giuliani et al., 2017, Patanè & Cosentino, 2010). But, Pulupol et al. (1996) found a giant reduction in dry mass yield for a greenhouse tomato cultivar using deficit irrigation. On the other hand, Zegbe et al. (2006) did not find a reduction within the tomato fruit yield of greenhouse-grown processing cultivars. Despite the fact that the effects of deficit irrigation (DI) on tomato fruit yield may be unique, many investigators have confirmed that deficit irrigation saves good quantities of irrigation water and increases water use efficiency (WUE). Therefore, the aim of this subject trial was to analyze the effect of growth stage-based regulated deficit irrigation on yield and irrigation water use efficiency in tomato.

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2. MATERIALS AND METHODS

2.1. *Description of the Experimental Site*

The experiment was conducted in the off-seasons of 2018 and 2019 at the Selekleka Research Farm of the Shire-Maitsebri Agricultural Research Center. The experimental site is located in the northern Tigray region of Ethiopia, approximately 38.15 ~~degrees~~degrees' east longitude, 13.5 degrees north latitude and 1307 meters above sea level. The long-term average maximum and minimum temperatures are 42.3 and 13.2 degrees Celsius, respectively. The average annual monthly rainfall in the region is 340.5 mm and is characterized by a monomodal rainy season with a rainy season from June to mid-September. The soils of the site have good drainage, are deep, light brown to dark brown in color, have a loamy and sandy texture, and are cultivated continuously. Field capacity, permanent wilting point and available water storage capacity per meter of soil profile in the root zone are 38.6, 29.8, and 145.28 mm, respectively.

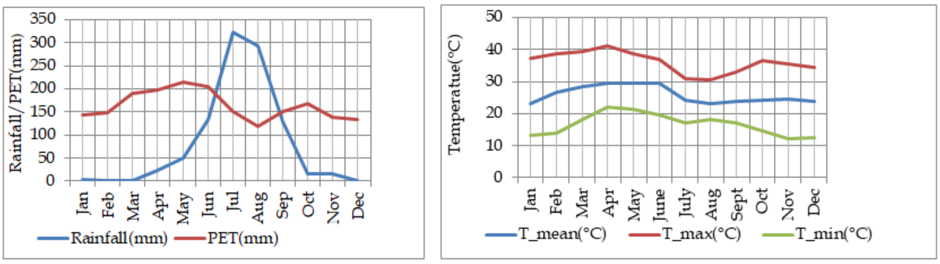

Figure 1. Monthly mean rainfall, Potential Evapotranspiration (PET) and Temperature

2.2. *Experimental Design and Treatment Set up*

Table 1. Treatment set-up

Treatment Code	**Treatment Descriptions**

T1	100% Crop evapotranspiration (ET_c) at all the growth stages
T2	50%ETc at initial stage and full amount at other stages
T3	50%ETc at development stage and full amount at other stages
T4	50% ETc at mid stage and full amount at other stages
T5	50% ETc at maturity stage and full amount at other stages
T6	25%ETc at initial stage and full amount at other stages
T7	25%ETc at development stage and full amount at other stages
T8	25 ETc at mid stage and full amount at other stages
T9	25%ETc at maturity stage and full amount at other stages

[1]

The experiment employed randomized complete block design (RCBD) with three replicates. The two factors were FAO-defined tomato growing stages and irrigation application rates. Table 1 shows the treatments, which included three irrigation levels (100%, 50%, and 25% of crop evapotranspiration, ETc) and four FAO-based tomato growth phases (initial, developmental, mid, and late/maturity). Each experimental plot was 9.6 m^2 and consisted of 5 furrows measuring 80 cm wide and 3 m long. The specified spacing of 30 cm between plants was followed. The distance between blocks and experimental plots was 2 and 1.5 meters, respectively. Irrigation water was given to each plot via a calibrated 2-inch partial flume based on the treatments. Each experimental treatment received an equal amount of the required fertilizer. The whole dose of DAP was applied at transplanting, whereas urea was applied in two parts, half during planting and the rest just 30 days after transplanting, depending on the size of the plots. All additional cultural techniques were applied uniformly to all plots in accordance with the crop's standard recommendations.

Full irrigation (100% ETc) denotes the amount of irrigation water applied as estimated by the Penman Monteith method with the CROPWAT computer program, whereas 50% ETc and 25% ETc irrigation levels meant water stressing the test crop by 50% and 75% of the full amount required by the crop at some growth stage, respectively.

