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Water usage and water use efficiency of drip-irrigated tomato under deficit irrigation

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Abstract

Efficient irrigation is essential for sustainable use of available water resources. A field experiment was conducted on two tomato cultivars (Melka Shola and Melkassa Marglobe) and four irrigation deficit levels (0%ET_c, 25%ET_c, 50%ET_c, and 75%ET_c). The objective was to determine crop factor (K_{cf}) and water use efficiency (*WUE*). The K_{cf} values of 0.62, 0.65, 0.70, and 0.71 during the respective four growth stages of the crop were determined. The highest (91.23 kg ha^{-1} mm^{-1}) and lowest (81.62 kg ha^{-1} mm^{-1}) water use efficiencies were recorded in 25 and 0% deficit levels, respectively. The yield and WUE of Melka Shola cultivar was higher than that of Melkassa Marglobe. Generally, it was found that irrigating the tomato crop with 75% of ET_c (*i.e.* 25%ET_c deficit) is the best irrigation practice in the area. In terms of both yield and WUE, Melka Shola tomato cultivar was found to perform better than Melkassa Marglobe.

Key words: Crop factor, drip irrigation, Ethiopia, tomato, water use efficiency.

Introduction

Irrigation is one of the most important inputs for agricultural production. However, limited water resources and increasing water demands for other uses are causing a decrease in the quantity of water available for agriculture. The use of water saving technologies such as drip irrigation is therefore essential. The possibility of applying water at a very low rates offers the drip irrigation system the means to deliver water to the soil in small and frequent quantities at a relatively low cost compared to other pressurized systems (Cetin *et al.*, 2002).

Irrigation scheduling can be established by using several approaches such as soil water balance estimates, plant stress indicator and pan evaporation. Irrigation scheduling with pan evaporation is one of the irrigation scheduling methods that has been used widely because of its simplicity and low cost (FAO, 1995). It can also be operated by farmers. Changes in weather conditions that cause variation in pan evaporation will have a similar, but not identical, impact on potential evapotranspiration from a (reference) crop. As such, pan evaporation (E_p) measurements can be used to estimate both reference evapotranspiration (ET_o) using a pan factor (K_p) and potential crop evapotranspiration (ET_c) using a crop factor (K_{cf}) (Paul, 2001). The crop factor use depends on the growth stage of the crop and crop type.

The upper limit for yield is set by soil fertility, climatic conditions and management practices. Where all of these are optimal throughout the growing season, yield reaches the maximum value as does evapotranspiration. Any significant decrease in soil water storage from field capacity water content has an impact on water availability to crops, and subsequently, on evapotranspiration and yield (Vaux and Pruitt, 1983). In order to increase the productivity of irrigation water, there is a growing interest in *deficit irrigation*, an irrigation practice where water supply is reduced below maximum level and mild stress is allowed with minimal effects on yield. Under conditions of scarce water supply and drought, deficit irrigation can lead to greater economic gains by maximizing yield per unit of water for a given crop.

In order to supplement the income and nutritional intake of Ethiopian farmers who live on very fragmented land holdings of less than a hectare, currently there is a great interest in rain water harvesting for family-level vegetable production. In an effort to use the harvested rain water efficiently, gravity drip irrigation system is also being made available to the farmers on credit basis. However, there is no documented study on this irrigation package which can help prepare guideline to be used by the farmers. The objectives of this study were to determine (i) crop factor using pan evaporation, and (ii) water use efficiency of drip-irrigated tomato using deficit irrigation at Awash Melkassa, Ethiopia.

Materials and methods

Site description: The study was conducted at Melkassa Agricultural Research Center in the Central Rift Valley of Ethiopia. It is located at 8°24´ N latitude and 39°21´ E longitude and has an elevation of 1552 m above mean sea level. The mean annual rainfall is 950 mm. The mean maximum and minimum temperature is 28 and 14°C, respectively. The soil of the experimental site is loam (sand 37%, silt 42%, and clay 21%). The field capacity and permanent wilting point of the soil is 38% and 22%, respectively.

Field experiment: Runoff water was harvested in a dome-shaped under-ground water storage structure. It was then pumped using a treadle pump into an elevated tanker 1.5 m above ground. Treadle pump is a simple, low cost, foot-operated water lifting device. Low head or gravity type drip irrigation set was used for the experiment. In addition to the pump and elevated water tanker, the system has a main line, filter, submains, manifiolds, and laterals. Each submain has a length of 3 m and supplies water to four drip laterals spaced 0.80 m apart.

The experimental treatments were factorial, consisting of two tomato cultivars (Melka Shola and Melkassa Marglobe) and four irrigation water deficit levels: 0 (optimal), 25, 50, and 75% (most stressed) expressed as percentage reductions from the potential crop water requirement ET_c. The treatments were conducted under three replications. The selected cultivars are known for their higher yield and disease resistance. The plants were transplanted in plots of 3 x 5 m at 0.30 m plant spacing and 0.80 m row spacing. Each treatment plot consisted of four rows of tomato with total number of 68 plants per plot. Irrigation water was applied equally for all experimental plots for the duration of plant establishment after transplanting *i.e.* for 10 days. There after, the plots were irrigated with drippers according to their respective treatment levels. Irrigation was carried out with drip emitters of an average flow rate 350 mL hr^{-1} at 1.5 m operating head.

Fertilizer was applied as per agronomists' recommendation as: DAP was side dressed at a rate of 200 kg ha^{-1} at transplanting and 100 kg ha^{-1} urea was applied in split at transplanting and 45 days after transplanting. To protect disease infection, Ridomil Gold RZ 63% was applied as 3.5 kg ha^{-1}. For insect protection Cypermethin or Karate was used at a rate of 100 g ha^{-1}.

Dripper characterization: Dripper emission uniformity (EU) was calculated as follows

$$EU = \left(\frac{q_n}{q_a}\right)100 \qquad (1)$$

where EU = emission uniformity (%), q_n = average low quarter emitter flow rate (L h^{-1}), q_a = average emitter flow rate (L h^{-1}).

The application efficiency of the drippers was calculated as (Vermeiren, 1998)

$$E_a = K_s * EU \qquad (2)$$

where, K_s is a coefficient which expresses the storage efficiency of the soil as (average water stored in the root volume/average water applied). It takes into account the losses of drip irrigation water application (K_s = 1 or 100% for loam soil) (Vermeiren, 1998).

Crop water requirement and irrigation requirement: Pan evaporation E_p was measured using pan evaporimeter installed just by the side of the experimental plots. Reference crop evapotranspiration ET_o was determined using FAO Penman Monteith equation (Allen *et al.*, 1998) as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} U_2(e_a - e_d)}{[\Delta + \gamma(1 + 0.34U_2)]} \qquad (3)$$

Where, ET_o = reference crop evapotranspiration (mm day^{-1}),
R_n = net radiation at crop surface (MJ m^{-2} day^{-1}),
G = soil heat flux (MJ m^{-2} day^{-1}),
T = average temperature (^{o}C),
U_2 = wind speed measured at 2m height (m/s),
e_a-e_d = vapor pressure deficit (kpa),
Δ = Slope vapor pressure curve (kpa $^{o}C^{-1}$),
γ = Psychometric constant (kpa $^{o}C^{-1}$),
900 = conversion factor. Daily weather data used in Eq. (3) was obtained from Melkassa Agricultural Research Centre weather station.