2.3. ***Test crop Characterization***

The experimental crop for this study was an improved tomato variety (Melkasalsa-Variety) which was cultivated in the study area for 120-125 days after transplanting. Based on FOA references (Allen et al., 1998 and Smith, 2000) and previous research findings in our research center from many field trials, the initial growth stage was set to 24 days from the transplanting date, 36 days from the end of the initial stage as the development stage, 40 days from the end of the development stage as the mid-stage of growth, and 24 days from the end of the mid-stage as the late-season stage of growth. The crop was sown during the off-seasons of December 9, 2018 and December 12, 2019. Tomato seedlings were transplanted into a plot size 3 meters by 3.2 meters. The plots within a block were spaced 1.5 m apart, and the blocks were separated by 2 m. According to the FAO irrigation and drainage report (Allen et al. 1998), a maximum root depth of 100cm, a crop coefficient of 1.15, and a permitted depletion level value of 0.35 were used to calculate water requirements and schedule irrigation.

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[1] Full irrigation requirement (100% ETc) denotes the amount of irrigation water equaling 1.0 times the crop water requirement (ETc) whereas 50% ETc and 25% ETc means applying irrigation water 0.5 and 0.25 times of the full crop water requirement (ETc) respectively.

2.4. ***Crop Water Requirement***

In this study, the estimation of water requirements and irrigation scheduling has been based on the climatic, crop, and soil conditions of the experimental site. The FAO Penman-Monteith method (Allen et al., 1998) was used to define reference evapotranspiration and irrigation requirements with the help of a computer program called “CROPWAT version 8.0".

2.5. ***Data Collection***

2.5.1. *Climatic Data*

Before the start of the experiment, secondary data such as climatic data from 20 years on rainfall (R.F.), min and max temperature, relative humidity (RH), wind speed (WS), and sunshine hours (SH) were collected from the nearby meteorological station. Irrigation efficiency for furrow irrigation, root depth of the tomato crop, tomato crop growth stages and their respective lengths of period, and soil infiltration rate data were also collected from previous records and FAO guidelines.

2.5.2. *Soil Data*

Soil sampling was carried out at the experimental site to measure soil physical properties. Soil texture was determined using the pipette method (Kroetsch & Wang, 2008, Huluka & Miller, 2014) at 0–25, 25–50, 50–75, and 75–100 cm depths for each of the three soil profiles. Bulk density was determined by the core method (Blake and Hartage, 1986) for each depth in the three profiles. Soil water content was determined from soil samples taken at the same locations using the gravimetric method. Field capacity and permanent wilting points were considered at 0.3 and 15.0 bars, respectively (Klute, 1986). The soil basic infiltration rate was determined in the field using the double-ring infiltrometer method at two separate sites in the experimental area, as described by Bouwer (1986) **(**Table 2**).**

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Table 2. Soil physical properties of the experimental site

Soil properties	**Soil depth (cm)**				
	0-25	**25-50**	**50-75**	**75-100**	**Average**
Particle size distribution					
- Sand (%)	60	56	54	56	56.5
- Clay (%)	16	18	18	18	17.5
-Silt (%)	24	26	28	26	26
-Textural Class	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Bulk density (g/cm^3)	1.38	1.34	1.33	1.31	1.34
Field capacity (weight basis %)	30.3	37.8	38.9	38.6	36.4
Permanent wilting point (weight basis %)	24.8	22.2	25.3	29.8	25.53
Total available water (mm/m)					145.28

2.5.3. *Yield and Yield Components*

Yield data were collected from three central furrows in a tomato planting plot. The number of fruits per plant and cluster number were determined using five plant samples from the three central rows. Yield and other yield component parameters were collected, and the analysis was performed with Gen-Stat software.

2.5.4. *Water-Use Efficiency (WUE)*

The phrase water use efficiency refers to the link between growths, especially dry matter output and water use (Oweis and Zhang, 1998). Water use efficiency (WUE) is defined as the yield per unit of water consumed by the plant. The total seasonal amount of water consumed by the crop per treatment was recorded, and crop water use efficiency (kg/m3) for each treatment was computed by dividing marketable fruit output (kg) by total seasonal irrigation water consumption (m^3).