Pan factor K_p was determined from E_p and ET_o using Eq. (4). Tomato crop coefficients available in literature (Allen *et al.*, 1998) were used to determine potential crop water requirement ET_c from ET_o (Eq. 5). Crop factor K_{cf} was determined from E_p and ET_c using Eq. (7).

$$ET_o = E_p \text{ x } K_p \qquad (4)$$

$$ET_c = ET_o \text{ x } K_c \qquad (5)$$

$$ET_c = E_p \text{ x } K_p \text{ x } K_c \qquad (6)$$

$$ET_c = E_p \text{ x } K_{cf} \qquad (7)$$

Crop water requirements determined by conventional methods should be corrected by a reduction factor K_r for drip irrigation. K_r = G_c/0.85 or 1.0, whichever is the smallest where G_c is percentage ground cover (Vermeiren, 1998). Net irrigation water requirement (IR_n) was calculated as

$$IR_n = ET_c * K_r - R \qquad (8)$$

where R is rainfall during the growing period. Gross irrigation water requirement (IR_g) can be calculated as

$$IR_g = \frac{ET_c * K_r}{E_a} - R \qquad (9)$$

$$IR_g = \frac{E_p * K_p * K_c * K_r}{E_a} - R \qquad (10)$$

$$IR_g = \frac{E_p * K_{cf} * K_r * A}{E_a} - R \qquad (11)$$

where E_a = irrigation system application efficiency, A = the wetted area allocated to each plant.

Water use efficiency: Crops' response to deficit irrigation is different due to the difference in their ability to tolerate water stress during their growth period (Vaux and Pruitt, 1983). Crop yield response to water deficit can be described (Doorenbos and Kassam, 1979) as:

$$1 - \frac{Ya}{Ym} = Ky\left[1 - \frac{ETa}{ETm}\right] \qquad (12)$$

where Y_a = actual yield (kg ha^{-1}), Y_m = maximum yield (kg ha^{-1}), ET_a = actual evapotranspiration (mm), ET_m = maximum evapotranspiration (mm) or ET_c, and K_y = yield response factor.

The crop water use efficiency, WUE, can be determined as

$$WUE = \frac{Y_a}{ET_a} = \left[\frac{(K_y - 1)}{\dfrac{ET_a}{ET_m}}\right]\frac{Y_m}{ET_m} \qquad (13)$$

Field data collection: To determine plant growth, water use and water use efficiency, plants were marked at random locations along the entire plots in each replication. Two plants per row were marked, giving a sample size of eight plants per plot for both tomato cultivars. Plant heights were measured every week starting from the beginning of the treatment period to the end of the midseason of growth stage. The two middle rows of each treatment were harvested and weighed at the end of the season.

Results and discussion

Dripper characterization: The emitter flow rate collected from randomly selected drippers was used to calculate the performance of the irrigation system. The average low quarter flow rate (9 out of 36 sample flow rates collected in this study) was 311 mL h^{-1} and the average flow rate was 329 mL h^{-1}. The emission uniformity EU was calculated to be 95% (Eq. 1). For the loam soil with K_s = 1, the application efficiency was found to be 95% (Eq. 2).

Crop water use: The crop water requirement and irrigation requirement for the tomato crop during the growing season determined on two-day basis is presented in Table 1a-d for the months of October, November, December and January. Eqs. 3, 4, 5, 7 and 8 were used to calculate ET_o, K_p, ET_c, K_{cf}, and IR_n. The crop coefficient K_c values were interpolated for the growing stages of the tomato crop from Doorenbos and Pruitt (1977). During the crop establishment period (until 28 October), equal amount of water (67 mm) was applied to all the treatment plots. The total amount of water applied to the non-stressed (0% deficit) treatment is 528 mm (Table 1a-d) + 67 mm = 595 mm. The amount of water applied to the 25, 50, and 75% deficit levels is 467 mm, 331 mm, and 199 mm, respectively.

The pan factor K_p and tomato crop factors K_{cf} determined for the growth stages and the total growing season are presented in Table 2. The K_{cf} values are of great importance for farmers interested to optimally schedule the limited harvested water using pan evaporation data. The K_{cf} value varies during the growing season with the average seasonal value indicating that about 70% of pan evaporation can be considered as potential crop evapotranspiration.