2.6 *Data Analysis*

An analysis of variance was performed following the standard procedures as explained in (Gomez & Gomez, 1986 and Clewer & Scarisbrick, 2013) using Gen Stat statistical software. Treatments showing significant differences were subjected to Duncan's multiple range test (DMRT) for mean separation at a 95% confidence level**.**

3. Results and Discussion

3.1. *Water consumption and Irrigation Demand*

A tomato-improved variety (Melkashola variety) was planted on December 9/2020 and December 12, 2021, off-seasons. Total precipitation during the months of December to May in both years was insignificant. As a result, throughout the growing period of the test crop, the only source of water was irrigation. The irrigation frequency was scheduled at four days for the initial and development growth stages and five and six days for the mid- and late-maturity growth stages, respectively. Totally, 27 irrigation events were made during the crop-growing period (124 days). The amount of net applied irrigation water according to treatments is presented in Table 3**.**

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Table 3. Total seasonal net irrigation depth applied to treatments

Treatment combination	**Net_depth_of irrigation (mm)**	**Water saving (m^3/ha)**
100% Crop ~~evapotranspitation~~evapotranspiration (ET_c) at all the growth stages (T1)	678.1	-
50%ETc at initial stage and full amount at other stages (T2)	644.8	333.4
50%ETc at development stage and full amount at other stages (T3)	601.0	770.9
50% ETc at mid stage and full amount at other stages (T4)	536.4	1416.7
50% ETc at maturity stage and full amount at other stages (T5)	592.7	854.2
25%ETc at initial stage and full amount at other stages (T6)	628.1	500.0
25%ETc at development stage and full amount at other stages (T7)	561.4	1166.7
25 %ETc at mid stage and full amount at other stages (T8)	464.5	2135.5
25%ETc at maturity stage and full amount at other stages (T9)	550.0	1281.3

Based on the CROPWAT 8 model output, the whole seasonal irrigation need in the area for tomato was found to be 678.13 mm (6781.3 m^3/ha) for the non-stressed condition, as shown in Table 3. Tomatoes require between 400 to 700 mm of seasonal crop water for optimum yields, depending on climate (Critchley and Siegert, 1991). Table 3 shows the amount of water applied to water-stressed treatments and the water-savings as compared to the indicator treatment (100% crop evapotranspiration at all growth stages). The amount of water applied to non-stressed irrigation treatments (100% crop evapotranspiration at all growth stages) was agreed upon within the range of water requirements stated above.

3.2. Yield and Yield Parameters

3.2.1. Fruit Length (FL) and Fruit Circumference (FC)

Combined statistical analysis over two years showed that changes in irrigation levels had a significant effect on the length and circumference of tomato plants ($P<0.01$). However, as shown in Table 4, there were no significant effects among treatments in terms of days to 50% flowering, days to 50% fruiting, or number of fruits per plant. Rosadi et al. (2005) showed that minor changes in water deficit levels do not affect plant growth indices. In this experiment, we found a strong relationship between yield traits (fruit length, fruit girth and market yield) and water use efficiency (Table 4).

Table 4. Analysis of variance on important agronomic parameters of Tomato (2020/2021)

Source of Variation	**50%DFl (days)**	**50%DFS (days)**	**FNPP (No.)**	**FL (cm)**	**FC (cm)**	**Myld (kg)**	**UnMyld (kg)**	**WUE (kg/m^3)**
Treatments	NS	NS	NS	***	**	*	***	***

NS=Not significant; *, **, *** indicates significant at 0.05, <0.01 and <0.001levels respectively; DFl, Days to flowering, DFS, Days to fruit setting, FL, Fruit length, FC, Fruit circumference, FNPP, fruit number per plant, Myld, Marketable yield, UnMyld, Unmarketable yield, WUE, Water use Efficiency

Treatments that irrigated with full amounts of irrigation water at all growth stages produced the longest fruit (7.47 cm) and largest fruit circumference (12.12 cm). The treatments that applied 25% of the full crop water demand/irrigation requirement at the development growth stage produced the shortest fruit length (3.48 cm) and fruit circumference (6.42 cm) (Table 5).

Table 5. Statistical comparison of the mean values of relevant parameters of Tomato (2020/2021)