The water use efficiency of the experiment was significantly

Table 1. Two-day average tomato water requirement at Melkassa Agricultural Research Center

a. October (mm day^{-1})**

Date	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	31
ET_o									6.00	5.59	6.56	6.40	6.49	6.73	6.33	6.43
E_p									8.95	7.85	9.18	9.68	9.87	10.98	8.60	8.84
K_p									0.67	0.71	0.71	0.66	0.67	0.62	0.74	0.73
K_c									0.75	0.79	0.81	0.83	0.85	0.87	0.89	0.91
ET_c									0.50	0.56	0.58	0.55	0.57	0.54	0.65	0.66
K_{cf}									4.47	4.40	5.32	5.42	5.60	5.93	5.59	5.83
R									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IRn									4.82	4.75	5.75	5.85	6.05	6.40	6.03*	6.30

* The day on which irrigation treatments started and total amount of water applied upto this day was 67.12 mm.

b. November (mm day^{-1})

Date	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	31
ET_o	5.59	6.61	6.40	6.44	6.44	6.36	5.57	4.00	4.53	4.55	5.07	6.57	7.14	5.62	5.94	
E_p	8.48	10.17	9.77	9.72	9.30	9.51	7.75	6.16	5.22	7.79	7.28	10.40	10.01	9.02	8.65	
K_p	0.66	0.65	0.65	0.66	0.69	0.67	0.72	0.65	0.87	0.58	0.70	0.63	0.71	0.62	0.69	
K_c	0.93	0.95	0.97	0.99	1.01	1.03	1.05	1.07	1.09	1.11	1.13	1.15	1.15	1.15	1.15	
ET_c	0.61	0.62	0.64	0.66	0.70	0.70	0.76	0.68	0.95	0.65	0.79	0.73	0.82	0.72	0.90	
K_{cf}	5.17	6.30	5.95	6.54	6.51	6.66	5.89	4.19	4.96	5.06	5.75	7.59	8.20	6.49	7.79	
R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.60	4.80	0.00	0.00	0.00	0.00	0.00	
IRn	5.58	6.80	6.43	7.07	7.03	7.19	6.36	4.53	5.35	5.47	6.21	8.20	8.86	7.01	8.40	

c. December (mm day^{-1})

Date	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	31
ET_o	5.62	5.16	5.41	5.77	5.58	6.17	5.57	5.48	5.20	5.95	5.34	4.86	5.73	5.92	4.94	5.43
E_p	8.74	8.97	8.10	8.86	8.13	9.56	8.66	7.97	9.07	8.13	7.81	7.87	8.25	9.24	7.02	8.08
K_p	0.65	0.58	0.67	0.65	0.69	0.64	0.64	0.69	0.57	0.73	0.68	0.62	0.70	0.64	0.70	0.67
K_c	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
ET_c	0.74	0.66	0.77	0.75	0.79	0.73	0.74	0.79	0.66	0.84	0.79	0.71	0.80	0.74	0.81	0.77
K_{cf}	6.47	5.92	6.24	6.65	6.42	6.98	6.37	6.29	5.98	6.84	6.17	5.59	6.60	6.84	5.69	6.22
R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IRn	6.98	6.39	6.74	7.18	6.94	7.54	6.55	6.80	6.46	7.39	6.66	6.03	7.13	7.38	6.14	6.72

d. January (mm day^{-1})

Date	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	31
ET_o	5.79	6.09	6.56	5.12	5.59	5.53	6.30	6.60	6.16							
E_p	8.78	8.14	7.94	7.64	8.13	8.27	8.55	7.91	8.43							
K_p	0.66	0.75	0.70	0.67	0.69	0.67	0.74	0.83	0.73							
K_c	1.15	1.06	1.06	1.02	0.98	0.93	0.89	0.84	0.80							
ET_c	0.76	0.79	0.74	0.68	0.67	0.62	0.65	0.70	0.58							
K_{cf}	6.67	6.46	5.88	5.22	5.45	5.12	5.56	5.54	4.89							
R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
IRn	7.29	6.97	6.35	5.64	5.88	5.53	6.00	5.98	5.28							

** The values given in this table are average of two consecutive days expressed as mm day^{-1} for concise presentation of the data.