Trts	50%DFl (days)	50%DFS (days)	FNPP	FL (cm)	FC (cm)	Myld (Q/ha)	UnMyld (Q/ha)	WUE (kg/m^3)
T1	57.83^{a}	67.83^{a}	14.21^{a}	7.47^{a}	12.12^{a}	431.9^{a}	44.10^{a}	6.9^{a}
T2	54.83^{a}	67.17^{a}	15.42^{a}	5.61^{bcd}	10.59^{ab}	413.9^{a}	17.31^{a}	7.6^{a}
T3	57.17^{a}	68.00^{a}	14.10^{a}	4.65^{d}	8.48^{c}	394.1^{a}	16.53^{a}	7.8^{a}
T4	57.17^{a}	67.50^{a}	16.93^{a}	6.75^{ab}	11.53^{a}	419.1^{a}	18.0^{a}	9.01^{a}
T5	57.50^{a}	69.17^{a}	15.94^{a}	5.86^{bcd}	11.27^{a}	386.4^{a}	18.53^{a}	7.7^{a}
T6	59.17^{a}	65.60^{a}	14.01^{a}	6.07^{bc}	10.77^{ab}	386.1^{a}	14.48^{a}	7.3^{a}
T7	55.00^{a}	68.17^{a}	12.86^{a}	3.48^{e}	6.42^{d}	144.3^{b}	101.88^{b}	3.5^{b}
T8	56.17^{a}	67.33^{a}	13.82^{a}	5.09^{cd}	9.04^{bc}	365.2^{a}	17.92^{a}	9.1^{a}
T9	54.83^{a}	68.00^{a}	16.86^{a}	5.88^{bcd}	11.79^{a}	427.3^{a}	25.52^{a}	9.2^{a}
Mean	56.63	67.85	14.91	5.65	10.22	382.7	21.0	7.56
LSD	ns	ns	ns	1.136	1.756	142	32.11	3.82
C.V	6.3	4.6	39.2	17.1	14.6	32.7	30.50	30

Columns assigned with the same letter have not significant difference. Trts, Treatments, DFl, Days to flowering, DFS, Days to fruit setting, FL, Fruit length, FC, Fruit circumference, FNPP, Fruit number per plant, Myld, Marketable yield, UnMyld, Unmarketable yield, WUE, Water use Efficiency, LSD,least significance difference,C.V, Coefficient of variance

3.2.2. Marketable and Unmarketable Yields

Table 4 shows that different levels of irrigation in different stages of crop growth had a significant effect on salable tomato yield ($P<0.5$). Non-marketable yield was also significantly affected ($P<0.001$). As a result, the lowest marketable yield (1443 kg/ha) and the highest non-marketable yield (10188 kg/ha) were obtained in the treatment that was irrigated with 75% water less than the full irrigation requirement of the crop during the developmental growth ~~stage(~~stage (Table 5). Reducing the amount of full irrigation water required by 75% during the developmental growth stage reduces yield by 66.5% compared to full irrigation treatments in all growth stages. As shown in Table 5, there is no statistically significant difference between the irrigated treatments at different levels of irrigation volume at different stages of growth, except for the reduction of up to 75% of water volume during development growth stages. The main findings are that the reduction of irrigation water up to 75% of the total irrigation requirement during the development phase leads to a significant yield reduction (66.5~~%)~~%) and high unmarketable yield. In contrast, we found that a 75% reduction in irrigation water at growth stages other than vegetative growth did not result in significant yield losses (Table 5).

3.3. Irrigation Water Savings

3.3.1. Water Use Efficiency (WUE)

Table 4 shows that the application of varied irrigation volumes at different growth stages resulted in a very significant difference at a 0.01 significance level. The highest and lowest water usage efficiency values were 9.2 kg/m^3 and 3.5 kg/m^3 obtained from plots that were irrigated with 25% ETc at maturity and development growth stages, with the full amount at all other stages, respectively.

4. Conclusions

Rainfall depth in the research area is low, and its distribution is uneven and inconsistent, making it difficult to achieve the daily crop evapotranspiration demand. Under these circumstances, the need to use available water efficiently is undeniable. This study focuses on comparing irrigation management options that can help save water and boost water use efficiency with no or minimal production loss in northern Ethiopia's semi-arid climate, notably in the study area-Tselemty district, Tigray

Results confirmed that different irrigation treatments significantly influenced tomato yield, water use efficiency, and other parameters. The highest marketable yield obtained from applying a full amount of irrigation at all growth stages of tomato has no significant difference compared to applying less water at different growth stages except at the development stage. In this study, we have found that the developmental growth stage of tomatoes is the most sensitive growth stage to water stress. Reducing the amount of irrigation water required up to 75% of the full amount at this growth stage can adversely affect marketable yields (by 66.5%) and water use efficiency. In terms of marketable yield and water use efficiency, we have not seen a significant difference among treatments except for the 25% irrigation amount applied at the development growth stages of the crop. Therefore, the results of this study verified that we can reduce the amount of irrigation water up to 75% of the full amount required at any growth stage, except the developmental growth stage, to save a substantial amount of water in the case of limited water availability conditions.

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