Table 2. Average values of the crop water use and crop factor parameters during the growth stages of tomato

Parameter	Crop growth stages			
	Development	Mid season	Late season	Total growing season
ET_o (mm day^{-1})	6.12	5.56	6.30	5.99
E_p (mm day^{-1})	9.05	8.44	8.18	8.57
K_p (mm day^{-1})	0.68	0.66	0.77	0.69
ET_c (mm day^{-1})	5.60	5.50	5.73	5.61
K_{cf}	0.62	0.65	0.70	0.71

different ($P<0.05$) for tomato cultivars (Table 4). The WUE of 25% ET_c deficit was significantly different from the others (Table 3). In both cases, the value was lower for irrigation treatment with high amount of water application. The 25% deficit level has got higher water use efficiency which was 1.12 times that of fully irrigated (0% deficit level) and the 75% deficit follows it with relative water use efficiency value of 1.06 times that of fully irrigated tomato (Table 4).

Table 3. Influence of moisture deficit levels on yield, water use efficiency of tomato

Parameter	Deficit level (%)			
	0	25	50	75
Total yield (t ha^{-1})	45.113^{a}	41.555^{a}	24.685^{b}	15.757^{c}
WUE (kg ha^{-1} mm^{-1})	81.62^{a}	91.23^{b}	82.96^{a}	86.11^{a}
Relative WUE		1.12	1.02	1.06
K_y		0.80^{b}	1.07^{a}	1.08^{a}

Table 4. Yield, water use efficiency and yield response factor of two cultivars of tomato

Characters	Tomato cultivars	
	Melka Shola	Melkassa Marglobe
Total yield (t ha^{-1})	32.688^{a}	30.868^{a}
WUE (kg ha^{-1} mm^{-1})	91.67^{a}	79.04^{b}
K_y	0.69^{a}	0.78^{a}

* Means within each row followed by the same letter are not statistically significant at the 1% level according to Duncan's multiple range test.

As crop yield response factor (K_y) increases, the crop water use efficiency decreases, which in turn implies that benefit from deficit irrigation is unlikely. Only those crops and growth stages with a lower crop yield response factor ($K_y < 1$) can generate significant savings in irrigation water through deficit irrigation. Seasonal K_y value for tomato is 1.05 (Doorenbos and Kassam, 1979) which is close to the K_y value of the 50% depletion level in this study.

From Table 5, it can be seen that the height of tomato was influenced by water deficit level with a general decrease in crop height as water stress increases.

Table 5. Average plant growth performance (mm) for deficit irrigated tomato cultivars

Character	Deficit level (%)			
	0	25	50	75
Melka Shola	358	380	357	314
Melkassa Marglobe	468	453	368	297

Pan evaporation data can be used to calculate potential crop evapotranspiration once crop factor is determined. In this study, crop factor values of 0.62, 0.65, 0.70 and 0.71, respectively were determined for crop development, midseason, late season, and total growing season of tomato. As the water stress level increases, the yield of tomato decreases. The 25%ET_c deficit level resulted in the highest water use efficiency. Melka Shola cultivar has higher yield and water use efficiency compared to Melkassa Marglobe cultivar. Besides being less water stress resistant, Melkassa Marglobe was easily susceptible to leaf diseases and bacterial wilting during the early growth stages. Yield response factor of Melka Shola is lower than that of Melkassa Marglobe. In the scenario of water shortage, the use of 25%ET_c deficit and Melka Shola cultivar can result in higher water use efficiency.

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